University of British Columbia

Seismic Resilience Study

Seismic Risk Assessment and Recommended Resilience Strategy

Issue 2 | Aug 11, 2017

This report takes into account the particular instructions and requirements of our client.

It is not intended for and should not be relied upon by any third party and no responsibility is undertaken to any third party.

Job number 248914

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Executive summary

Background

In the early 1990s, the University of British Columbia, Vancouver (UBC) commissioned a study to assess the seismic vulnerability of its building stock on the Point Grey campus. Since the original study, the known seismic hazard demands in Vancouver have increased significantly due to new scientific developments and discovery of active faults in the Pacific Northwest (including the Cascadia Subduction Zone). In addition, a number of global earthquakes have revealed previously unknown building deficiencies that lead to poor seismic performance. This additional knowledge has been incorporated into improved structural and seismic design provisions in today's building codes. Since most of the buildings on campus were not designed to the latest code, a greater proportion of the university's existing building stock than previously identified may have unacceptable performance in a large earthquake.

Purpose

The purpose of this study is to:

- Refresh the previous assessments based on new methods and knowledge.
- Quantify the risks to people, assets, and core functions on campus under various earthquake scenarios in explicit terms.
- Identify critical vulnerabilities in buildings, utilities, and operations and propose initial financial strategies for cost-effective mitigation.

This study employs a state-of-the-art approach to virtually simulate earthquake damage and consequences to buildings and utilities. A holistic resilience-based approach was used to develop mitigation strategies, integrating physical intervention, business continuity planning, and cost-benefit analysis. The earthquake intensity levels considered, based upon the current state of seismic hazard knowledge, are tabulated below:

Intensity Level of Earthquake	Return Period (years)
Frequent	43
Probable	200
Rare	475
Very Rare	2,475

Key findings

The key risks identified in this study are as follows:

- **Building collapse vulnerability:** approximately 25% of the buildings on campus have significantly greater (2x or more) risk of structural collapse relative to modern code benchmarks (which are defined at the Very Rare level of shaking). These are denoted as Tier III and IV buildings in the summary table below. We anticipate that approximately 30 buildings may collapse at Very Rare (2475 year) level of shaking, and a handful may collapse in Rare shaking. In comparison, previous assessments (GS/JM 2012) identified roughly 30 buildings that are "likely to have full or partial collapse during a *moderate* seismic event or higher". Our assessment indicates a significantly less dire view of the collapse vulnerability on campus. The evaluation approach is described in Section 5 and a list of buildings and their corresponding designations is provided in Appendix H.

Structural Vulnerability Tiers	Probability of Collapse in Very Rare Earthquake Shaking	Number of buildings
I	0% to 10%	165
II	11% to 19%	79
III	20% to 49%	55
IV	50% to 100%	29
	TOTAL	328

- **Life safety risks:** we anticipate that approximately 30 buildings may collapse at Very Rare level of shaking, and a few may collapse in Rare shaking. The table below shows our best estimates (median) and probable maximum (90%-tile) estimates for the total number of injuries and fatalities caused by building damage across campus — the range reflects the significant uncertainty in such predictions. The predicted number of injuries and fatalities for each building under each earthquake intensity level is provided as an electronic addendum (see Appendix H). Some non-structural components also pose a life safety risk (see Section 5.4.2). A list of buildings with these features is provided in Appendix H.

Earthquake Intensity Level	Estimated Injuries		Estimated Fatalities	
	Best Estimate	Probable Maximum	Best Estimate	Probable Maximum
Frequent	58	61	0	0
Probable	60	197	0	34
Rare	192	603	33	135
Very Rare	678	4547	153	1095

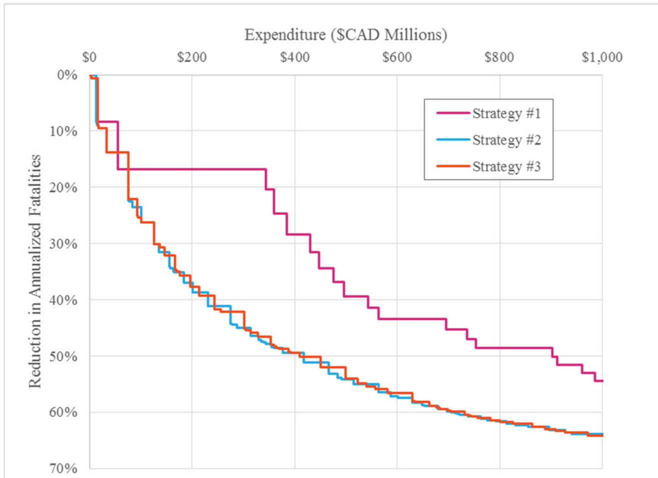
- **Downtime:** while we recognize that life safety concerns from building collapse, in rare earthquakes, is of paramount importance, economic and continuity impacts from moderate shaking are more likely. The table below indicates the proportion of campus space that is anticipated to be functional after various earthquake intensities and the time required to restore functionality to disrupted areas (not including delays to re-opening due to inspection and not including utility disruption). Non-structural component damage is demonstrated to contribute significantly to the downtime (see section 5.5.3). In addition, our assessment indicates that several essential facilities required for emergency response, such as hospitals and designated post-disaster buildings, may not be operational (see section 5.5.2).

Earthquake Intensity Level	% of Total Floor Space Functional Immediately Following Earthquake	Time to Restore 50% of the Total Floor Space to Functionality	Time to Restore 75% of the Total Floor Space to Functionality	Time to Restore 90% of the Total Floor Space to Functionality
Frequent	97%	0 days	0 days	0 days
Probable	35%	3.5 months	5 months	6.5 months
Rare	2%	6.5 months	7.5 months	1 year
Very Rare	<1%	10.5 months	<2 years	4+ years

- **Economic losses**: the direct financial losses to repair damage or replace building components and contents has been estimated. The cultural, research, and academic value of contents is difficult to quantify, but arguably more impactful than the monetary losses. The economic losses caused by "business interruption" were calculated based on loss of revenue from tuition and research grants. These are not tabulated herein but are utilized on an individual building basis to aid in prioritizing retrofit strategies. See section 5.6 for further detail.

Earthquake Intensity Level	Costs to Repair Building Damage		Contents Losses	
	Best Estimate	Probable Maximum Loss (90%-tile)	Best Estimate	Probable Maximum Loss (90%-tile)
Frequent	$70m	$101m	$9m	$44m
Probable	$325m	$543m	$200m	$484m
Rare	$794m	$1.28bn	$621m	$1.22bn
Very Rare	$2.58bn	$4.22bn	$1.91bn	$3.06bn

- **Costs:** cost-benefit analysis has been performed to understand the effectiveness of renewing the most vulnerable buildings to reduce life safety and other risks (including downtime). The graph below provides the renewal costs (construction hard costs) for buildings which were identified as potential candidates for seismic mitigation and the corresponding reduction in fatality risk for three mitigation strategies (see section 5.7 for further detail). This can be used to set overall budgets for upgrades. Further refinement of these budgets will be needed as individual buildings are studied in more detail at later stages.



- **Utilities:** the Energy and Water team appear to be acutely aware of the vulnerabilities to the utility network and have taken actions to begin addressing them. The water supply to campus is at significant risk due to the location of the water pumps within the collapse prone Power House. This will impede the ability to suppress potential fires ignited by the earthquake since there is no backup supply. Access to potable water will also be disrupted — UBC has plans to supply potable water from a creek on campus but there is currently no protocol for widespread distribution. Risks to other utilities are less pronounced but still may be significant. For example, the natural gas system may take weeks to re-pressurize and re-light after shake-actuated shut off valves are triggered by higher intensity shaking. The table below provides a summary of anticipated disruption times for the various utility systems under the different earthquake scenarios. See Section 6 and Appendix L for further details.

Earthquake Intensity Level	Electric Power	Water	Natural Gas	Thermal Energy	Sanitary Sewer
Frequent	6 hours	1 day	12 hours	0 days	0 days
Probable	1 day	61-65 days	2-6 days	0 days	4 days
Rare	2-3 days	65-70 days	7-13 days	0 days	6 days
Very Rare	7-13 days	68-76 days	14-40 days	0 days	8 days

- **Operations:** in general, UBC staff have been proactive in identifying operational risks and are aware of operational vulnerabilities. However, further effort is required to complete, implement, and validate operational preparedness and continuity plans, many of which are in draft. Key findings are presented in Section 7.

We have provided a Glossary of Terms in Appendix A

Limitations

The building risk results from this study are based on a "screening level" assessment, which identifies the highest-risk buildings with a reasonable level of confidence. Screening is inherently conservative so it is likely that the collapse risks (and corresponding budgets to renew collapse-prone buildings) is overstated.

There also remains a risk in screening level assessments that building defects will not be detected until a more detailed study is carried out. While this study has identified the most likely buildings to perform poorly during earthquakes, there remains a small, but not insignificant, chance that some vulnerabilities may have been missed.

In addition, this study does not include non-building structures, including covered walkways and bridges, which may pose a further life safety risk in large earthquakes.

Next steps

This study has identified key vulnerabilities and risks and recommendations for addressing them. The next phase is implementation. This is the key to prepare the university for the next big earthquake. We recommend that UBC undertake the following actions:

- Review the recommended list of actions for buildings, utilities, and operations to reduce the identified risks to the campus (see section 8).
- Develop an implementation plan based on the recommendations and on overall budget and target schedule.
- Initiate the following highest priority actions (further detail is provided in section 8):
    - Agree to the list of candidate buildings (and schedule) for potential renewal or replacement, based on identified prioritization strategies. Further surveys and detailed structural analysis should

be undertaken on each candidate building prior to undertaking renewal or replacement.

- Inventory and retrofit nonstructural elements which pose a life safety risk and develop a guide for protecting contents.
- Accelerate plans to relocate water pumps from Power House and develop backup water supply strategies for suppressing fires following earthquake.
- Develop distribution strategies for backup diesel supply and potable water from creek.
- Expand and accelerate implementation of operational preparedness plans including those that will reduce life safety risks, improve emergency response, shorten recovery, and more effectively manage data.

1 Introduction

It is a cool and clear spring morning in Vancouver. The campus is bustling. Some students are already attending early morning lectures, while others are still in their dorm rooms after a long night of studying. Suddenly the ground starts shaking, at first gently, and then violently, for what seems like an eternity. An earthquake has ruptured the Cascadia Subduction Zone. Scientists had predicted it would come one day — it ruptures every 300 to 500 years based on the historical record, the last time in the year 1700 — but everyone had hoped that it would not happen in their lifetime. Damage to buildings and utilities on campus is significant and widespread. Some older and vulnerable buildings collapsed, causing many injuries and some fatalities. Water is unavailable, making the fires ignited by overturned Bunsen burners in lab spaces difficult to extinguish. A significant proportion of the dorms are too damaged to reoccupy, and the lab and research facilities have suffered significant damage to valuable (and invaluable) contents. Researchers have lost years of investment. With classes suspended due to lack of available useable space, utilities supplying electricity and water disrupted, and aftershocks continuing to shake the campus, students are displaced, returning to their parents' homes in unaffected regions. When all is said and done, it will cost hundreds of millions of dollars to repair the damage and several semesters to restore most of the space on campus for functional purposes. Research grants and tuition dollars will dry up.

This is one version of the future.

There is an alternative version. It was initiated by UBC several months ago and has culminated in the recommended actions in this report. These recommendations represent significant additional monetary investment and commitment on the part of the university over an extended time horizon. Following this strategy would ultimately fulfill the university's seismic resilience mission to do the following:

- Make every effort to protect the lives of students, faculty, and staff
- Reduce the impact of natural hazards on the continuity of teaching and research
- Preserve assets such as buildings and building contents (including research specimens, data, and archives)
- Be a resource for the local community in the aftermath of a natural disaster

Already a world-recognized leader in sustainability, UBC would become one of the most resilient campuses in the world and an example for other organizations to emulate.

2 Scope of work and report outline

UBC contracted Arup to conduct a seismic risk assessment of campus buildings, utilities, and operations and develop a resilience strategy over multiple phases. Arup's assessment aims to refresh and update the previous studies conducted over the past 25 years, in order to do the following:

- Account for the current state of knowledge about the regional seismic hazard, vulnerability, and risk
- Incorporate a holistic resilience-based approach to help achieve the university's mission to protect lives and assets, and preserve critical functions
- Integrate a new risk assessment with cost-benefit analysis to prioritize actions including physical retrofit of individual buildings, nonstructural components, and contents
- Identify gaps and key vulnerabilities in operational preparedness and propose mitigation strategies

The scope of work covers 328 buildings located on the Point Grey campus, all owned by the university (buildings owned by UBC Properties Trust were excluded from the scope of work), and the water, natural gas, electricity, thermal energy, and sewer system infrastructure on campus.

The following tasks were undertaken for this study and are contained in this report:

- **Section 3 Seismic hazard assessment**: Identification of seismic hazards utilized for this study
- **Section 4 Description of campus infrastructure and operations**: Overview of building typologies and inventories, utility infrastructure, and operations
- **Section 5 Evaluation of building risks**: Overview of building risk assessment methodology and results
- **Section 6 Evaluation of utility risks**: Overview of utility risk assessment methodology and results
- **Section 7 Evaluation of operational risks**: Overview of campus operations and preparedness
- **Section 8 Recommended actions**: Detailed list of actions to improve the resilience of the campus

A number of Appendices provide detailed technical support to the sections described above.

The following tasks were undertaken for this study and are contained in companion reports:

- Review of existing seismic studies performed on campus by Delcan (Part 1 and Part 2, 1994) and Glotman Simpson/JM Engineering (2012, 2013) – Arup recommended a revised approach to the ranking methodology and prioritization of mitigation efforts. See *Review of Existing Seismic Assessment Reports* by Arup (2016a).
- Multi-hazard assessment identifying natural hazards (including the impacts of climate change) that may pose a risk to the campus – earthquakes, fire following earthquake, and wildfires were identified as a high risk. See *Multi-Hazard Assessment* by Arup (2016b).
- Evaluation of the risks posed to the campus by fire following earthquake, including potential sources of ignition and fuel, fire spread, and fire suppression resources including a review of firefighting protocols. See *Qualitative Risk Assessment of Fire Following Earthquake* by Arup (2017).

2.1 Limitations of study and level of assessment

One of the primary focuses of this study is to determine the vulnerability of individual buildings that may pose a life safety risk. There are 328 buildings on campus, each with unique characteristics. The anticipated behavior and movements of buildings in various earthquakes is a key component for understanding vulnerabilities and risks.

The building movement estimates described in section 5.3 (and corresponding risk assessment results) are predicated upon an understanding that, within this scope of work, individual buildings were not subject to a detailed engineering evaluation. In addition, the performance of foundations and soil-structure interaction was not considered. While our initial evaluation process exceeds the current standard of practice for initial screenings, which largely rely solely upon rapid visual screening (RVS), it stops well short of a detailed investigation of each building to understand specific construction details, deficiencies, strengths above the base level, and material properties. Thus, this study is analogous to the Initial Evaluation Process (outlined in the Canterbury Earthquakes Royal Commission [CERC 2010, Vol 4] report completed in the aftermath of the Christchurch, New Zealand earthquakes) to provide "an approximate assessment of likely performance of a building in an earthquake."

The intention of this study is to screen buildings and to "identify, with an acceptable level of confidence, all high risk buildings" while "at the same time… not catch an unacceptable number of buildings that would, on detailed evaluation, be outside the high risk category" (CERC 2010, Vol 4). Arup is of the opinion that the quantitative assessment utilizing simplified nonlinear time-history structural analysis used for this study (described in Section 5.3 and Appendix D) increases confidence in the ability to identify high-risk buildings at this initial stage, given the data and information available.

The results of the risk assessment for individual buildings should thus be utilized to identify which buildings are candidates for further detailed evaluation, potentially including advanced nonlinear time-history structural analysis utilizing 3D computer simulation (see Appendix A). See Section 5.4 for building-risk results and Section 8.1 for further recommended actions. This study does not evaluate the performance of buildings and building components against the prescriptive building code life safety requirements.

3 Seismic hazard assessment

The following sections describe the seismic hazard adopted for this study. Further details are provided in Appendix B.

3.1 Probabilistic seismic hazard assessment

The first step in the risk assessment process requires the quantification of the seismic hazard on campus. We adopted the probabilistic seismic hazard assessment (PSHA) undertaken by UBC faculty Dr. Carlos Ventura and Armin Bebam-Zadeh (VC 2017). This assessment reflects the current state of knowledge about earthquake faulting, activity, and shaking attenuation, and was also used as the basis for the British Columbia Seismic Retrofit Guidelines (APEGBC 2013), also known as SRG2. Arup undertook a peer review of the PSHA and provided comments, which were satisfactorily addressed by Dr. Ventura and Mr. Bebam-Zadeh.

3.2 Soil conditions

Soil conditions across the campus were characterized by exp Services Inc. (exp 2017) and found to be generally uniform, with shear wave velocity in the top layers (Vs30) of approximately 400m/s (which is classified as Site Class C). See Appendix A for the definition of these terms. In general, the soil is very dense "till-like" silty sand/sandy silt below a nominal amount of fill. This information was incorporated into the PSHA. Additional detail about the soil conditions, including a soils map of the campus and the underlying geotechnical investigations, is provided in the exp report (2017).

3.3 Intensity levels considered

The risk assessment described herein is undertaken at four discrete intensity levels of earthquake ground shaking, described in Table 1. The risks (or losses) are quantified for each intensity level and also annualized to determine the anticipated losses, averaged over a long span of time by integrating the risk results at each intensity level with the hazard curve.

Each intensity level represents multiple earthquake scenarios. The deaggregation of the hazard for each intensity level (which defines the contributing earthquake sources and scenarios) is shown in Appendix B.

Table 1 Seismic hazard intensity levels

Intensity Level of Earthquake	Return Period (years)	% Probability of Exceedance
Frequent	43	50% in 30 years
Probable	200	20% in 50 years
Rare	475	10% in 50 years
Very Rare	2,475	2% in 50 years

3.4 Development of ground motions

Unidirectional earthquake time histories, scaled to the appropriate hazard level and based upon the deaggregation of the hazard, were also adopted from SRG2 (APEGBC 2013) and used as inputs to the structural analysis models described below (see Section 5.3). Additional detail about the earthquake ground motion development is provided in Appendix B.

4 Description of campus infrastructure and operations

To undertake the risk assessment, Arup collected information about buildings and utilities based on data provided by UBC and on-site evaluations. Information about operations was based on meetings and discussion with UBC staff and review of documents provided by UBC.

4.1 Buildings

The building stock on the Point Grey campus comprises an array of various building typologies including different construction materials, seismic resisting systems, sizes, shapes, and ages (see Figure 1 and Figure 2). A significant proportion, roughly 70%, were built either before seismic codes existed or in accordance with the seismic design principles of the first code, which has improved considerably based on lessons learned from damaging earthquakes in the intervening time period.

In addition, each building on campus is unique, and many take unusual architectural and geometric forms. Thus, approximately 75% of the buildings contain some defined structural irregularity and 40% contain severe structural irregularities. This indicates that they may be prone to poor seismic performance.

Figure 3 shows the proportion of total campus square footage and number of buildings for each of UBC's primary occupancy types. Further details about building exposure, including occupancy, populations, and replacement values is included in Appendix C.

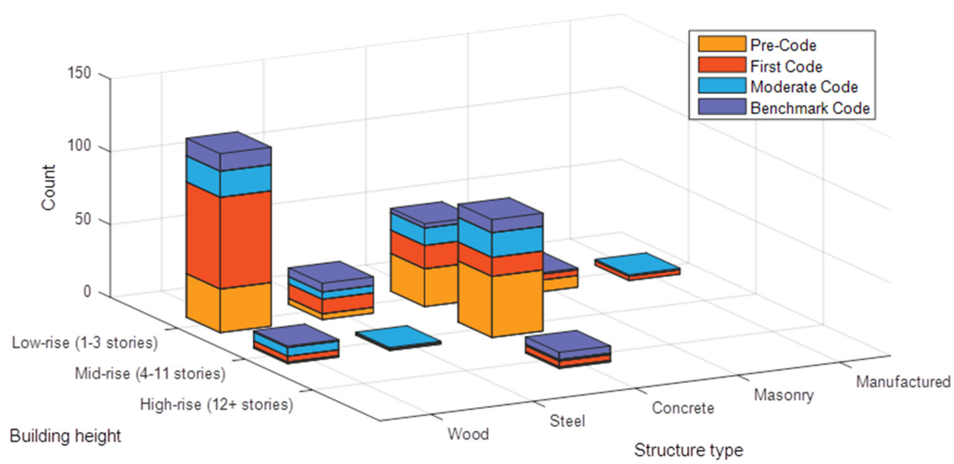


Figure 1 Inventory count of buildings showing building age, structure type, and number of stories

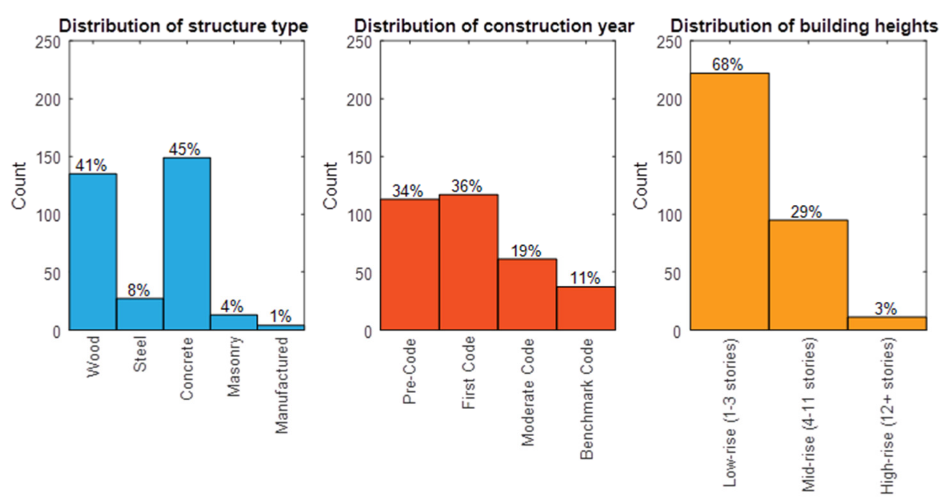


Figure 2 Proportion of inventory count of buildings showing building age, structure type, and number of stories

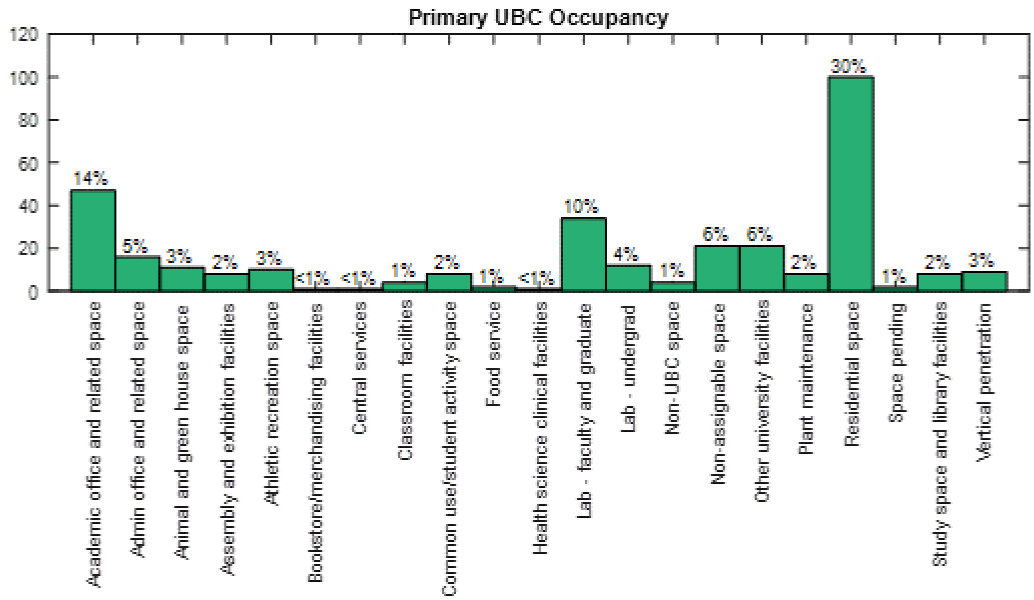


Figure 3 Proportion of total square footage and building count for each primary occupancy type

4.2 Utilities

UBC owns and maintains a significant network of facilities, equipment, and distribution systems that enable delivery of critical utility services from municipal suppliers to end users on the Point Grey campus. Reliable utility service — including electric power, water, natural gas, thermal energy, and sanitary sewer — is a critical requirement for normal campus operations.

Earthquakes have the potential to damage critical assets within each utility system, which due to the highly networked and interdependent nature of these systems, can result in service disruptions to part or all of campus. Utility disruption after an earthquake can impact the ability of the university to provide basic services to students (e.g., shelter, potable water, food, sanitation), maintain core academic functions (e.g., teaching, research), protect assets (e.g. refrigerated research specimens or electronic data), and even protect lives (e.g. loss of water can impede firefighting capability).

Like most cities and municipalities in Canada, the utility infrastructure on campus varies in terms of age and vulnerability to earthquake damage. UBC provided data on the material type, size, and length of piping transmission and distribution systems on campus. Information about critical infrastructure, including the electrical transformers at the main substation, water pumps, gas shut-off valves, and backup systems, was collected from on-site evaluations and data provided by the UBC Energy and Water Services Department.

Additional detail is provided in section 6 and Appendix L.

4.3 Operations

UBC is a sizable organization. With an annual operating budget of $2.5bn CAD, the university employs nearly 15,000 faculty and staff across more than two dozen schools/faculties and numerous administrative departments. Staff is responsible for ensuring that essential campus operations, in particular teaching and research, are running smoothly and efficiently. The Point Grey campus supports over 54,000 students and 8,000 research projects. At this scale, successful operation is difficult in a normal environment; in the aftermath of a major earthquake, it becomes even more challenging, especially if normal systems and resources are unavailable. In these emergency situations, robust operational structures and protocols are essential to maintaining important campus services in the short term and ensuring the health and viability of the organization in the long term.

Additional detail is provided in 7 and Appendix M.

5 Evaluation of building risks

5.1 Overview of approach

The purpose of the building risk assessment is to provide an estimate of damage and related consequences (casualties, repair costs, repair time, downtime, and contents losses) for each building on campus under various earthquake intensity levels with specified levels of confidence, given the uncertainty in such estimates. The information can be utilized to identify individual buildings with the highest relative risks to each other and to develop estimates of aggregated risk across the entire campus. In combination with cost-benefit analysis, the building risk assessment provides a robust quantitative basis for developing a mitigation strategy to reduce building risks.

Appendix H provides the risk results for individual buildings. Appendix I provides the risk results aggregated across campus. This section describes the general assessment approach and summarizes the key findings.

5.1.1 Methodology

The building risk assessment relies on thousands of virtual simulations (Monte Carlo analysis) and various earthquake scenarios to predict building damage and building risks. This is known as a fully probabilistic risk assessment. The methodology is detailed in Appendix C and integrates the following:

- Quantification of the seismic hazard (see section 3)
- Anticipated building movements from simplified nonlinear time-history structural analysis (see section 5.3 and Appendix D)

- Exposure data, including number of people within the building, quantity and type of building components, contents, and value of each building (see Appendix C)
- Vulnerability, expressed as fragility functions, that relate the anticipated building movements to damage in structural and nonstructural components and contents (see Appendix C)
- Consequences that relate the anticipated damage in each building to repair costs, repair time, downtime, casualties, and contents losses (see Appendix C)

5.1.2 Confidence levels

There is significant uncertainty in predicted estimates of ground shaking, building movements, building damage incurred from those movements, and corresponding consequences. However, this uncertainty is quantified and integrated within the probabilistic risk framework, allowing the estimated results to be specified with a certain degree of confidence.

In this report, our risk estimates are generally qualitatively expressed in terms of "anticipated" or "best estimate." Quantitatively, this corresponds to the median estimate (or 50th percentile confidence level). Sometimes, it is instructive to express the "probable maximum loss" risk estimates, which correspond to the 90th percentile confidence level (i.e., there is a 90% confidence that the risk will not exceed some specified value). The risk results for 10, 50, and 90% confidence are tabulated in Appendix H for individual buildings and shown in Appendix I for the entire portfolio.

5.2 On-site evaluations

On-site evaluations are important for collecting information to inform the qualitative and quantitative assessment of individual building risks. Readily observable vulnerabilities/deficiencies , falling hazards, and general conditions from the on-site evaluations, along with other building information provided by UBC, such as age and height, was used to score buildings in relation to their collapse risk utilizing the FEMA P-154 (2015) RVS approach (see Appendix J). There are sufficient limitations to the FEMA P-154 approach for assigning collapse risk (see below in this section); therefore, this assessment does not directly adopt the collapse results, instead opting to use them to confirm our quantitative collapse risk estimates (from the structural analysis) or to provide reason to question the quantitative results.

The information from the on-site evaluations also informs some of the key input parameters for the simplified structural analysis (e.g., actual story heights are increased to account for moderate or severe structural irregularities) and is used to modify some of the resulting building movement estimates used as the basis for the quantitative risk assessment (e.g., floor drifts are increased to account for plan irregularities). See section 5.3 for more information.

Arup performed on-site evaluations for roughly 130 buildings utilizing the FEMA P-154 approach. For the remainder of the building stock, we relied largely upon on-site evaluations undertaken by Delcan (Part 1, 1994) and Glotman-Simpson/JM Engineering (2012 and 2013), which did not follow the FEMA P-154 approach. Of the 130 buildings Arup screened, roughly 80 of them were newer buildings that Delcan had not reviewed (since they were not yet constructed in 1994), 20 were buildings that had been constructed prior to 1994 but were not included in Delcan's review, and 30 were buildings that Delcan had reviewed but were selected to audit Delcan's observations. For the buildings that Delcan reviewed, we translated Delcan's qualitative observations into the FEMA P-154 data-collection template based on our engineering judgment. Ultimately, FEMA P-154 data-collection sheets, scores, and collapse probabilities were developed for the entire building stock (see Appendix J).

When available, structural drawings were reviewed to supplement on-site observations; the primary purpose was to confirm the construction type and to generate approximations of the base shear strength for the simplified structural analysis. Base shear strength is an important parameter for assessing the probability of collapse, and it is conspicuously absent from the FEMA P-154 methodology, likely because it cannot be obtained from visual inspection alone.

5.3 Estimates of building movements

The anticipated building behavior in various earthquake intensity levels is critical to understand the risks to the building stock and the populations within each building. Building movements, such as the interstory drifts (displacements between each floor) and floor accelerations, indicate the level of damage anticipated to structural and nonstructural components (including contents). Large residual interstory drifts (permanent post-earthquake displacement or lean) indicate that a building may be irreparable. Building interstory drifts that exceed a certain threshold indicate that a building may experience either partial or catastrophic collapse, rendering it irreparable and posing a significant life safety risk.

5.3.1 Methodology for predicting building movements

We quantified building movements explicitly via simplified nonlinear time-history structural analysis, largely based on the SRG2 (APEGBC) database, for the various earthquake intensity levels. The input parameters for the analysis were guided by observations from on-site evaluations and by general review of structural drawings, when available, to determine the base shear strength of the building. See Appendix D for further details on the methodology and the input parameter assumptions.

5.3.2 Calibration of simplified structural analysis

As part of this scope of work, we performed advanced 3D nonlinear time-history structural analysis on three buildings with the intent of calibrating the relatively simplified structural analysis method described above. The three buildings selected include Walter Gage Tower, Place Vanier Residence (Building ID 545-01), and Frederic Lassere. The comparison between the simplified and advanced analysis revealed that the simplified analysis likely overpredicts building interstory drifts prior to the yield point. The result is that the anticipated damage at lower-intensity earthquakes (which are not anticipated to induce significant ductility in most structures) may be overpredicted. This is because the simplified analysis relies on a bilinear backbone curve (defined in SRG), which does not capture the initial higher stiffness of the structure. Thus, we modified the interstory drift results of buildings to account for this effect. See Appendix E for further details.

While the scope of performing the advanced analysis is not intended to explicitly quantify the absolute probability of collapse for these three buildings (this would require additional effort, including development of an appropriate suite of bidirectional ground motions; only unidirectional motions were adopted for the purposes of this study), the results provide insight into the significant value of performing such analyses. For the buildings analyzed, the results showed significantly higher capacity to resist collapse than indicated by the qualitative observations (RVS) and simplified analysis methods for two of the buildings (Place Vanier and Frederic Lassere). The advanced structural analysis also revealed specific structural deficiencies that could be mitigated with localized retrofits (e.g., the roof penthouse for Lassere, see Appendix H), rather than full upgrades of the entire structural system, a cost-effective way for reducing life safety hazards. All three buildings are unlikely to satisfy the prescriptive building code life safety requirements, but they do not seem to pose the greatest risks on campus.

5.3.3 Lessons from Christchurch

In recognition that life safety concerns are paramount to the university, it is instructive to reflect upon the lessons learned from the September 2010 and February 2011 earthquakes in Christchurch, New Zealand, which are arguably the most well documented in history. The building stock in Christchurch is similar to that on the campus of UBC, mostly comprising timber and reinforced concrete buildings. The earthquake of February 22, 2011 imposed ground accelerations that were consistent with Rare to Very Rare shaking predicted for Christchurch. For comparison, the spectral displacements demands (a measure of the magnitude of imposed building movements) were approximately double what is expected in Vancouver for Very Rare shaking, for the vast majority of buildings.

The 22 February 2011 earthquake (M6.2) resulted in 185 fatalities. Forty-two people were killed primarily due to partial collapse of unreinforced masonry

(URM) buildings and facades, most of whom were located outside the buildings and crushed by collapsed URM facades, external walls, and parapets. URM buildings account for only 3% of the building stock in Christchurch (25% of the central business district) yet caused almost 25% of the fatalities. There are few URM buildings on the UBC campus, but several buildings have masonry parapets, brick veneer, and heavy precast cladding, which could lead to similar consequences (see section 5.4.2 and Appendix H).

Ten deaths were not building-related (e.g., due to rock fall). Our risk assessment does not account for outdoor casualties or deaths unrelated to building damage or collapse. The majority of fatalities in Christchurch was caused by two catastrophic building collapses (the Pyne Gould Corporation [PGC] and Canterbury Television [CTV] buildings), which led to 133 lost lives — 18 in the five-story PGC building and 115 in the six-story CTV building. Both were composed of nonductile reinforced-concrete shear walls to resist seismic demands. The PGC building was constructed in the mid-1960s and the CTV building in the mid-1980s. This is one of the prevalent building typologies on the UBC campus. Both also exhibited major structural irregularities (common in the buildings on UBC's campus), including offset shear walls and much stronger ground floor relative to stories above in the case of the PGC building, which contributed to their failure, according to the Royal Commission report (CERC, Vol 2., 2012). The primary cause of collapse, according to the report, was the lack of strength to resist the ground shaking and the lack of ductility, which caused the shear walls to fail.

It is possible that initial evaluation methods overpredict collapse. In Christchurch, there were only 2 catastrophic collapses of reinforced concrete buildings out of approximately 2000 buildings in the Central Business District (GNS 2013). That represents an almost miraculously small probability of catastrophic collapse which exceeded expectation given the intensity of ground shaking relative to what even modern buildings in Christchurch were designed for. Some engineers suggest that many buildings may have been spared because the duration of shaking was short (unlike that expected from a Cascadia Subduction Zone earthquake in Vancouver).

Building collapse is notoriously difficult to predict, particularly when relying on qualitative observation alone. The PGC building was visually inspected multiple times between the September 2010 and February 2011 earthquakes by structural engineers and deemed fit for occupancy. In the aftermath, the Royal Commission thoroughly investigated the poor performance of buildings in Christchurch including the PGC and CTV building to assess the cause of collapse. They concluded that "of the different analytical techniques available, the inelastic time-history method potentially gives the most accurate predictions." It is our opinion that advanced nonlinear (aka inelastic) time-history structural analysis provides an order of magnitude greater confidence in predicted building behavior, relative to visual inspection and simplified structural analysis.

Only the most robust, rigorous, and well validated analytical methods can capture the highly dynamic and nonlinear behavior associated with catastrophic collapse. To enable less sophisticated structural analysis methods utilized by the majority of structural engineers, guidelines to assess collapse set conservative limit states for interstory drift exceedance and structural component damage. Thus, collapse risk may be overstated. As mentioned in the preceding section (and shown in Appendix E), advanced structural analysis, while time-consuming, provides a much higher level of confidence in the anticipated performance of individual buildings relative to the simplified analysis. This understanding provides the basis for recommending further evaluation for buildings identified by the initial screening methods as collapse prone.

5.4 Life safety risks

Earthquake-induced collapse of buildings and other falling hazards contribute to casualties. We have assessed the collapse probability of individual buildings, based on initial screening and analytical methods, and related that to the anticipated casualties in a building (based on data about the population within it). Internal nonstructural falling hazards are also explicitly included in the risk assessment. Casualties caused by external nonstructural falling hazards were not explicitly quantified but we have identified those that pose the greatest risks.

5.4.1 Structural collapse vulnerability

The best estimate from our risk assessment indicates that approximately 31 buildings may collapse (partially or catastrophically) in the event of Very Rare earthquake shaking (2,500 year return period), causing approximately 678 injuries and 153 fatalities. The risk assessment also indicates that some particularly vulnerable buildings may be susceptible to collapse in less intense shaking. The anticipated number of collapsed buildings in the Very Rare earthquake total roughly 9% of the building stock.

The probability of collapse for some individual buildings significantly exceed the acceptable collapse risk targets implied in modern codes. On the other hand, our risk assessment results indicate an almost negligible probability of collapse for a majority of the newer building stock. In combination, the total collapse risk across the campus is not dissimilar to acceptable collapse targets for individual buildings. For reference, the acceptable collapse probability in the current US building code (ASCE 7 2010) for normal occupancies is 10% for Very Rare shaking (the Canadian code does not provide explicit performance objectives). Many Californian structural engineers contend that this target is too lenient, particularly in comparison to acceptable risk targets associated with other types of loading specified in the code. At the same time, there is general acknowledgement that new buildings, designed in accordance with the code, are likely to perform significantly better than this target in actual earthquakes (on account of very few instances of partial or catastrophic collapse of newer buildings in modern recorded earthquakes).

We assigned each building into Structural Collapse Vulnerability Tiers (see Appendix H) based on the probability of collapse in Very Rare earthquake shaking explicitly calculated by the simplified nonlinear time-history analysis. Collapse is defined when a certain collapse drift threshold is exceeded (see Appendix D), intended to indicate when a building may experience either partial or catastrophic (full) collapse of the building. In some cases, we modified the tier ranking of individual building based on the qualitative observations from on-site evaluations, primarily when we judged that the simplified analysis could not adequately capture a building's unique features. The number of buildings, which have not been previously retrofitted, that fall within each tier are shown in table Table 2.

Table 2 Structural Collapse Vulnerability Tiers and counts for un-retrofitted buildings

Structural Vulnerability Tiers (Collapse Risk)	Probability of Collapse in Very Rare Earthquake Shaking (2475 year Return Period)	Number of Buildings
I	0% to 10%	155
II	11% to 19%	63
III	20% to 49%	46
IV	50% to 100%	29
	TOTAL	**293**

The expected performance of previously retrofitted buildings is more difficult to ascertain because the nature and extent of the retrofit can vary significantly and often the retrofits are undertaken nonconventionally (e.g. external buttresses). Thus, we rank retrofitted buildings based on the code year and the minimum level of strength that the retrofit adhered to (see Appendix H). Table 3 shows the tiers for previously retrofitted buildings.

Table 3 Structural Collapse Vulnerability Tiers and counts for previously retrofitted buildings

Structural Vulnerability Tiers (Collapse Risk)	Probability of Collapse in Very Rare Earthquake Shaking (2475 year Return Period)	Number of Buildings
I	0% to 10%	10
II	11% to 19%	16
III	20% to 49%	9
IV	50% to 100%	0
	TOTAL	**35**

Figure 4 shows the assignment of Structural Vulnerability Tiers by the type of building construction and the building code used for the design of the building. As expected, buildings designed prior to the building code or to the first iteration of the building code are more collapse prone.

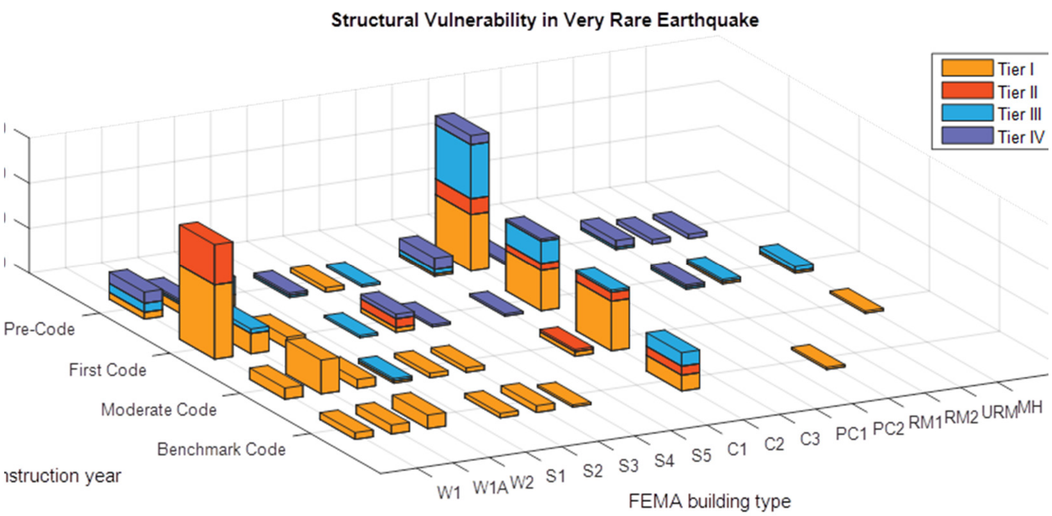


Figure 4 Structural Vulnerability Tier assignments by building code and construction type. W = wood, S = steel, C = concrete, RM = reinforced masonry, URM = unreinforced masonry, MH = manufactured housing

5.4.2 Life safety hazards from nonstructural components and contents

Falling hazards from nonstructural building components and unattached contents have caused injuries and fatalities in past earthquakes. From on-site evaluations and a literature review, we developed a list of nonstructural components and contents that could pose a Very High or High risk to life safety. A list of buildings which were observed to contain identified Very High components is provided in Appendix H (these components are noted below in this section). This list is based on our interpretation of observations from Delcan (1994) and Arup's observations from the buildings for which we conducted on-site evaluations. The list of buildings should be confirmed, as it may not be exhaustive.

Several of the items listed below were responsible for causing injuries and fatalities in the Christchurch earthquake, particularly unreinforced brick and masonry facades. Damage to stairs was also prevalent due to inadequate seismic connections and movement joints. In general, unbraced heavy building contents also pose a life safety risk.

We identified a number of components and contents which may pose a sufficiently elevated risk to life safety to warrant prioritization. We have assigned components which pose a direct, significant, and potentially widespread threat to life safety (i.e. can directly cause multiple injuries or deaths in earthquake shaking) a Very High designation. We have assigned components which pose some direct threat to life safety and/or indirect threat to life safety (e.g. generators which support emergency egress lighting) a High designation. Recommended next steps for each identified component are identified in section 8.1 and conceptual retrofit measures (and costs) are provided in Appendix K for each component and contents.

5.4.2.1 Nonstructural components

Attached non-structural components that are associated with an elevated risk to life safety include:

Very High Life Safety Impact

- Unreinforced masonry chimneys (see section K2.5) and parapets (see section K2.23). (see list of buildings which we are aware contain these components in Appendix H; note that this list may not be exhaustive).
- Masonry interior partition walls (see section K2.8) that are likely unreinforced (see list of buildings which we are aware contain these components in Appendix H; note that this list may not be exhaustive).
- Inadequately braced HVAC ducting (see section K2.14)
- Heavy pre-cast cladding (see section K2.25) and brick veneer (see section K2.21), particularly on older buildings which may have deficient connections (see list of buildings which we are aware contain these components in Appendix H, note that this list may not be exhaustive. This list also contains new buildings for completeness – these are not anticipated to pose a significant life safety risk).
- Brittle glazing above egress and occupied spaces (see section K2.26)
- Egress stairways with deficient connection details (see section K2.27)

High Life Safety Impact

- Heavy suspended ceiling elements including heavy ceiling tiles and unbraced metal grid backing systems (see section K2.1), and heavy elements incorporated into the ceiling such as speakers and lighting (see section K2.2 and K2.4)
- Pendant lighting without adequate restraint (see section K2.3)
- Fire sprinkler piping that is inadequately braced (see section K2.6) and sprinkler heads (see Section K2.7)
- Natural gas piping (see section K2.6) and piping that may contain hazardous materials (see section K2.11)
- Unbraced boilers and furnaces (see section K2.10) and water heaters (see section K2.19)
- Heavy mounted overhead equipment or components including athletic equipment (see section K2.15)
- Inadequately braced tall cabinets (see section K2.17)
- Generators, batteries, inverters, motors, transformers (see section K2.18)
- Heavy appendages and ornamentation on older buildings (see section K2.24)

Although each item above represents either a High or Very High possible life safety impact, the actual performance of several of these items is dependent upon the component characteristics, detailing of connections, and conditions, a wide range of which are likely present within the building stock. Consequently, further detailed review of some of these components is warranted.

5.4.2.2 Contents

Building contents which pose a life safety hazard typically include unbraced or inadequately braced storage/shelving units, heavy equipment stored overhead, building contents that contain hazardous materials, and building contents that are essential for life safety in the event of an emergency. Many contents clearly do not pose a life safety threat, yet damage to them may cause a significant loss to the university if they are priceless, or mission-critical. These are identified in Appendix K.

Contents that are associated with an elevated risk to life safety include:

Very High Life Safety Impact

- Unrestrained building maintenance chemicals in vulnerable containers (see section K3.3), other hazardous materials (see section K3.17), and laboratory chemicals (see section K3.19)

- Unrestrained gas cylinders (see section K3.14)
- Unrestrained laboratory incubators containing potentially hazardous microbiological material (see section K3.20)
- Live laboratory animals (see section K3.24)

High Life Safety Impact

- Unrestrained heavy artifacts such as tall sculptures (see section K3.1 and K3.27)
- Unrestrained fume hoods (see section K3.13)
- Unrestrained washers/dryers (stacked) (see section K3.7)
- Unanchored electron microscopes (see section K3.8)
- Unrestrained storage and equipment racks and heavy contents on shelves (see section K3.9), filing cabinets (see section K3.10), shelving (see section K3.11), laboratory work benches (see section K3.21), library shelves (see section K3.23), lockers (see section K3.25), and wall shelving units (see section K3.34)
- Unrestrained freezers and refrigerators (see section K3.12)
- Laterally unrestrained handheld fire extinguishers (see section K3.16)
- Unanchored heavy and tall laboratory machinery (see section K3.18) and other experimental set ups (see section K3.33)
- Large overhead mounted televisions and monitors (see section K3.22) and speakers (see section K3.29)
- Inadequately braced building signs above egress routes (see section K3.31)

5.4.3 Estimated casualties

Casualties are defined as the total number of people that are injured or killed. The primary cause of fatalities is from building collapse. Injuries can occur from internal falling hazards. Our assessment does not include potential casualties in outdoor populations (e.g. from exterior falling hazards) and from other nonbuilding related failures (such as heart attack). It also does not explicitly include casualties caused by interior masonry partitions, but we have identified this as a high risk concern based on performance in past earthquakes.

The number of estimated casualties is dependent on the populations within the buildings. We developed the population models based on FEMA P-58 and cross-referenced them against information provided by UBC. The casualty estimates across the campus are based on the Equivalent Continuous Occupancy (ECO) model which accounts for the fluctuations and duration of time the population spends within the building (and thus accounts for the unlikeliness that an earthquake strikes at the time of peak population). For reference, the peak indoor population on campus (assuming all buildings are fully populated at the same time) is roughly 59,800. The ECO indoor population (the total number of people assumed to be indoors across all campus buildings at the time of an earthquake) is roughly 22,100. Appendix C provides further details on the assumptions and methods for estimating casualties.

Table 4 provides estimated injuries and fatalities for the various earthquake intensity levels. The significant range between the best estimate and probable maximum casualties underscores the great uncertainty in these types of predictions (largely due to the great uncertainty in building collapse prediction). By incorporating the probability of the various earthquake scenarios and the resulting casualties, it is possible to estimate the average annualized number of total injuries and fatalities across campus (see Appendix G for description of average annualized losses and their relevance). The best estimate is 6 – 7 total injuries and 1 fatality will be caused on average, per year, due to future earthquakes.

Table 4 Estimated casualties across campus

Earthquake Intensity Level	**Estimated Injuries**		**Estimated Fatalities**	
	Best Estimate (Median)	Probable Maximum (90%-tile)	Best Estimate (Median)	Probable Maximum (90%-tile)
Frequent	58	61	0	0
Probable	60	197	0	34
Rare	192	603	33	135
Very Rare	678	4547	153	1095

5.5 Disruption of campus functions (downtime)

Safety is of primary concern at very high levels of shaking which by definition have a very low likelihood of occurrence. At lower levels of shaking (which are more likely to be observed on campus in the next 100 years), the disruption of operations and damage to important assets may pose the greatest threat to the long term health of the university. Utility disruption is also anticipated to hinder campus functions (see section 6)

Downtime is estimated by relating the predicted earthquake damage sustained by various building components to the anticipated repair times and accounts for the delay to the initiation of building repairs (e.g. scarcity of contractors after the earthquake). See Appendix C for further details on the downtime assessment methodology.

5.5.1 Downtime across campus

Table 5 provides a summary of total floor space on campus that will be functional immediately after the earthquake and the time required to restore functionality in 50%, 75%, and 90% of the total floor space for the various earthquake intensity levels. The total functional floor space that is reported does not account for delays that may impede the ability to re-occupy or use the space, including the time required to perform post-earthquake inspection, and utility disruption times (see section 6.3). See Appendix I for the restoration curves by various campus occupancies. Residential occupancies recover quicker than academic or research occupancies, primarily because residential housing is often located in timber buildings, which are easier to repair. Our analysis assumes that severely damaged or collapsed buildings will be repaired or replaced within a maximum time period of 48 months.

Table 5 Anticipated available floor space which is functional immediately after an earthquake and restoration times

Earthquake Intensity Level	% of Total Floor Space Functional Immediately Following Earthquake	Time to Restore 50% of the Total Floor Space to Functionality	Time to Restore 75% of the Total Floor Space to Functionality	Time to Restore 90% of the Total Floor Space to Functionality
Frequent	97%[1]	0 days[1]	0 days[1]	0 days[1]
Probable	35%[1]	3.5 months	5 months	6.5 months
Rare	2%[1]	6.5 months	7.5 months	1 year
Very Rare	<1%[1]	10.5 months	<2 years	4+ years

[1]Assuming that post-earthquake inspection happens immediately following the earthquake. Our experience indicates that it may take a few days to inspect all the buildings.

5.5.2 Downtime of critical and essential facilities

Perhaps of greatest concern is the performance of "essential" facilities, critical for post-disaster emergency response. For reference, the intent of the current code is that essential facilities remain operable after a design level earthquake (which is analogous to the Rare earthquake in this study).

5.5.2.1 Hospitals

Our risk assessment indicates that the main hospital on campus (Koerner Pavilion) may not be operational in the Probable or Rare earthquake due to significant earthquake damage. Table 6 provides a summary of the anticipated times to repair building components hindering functionality (assuming repairs would begin immediately) and the corresponding total downtime (assuming it would take some time to mobilize contractors and for the contractor to locate materials, labor, and equipment to make repairs) for all buildings identified by UBC as hospitals. The time to achieve full functionality may lie somewhere between the two extremes so the range is tabulated (first value is repair time and second value is downtime). The restoration of specific hospital services may not occur simultaneously, and we recognize that extraordinary measures may be taken to bring specific emergency services back online (including triage areas set-up outside the building), but this was not considered at this time as it is outside the scope of this study and would rely on assumption.

Table 6 Anticipated repair times and downtime to achieve full functionality in hospitals on campus

Earthquake Intensity Level	Anticipated Range of Time to Restore Full Functionality to Hospitals		
	Koerner Pavilion	**Detwiller Pavilion I**	**D.M. Centre for Brain Health**
Frequent	1 day[1]	1 day[1]	1 day[1]
Probable	1 week – 6 months	2 weeks – 7 months	1 day – 1 week
Rare	1.5 – 6 months	1.5 – 8.5 months	1 week – 6 months
Very Rare	7 – 12 months	4.5 – 11 months	1.5 – 8.5 months

[1] Restoration of functionality is governed by anticipated utility disruption (see Table 10), as none of the buildings appear to have backup systems

5.5.2.2 Post-disaster facilities

Our risk assessment indicates that buildings indicated as post-disaster facilities by the university may not be functional after Probable or Rare earthquakes. Of particular concern are the two older buildings — University Services Building and Doug Mitchell Thunderbird Sports Centre. For the latter, our analysis assumes that the estimated downtime is for the entire building (it does not distinguish between the three different buildings that comprise the Sports Centre, the latest addition in 2008). We understand that the university's Emergency Operations Command Center will be hosted in the University Services Building.

Table 7 Anticipated repair times and downtime to achieve full functionality in hospitals on campus

Earthquake Intensity Level	Anticipated Range of Time to Restore Full Functionality to Post-Disaster Facilities		
	UBC Tennis Centre (New)	University Services Building	Doug Mitchell Thunderbird Sports Centre
Frequent	1 day[1]	1 day[2]	1 day[3]
Probable	1 day – 1 week[1]	1 months – 6 months	2 weeks – 6 months
Rare	1 day – 1 month[1]	4 months – 12 months	4 months – 12 months
Very Rare	6 - 12 months	4+ years	4+ years

[1] Restoration of functionality is governed by anticipated utility disruption (see Table 10); building has no backup systems to help mitigate disruption

[2] Restoration of functionality is governed by anticipated utility disruption (see Table 10), but building has 26 hours of backup power capacity

[3] Restoration of functionality is governed by anticipated utility disruption (see Table 10), but building has 12 hours of backup power capacity

5.5.3 Drivers of downtime

In general, our risk assessment indicated that downtime is primarily caused by damage to certain components (see Figure 5).

In the Probable level earthquake, downtime in the majority of buildings which experience it is almost entirely caused by damage to the exterior enclosure, primarily to heavy cladding (particularly in older buildings) and brick veneer (see also section 5.4.2). Damage to these components occurs at relatively low interstory drift levels, owing to their relatively brittle characteristics. When damaged, these components can pose a life safety hazard from falling debris and inspectors may shut a building (or certain parts of it) to avoid potential injuries in future aftershocks (several buildings in Napa were shut after the recent earthquake there for similar reasons). The damaged exterior enclosures can also hinder functionality, as air and water can intrude upon the interior floor space and cause molding, condensation (a hazard for lab and computer equipment), and occupant comfort issues. In the Rare level earthquake, the issues with exterior enclosures are exacerbated by the higher level of shaking. In addition, damage to egress routes (stairs), and mechanical piping distribution systems (which can cause water leakage/flooding and can shut a building due to electrical hazards), are the main causes of downtime.

In addition to the components highlighted above and in Figure 5**Error! Reference source not found.**, the impact of non-structural components and contents on business continuity are discussed in more detail in Appendix K. Conceptual mitigation measures are also described.

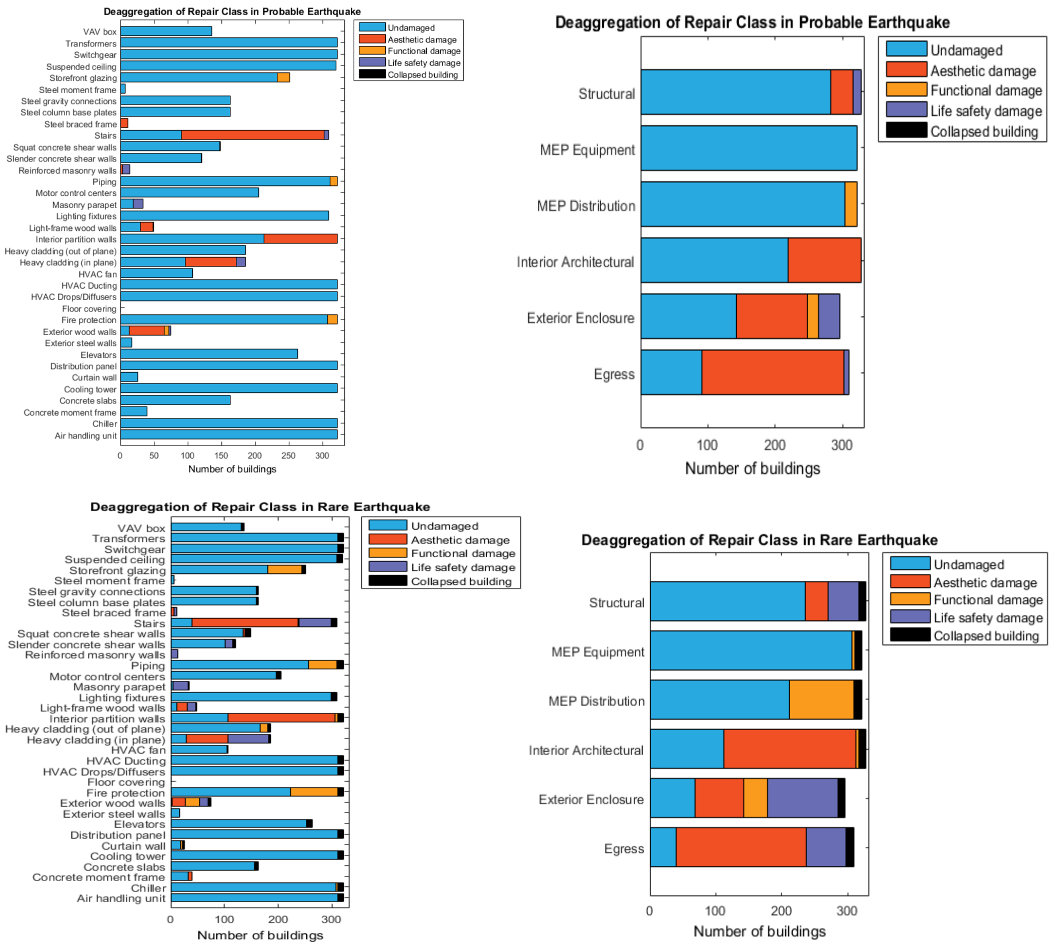


Figure 5 Inventory of building components which trigger downtime (yellow = damage hindering functionality, purple = damage hindering re-occupancy and functionality) in Probable (top) and Rare (bottom) level shaking

5.6 Repair costs and contents losses

The anticipated costs to repair earthquake damage across the portfolio of buildings and the costs to repair or replace damaged contents is tabulated in Table 8 below. The average annualized loss for the entire portfolio is $12m CAD, excluding contents losses. For reference, the total replacement value of the buildings on campus is roughly $6.5bn CAD, provided by the cost estimator appointed by UBC (see Appendix F for replacement costs for individual buildings). The value of contents was obtained from the insurance data provided by UBC. For reference, the total value of contents is $4.7bn CAD. The assumptions and methodology for undertaking the loss analysis are described in Appendix C.

It is clear from the results that the costs to repair or replace contents is generally equivalent to the cost to repair building earthquake damage. This highlights the criticality in protecting building contents from incurring damage.

Table 8 Costs to repair earthquake damage and to repair or replace building contents across entire portfolio of buildings (CAD)

Earthquake Intensity Level	**Best Estimate (Median) Repair Costs**	**Probable Maximum Loss (90%-tile) Repair Costs**	**Best Estimate (Median) Contents Losses**	**Probable Maximum Loss (90%-tile) Contents Losses**
Frequent	$70m	$101m	$9m	$44m
Probable	$325m	$543m	$200m	$484m
Rare	$794m	$1.28bn	$621m	$1.22bn
Very Rare	$2.58bn	$4.22bn	$1.91bn	$3.06bn

5.6.1 Losses in relation to insurance policies

The University has two insurance policies: 1) "core academic" which is underwritten by the province and 2) "optional" which is underwritten by private insurers. For reference, the total replacement value of the buildings in the "core academic" policy is roughly \$4.7bn CAD and the total replacement value of the buildings in the "optional" policy is roughly \$1.8bn CAD. Table 9 shows the repair costs for buildings, separated by the insurance policy.

Insurance limits are often based on 90% loss estimates in the 475 year earthquake (Rare earthquake in this study). For the optional policy, this is \$456m. We understand that the current limit for the optional policy is approximately \$225m.

Table 9 Costs to repair earthquake damage, separated by insurance policy (CAD)

Earthquake Intensity Level	**"Core Academic"**		**"Optional"**	
	Best Estimate (Median) Repair Costs	Probable Maximum Loss (90%-tile) Repair Costs	Best Estimate (Median) Repair Costs	Probable Maximum Loss (90%-tile) Repair Costs
Frequent	\$24m	\$46m	\$50m	\$57m
Probable	\$197m	\$361m	\$119m	\$186m
Rare	\$549m	\$853m	\$235m	\$456m
Very Rare	\$1.75bn	\$3.22bn	\$813m	\$1.13bn

5.7 Renewal prioritization strategy and cost-benefit analysis

Appendix H provides a list of buildings, their corresponding Structural Collapse Vulnerability Tiers, and corresponding prioritization rankings based on three strategies described below. Further detail about each strategy and the underlying methodology is presented in Appendix G.

5.7.1 Strategy #1

A typical engineering approach for prioritizing buildings for seismic retrofit/renewal would rely on identifying the most vulnerable buildings, identified in this study by the Structural Collapse Vulnerability Tiers. The problem with this approach is that it neglects casualty risks. The risk assessment herein addresses this concern by accounting for the exposed population within each building and the building occupancy type (to understand the duration of time occupants spend within each building and thus the likelihood the building would occupied at the time of an earthquake), thus allowing buildings to be ranked in order of highest anticipated casualties. This is referenced as Strategy #1 in Appendix H.

5.7.2 Strategy #2

While it may be an appropriate strategy to retrofit buildings in order of highest casualties, Strategy #1 is unlikely to be cost-effective. Arup undertook a cost-benefit analysis to determine alternative strategies. The cost-benefit analysis was undertaken with the aid of a cost estimator who provided costs to seismically retrofit, fully renew, and demolish and replace (with a new building) each building on campus (see Appendix F). Conceptual seismic retrofits, upgrading to 100% of current code strength, for 15 different building typologies were developed by Arup for this purpose (see Appendix F). The structural analysis was re-run to consider the improved performance of retrofits and the risks (casualties, downtime, repair costs, etc.) were re-calculated for each building. An average of the risk results from buildings constructed after 2010 was adopted to represent the risk associated with "new buildings." With the cost information and the quantified reduction in risks (reduced fatalities, repair costs, downtime) for each building for each retrofit measure (retrofit, renew, demolish and replace), a cost-benefit analysis was performed. The methodology is described in detail in Appendix G. Strategy #2 differs from Strategy #1 by incorporating the costs in determining the prioritization strategy for saving lives. In Strategy #2, buildings are ranked by the least cost required to save a life, on an annualized basis, thus maximizing the number of lives saved given a specified capital expenditure.

5.7.3 Strategy #3

Strategy #3 incorporates the avoided repair costs and business interruption losses (e.g. tuition, research grants) caused by downtime with saving lives to provide the most holistic resilient and cost-effective approach. In Strategy #3, the cost-benefit analysis indicates that it may be more beneficial to demolish and replace with new buildings (instead of renewing) that have higher performance objectives than the current code (i.e. the new building should satisfy REDi Gold or Platinum objectives for reduced downtime and losses).

5.7.4 Summary of strategies

The relative reduction in casualty and downtime risk corresponding to each strategy for a given capital expenditure is shown in Figure 6 and Figure 7, respectively. Individual building rankings, based on each strategy, are tabulated in Appendix H. Strategy #2 and #3 are shown to be significantly more cost-effective than Strategy #1.

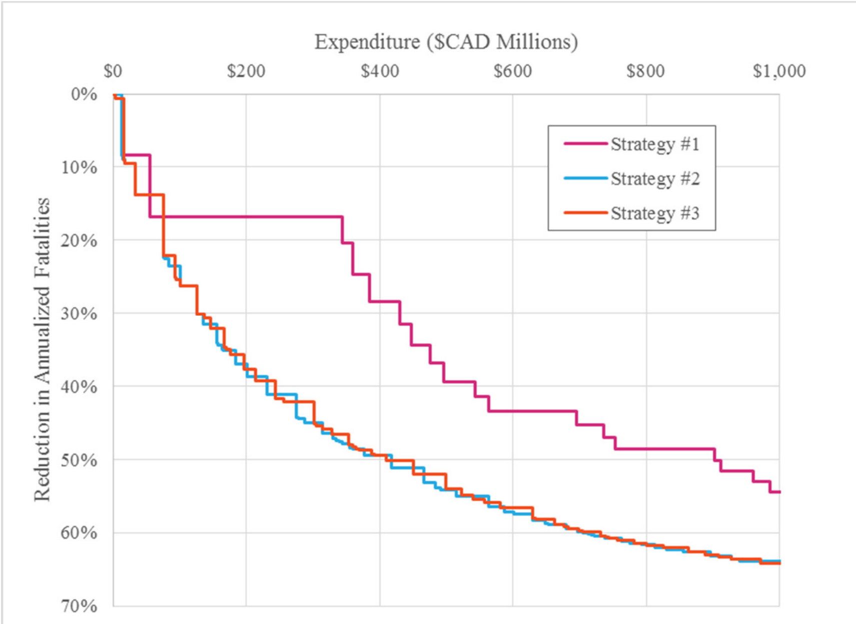


Figure 6 Reduction in annualized fatalities as a function of expenditure for each mitigation strategy

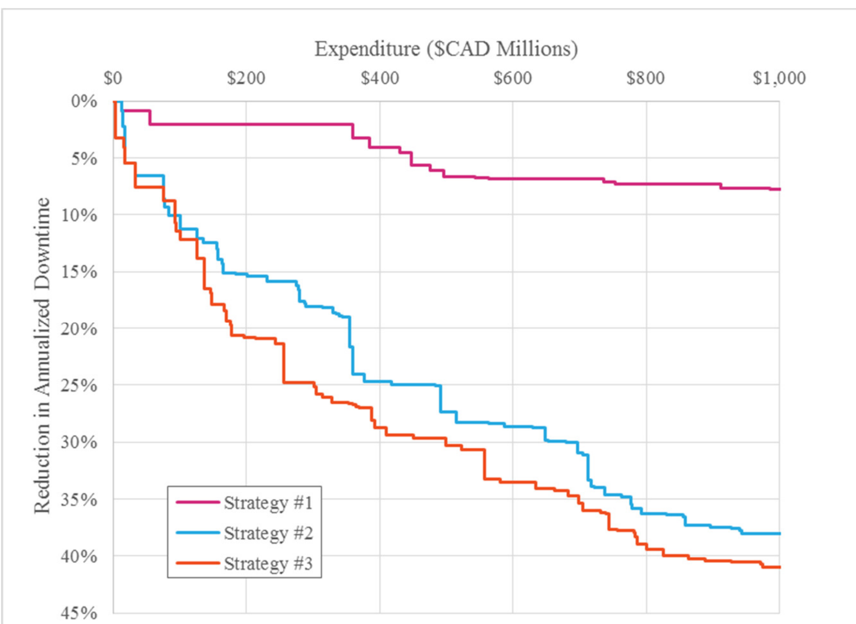


Figure 7 Reduction in annualized downtime as a function of expenditure for each mitigation strategy

6 Evaluation of utility risks

6.1 Overview of approach

Arup performed quantitative risk assessments of five campus utility systems: electric power, water, natural gas, thermal energy, and sanitary sewer. The first step in this process involved developing a detailed understanding of the current configuration of each utility system, which was gleaned from on-site evaluations of critical facilities and equipment, discussions with staff in the Energy and Water Services Department, and review of drawings and other printed and online resources. Using these sources of information, we developed a simplified network model for each utility system and performed Monte Carlo simulations to predict expected damage and restoration times at different earthquake intensities. The simplified network models use fault trees to capture a wide range of asset failures and events, including damage to equipment and the facilities that house them, pipe breaks within transmission and distribution systems, critical interdependencies, and failure of offsite municipal supply (e.g., damage upstream from UBC prevents Fortis BC from delivering natural gas to campus).

Given the large number of components within each utility system and their complex interactions, the simplified utility models are unable to predict which campus buildings will experience loss of service after an earthquake. Instead, the models were developed to capture failures that have the potential to disrupt service to the entire campus or a proportion thereof. The simplified models can also predict the number of pipe breaks within campus distribution networks, but not the specific locations of the breaks. Subsequently, the utility restoration times presented in section 6.3 should be considered baseline values; restoration times for individual facilities could potentially be longer depending on the exact nature of damage to the utility system.

For a more detailed discussion of the risk assessment methodology, please refer to Appendix L.

6.2 Key vulnerabilities

Based on results from the risk assessment and discussions with UBC staff, we have identified several important vulnerabilities within campus utility systems.

In general, the Point Grey campus is vulnerable to disruption of offsite supply from municipal utility providers (e.g., BC Hydro, Fortis BC, Metro Vancouver). As documented in most major earthquakes, municipal utility systems can experience damage that takes several days or months to repair. We expect municipal utility systems throughout the greater Vancouver region to be damaged in relatively frequent earthquake scenarios, which can result in service disruptions to campus. Our predictions for offsite supply disruption are largely based upon data from past earthquake performance of utility systems in similarly developed countries. We are unaware of any studies conducted by Vancouver's municipal suppliers to explicitly quantify anticipated earthquake disruption.

6.2.1 Electrical power

While UBC maintains an extensive network of backup diesel generators in the event of a loss of electric power, these generators have limited capacity and run time. Large amounts of diesel are stored on campus in discrete locations but there is currently no method for distributing it. If normal service is disrupted from BC Hydro or due to damage to the campus network for several days, the generators will be unable to support baseline energy demands required for normal campus operations. Furthermore, in the aftermath of a major earthquake, transportation systems are likely to be disrupted, meaning that diesel fuel resupply might not be possible. Electric power is especially important because most campus utility systems depend on it to successfully maintain service (e.g., water pumps, lift stations, computers, etc.).

Our risk assessment also indicated that the anticipated earthquake performance of the main electrical substation transformers may warrant further study due to the consequences of their failure to the entire power network. Our current study relies on studies of much smaller transformers (which perform relatively well in earthquakes) due to lack of data on the performance of very large transformers. Thus, our risk assessment may be unconservative.

6.2.2 Water

UBC currently has limited onsite water storage capabilities, meaning that if service from Metro Vancouver were disrupted for several days or weeks after an earthquake, the campus would essentially be without water for domestic purposes. UBC has plans to treat water from an on-campus creek but no plans for distribution. Of potentially greater concern is that even a brief water disruption could still impede the ability of firefighters to suppress conflagrations. Not only does this affect the university's ability to maintain normal campus operations, but it also has important life safety consequences in the event of fire following earthquake (see Arup 2017).

Another critical vulnerability is the Power House, a building constructed in the 1920s that houses water pumps that are essential to maintaining water service on campus. The Power House is highly vulnerable to partial or full collapse in strong earthquake shaking, an event that will likely damage the water pumps inside (or impede access to them) and result in loss of water service throughout campus, potentially for a significant period of time until a temporary facility can be brought online.

6.2.3 Natural gas

Buildings on campus are equipped with shake-actuated gas shut off valves which are triggered above a certain shaking threshold. This is beneficial for preventing gas leakage and fires. However, it will require significant time to re-light, re-pressurize, and test each building before gas service can be restored.

6.2.4 Sanitary sewer

The municipal sewer line at the north end of campus is close to the edge of a rapidly eroding cliff. While UBC is aware of this vulnerability, jurisdictional issues are making it challenging to mitigate because the university does not own the pipe or the cliff. Furthermore, while damage to the campus sanitary sewer system would not render buildings uninhabitable, continued use of toilets and sinks could result in raw sewage leaking from damaged pipes and contaminating parts of campus.

In addition, if the municipal sewer system is unavailable (due to treatment facilities being offline, for example), backflow on to campus is possible. For certain buildings on campus, flooding of basements due to inoperability of wastewater pumps and/or adjacent lift stations (due to disruption of electricity) is also a concern.

6.2.5 Thermal energy

The thermal energy network appears to be fairly resilient and no significant vulnerabilities were identified.

6.3 Anticipated utility disruption and restoration times

Table 10 summarizes the best estimates of how long it will take to restore 90% of utility service following a seismic event. The restoration times in Table 10 include the time it takes to restore municipal supply, which is beyond the control of UBC staff. Further detail is provided in Appendix L.

Table 10 Anticipated service disruption times for various utilities

Earthquake Intensity	**Electric Power**	**Water**	**Natural Gas**	**Thermal Energy**	**Sanitary Sewer[1]**
Frequent	6 hours	1 day	12 hours	0 days	0 days
Probable	1 day	61-65 days	2-6 days	0 days	4 days
Rare	2-3 days	65-70 days	7-13 days	0 days	6 days
Very Rare	7-13 days	68-76 days	14-40 days	0 days	8 days

[1] Indicates the time to repair sewer pipe breaks. The sanitary system will be unusable as long as water is disrupted. This will almost always govern.

For all utility systems except thermal energy, we predict complete disruption of service at all earthquake intensities. At lower earthquake intensities, this is due primarily to loss of offsite supply. At higher intensities, our models predict substantial damage to campus infrastructure, including the Power House building and distribution pipes across all utility systems. Transmission systems and equipment is generally rugged.

The following observations can be made for each utility system:

- *Electric Power*: In general, we do not expect critical equipment (e.g., transformers, switchgear) in the two primary substations to be damaged, even at higher earthquake intensities, which explains the relatively quick restoration times. However, our models of these critical assets are based on limited empirical data from smaller equipment, which perform well in earthquakes. It is not clear how larger transformers will perform as we are not aware of documented earthquake performance.

- *Water:* At all intensities except the Frequent earthquake intensity, restoration times are dominated by unavailability of the Power House, which our models predict will be significantly damaged and, at higher intensities, might even collapse. In either event, the Power House will be rendered unusable for many months or even years. However, as reflected in Table 10, we assume a restoration time of approximately two months, which is the amount of time we assumed it would take to set up a temporary pumping station adjacent to the Power House.

- *Natural Gas*: While loss of offsite supply is a significant contributor to downtime at lower intensities, at higher intensities our models predict significant downtime due to tripping of automatic gas shut off valves throughout campus. Based on discussions with UBC staff, we expect it would take approximately 2-3 hours per building to reset shut off valves and restore gas service. When aggregated across the entire campus, this results in significant restoration times.

- *Thermal Energy*: In general, the thermal energy system is highly redundant and consequently has essentially no downtime at any earthquake intensity. While our model of the thermal energy system includes critical interdependencies, it does not account for depletion of diesel fuel reserves, an event that is likely to occur if the natural gas supply is disrupted for longer than a few days.
- *Sanitary Sewer*: Unlike other utility systems, the primary contributor to downtime for the sanitary sewer system is pipe breaks. This would allow leakage into the environment and also potentially cause blockage of the pipes. In addition, the water and sanitary sewer systems are tightly coupled: if there is a loss of water service, the sanitary sewer system will be rendered unusable. Furthermore, our model does not include the impact of downstream failures on the campus system (i.e., the Iona Island Wastewater Treatment Plant is damaged and goes offline) because it is unclear what impact these failures will have on the campus (i.e., Metro Vancouver may decide to discharge untreated wastewater into the Strait to prevent sewer backups throughout the region).

7 Evaluation of operational risks

Operations planning is a critical element of resilience for cities, corporations, and universities. Understanding how UBC will respond after a major disaster from an organizational standpoint is as important as understanding how each building will perform in an earthquake. The operational risk assessment conducted by Arup evaluates both emergency response capabilities in the hours and days immediately after an event and also the capacity for long term recovery over the span of weeks and months. Successful operation of the Point Grey campus is contingent on internal organizational structures and protocols to ensure continued delivery of essential services and functions.

We used the risk assessment described herein to identify gaps and vulnerabilities which ultimately led to a series of recommendations described in section 8.3.

7.1 Overview of approach

Arup has conducted a detailed assessment of UBC's operations which evaluates the university against a hierarchy of four critical dimensions and associated drivers and indicators characteristic of highly resilient organizations. Arup developed a framework for this purpose, the Campus Resilience Index, which is an adaptation of the Arup/Rockefeller City Resilience Index, which has been deployed globally as part of the 100 Resilient Cities project (Arup 2015). Table 11 provides an overview of the dimensions, drivers, and indicators included in the Campus Resilience Index for which UBC was evaluated against.

We refer the reader to Appendix M for a comprehensive assessment of each indicator, including relevant background information, and identification of current progress and gaps.

Table 11 Overview of dimensions, drivers, and indicators within the Campus Resilience Index

Dimension	Driver	Indicators
People	Basic Needs	Food Supply; Water Supply; Sanitation Systems; Waste Management; Climate Control
	Healthcare	Medical Services; Medication Availability; Mental Health Counseling; Emergency Response
	Safety	Campus Guidelines; Security; Safe Environments; Fire Response
Business	Finance	Insurance; Funding; Student Financing; Managed Expenditures
	Revenue	Services; Market; Investment; Business Impact Assessment
	Operations	Asset Management; Logistics; Business Continuity Planning; Emergency Operations Center
Assets	Facilities	Housing Capacity; Emergency Shelter; Instruction Space; Codes, Standards, and Enforcement
	Utilities	Energy Supply; Energy Dependence; Communication Systems; Data Storage; Maintenance Programs
	Mobility	Accessibility; Transportation; Land Use Planning; Way Finding
Organization	Strategy	Mission; Emergency Planning; Policy; Hazard and Risk Mapping
	Community	Stakeholders; Support Networks; Engagement; External Ties
	Leadership	Communication Plan; Management Team; Commitments to Resilience; Staffing Plan

7.1.1 Data sources

Given the diverse set of indicators included within the index, we compiled information from a wide range of sources, including:

- Workshops, interviews, and personal communications with UBC staff, including:
    - Danny Smutylo, Emergency Manager, Risk Management Services
    - Ron Holton, Chief Risk Officer, Risk Management Services
    - Michael Frost, Manager, Financial Operations
    - John Madden, Director of Sustainability and Engineering, Campus and Community Planning
    - Ian Burges, Comptroller
    - Edmond Lin, Chief Building Official, Campus and Community Planning
    - David Woodson, Paul Holt, Richard Hugli, and Aleksander Paderewski, Energy and Water Services
- Documents shared by UBC staff or available publicly, including the draft emergency management plan (EMP) and annexes, business continuity plans, risk register, land use plans, and department websites.
- Best practices from other universities, including emergency management plans and resilience plans for the University of California, Berkeley and the University of Washington.
- International business continuity standards, including BSI (2012) and NFPA (2016)

7.2 Operational risk assessment

Using information gathered from the sources described above, we estimated a score for each indicator and then combined these scores to derive an overall resilience score for the university. These scores are bound between 1 and 5, with a score of 1 indicating significant vulnerability and a score of 5 indicating robustness.

Table 12 provides scores for each resilience driver, including a summary of the contributing factors that led to the score (Figure 8 provides a graphical representation of the scores in Table 12). These scores are derived from the average scores for each of the indicators in Table 11. Despite efforts to be as comprehensive as possible, we were unable to gather sufficient information to assign scores for a small number of indicators. For more information about how each indicator was scored, refer to Appendix M. Based on these numbers, we estimate the university currently achieves an overall resilience score of 2.9 out of 5. This indicates that there is opportunity for improvement of operational performance through increased planning and preparedness for shocks and stresses, as discussed in the following paragraphs and Appendix M and outlined in our recommendations in section 8.3.

In general, UBC has developed a strong collection of planning and preparedness documents for responding to emergency events and long term stresses. This groundwork signifies a good understanding of the importance of risk management and, to a degree, long term resilience planning. However, implementation of these plans (in terms of developing necessary organizational structures and protocols and assigning clear roles and responsibilities) is still under development in many areas.

Table 12: Resilience score for each driver within the Campus Resilience Index

#	Driver	Score	Contributing Factors
1	Basic Needs	3.0	UBC has set ambitious goals for providing basic needs to the campus population for 72 hours after an emergency, but progress towards achieving these goals appears to be limited.
2	Healthcare	3.0	UBC has significant healthcare infrastructure on or near campus, but it is vulnerable to seismic damage and contingency plans have not been developed.
3	Safety	3.0*	Crime on campus is low but earthquakes, fire following earthquakes, and wildfire pose a significant risk to the safety of students and staff.
4	Finance	3.0*	UBC has insurance for most campus buildings and roughly $20m CAD for emergency response, but there is uncertainty about the timing of insurance payouts and adequacy of coverage (for the Optional policy).
5	Revenue	2.0*	UBC has a large endowment but has not conducted a campus-wide business impact assessment to identify and protect important revenue streams.
6	Operations	3.3	Some campus departments have completed continuity plans but most are incomplete and a campus-wide plan to ensure operational continuity has not been developed.
7	Facilities	3.3	UBC has renewed several high-risk buildings and made significant investments in housing, but swing space is limited and plans for accommodating displaced students and staff are lacking.
8	Utilities	3.0	Utility systems on campus are generally robust but there are critical vulnerabilities. Backup systems are inadequate to meet normal campus operational demands and emergency response

			needs. UBC staff are aware of these vulnerabilities and taking steps to address them.
9	Mobility	3.0	Students and staff utilize a diverse set of commute options but access to campus is limited by geography and contingency plans for disrupted transportation are lacking.
10	Strategy	3.5*	Emergency response planning is robust but continuity and recovery planning is lacking. UBC is taking steps to address this, including the assessment provided herein to aid in developing a resilience strategy.
11	Community	2.3	Staff recognizes the importance of collaborative, multi-jurisdictional planning but has a limited number of MOUs in place with community organizations.
12	Leadership	2.3	Roles and responsibilities in an emergency situation are unclear; campus lacks a chief resilience officer to take ownership and lead related efforts.

* Score based on two or fewer indicators, therefore it may not be an accurate representation of risk

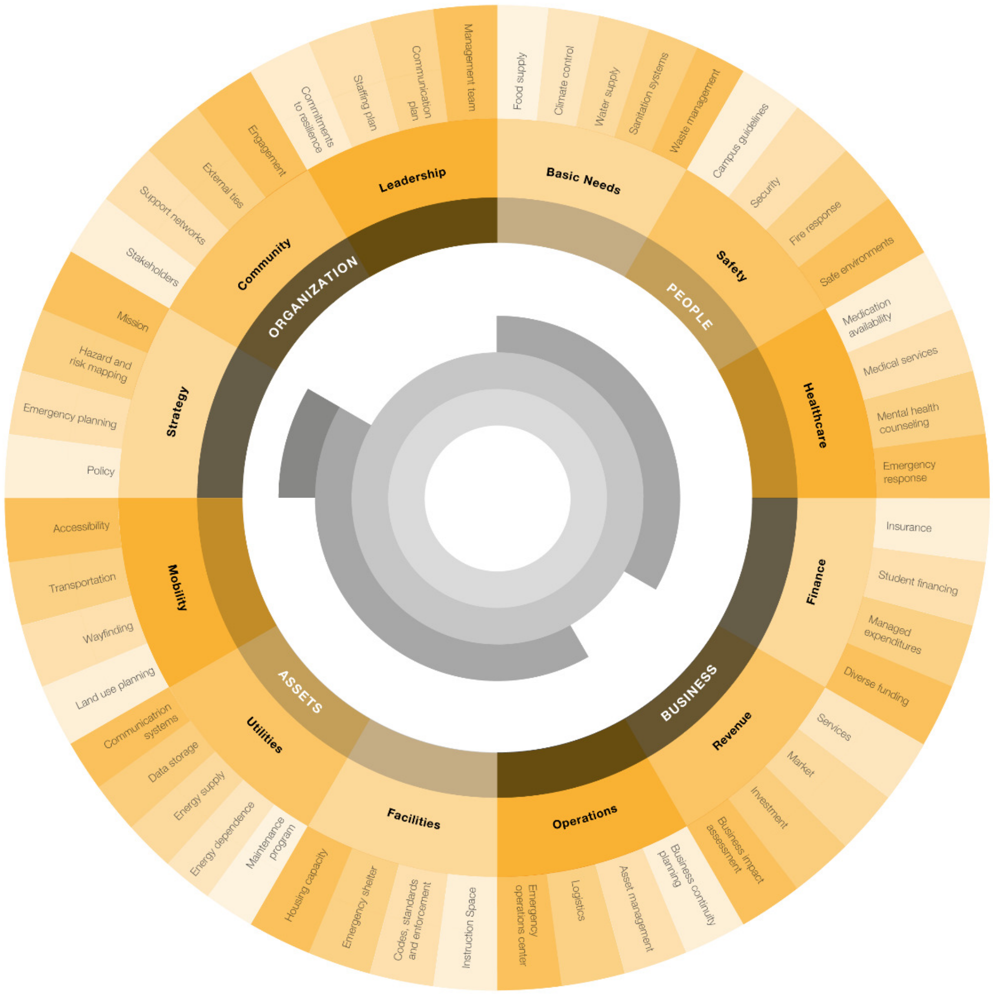


Figure 8: Resilience score for each driver within the Campus Resilience Index

8 Recommended actions

Based on the risk assessments described above, Arup has developed a list of recommendations for buildings, utilities, and operations. The recommendations are divided into highest priority actions and additional priority actions. The list is not necessarily exhaustive, but identifies what we believe to be the highest priorities on campus.

8.1 Buildings

8.1.1 Highest priority actions

1. **Additional building evaluations**: Based upon a screening-level risk assessment, Arup has identified individual buildings that potentially pose the greatest risk on campus (see Appendix H). Multiple strategies have been developed in order to prioritize mitigation of these risks, in large part aided by cost-benefit analysis (see section 5.7). Detailed engineering evaluations (including advanced structural analysis) should be conducted on a proportion of these buildings, to be decided by UBC, in order to do the following:

    - Identify specific deficiencies and vulnerabilities unique to each building
    - Confirm the results of the initial risk assessment, including collapse probability
    - Determine whether retrofit is warranted based on collapse risk
    - Propose targeted retrofit solutions
    - Estimate related costs
    - Reassess the benefits versus costs, if so desired

2. **Nonstructural component retrofits**: The table below provides next steps for addressing the Very High nonstructural life safety hazards identified in section 5.4.2. Mitigation of High life safety nonstructural hazards (see Section 5.4.2) and those having a significant impact on business continuity (see Section 5.5.3) should also be pursued but may be part of a longer term strategy.

Table: Recommended mitigation of Very High nonstructural life safety hazards

Nonstructural Component	Recommended Next Steps
• Masonry interior partition walls • URM chimneys • Parapets	Confirm inventory (see Appendix H) and retrofit (see Appendix K for conceptual mitigation measures and costs)
• Heavy exterior cladding (brick, brick veneer, precast concrete)	Confirm inventory (see Appendix H). Identify egress routes and areas of congregation that could be most vulnerable. Temporary mitigation measures may include restriction of pedestrian access or safety nets for the most vulnerable locations. Detailed evaluation of connection conditions and details for a representative sample of buildings to confirm anticipated seismic performance (see Appendix K). Cost-benefit analysis may be pursued to determine whether retrofit is warranted.
• Brittle glazing	Confirm inventory. Identify egress routes and areas of congregation that could be most vulnerable, particularly from overhead glazing. Use safety film, replace brittle glazing, or restrict pedestrian access to vulnerable locations (see Appendix K).
• Egress stairs	Perform inventory of stairs and connection details, focusing on older buildings. Those with seismic joints with inadequate bearing pose the greatest life safety threat. Once identified, retrofit. (see Appendix K for conceptual mitigation measures)
• HVAC ducting (inadequately braced)	Perform inventory of HVAC ducting and bracing details, focusing on older buildings. Cost-benefit analysis may be pursued to determine whether retrofit is warranted.

3. **Protection of contents**: The risk assessment indicates that loss of contents could be significant — of equivalent value to costs to repair building damage. Contents which pose a life safety threat are identified in section 5.4.2. We recommend developing guidelines for protection of valuable (and invaluable) contents to be implemented as retrofits in existing buildings and as the standard of care in new buildings. The University of California, Berkeley has developed and implemented similar guidelines. Cost-benefit analysis may be pursued to determine the highest priority contents for protection.

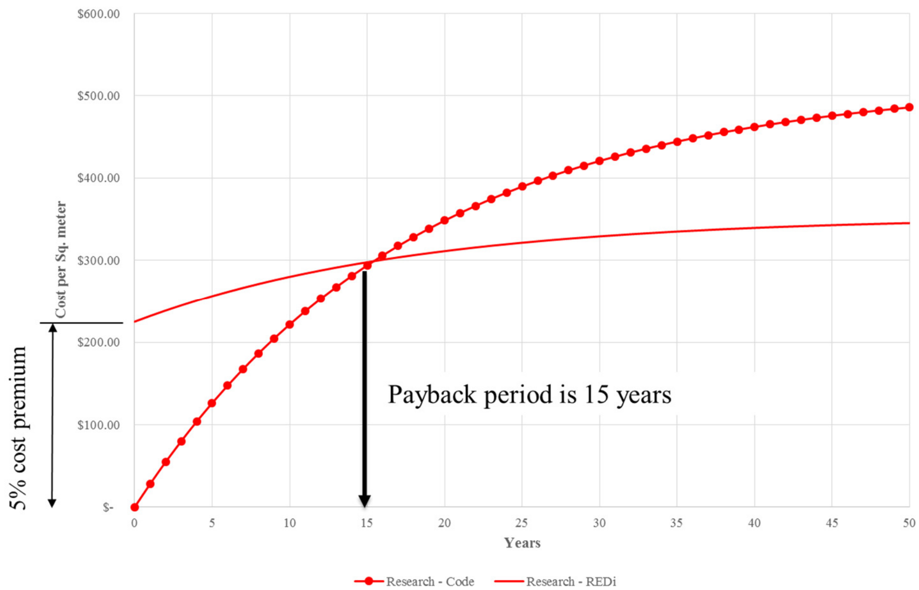
8.1.2 Additional priority actions

1. **Guidelines for seismic retrofit of existing buildings**: Prior to the recent "Renew" program (aiming to retrofit to a minimum of 75% of current code), there appeared to be significant variation in the performance targets for the seismic retrofits performed over the past 25 years. At the same time, the lack of well-defined methodologies for both the evaluation and retrofit of existing buildings within the Canadian context has led to some ambiguity of the specifics within the approach to achieving the current goal (i.e. the inclusion or exclusion of façade within the retrofit). While this variation mirrors the evolving knowledge base in seismic retrofit within the practice of structural engineering over this same time period, the lack of consistency means that relative risks between retrofitted, and even un-retrofitted buildings, may not be well understood.

   We recommend development of a retrofit guideline that clearly indicates performance objectives (for structural and nonstructural components), an assessment method, and acceptance criteria. We also recommend that clear criteria for what triggers a seismic retrofit is developed. The results from the additional building evaluations will greatly aid this.

2. **Guidelines for seismic design of new buildings**: We performed approximate cost-benefit studies (see Figure below) that indicate that there is a significant return on investment in designing new buildings to beyond-code performance objectives, targeting higher functionality targets (e.g., REDi Gold rating). This can be achieved by reducing anticipated damage to structural and nonstructural components via enhanced design. We recommend that the cost-benefit analysis be refined via new pilot projects, that performance objectives be optimized, and that resilience-based design guidelines be either developed or modified to suit UBC's needs. This could be undertaken as a series of pilot studies for new buildings.

   Figure: Example showing payback period for designing new research facilities on campus to higher resilient standards assuming 5% cost premium relative to code



8.2 Utilities

8.2.1 Highest priority actions

1. **Power House decommissioning**: Water pumps in the Power House are responsible for distribution of water to campus buildings and firefighting infrastructure. As noted previously (see section 6.2.2), the Power House is highly vulnerable to partial or full collapse in strong earthquake shaking and is the primary contributor to water disruption (see also Appendix L). We understand that mitigation efforts are currently underway, including decommissioning of diesel-fired backup water pumps and a brittle transmission line in the Power House. These are positive developments, but the most important action is to move the water pumps to a new location or facility, and reroute transmission and distribution lines accordingly. Based on cost estimates from LEC Group, this would require an investment of $16m CAD.

2. **Provision of backup water supply for firefighting**: Arup has performed a qualitative desktop evaluation of the risks posed by fire following earthquake (see Arup 2017). Recommendations and next steps for reducing fire following-earthquake risks are outlined in that report. A consequence of having water disruption after an earthquake, even for a short amount of time, is the inability to fight potentially multiple fires at once, which could then turn into a conflagration. Our utility assessment indicates that even if the Power House is decommissioned, the supply of water from Metro Vancouver will still likely be disrupted due to damage upstream from campus. Given the lack of onsite water storage capabilities, we recommend UBC investigate options for providing a permanent source

of water and accessibility for firefighting. Potential sources include the swimming pool at the Aquatics Centre, the water feature at W. University Ave, storm water catchments, new wells, and the Strait of Georgia.

3. **Diesel storage and distribution**: Given the strong dependence of most campus utility systems on electric power, we recommend that UBC develop the necessary physical and operational infrastructure for storing 2 to 3 days of diesel fuel (the anticipated disruption in the Rare earthquake) and distributing it to campus buildings and facilities. We understand that UBC has significant diesel fuel storage capacity at the Power House, and has also commissioned a preliminary design of a diesel tank farm in south campus. We recommend UBC evaluate both options further. Once a storage facility is established, we recommend UBC develop robust operational procedures for transporting fuel from the central facility to end users (e.g., Campus Energy Centre, backup diesel generators at critical research facilities and lift stations), in addition to establishing contracts with local diesel suppliers to refill the central facility after an earthquake.

4. **Access to potable water:** UBC has a portable pumping and filtration station that can provide potable water to the campus population in the event of a disruption to normal service. However, this station will likely be unable to meet the needs of the campus population (5-9 liters per person per day recommended), especially in the event of a protracted disruption to municipal supply or damage to the Power House, as currently predicted in our utility risk assessment. Furthermore, UBC currently lacks both a strategy and the necessary infrastructure for distributing potable water from the filtration station to students and staff on campus. Consequently, we recommend UBC develop and implement a strategy for securing and distributing an adequate supply of potable water in an emergency (including arranging contracts with private water suppliers to deliver potable water after an earthquake).

8.2.2 Additional priority actions

1. **Protection of electrical transformer**: There are two electrical transformers at the main substation that supply power to most campus buildings. If significantly damaged, the consequences can be severe — UBC staff indicate that it could take up to 6 months to repair them because they need to be sent off-site for repair. We performed a comprehensive literature review and found that much smaller transformers performed relatively well in earthquakes. However, we could not find anecdotal evidence or testing results for transformers as large and tall as the existing transformers. In our utility assessment, we adopted the vulnerability functions for the smaller transformers, having no other alternative. This may be unconservative since the center of gravity of the electrical transformers on campus is higher and therefore potentially more

susceptible to toppling. Given the potential consequences, we recommend performing a virtual shake-table test (i.e., computer simulation) to confirm the anticipated performance. We also recommend that the adequacy of the anchorage details be verified and strengthened if required, regardless of whether the virtual simulation is undertaken.

2. **Coordination with municipal suppliers and other organizations**: Because loss of municipal supply is a major contributor to utility outages on campus (see Appendix L), we recommend working with local utility providers (e.g., BC Hydro, Fortis BC, Metro Vancouver) to understand the likely performance of Vancouver utility systems and obtain better estimates of expected service disruptions following different earthquake scenarios. Depending on the findings, UBC may advocate for strengthening of municipal utility systems or seek assurances of performance. In addition, we recommend engaging with staff at the University Endowment Lands (UEL) to develop a mutual aid agreement to speed the repair of potential damage to water mains on their property after an earthquake, as damage to these water mains would completely disrupt water service on campus. This is important because the UEL likely lacks the resources to make repairs in a timely manner.

3. **Measures to speed post-earthquake repairs:** We recommend UBC evaluate and expand its inventory of its pipe clamps in accordance with damage estimates presented in Table L.25 in Appendix L. In particular, we recommend to have an inventory of at least three pipe clamps for each of the most common pipe diameters on campus to prepare for the number of pipe breaks expected in the Very Rare earthquake. We also recommend having a welder on retainer or staff to help speed pipe repairs, and a company on retainer to deliver a hydrovac to campus within 24 hours of a damaging earthquake to speed excavation of damaged pipes.

4. **Strategy for restoring natural gas service:** After a large earthquake, we anticipate a large number of automatic gas shut off valves will be triggered. It will require intervention from campus staff before gas service can be restored to a building. We understand it takes approximately 2-3 hours to restore service to an individual building, including resetting the valve, pressure testing the building's gas lines, and relighting appliances (assuming no issues are discovered). When aggregated across the entire campus building stock, it could take weeks to restore gas service to all buildings. To speed this process, we recommend developing a comprehensive response strategy, including development of a prioritized list of buildings for restoring service.

5. **Additional strengthening of Campus Energy Centre:** We understand staff at the Campus Energy Centre is planning to put additional equipment on the backup circuit; we recommend pursuing this activity as it increases the capacity of the thermal energy system in the event of a gas disruption.

6. **Mitigation of critical sewer catchment pipe:** The sewer catchment pipe at the north end of campus is near an eroding cliff, which if not mitigated will impact the pipe in the next 10 years. Given the consequences for campus if this pipe were to fail, we recommend UBC lead the effort to engage the necessary stakeholders to mitigate this vulnerability.

8.3 Operations

8.3.1 Highest priority actions

1. Appoint a Chief Resilience Officer to implement the seismic risk mitigation strategy developed herein and to lead future resilience initiatives. This role would also include coordination and integration of the various emergency response and business continuity planning efforts.
2. Reduce life safety risks through operational measures:
    - In buildings identified as highly vulnerable (Tier III and IV), provide sturdy furniture (e.g. desks) that can be used to huddle beneath. This has proven to save lives in past earthquakes.
    - Reduce exposure of populations within highly vulnerable buildings (Tier III and IV) including moving classes to newer buildings and/or modify (shorten) class times. Based on data provided by UBC, a preliminary assessment of classroom utilization rates suggests there is flexibility to accommodate this.
    - Prevent people from congregating adjacent to buildings identified as having Very High external falling hazards (see Appendix H).
    - Continue regular Drop, Cover, and Hold exercises.
    - Identify a procedure for evacuating people from trapped elevators.
3. Complete, validate, and implement emergency management plan which is currently in draft form:
    - Clearly assign roles and responsibilities for individual staff members and contingency plans for unavailability of off-site staff in the first 24 – 72 hours.
    - Develop contingency plans for emergency medical response in the event the hospital is significantly damaged and not functional (as predicted by our risk assessment). Confirm MOU to permanently locate mobile ambulance unit on campus.
    - The risk assessment indicates that the University Services Building may not be operational in moderate shaking. We recommend relocating the EOC to a newer building (we understand this may already be underway). In general, we also recommended utilizing the risk results to re-assess the selection of post-disaster facilities and to understand the performance of mission-critical facilities.
    - Develop clear protocol and regular training for staff usage of virtual EOC.
    - Upgrade mass notification system technology and infrastructure to increase speed and reliability.

- Implement a safety check-in system for students, faculty, and staff using available technology or via social media (e.g. can check-in safe on Facebook).
- Review feasibility of goal attainment thresholds (e.g., food, water and sanitation for 72,000 people for 72 hours).
- Ensure training exercises (such as the vehicle-induced mass casualty training event held on June 28, 2017) are performed regularly, including all responsible staff and partner stakeholders, and for multiple earthquake (and fire following earthquake) scenarios which will damage and disrupt infrastructure (the risks identified by this study may be used for disaster scenario simulations). The scenarios should also include aftershocks.
- Review plans for emergency food, fuel, water, sanitation and medical relief supply. Undertake a risk assessment of supply chains and identify sources of emergency supplies. This may also include, for example, delivery logistics, over damaged bridges and alternative strategies including identification of helicopter landing areas or provisions from the sea.
- Develop plans and roles for securing damaged buildings.
- Develop animal welfare plans.

4. Prepare, complete, and validate business continuity and contingency plans for hastening post-earthquake recovery:
    - Comprehensive review of existing business continuity plans (which have been developed to varying levels of detail by different groups), to ensure that each department (or group) has a detailed plan and that there is consistency between departments.
    - Establish campus-wide recovery plans for business functions and services including continuity of teaching, research, and other revenue-generating activities, in coordination with individual departments. Recovery timelines and plans may be greatly aided by the predicted downtime to buildings and utilities from this study. Clearly identify responsibilities and roles for individual staff.
    - Complete building inspection protocols and clearly identify roles and responsibilities for individuals. Establish timelines, priority buildings, and ensure consistent inspection procedures (e.g. ATC-20). In addition, supply each building with a "go bag" which includes inspection checklist, structural plans for the building with lateral system identified, different color placards, and ATC-20 field manual. Prioritization of post-earthquake inspection may also be aided by real-time risk assessment and drone technology (see below).

- Upgrade electronic data backup system (currently have cold backup site on Okanagan campus and data may take up to a year to retrieve). Ideally, this would be a protected hot site nearby (which would perform well in an earthquake) so that responsible staff could access it. Provide guidance for individual departments and researchers to backup critical research data.
- Review the list of essential facilities and confirm that all are equipped with backup systems. Ensure capacity is sufficient in preventing loss of research specimens and data.
- Initiate goal setting efforts to define critical continuity thresholds (e.g., Stanford University has identified maximum allowable space loss for academic spaces). This may also include completing a resilience matrix of performance objectives (including downtime and asset protection) for various earthquake scenarios.
- Set up contracts and retainers with local businesses (e.g., contractors, engineers) to mitigate impeding factors that delay initiation of building repairs.
- Confirm funding triggers and payout schedules for insurance and federal/provincial disaster aid and confirm that insurance coverage for buildings in the Optional policy are adequate.

5. Develop an interactive digital risk management platform to capture current building risks and dynamically chart progress of mitigation. Platform can also be used to store important data in one place. This may be integrated with UBC's Archibus system.

8.3.2 Additional priority actions

1. Train volunteers for emergency response, including students, faculty, and staff (similar to Neighborhood Emergency Response Teams in San Francisco)
2. Install earthquake sensors on campus to measure ground motions and connect to digital risk mitigation platform (identified above) to run real-time assessment of infrastructure damage after an earthquake. This would aid in decision-making in the hours, days, and months after the earthquake.
3. Implement earthquake early warning system, in coordination with regional efforts, if the technology is sufficiently developed. This could provide enough time to allow campus populations to find shelter from falling debris.
4. Develop a process for post-earthquake permitting, including criteria for which type of damage requires a permit.
5. Audit existing data on buildings. The risk assessment is based on this data, including building properties and contents. We found that the data was located

in multiple source documents and that some data was either incomplete or appeared incorrect.

6. Acquire a drone and use it to provide real-time assessment of damage. This may help inform the decision-makers in prioritizing emergency response.

7. Set up agreements with contractors on campus to use their heavy equipment in the event of an earthquake for the purpose of rubble/debris removal. This may also aid in search and rescue, and potentially used for repairing buried pipelines, but personnel would need proper training.

8. Relocate materials from South Campus Warehouse, which is prone to collapse.

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Appendix A

Glossary of Terms

A1 Glossary of Terms

It is important to define some terms, as they are used throughout the report:

- **Building vulnerability**: the expected damage of a building or specific components within the building, given a certain demand parameter (such as intensity of ground shaking or acceleration/drift demands within the building). See also "Fragility function".

- **Collapse:** this refers to either partial or catastrophic (full) collapse of a building. Collapse is predicted to occur through the structural analysis when a transient interstory drift threshold is exceeded and/or if "run-away" drifts are observed in the analysis model. FEMA P-154 defines collapse when the gravity load carrying system in one part or all the building loses the ability to carry the weight.

- **Confidence levels**: see Section 5.1.2.

- **Downtime**: the time required to achieve either re-occupancy, functionality, or full recovery in the aftermath of an earthquake, considering the time it takes to repair the building and delays to initiation of repairs (i.e. impeding factors). See Appendix C for further details.

- **Exposure:** the location of buildings relative to the areas of varying hazard levels (i.e. buildings in high hazard zones have high exposure) and the number of people, value of assets, and mission-critical contents that could be impacted by building performance.

- **Fragility function**: each building component has a unique fragility function which defines the probability that the component would incur a discrete level of damage (damage state) given a specified seismic demand parameter.

- **Hazard:** the intensity of earthquake shaking measured at the site. This could be intensity-based (i.e. corresponding to specific return periods calculated utilizing probabilistic methods) or scenario-based (i.e. corresponding to a specific magnitude and distance). For this study, the seismic hazard is intensity-based.

- **Life safety and target probability of collapse for new buildings**: Non-essential facilities designed to meet minimum US code design requirements are intended to protect occupants from "life-threatening damage" (NEHRP, 2009) due to structural collapse or failure of non-structural component in a design level ground motion. In the US, the intended performance objective is low probability of collapse in the Maximum Considered Earthquake (MCE) which is analogous to the Very Rare earthquake in this study. The probability of collapse target is 10% for new buildings in the MCE (ASCE 7 2010). This performance is not explicitly verified – it is an implied outcome of satisfying the code design provisions. The intended performance of buildings satisfying the Canadian building codes is expected to be similar, although it is not explicitly defined.

- **Performance-based seismic analysis:** see time-history analysis.

- **Risk:** the consequences of the expected damage of a building in terms of casualties, repair costs, and downtime. The risk integrates the hazard, building vulnerability, and exposure. The term “losses” is also used interchangeably with risks.

- **Shear wave velocity:** a measure of the stiffness of soil.

- **Site Class:** classification assigned to a site based on the types of soils present and their engineering properties. The Site Class provides an indication of how the soils may amplify or attenuate ground shaking at various structural periods. The campus is classified as Site Class C, which is Very Dense Soil and Soft rock according to ASCE 7.

- **Structural period:** the period of a building is a dynamic properties which typically refers to the time it takes for a building, if excited horizontally by ground shaking, to complete one cycle of sway from back and forth. This is known as the “fundamental” or “natural” period of vibration.

- **Time-history analysis**: a mathematical representation of an individual building is subjected to recordings of real earthquake ground motions (sometimes scaled) to virtually simulate the expected seismic performance. The most sophisticated time-history analyses (utilized for our analysis of 3 buildings on campus, see Appendix E) include a 3D representation of the building with all structural components modeled with nonlinear material properties (to model how the structure would behave after it cracks and yields). This is essential for assessing building behavior in large earthquakes and its collapse potential to the greatest level of accuracy possible using such predictive methods. In addition, time-history analysis can refer to application of unidirectional motions (one direction of earthquake shaking at a time), or bidirectional motions which better reflect the true motions a building would experience. For reference, the SRG2 approach utilizes a simple 1D representation of the building with nonlinear behavior represented for each story (not each structural component) and is subjected to unidirectional motions. Our LS-DYNA analysis also utilizes the same unidirectional motions (as opposed to bidirectional motions) because the purpose of LS-DYNA analysis was to calibrate the SRG2 analysis results.

Appendix B

Seismic Hazard and Earthquake Ground Motions

B1 Introduction

The seismic risk assessment study undertaken by Arup for UBC was based upon a probabilistic seismic hazard assessment (PSHA) performed by VC Dynamics Ltd. as described in their report entitled "Seismic Hazard for the UBC Campus" (VC 2017). Ground motion time-histories (used for the purposes of the structural analysis) and scaled to the hazard intensity levels considered in the risk assessment, were adopted from the Seismic Retrofit Guidelines (APEGBC 2013).

Relevant portions of this work are summarized herein.

B2 History of Seismic Hazard in Vancouver

The known seismic hazard in Vancouver has significantly changed over time, as denoted in Figure B1 (Mitchell et al. 2010 and Heidebrecht 2003), owing to the discovery of new faults, better characterization of earthquake magnitude recurrence intervals, and improvement in predictive ground motion attenuation relationships. In just the past 20 years, the seismic hazard has effectively doubled. The implication is that buildings designed to older codes are particularly vulnerable.

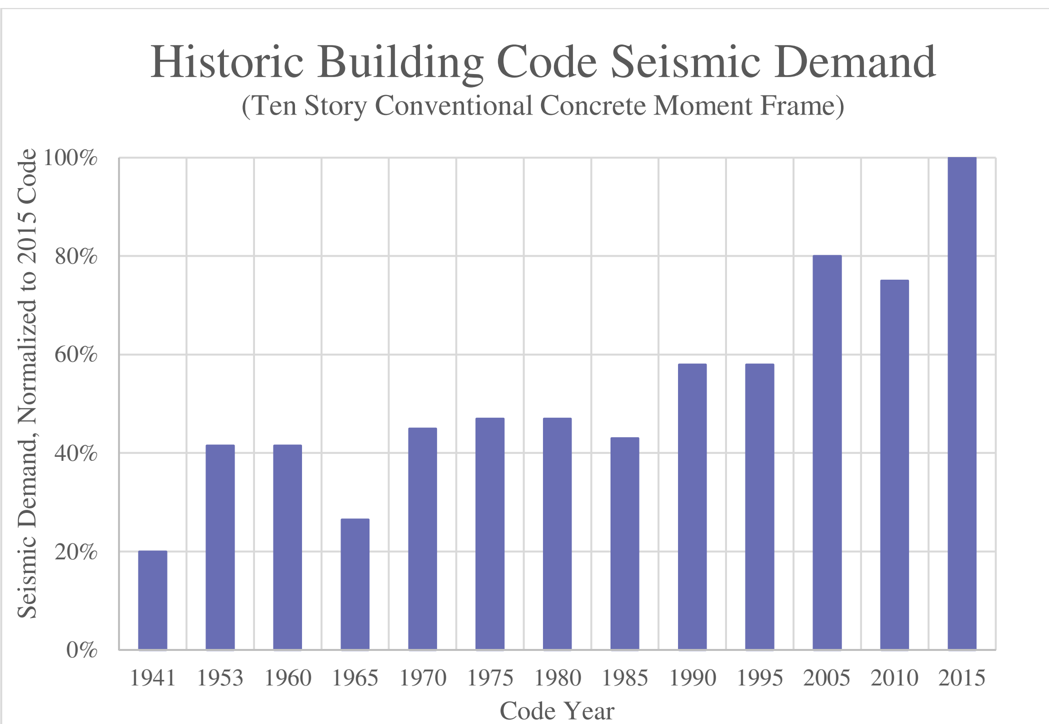

Figure B1 Increase in seismic demand over time per building code in Vancouver

B3 Seismic Hazard and Deaggregation

B3.1 Intensity Levels

Various hazard intensity levels (or return periods) of earthquakes were considered for this study, colloquially denoted as 'frequent', 'probable', 'rare', and 'very rare'. Each of the selected intensity levels and their respective return period are shown in Table B1.

Table B1 Selected intensity level earthquakes for seismic risk study

Intensity Level Earthquake	Return Period (years)	% Probability
Frequent	43	50% in 30 years
Probable	200	20% in 50 years
Rare	475	10% in 50 years
Very Rare	2475	2% in 50 years

B3.2 Response Spectra

Figure B2 shows the 5% damped acceleration and displacement response spectra for the various intensity levels. These correspond to geomean estimates of the hazard. Since there are no faults in the near-field of campus, there is no bias in terms of the maximum demand orientation. In addition since the entire campus has similar site properties (i.e. NEHRP Site Class C, see soil conditions report by exp Geotechnical Engineers (exp 2017)), there was no additional distinction for soil type.

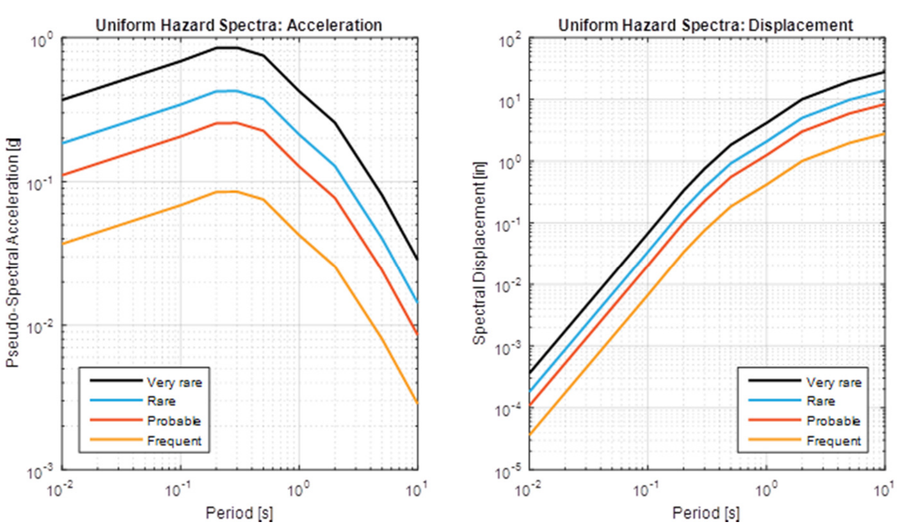

Figure B2 Hazard at each intensity level in terms of acceleration (g) and displacement (meters)

B3.3 Deaggregation

For each of these intensity levels, a different scenario (source, magnitude, distance, and shaking strength) was identified as controlling. These controlling scenarios are shown in Table B2. See VC (2017) for additional detail.

Table B2 Controlling scenarios for selected intensity levels

		Governing Earthquake Scenario				
Reference Name	**Return Period**	**Magnitude**	**Seismic Source**	**Source Type**	**Distance**	**Shaking Strength ***
Very Rare	2,475 years	M7.1	Georgia Strait & Puget Sound	Intraslab	70km	+0.9 to +1.1
		M8.9	Cascadia Subduction Zone	Interface	130km	+0.7
Rare	475 years	M7.1	Georgia Strait & Puget Sound	Intraslab	70km	+0.3 to +0.5
		M8.9	Cascadia Subduction Zone	Interface	130km	-0.5
Probable	200 years	M6.9	Georgia Strait & Puget Sound	Intraslab	70km	-0.9 to +0.3
		M8.9	Cascadia Subduction Zone	Interface	130km	-0.9
Frequent	43 years	M6.9	Georgia Strait & Puget Sound	Intraslab	70km	-0.9
		M6.7	Vancouver Island & Puget Sound (Shallow)	Crustal	30-90km	-0.9
* Number of standard deviations, where 0 standard deviations is the best estimate shaking (50th percentile) from the Magnitude specified, +1 standard deviations is the 84th percentile, -1 standard deviations is the 16th percentile						

B4 Selection and Scaling of Earthquake Ground Motion Time Histories

In order to perform structural analysis to obtain probabilities of collapse and building movement data (see Appendix D), multiple ground motion time history records at each intensity level were required. For this purpose, a subset of the ground motions selected to develop the database of building movements in the Seismic Retrofit Guideline (APEGBC 2013) were utilized.

B4.1 Scaling

The SRG2 database (APEGBC 2013) used the 2,475 year seismic hazard as a reference point and other hazard intensity levels were based on linear scaling of the 2,475 year level. For this reason, the scaling procedure results in approximate return periods at all other hazard levels (other than 2,475 year). See Figure B3.

Two suites of uni-directional ground motion time histories were linearly scaled to match a target conditional spectrum at a conditioning period of either 0.5 seconds or 1.0 seconds. These conditioning periods are appropriate for the building stock in the period range of roughly 0.1 and 2.0 seconds (this covers the entire building stock on the UBC campus).

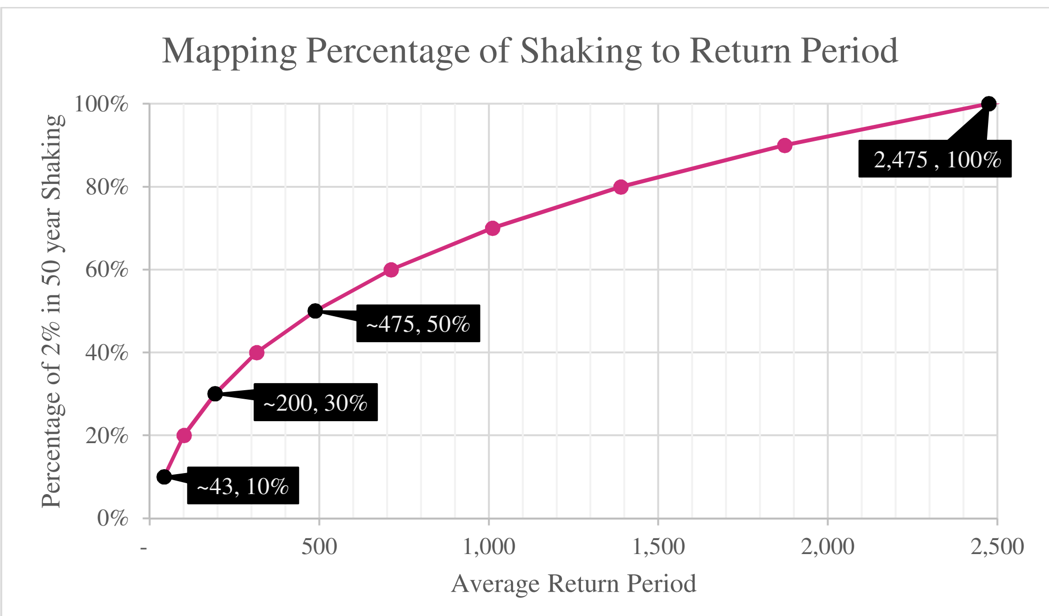

Figure B3 Scale factors from 2475yr return period to other intensity levels of interest

B4.2 Selected Ground Motion Suites

A short-period (Tc=0.5s) suite and a long-period (Tc=1.0s) suite with 20 motions each were selected, with the proportion of motions from each contributing source type chosen based on the deaggregation of the hazard to most accurately match their respective contribution to the overall hazard rate at that intensity level and conditioning period (see Table B3).

This is important because different scenario earthquakes feature different ground motion characteristics, such as duration of strong shaking or long-period accelerations. These different features of ground motions and scenarios can result in detrimental behavior of different subsets of buildings and building typologies. Thus, it is important to consider the correlation of ground motion between buildings for a given scenario earthquake. For the purpose of this study, it was deemed sufficient to consider the entire portfolio as one site (i.e. each building experiences the same ground motion acceleration history for a given earthquake scenario).

Table B3 Contribution of crustal, subcrustal, and subduction sources to each hazard level

Level of Shaking (% of 2% in 50 years)	T_c = 0.5 sec					T_c = 1.0 sec				
	$S_a(T_c)$ (g)	λ_{cr}	λ_{scr}	λ_{sd}	λ_{total}	$S_a(T_c)$ (g)	λ_{cr}	λ_{scr}	λ_{sd}	λ_{total}
10	0.075	23%	70%	7%	100%	0.043	29%	59%	12%	100%
30	0.225	15%	71%	15%	100%	0.128	18%	58%	23%	100%
50	0.376	13%	70%	17%	100%	0.213	15%	53%	32%	100%
100	0.751	15%	69%	16%	100%	0.425	15%	44%	41%	100%

The full set of motions is compared with the uniform hazard spectrum (UHS) in Figure B4.

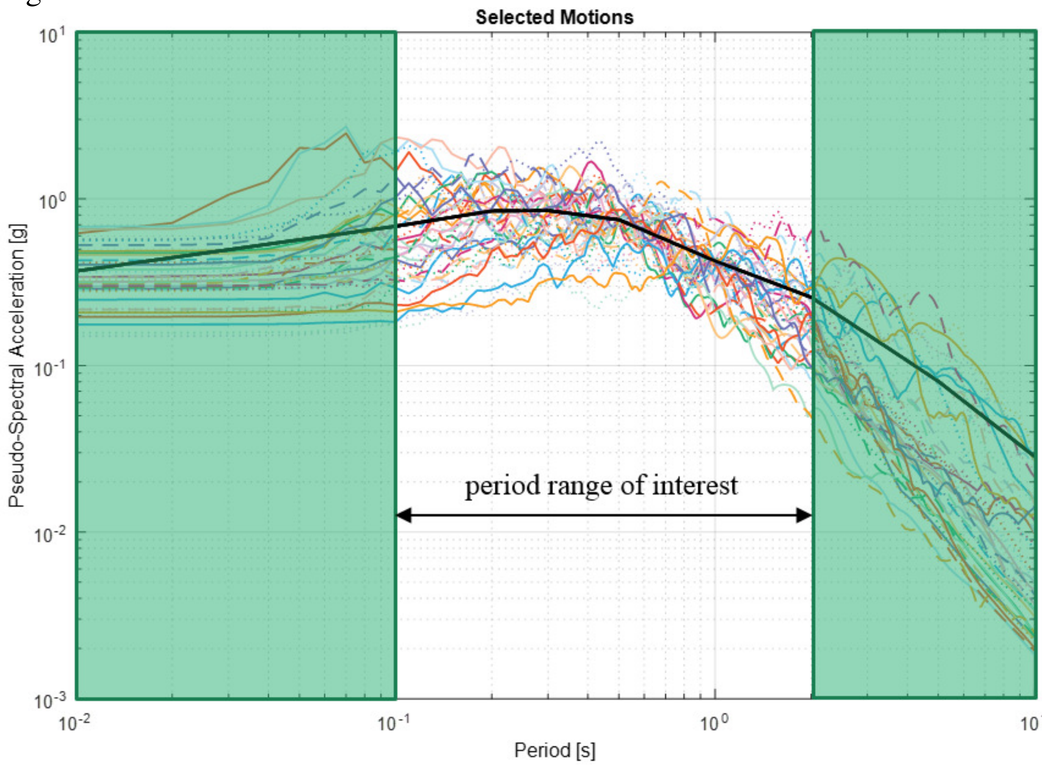

Figure B4 Suite of 40 selected ground motions for 2475yr compared with uniform hazard spectrum (UHS)

The set of motions included in the short-period suite and long-period suite are shown separately in Figure B5 and Figure B6. The motions are further broken down by source in Figure B7 through Figure B12.

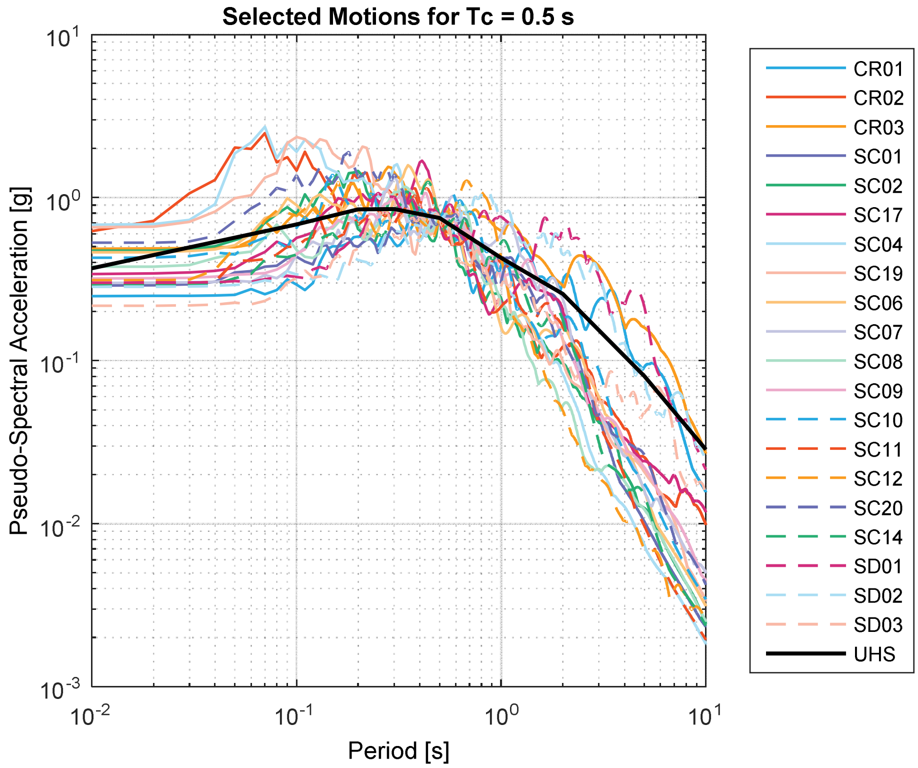

Figure B5 Selected 20 ground motions for the short period set (Tc=0.5s) at 2475yr

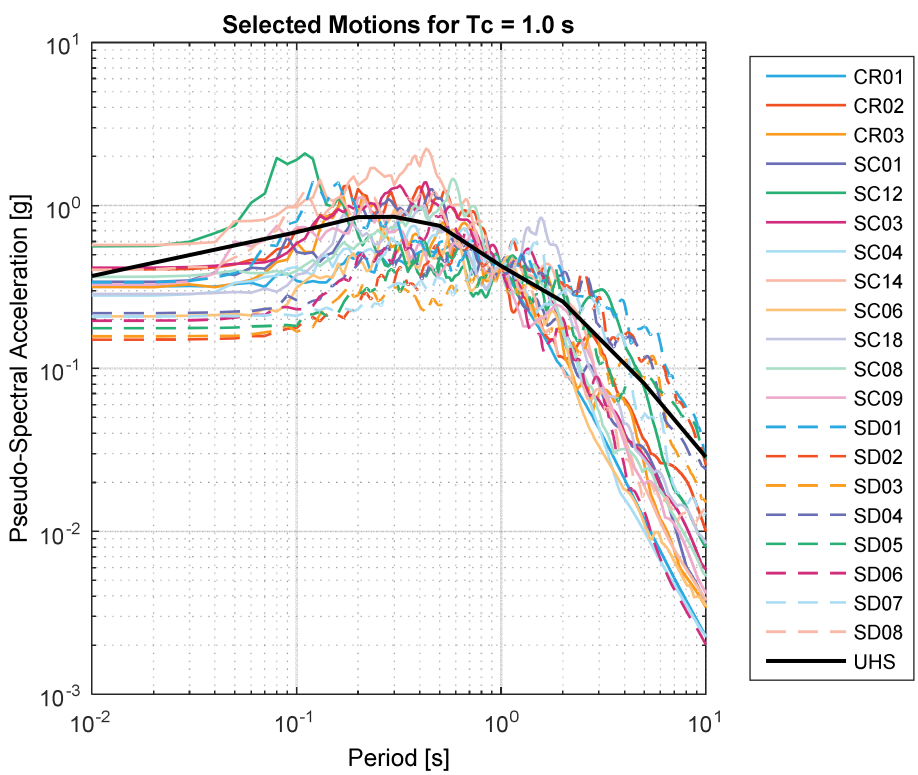

Figure B6 Selected 20 ground motions for the long period set (Tc=1.0s) at 2475yr

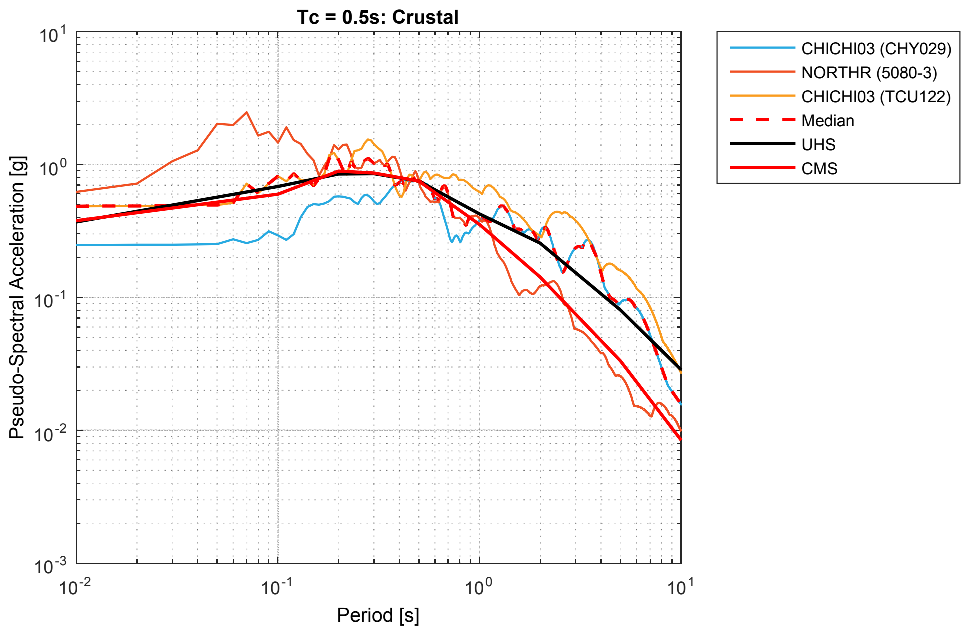

Figure B7 Selected short-period (Tc=0.5s) crustal motions for 2475yr compared with uniform hazard spectrum (UHS) and conditional mean spectrum (CMS)

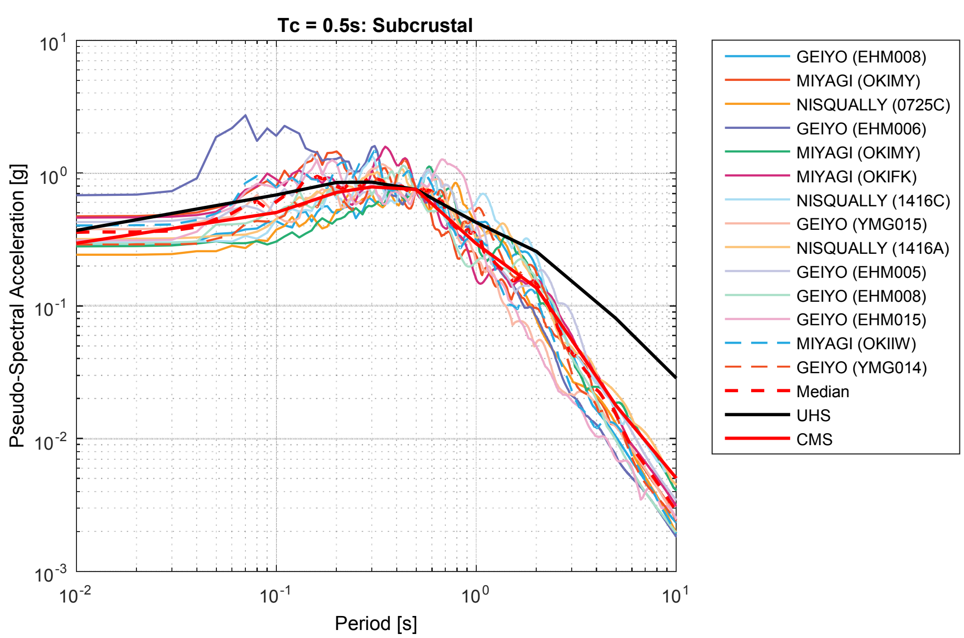

Figure B8 Selected short-period (Tc=0.5s) subcrustal motions for 2475yr compared with uniform hazard spectrum (UHS) and conditional mean spectrum (CMS)

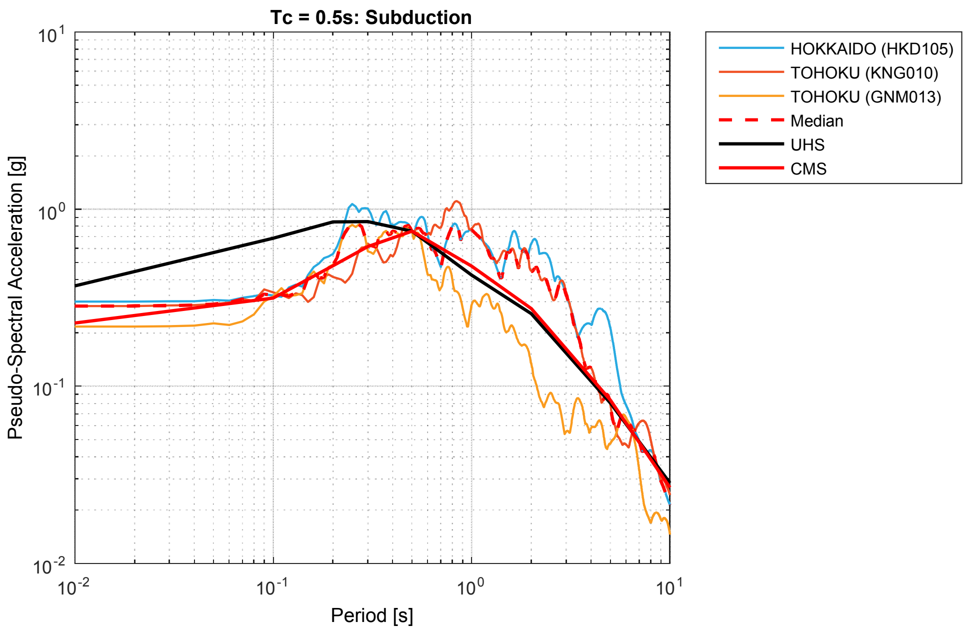

Figure B9 Selected short-period (Tc=0.5s) subduction motions for 2475yr compared with uniform hazard spectrum (UHS) and conditional mean spectrum (CMS)

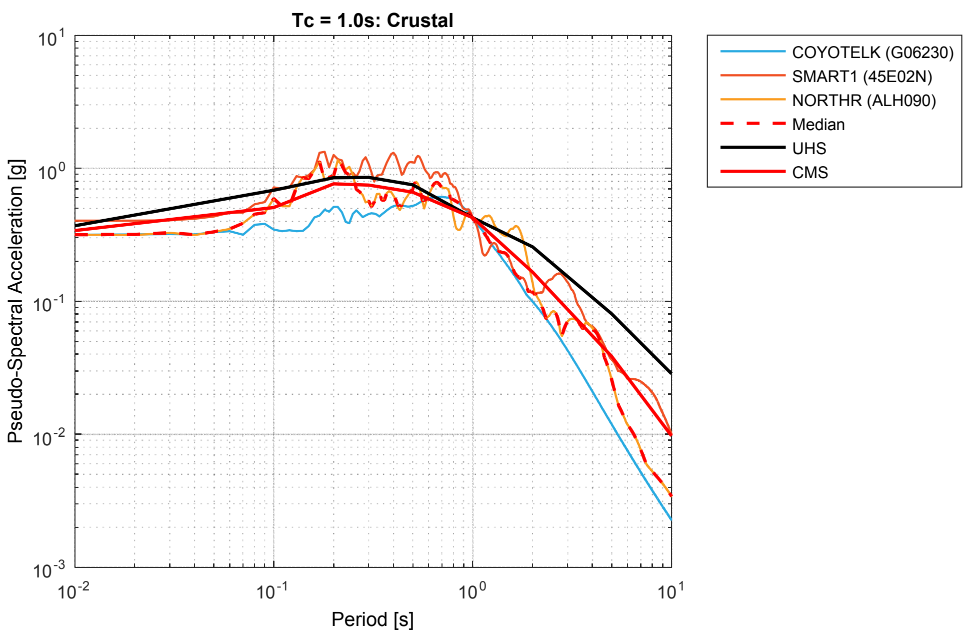

Figure B10 Selected long-period (Tc=1.0s) crustal motions for 2475yr compared with uniform hazard spectrum (UHS) and conditional mean spectrum (CMS)

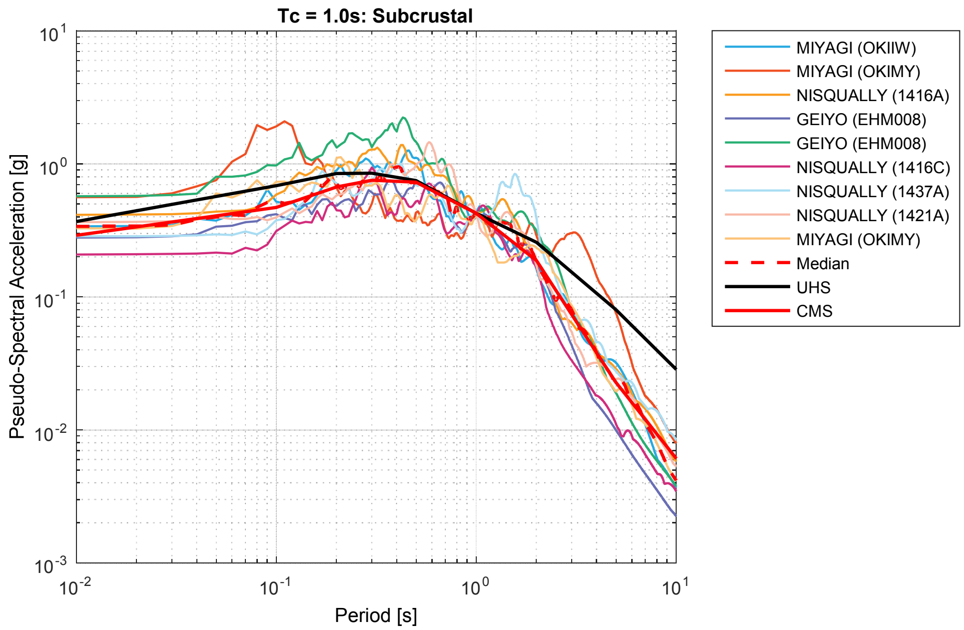

Figure B11 Selected long-period (Tc=1.0s) subcrustal motions for 2475yr compared with uniform hazard spectrum (UHS) and conditional mean spectrum (CMS)

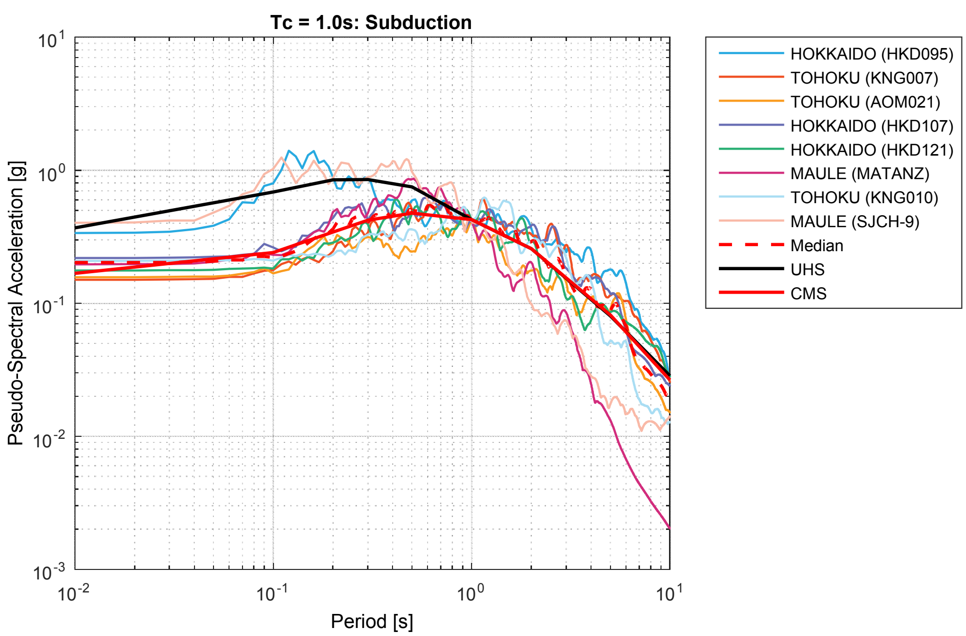

Figure B12 Selected long-period (Tc=1.0s) subduction motions for 2475yr compared with uniform hazard spectrum (UHS) and conditional mean spectrum (CMS)

B5 References

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Appendix C

Building Risk Assessment Methodology

C1 Introduction

This appendix presents the methodology utilized for the seismic risk assessment of the 328 buildings on campus in both their 'existing' state and their hypothetical 'retrofitted' state. The risk results are presented in Appendix I for the four earthquake intensity levels of interest: frequent, probable, rare, and very rare (see Appendix B). In this assessment, the key risk metrics considered are building collapses and demolitions, indoor casualty rate, repair costs, downtime, and content losses. These metrics are also annualized in order to perform a benefit-cost analysis (Appendix G) that ultimately offers prioritization of actions for various strategies to achieve the resilience objectives of the campus.

C2 Risk Analysis Framework

The modeling framework is largely comprised of the loss assessment approach outlined in the FEMA P-58-1 report (FEMA, 2012). This methodology represents the state-of-the-art in site specific risk assessment and is based upon ten years of research by FEMA. This methodology relates anticipated building movements (e.g. peak floor accelerations, drifts, and residual drifts) to damage of individual components (e.g. concrete walls, architectural glazing, domestic water piping) and their associated consequences (i.e. repair cost, repair time, casualty rate). Upon this framework, the REDi Downtime Assessment methodology (Merrifield and Almufti, 2013) was overlaid in order to convert the repair times into downtime through consideration of labor allocation, delays to initiation of repairs (i.e. impeding factors), and intermediate recovery states (i.e. re-occupancy and functional recovery) along the path to full recovery.

These calculations were performed at each of the four intensity levels for the set of 328 buildings on campus in both their 'existing' state and 'retrofitted' state. At each intensity level, 1,000 Monte Carlo simulations were performed for each building. Each realization corresponds to a specific earthquake scenario, from which the building movement data is extracted and the associated risk is determined as depicted in Figure C1 and Figure C2. See Appendix B for details on the seismic hazard and Appendix D for details on the estimation of structural response.

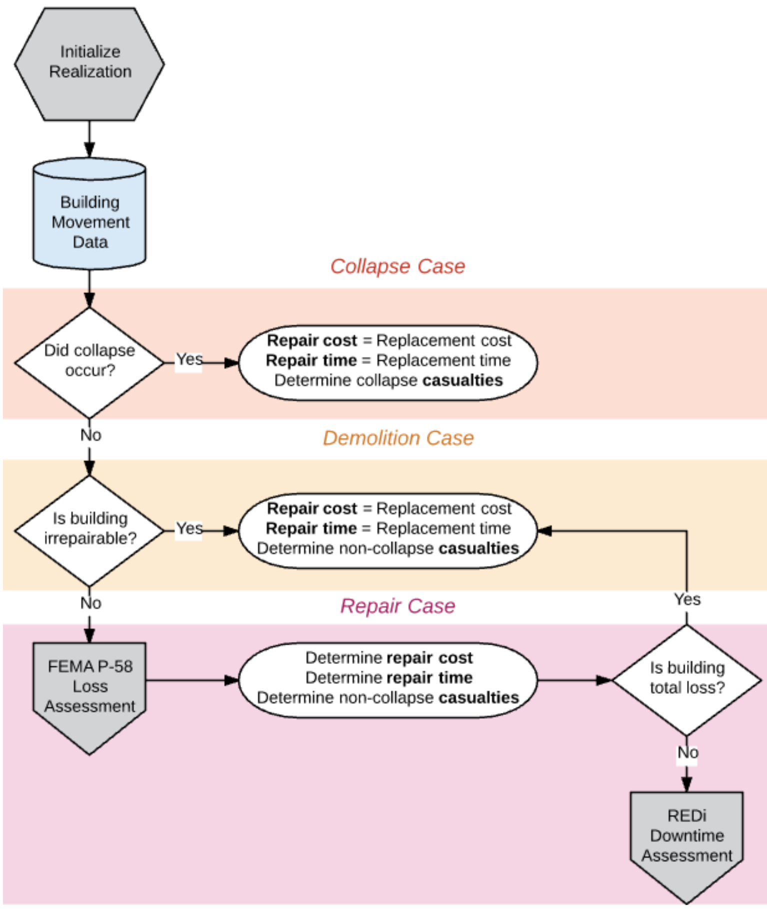

Figure C1 Flow chart depicting overall risk assessment framework

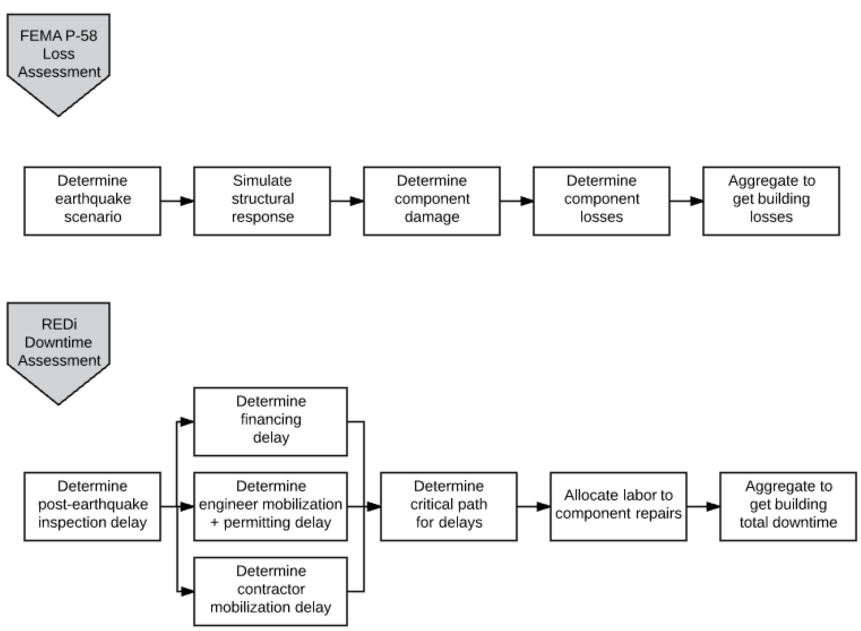

Figure C2 Flow chart outlining FEMA P-58 and REDi methodologies

C3 Modeling Inputs and Sources

C3.1 Exposure Data

C3.1.1 Building Typologies

Basic building information such as structure type, structural irregularities, number of stories, floor areas, perimeter wall area, roof height, construction year, retrofit status, and essential indicators were either provided directly from the university or determined by Arup via on-site evaluations and drawing reviews. The key data fields and data sources are summarized in Table C1.

Building Field	Provider	Source Name (if provided by UBC)
Structural type(s)	Arup	N/A (On-site inspection and drawing review)
Structural irregularities	Arup	N/A (On-site inspection and drawing review)
Number of stories	UBC	GROSxFL2.xlsx
Floor areas	UBC	GROSxFL2.xlsx
Perimeter wall area	UBC	
Roof height	UBC	Building_Heights.xlsx
Construction year	UBC	http://www.infrastructuredevelopment.ubc.ca/rrs2/
Retrofit status	UBC	Originally: Seismic Rankings 9Sept16 plus retrofit info.xlsx Updated: Copy of UBC Final Building List with Clarifications – v1.0.xlsx
Essential facilities	UBC	Essential Building Survey (FINAL).xlsx
Occupancy category	UBC	BCU CAT Summary.xlsx
Insured values	UBC	Optional and Academic Buildings 2016-2017.xlsx

Table C1 Summary of data sources for building typology information

The resulting structural type, building height, and construction year distribution on campus is shown in Figure C3, Figure C4, and Figure C5. Prevalent building typologies on campus include low-rise wood frame structures and low to mid-rise concrete wall structures. Altogether, wood and concrete buildings make up approximately 87% of the existing building stock on campus. In addition, older construction ('pre-code' and 'first code') outnumbers newer construction ('moderate code' and 'benchmark code') by nearly 250%. The building typology and age is important for determining input parameters for the structural analysis to estimate building movements.

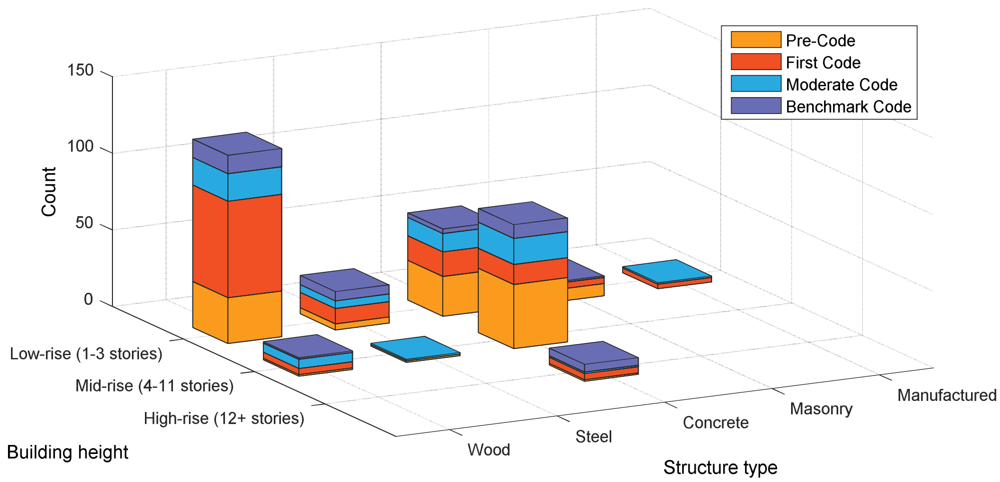

Figure C3 General breakdown of building typologies on campus

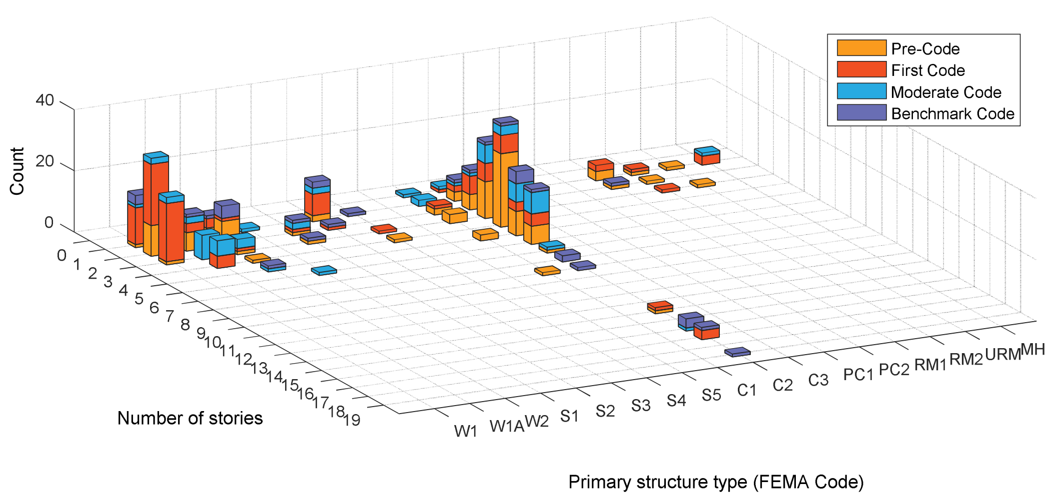

Figure C4 Detailed breakdown of building typologies on campus

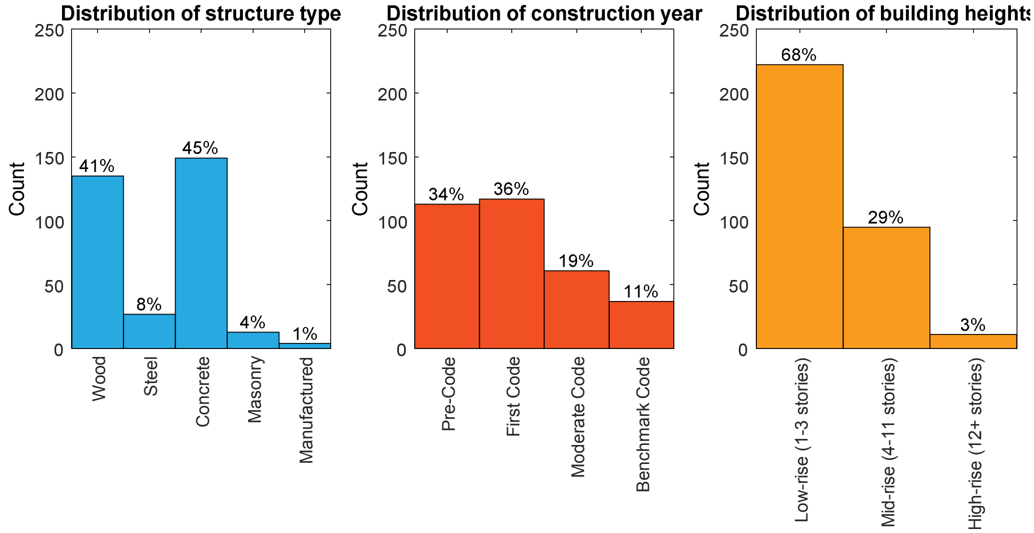

Figure C5 Characteristics of buildings on campus

C3.1.2 Occupancy Categories

The occupancy of individual buildings is used to estimate the number of people in the buildings and the type and quantity of various non-structural components. The occupancy data for each building was provided by UBC, broken down by square footage within each building. From this data, a primary occupancy was assigned by using the category that was allocated the largest percentage of the building's total area. This resulted in a significant percentage of buildings being declared 'Non-assignable space'. Thus, any buildings that were primarily composed of 'Non-assignable space' but that did not exceed 50% of the building's total square footage was instead assigned to its second most dominant occupancy type. The results of this approach are represented in Figure C6.

In order to facilitate population and component quantity estimation (Section C3.1.3 and Section C3.1.6), these UBC occupancy categories were mapped to corresponding FEMA occupancy categories. The results of this mapping are represented in Figure C7. The mapping is presented in Table C2. For UBC occupancy categories that did not have a clear FEMA mapping, 'Hospitality' was chosen as it offered average population and component quantity results.

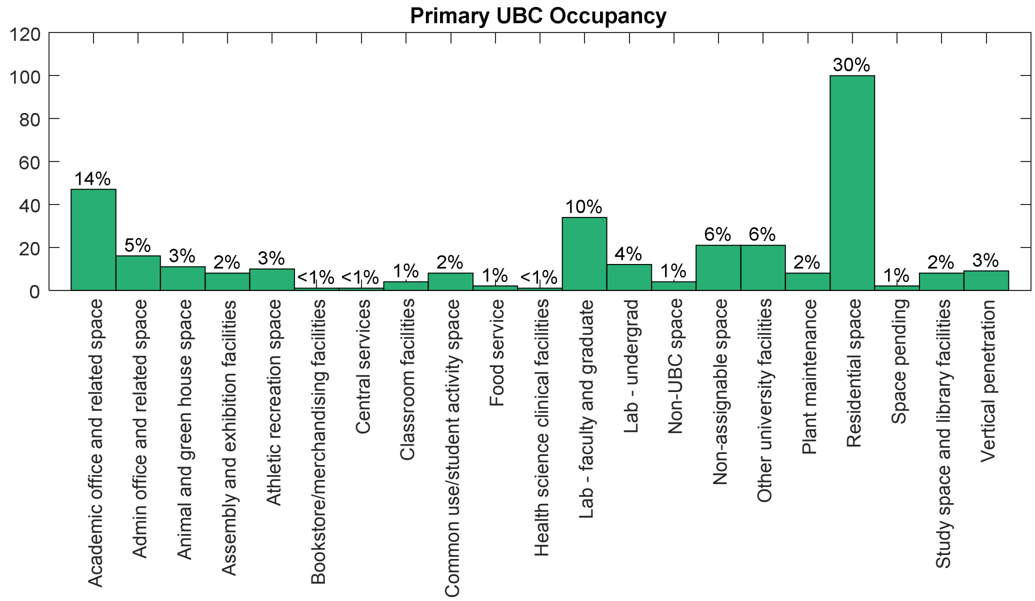

Figure C6 Primary building occupancy assigned using UBC categories

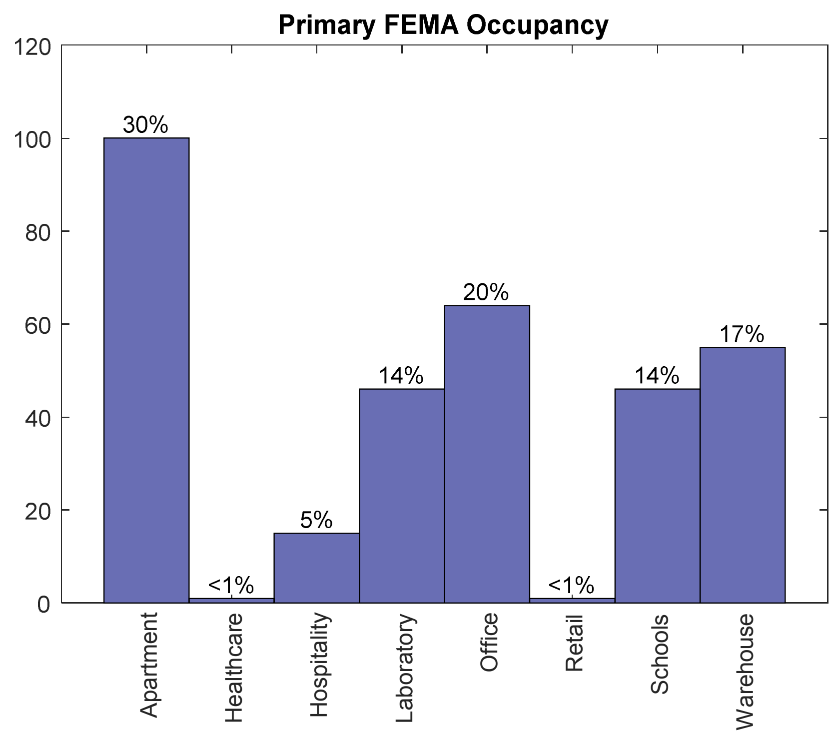

Figure C7 Primary building occupancy mapped to FEMA categories

UBC Category	FEMA Mapping
Academic office and related space	Office
Admin office and related space	Office
Animal and green house space	Warehouse
Assembly and exhibition facilities	Schools
Athletic recreation space	Warehouse
Bookstore/merchandising facilities	Retail
Central services	Warehouse
Classroom facilities	Schools
Common use/student activity space	Schools
Food service	Hospitality
Health science clinical facilities	Healthcare
Lab - faculty and graduate	Laboratory
Lab - undergrad	Laboratory
Non-UBC space	Hospitality
Non-assignable space	Warehouse
Other university facilities	Schools
Plant maintenance	Warehouse
Residential space	Apartment
Space pending	Hospitality
Study space and library facilities	Schools
Vertical penetration	Hospitality

Table C2 Mapping from UBC occupancy categories to FEMA occupancy categories

C3.1.3 Population Models

In order to calculate casualty rates based upon building damage, a population model is required to estimate the indoor population. Within FEMA P-58, peak population models are recommended based on the previously defined occupancy categories. These recommended models stem from data gathered through ATC-13, HAZUS CA, and Southern Californian schools.

However, peak populations do not persist within buildings and the indoor population can vary drastically due to hourly, daily, and monthly fluctuations. For instance, peak classroom populations occur between 10AM-2PM during weekdays but classrooms are vacant during the night. On the other hand, residential populations are at their peak between 9PM-6AM throughout the week. In order to account for the movement of populations on campus and in recognition that a single earthquake cannot strike while all buildings are simultaneously at peak population, an 'equivalent continuous occupancy' (or ECO) was calculated to obtain an averaged population per building at any given time in the day, week, month, or year (Comerio 2000). The ECO population is more appropriate for estimating casualties for the entire portfolio of buildings given a single earthquake scenario while the assumption of peak populations would incur the highest casualty rate for individual buildings. Both are useful for weighing the risks. A comparison of the peak populations versus equivalent continuous occupancy populations are shown in Table C3. Some occupancies, such as Apartment (residential) do not differ significantly while others, like Education, have vastly different peak and ECO populations.

FEMA Occupancy	Peak per 1000 SF	ECO per 1000 SF
Apartment	3.1	2.1
Education	12	2.4
Healthcare	5	3.2
Hospitality	2.5	1.7
Laboratory	3	1
Office	4	0.9
Retail	6	1.7
Warehouse	1	0.3

Table C3 Population models per square footage for each occupancy category

Aggregating the total equivalent continuous occupancy population across all the buildings in this study, the total indoor population at any given time on campus is calculated to be roughly 22,100. In comparison, the aggregated indoor peak population on campus is roughly 59,800.

Upon inspection, due to the large square footage of parking structures, it was apparent that the estimated populations in parkades (buildings 052, 467, 528, 551, 792, and 900) were too large even when using the 'warehouse' occupancy. In order to adjust for this, 25% of the warehouse populations were assumed instead.

C3.1.4 Building Replacement Valuation

Arup coordinated with a cost estimator hired by the university in order to estimate the total building replacement value (TBRV) and demolition costs. The TBRV includes the total hard costs plus soft costs. The TBRV for the portfolio is roughly $6.5 billion 2017 CAD.

C3.1.5 Content Valuation

In order to estimate content losses, the insured content loss values provided by UBC were assumed to be the total value of contents within each building. It is not clear what type or the quantity of the contents in each building. For buildings that did not have insured content values, an assumption between 50-150% of the building replacement value was assumed, per recommendation by occupancy type in HAZUS.

C3.1.6 Building Component Quantities

The risk assessment methodology relates the likelihood of damage in each building component to the consequence for repairing damage (e.g. repair cost and repair time). This includes both structural components (e.g. concrete walls) and non-structural components (e.g. architectural elements or piping). In all cases, the type and quantity of various building components within a building were estimated using normative quantity estimates, developed by FEMA based on surveys conducted of various construction types, occupancy types, and floor area.

Structural component normative quantities were developed based upon a limited drawing review for the different building typologies on campus and extrapolated to all other buildings of that type.

Non-structural component normative quantities were largely taken from FEMA P-58 recommended values for the different occupancy categories. Two exceptions to this were taken – for exterior enclosure and for stairs. For exterior enclosure estimates (e.g. heavy cladding, exterior enclosure), each building was reviewed using Google Earth to get approximate percentages of each enclosure type. These percentages were then multiplied by the perimeter wall areas provided by UBC in order to get their respective quantities. We believe that this additional effort was justified because different enclosures perform vastly different relative to each other, some like precast heavy cladding and brick veneer are much more susceptible to damage that unitized glazing systems. For stair estimates, a higher bound on the FEMA P-58 normative quantity estimates was applied as those predictions better matched on-site observations. In addition, all structures that were primarily constructed from concrete or masonry were assumed to have concrete stairs, while other structures were assumed to have unknown stair types. This assumption was based on on-site evaluation of stairs for 88 different buildings (Figure C8).

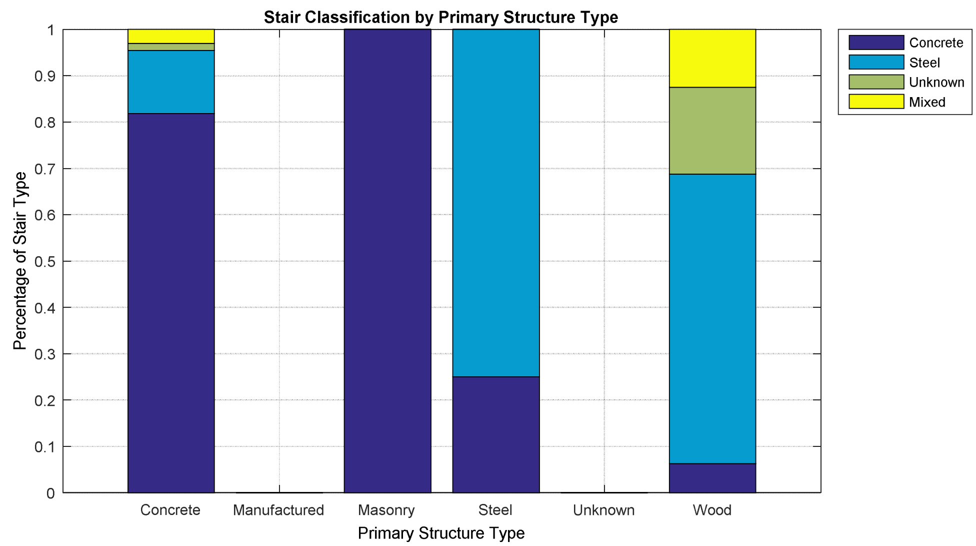

Figure C8 Distribution of stair types based on structure type from on-site evaluations

C3.2 Vulnerability Data

C3.2.1 Building Movement Data

The risk assessment for individual buildings is based upon the anticipated building movements (e.g. interstory drift ratio, peak floor acceleration, residual drift) and likelihood of collapse. These were calculated using simplified structural analysis for 40 different earthquake scenarios at each of the 4 intensity levels. Details of this calculation are discussed in Appendix D.

For each earthquake scenario, the building movement data from the simplified structural analysis was assumed to be 'best estimate' values. From this data, motion to motion variability (at a given intensity level) is explicitly captured. On top of these values, additional variability is applied in order to account for uncertainty in construction and analysis quality. This additional variability is referred to as the 'modeling dispersion' and is described in more detail in FEMA P-58-1 Chapter 5. Per recommendation in FEMA P-58, a modeling dispersion value of 0.5 was used for all buildings.

C3.2.2 Component Fragility Functions

The likelihood of damage for various components is modeled using 'fragility functions'. These fragility functions indicate a probability of being in a given damage state (e.g. aesthetic or life-safety critical) given a certain amount of building movement. Certain components are sensitive to building displacements (e.g. interior gypsum partition walls or steel moment frames) while other components are sensitive to building accelerations (e.g. suspended ceilings or motor control centers). A sample fragility curve for partial-height gypsum partition walls is shown in Figure C9, which is sensitive to building displacements (i.e. story drift ratio). As can be seen by the colored regions, at increasing levels of building displacement, the likelihood of being in a more severe damage state is larger.

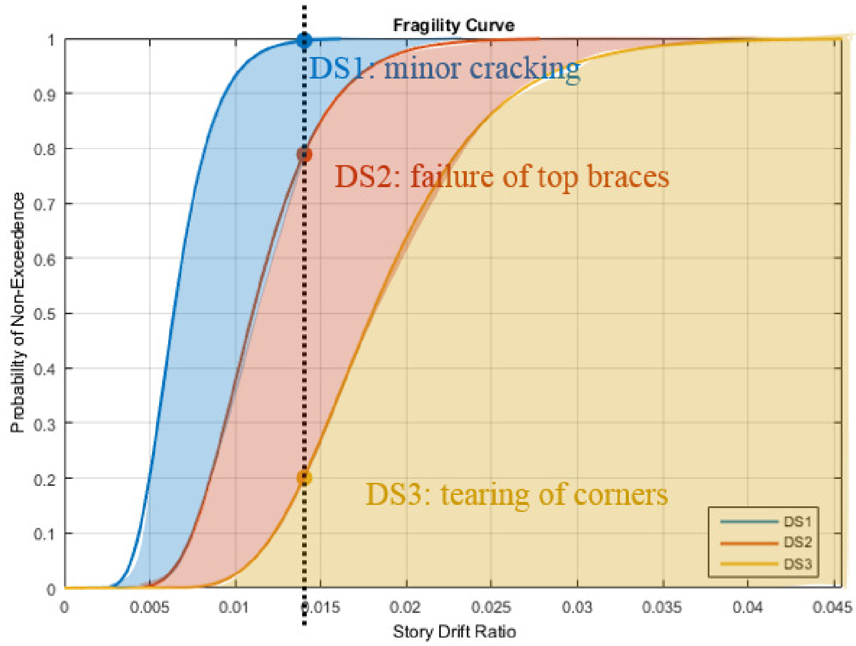

Figure C9 Sample fragility curve for partial-height gypsum partition walls

FEMA P-58 provides a large library of fragility curves for both structural and non-structural components. These fragility functions were developed by various researchers, often by compiling data from dynamic or quasi-static testing or from observations during past earthquakes. In some cases, the fragility functions can be based off of expert opinion.

For components that are prevalent on campus, some fragility functions were modified from the FEMA P-58 default values. This was done for both the exterior enclosure (e.g. heavy cladding, storefront glazing, unitized curtain wall) and the concrete stairs. In order to create these user-defined fragility curves, Arup conducted a literature review, compiled test data, and gathered in-house expert opinion.

For the retrofitted buildings, ceiling components (e.g. suspended ceilings or piping) were assumed to be braced per current standards.

C3.2.3 Impeding Factor Delays

Factors that can cause the delay to the initiation of building repairs are referred to as 'impeding factors'. These include post-earthquake inspection, financing, engineer mobilization, permitting, and contractor mobilization. These delays can be significant, and for low to moderate amounts of building repairs can dominate the overall building downtime. These delay paths are depicted in Figure C10.

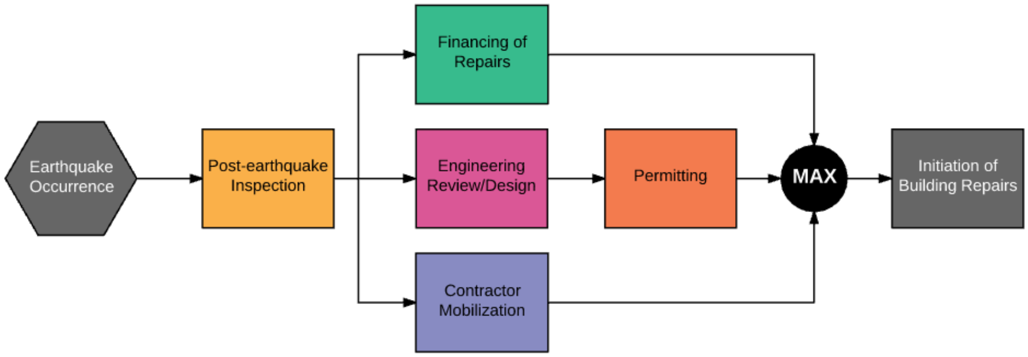

Figure C10 Delay paths due to impeding factors after an earthquake

Typical values assumed for each of the impeding factors typically came per recommendation in REDi (2013). Exception was taken for contractor mobilization due to improved data from previous projects and research efforts, largely based upon a survey of contractors and subcontractors assessing the number of weeks anticipated to procure materials and equipment and mobilize labor for different types of repairs. For this study, it was also assumed that financing would not be critical path to get to repairs. This assumption was largely based off of conversations with the university that indicated that there was full insurance penetration on campus and that there was enough liquid funds to initiate repairs immediately after an event. **Error! Reference source not found.** and **Error! Reference source not found.** summarize typical delay values assumed for this study.

Table C4 Typical impeding factor delays per REDi 2013 by case

Inspection	*Non-essential facility*	*Essential facility*
	5 days	2 days
Engineer mobilization	*Aesthetic structural damage*	*Life-safety structural damage*
	6 weeks	12 weeks
Permitting	*Aesthetic damage*	*Functional or life-safety damage*
	1 weeks	8 weeks

Table C5 Typical contractor mobilization impeding factor delays, update to REDi 2013

Contractor Mobilization		
	Aesthetic damage	*Functional or life-safety damage*
Structural	14 weeks	22 weeks
Architectural	7 weeks	18 weeks
Exterior enclosure	13 weeks	21 weeks
Mechanical	12 weeks	19 weeks
Electrical	9 weeks	11 weeks
Elevators	19 weeks	28 weeks
Stairs	8 weeks	17 weeks

C3.3 Consequence Data

C3.3.1 Building Component Consequence Functions

The baseline repair cost, repair time, and casualty rate corresponding to each damage state for each building component was obtained from the FEMA P-58 database. The repair costs for each component at different levels of damage were provided to the cost estimator for review and some were modified to be consistent with local construction practice.

For buildings that contain hazardous materials, the component repair costs are multiplied by a factor of 1.1 to account for additional remediation. This factor is in the recommended range per FEMA P-58. In addition, components that are higher up in the building are multiplied by a small factor (<1.1) to account for the difficulty to get to higher up floors in damaged buildings.

C3.3.2 Repair Classes

Each building component is assigned a Repair Class based on the extent and severity of damage and the criticality of the component. Repair Classes are used to determine whether any damaged component in the building would hinder re-occupancy or functionality. This is described further in REDi (2013).

C3.3.3 Building Consequence Functions

For simulations of buildings that result in collapse or demolition (due to excessive residual drift), the repair costs are assumed to equal the total building replacement value plus demolition cost and it is assumed to take 4 years to replace the building.

A building is likely to be demolished if it has significant permanent displacement (i.e. residual drift) after an earthquake. Heavy structures such as concrete are especially vulnerable to demolition due to permanent displacement. Lighter structures such as wood structures are more likely to be repaired at equivalent levels of permanent displacement in heavier buildings This is explicitly accounted for in the risk assessment, such that a heavy structure has a 50/50 probability of demolition at 1% residual drift and a light structure at 2% residual drift.

A building is considered a complete loss if the aggregated repair cost is estimated to exceed 70% of the total building replacement value. This is based on our understanding that UBC will not renew a building with a Facility Condition Index (FCI), the ratio of deferred maintenance to total building replacement value, exceeding roughly 70%.

C3.3.4 Casualties

The associated casualty rate in terms of injuries and fatalities for non-collapse cases was taken directly from the FEMA P-58 fragility and consequence function library. However, casualties tend to be dominated by building collapses as opposed to component-related damage in earthquakes. Thus, an assumption had to be made regarding the casualty rate for collapsed structures.

Based upon a literature review, the probability of casualty given collapse per HAZUS seemed to largely corroborate empirical data from previous earthquake events where it existed. The probability of fatality given collapse per HAZUS is between 8-15% of the indoor population, with the smaller value for lighter structures and a larger value for heavier structures. The injury rate given collapse is constant at 60% of the indoor population for all structure types.

C3.3.5 Contents Consequence Functions

In order to estimate the vulnerability and associated consequence of content damage, a fragility that directly mapped peak floor accelerations to percent loss of contents was developed based upon Porter et al. 2012. Since the resolution of information regarding content category and anchorage quality did not exist, a contents fragility the spanned over those provided by Porter was implemented. The result was a combined fragility and consequence function that resulted in 50% content loss at floor acceleration levels of 0.6g.

C4 References

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Appendix D

Estimation of Building Movements using Simplified Time-History Analysis

D1 Introduction

This appendix provides an overview of the methods used in estimating engineering demand parameters (EDPs) utilizing structural analysis required to enable the seismic risk assessment (see Appendix C). An outline is provided for the two different methods used across the portfolio: 1) the Seismic Retrofit Guidelines (SRG) prepared for a seismic upgrade program of British Columbia schools, and 2) a multi-DOF nonlinear analysis using LS-DYNA.

Appendix E provides additional information about the calibration of the simplified methods to more sophisticated analysis methods. It is noted that the results from the simplified estimation methods rely on a number of assumptions, intended to generally capture the expected building behavior in various earthquake scenarios for "screening" purposes. The input parameters are based largely on non-detailed evaluation including rapid visual screening and the simplified analysis is not capable of capturing some building-specific deficiencies (e.g. setbacks, vertical offsets, etc.). Thus, the analysis methods described herein are not a substitute for detailed advanced analysis.

D2 EDP Estimation Methodology Overview

The engineering demand parameters (EDPs) of interest in this project are interstory drift, residual drift, and peak floor acceleration. Additionally, an estimate of collapse probability is implicit within this, as a direct consequence of interstory drift exceeding a collapse drift threshold. These are estimated for all buildings in the portfolio across a suite of ground-motions capturing different sources and intensities (see Appendix A).

Two methods are used, depending on the height of the building in question. The SRG methodology is used for structures 5 floors and lower, while the simplified LS-DYNA approach is used for taller structures which exhibit higher mode behavior. We extended the applicability of the SRG dataset beyond 3 stories to cover buildings of 4 (and a few of 5 floors), given that it is likely to yield results closer to real-world behavior than the alternative methods.

D2.1 SRG Methodology

This methodology employs the dataset that powers the Seismic Retrofit Guidelines Analyzer I tool, querying this data directly in order to find expected drift in each ground motion for a given structural input parameters. Consequently, this approach inherits the assumptions and methodology described in the accompanying documentation, Seismic Retrofit Guidelines 2nd Edition (APEGBC. 2013). The dataset and accompanying documentation was kindly made available for this study by Professor Carlos Ventura and Dr. Armin Bebamzadeh.

The SRG dataset consists of millions of nonlinear time history analysis results, based on simplified models like those above, reflecting a large set of the possible permutations of inputs shown in Figure D.1. We adopted the SRG dataset because it relied upon local state-of-the-practice knowledge based on a detailed review of typical construction practices for each structural type and because the inputs required could be obtained from either information already on hand or from relatively simple investigation of the structural drawings (to establish a best estimate of strength).

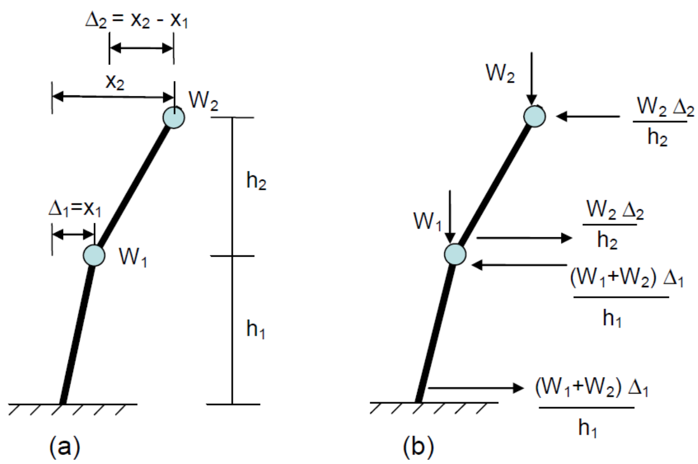

Figure D.1 Overview of 2-DOF system used by SRG for modelling in the CANNY solver, showing (a) the lumped mass model, and (b) the force equilibrium including P-delta effects. Reproduced from the Seismic Retrofit Guidelines Volume 4.

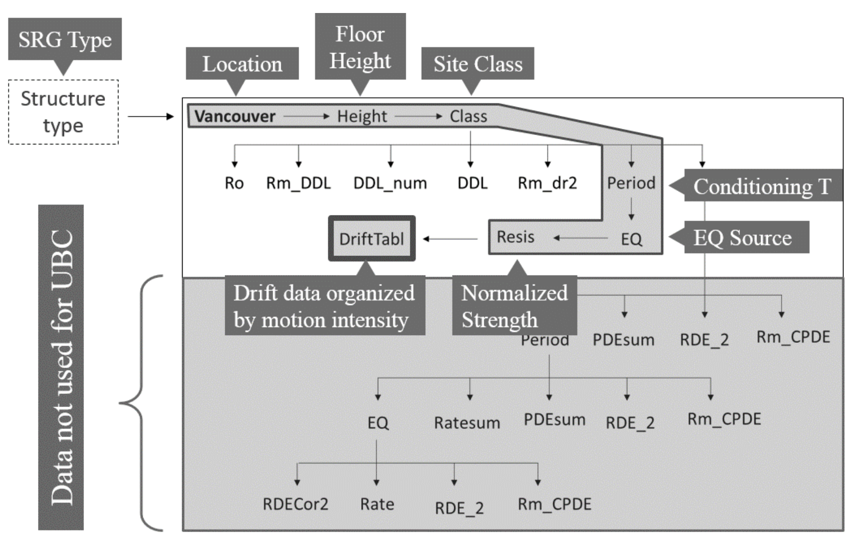

Figure D.2 Structure of SRG web-interface dataset, with annotations showing the data that was used in this project.

Location, site class, conditioning period (T), and earthquake source are all determined by the location and hazard, which is known and defined in Appendix A. This leaves the SRG type (or structural types), floor height and normalized strength to be determined from the building specific information available, as is discussed further below.

It is worth noting that the approach to this building specific data varies to suit the modelling approach taken for the different SRG types, which can be either flexural or shear types. Flexural types, such as slender concrete shearwalls require inputs formatted to reflect a single degree of freedom (SDOF) approximation of the system, using effective height and mass for the equivalent SDOF. Shear types conversely require inputs floor-by-floor, reflecting the height and seismic mass acting on each floor's lateral system.

D2.1.1 Interstory Drift

The SRG methodology provides interestory drifts, based on the input parameters described above.

D2.1.2 Residual drift

The SRG method does not provide predictions of residual drift, an important indicator of reparability.

Thus, residual drift (Δ_r) is estimated according to FEMA P-58-1 equation 5-25, (ATC. 2012):

- $\Delta_r = 0$ if the yield displacement (Δ_y) has not been exceeded
- $\Delta_r = 0.3$*(max inelastic deformation) after the yield displacement (Δ_y) has been exceeded, up to 4 times the yield displacement
- $\Delta_r = (\Delta - 3\Delta_y)$ if four times the yield displacement ($4\Delta_y$) has been exceeded

The yield displacements used are those provided by SRG, specific to each prototype. The maximum total interstory drifts are from the SRG analysis.

D2.1.3 Peak Floor Acceleration

The SRG method does not provide predictions of peak floor acceleration, which is utilized for the risk assessment.

Thus, the peak floor acceleration is estimated for each ground motion based on the methodology suggested by FEMA P-58:

Table 5-4 Correction Factors for Story Drift Ratio, Floor Velocity, and Floor Acceleration for 2-Story to 9-Story Buildings

Demand	Frame Type	a_0	a_1	a_2	a_3	a_4	a_5
Story drift ratio	Braced	0.90	-0.12	0.012	-2.65	2.09	0
	Moment	0.75	-0.044	-0.010	-2.58	2.30	0
	Wall	0.92	-0.036	-0.058	-2.56	1.39	0
Floor velocity	Braced	0.15	-0.10	0	-0.408	0.47	0
	Moment	0.025	-0.068	0.032	-0.53	0.54	0
	Wall	-0.033	-0.085	0.055	-0.52	0.47	0
Floor acceleration	Braced	0.66	-0.27	-0.089	0.075	0	0
	Moment	0.66	-0.25	-0.080	-0.039	0	0
	Wall	0.66	-0.15	-0.084	-0.26	0.57	0

$$\ln(H_{ai}) = a_0 + a_1 T_1 + a_2 S + a_3 \frac{h_i}{H} + a_4 \left(\frac{h_i}{H}\right)^2 + a_5 \left(\frac{h_i}{H}\right)^3 \quad (5\text{-}13)$$

$$S = \frac{S_a(T_1)W}{V_{y1}}$$

Figure D.3 Excerpt from FEMA P-58 and interpretation showing coefficients used to estimate peak floor accelerations

Using the PGA for each ground motion, a coefficient for each floor up the height of the building can be calculated using the above relationship and the structure type.

This measure is reliant on T_1, the fundamental period of each structure. This is estimated using a modified version of the ASCE 7-10 formulation as described below. Finally, an assumption in the calculation of S is made, that the influence of the spectral acceleration can be neglected on a ground-motion to ground motion basis, as a_2 is small, this has a small impact on the results.

D2.2 Simplified LS-DYNA Methodology

For those structures exhibiting significant higher mode effects (for which the SRG Analyzer I dataset is inapplicable), simple multi-degree of freedom (MDOF) models were built in LS-DYNA, a nonlinear dynamic software package. These models take the approach of condensing each floor slab into a single node, and each floor's lateral system into a single beam element. These beam elements employ explicit nonlinearity (backbone curves) based on SRG's dataset, and produce hysteretic behavior with degradation. Axial interaction is not considered, as changes throughout the ground motion in axial-moment or axial-shear interaction were not considered significant at the global level. These are likely to be important for consideration in more detailed analytical models.

While building these models a similar distinction applies between "flexural" and "shear" type structures as within SRG. In the simplified LS-DYNA methodology, flexural type structures allow the kind of behaviour seen in slender concrete shearwall buildings, in which most curvature is concentrated in the lowest floor or floors of the building, with behaviour approaching rigid-body rotation above that (see Figure D.4, left). Conversely, in shear type structures the floor slabs do not tend to rotate with respect to their original orientation (see Figure D.4, right). Instead, each storey's lateral system is subject to shear or double curvature (in the case of a moment frame system). This difference is reflected in the different constraints applied to the nodes in each structure, and differing implementations of the stiffness matrix.

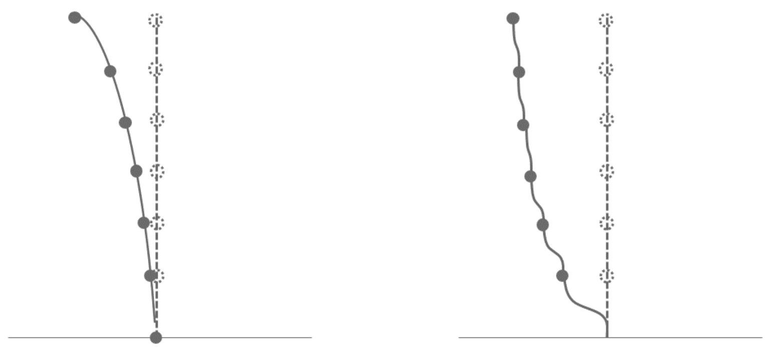

Figure D.4 Left: flexural type structure. Right: shear (sidesway) type structure.

The stiffness of each of these systems is matched to the period estimated from the modified ASCE 7-10 formulation as described in the section below. See Figure D.5 which demonstrates the methodology – the ground motion acceleration record is applied at the base of the MDOF "stick" and the resulting EDPs on each floor are recorded.

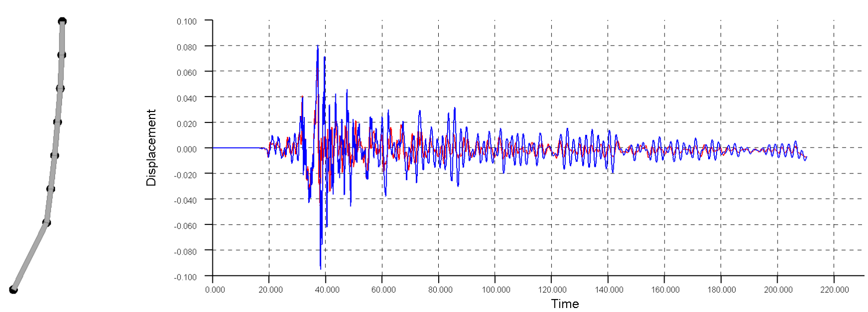

Figure D.5 Left: MDOF "stick" model, showing magnified deformations during ground motion. Right: matching time history showing structural amplification of ground motion (subject to subcrustal motion 20, conditioned at 0.5 seconds).

D3 Inputs for EDP Estimation

The building data used as inputs for the EDP estimation procedure are generally the same for both methodologies. An overview of the data sources and methods used to establish these inputs are discussed below.

D3.1 Structural Typologies

The SRG Analyzer I dataset is designed to be applicable to a wide range of structural types up to 3 floors. Arup conducted a Rapid Visual Survey utilizing the FEMA P-154 (FEMA, 2002) approach which assigns buildings to certain FEMA structure types. Since SRG utilizes a different naming convention and other slight variations, the FEMA types were mapped to corresponding SRG types (see Table D.1) to enable the estimation of EDPs using SRG. Since there is no equivalent SRG type for manufacturer housing (MH), these were mapped to a light timber framing alternative, to reflect the most common prefabricated construction type observed within this population.

Table D.1 Mapping between FEMA types recorded in site survey and the prototypes available in the SRG dataset

FEMA Type	SRG Type			
	Benchmark	Mod. Code	First Code	Pre-Code
	>=2006	>=1992/1985	>=1970	<1970
W1	W-2,3	W-2,3	W-2,3	W-2
W1A	W-2,3	W-2,3	W-2,3	W-2
W2	W-1	W-1	W-1	W-1
S1	S-8	S-8	S-8	S-8
S2	S-7	S-7	S-7	S-7
S3	S-4	S-5	S-5	S-2
S4	S-8+C-7	S-8+C-7	S-8+C-7	S-8+C-7
S5	S-8+M-5	S-8+M-5	S-8+B-1	S-8+B-1
C1	C-1	C-2	C-3	C-3
C2	C-8	C-6	C-7	C-7
C3	-	-	-	C-3+B-1
PC1	C-6	C-7	C-7	C-7
PC2	C-2	C-3	C-3	C-3
RM1	M-3	M-3	M-2	M-2
RM2	M-3	M-3	M-2	M-2
URM	B-1			
MH	-	-	-	-

D3.2 Normalized Strength (Rm)

The base shear strength is an important parameter for estimating EDPs, particularly the probability of collapse.

D3.2.1 Code-based strength

The base shear strength of each building was initially estimated based on nominal design strengths required by the corresponding building code (determined from the year the building was constructed, and assuming that the design had adhered to the version of the code in use approximately two years earlier) and the various design attributes it takes into account. This strength is represented as a value normalized to the seismic mass of the structure (i.e. the base shear coefficient). Assumptions regarding ductility are necessary, so these vary according to the year of design for each building.

D3.2.2 Building-specific strength

Since the code strength is a minimum and many older buildings have significantly more walls, it was recognized that older buildings would be severely penalized by the code-based strength assumption. Thus, a review of structural drawings, when available and legible, was conducted to explicitly calculate shear capacity for concrete shear wall and timber wall buildings, the most common typology represented in campus portfolio.

Since the performance of a given building will be dictated by the drifts and acceleration in whichever direction produces larger demands, and that the hazard is not directional, only the strength in the weaker direction is adopted for estimating the EDPs.

D3.2.2.1 Concrete shear wall buildings

This review covered 98 out of roughly 140 concrete shear wall buildings. Wall lengths were measured on the building's plan, and the thickness of each section of structural wall was noted. Finally, the area of wall acting to resist forces in the x and y plan directions was calculated. Using these values, the strength in each direction is estimated based on an empirical relationship between global shear strength and wall area, calibrated to the detailed LS-DYNA analyses (see Appendix E) for older concrete buildings (found to be a factor 4 on the square root of the concrete's compression strength expressed in psi). This may be conservative for newer buildings where strength may be closer to 6 – 8 sqrt(f'c) where f'c is expected strength in psi.

Finally, the value calculated above is now an absolute strength, whereas both methods described above have been formulated to work with normalized strengths. Due to this, the global seismic mass of the structure must be estimated, in order to map the absolute strength back to a normalized strength. To achieve this we used data from the detailed building analyses to establish a typical mass per unit area, from which the seismic mass of each structure could be calculated enabling the normalized strength to be found.

D3.2.2.2 Timber buildings

A similar study of base shear strength was conducted for timber buildings. Out of 97 buildings, only 15 had sufficient information about the wall panel thickness, nail spacing, stud spacing, and hold downs to enable a calculation of strength. Only 6 of the 15 buildings are unique (10 of the buildings are all part of Acadia Family Housing). Thus, for the majority of timber wall buildings, the base shear strength was based on the minimum code strength requirements, except for pre-code buildings (generally before 1950) where the minimum 11% from the base shear strength study was used. Further on-site evaluation may be warranted to determine actual strengths with more accuracy.

D3.2.3 Overstrength Effect

An overstrength factor is applied to the nominal strength values from code, to account for expected material strengths and other factors. The overstrength concept is based on the NBC 2005, which introduced an explicit system overstrength factor, Ro, in the calculation of the lateral seismic force, V. This factor was carried over to NBC 2010 and continues in NBC 2015 – so is still present in the code. However, it is also being used as a framework to describe the overstrength effect anticipated as a consequence of the design process for designs undertaken based on earlier code. The rationale for the use of factors Rd and Ro as well as the reasons for particular values or ranges of values for various structural systems are given by Mitchell et al (2003). This overstrength is given by:

$$Ro = (Rsize.R\varphi.Ryield.Rsh.Rmech)$$

Where each of these components is defined as representing:

- *Rsize*: Limited/quantized availability of structural shapes – Mitchell et al (2003) also note "In addition, practical considerations often lead to conservative rounding of dimensions such as spacing of connectors and reinforcing elements".
- *Rφ*: Takes into account nominal vs factored resistances
- *Ryield*: Ratio of "actual" or "expected" yield strength to minimum specified yield strength
- *Rsh*: Strain hardening
- *Rmech*: Redistribution in effect at collapse mechanism

Considering the above, this project estimates the overstrength factor for each FEMA type and corresponding SRG lateral drift resisting system typology over the different years of construction (see

Table D.2).

Note that overstrength factors are inherently incorporated in the building-specific strength assignments which were based on wall reviews. This is because the strength was calibrated to the advanced analysis results which already included the “expected” material properties. In other words, the 4 sqrt(f’c) noted above already includes the overstrength factor.

Table D.2 Overstrength factors used, shown as applied over the mapping between FEMA types SRG prototypes

FEMA Type	**LDRSs**			
	Benchmark	Moderate Code	First Code	Pre-Code
Code Year	>=2006	>=1992/1985	>=1970	<1970
W1	W-2,3	W-2,3	W-2,3	W-2
Ro:	1.7	1.7	1.7	1.445
W1A	W-2,3	W-2,3	W-2,3	W-2
Ro:	1.7	1.7	1.7	1.445
W2	W-1	W-1	W-1	W-1
Ro:	1.7	1.7	1.7	1.445
S1	S-8	S-8	S-8	S-8
Ro:	1.5	1.5	1.5	1.275
S2	S-7	S-7	S-7	S-7
Ro:	1.3	1.3	1.3	1.2
S3	S-5	S-5	S-5	S-2
Ro:	1.3	1.3	1.3	1.2
S4	S-8+C-7	S-8+C-7	S-8+C-7	S-8+C-7
Ro:	1.3	1.3	1.3	1.2
S5	S-8+M-5	S-8+M-5	S-8+B-1	S-8+B-1
Ro:	1.5	1.5	1.5	1.275
C1	C-1	C-2	C-3	C-3
Ro:	1.7	1.4	1.3	1.2
C2	C-8	C-6	C-7	C-7
Ro:	1.4	1.4	1.3	1.2
C3	-	-	-	C-3+B-1
Ro:				1.2
PC1	C-6	C-7	C-7	C-7
Ro:	1.4	1.3	1.3	1.2
PC2	C-2	C-3	C-3	C-3
Ro:	1.4	1.3	1.3	1.2
RM1	M-3	M-3	M-2	M-2
Ro:	1.5	1.5	1.5	1.275
RM2	M-3	M-3	M-2	M-2
Ro:	1.5	1.5	1.5	1.275
URM	B-1			
Ro:	1.5	1.5	1.5	1.275

D3.2.4 Contribution of Nonstructural Components to Strength of Timber Buildings

Nonstructural components provide significant resistance in timber buildings. Thus, methods to estimate strength based on the structural resistance alone is likely to underestimate the strength of a timber building.

A literature review was conducted, and the paper *New Developments in FEMA P-58 Seismic Risk Assessment of Wood Light-Frame Buildings* (DeBock et al. 2016) offered two key insights that resolved our questions around modelling timber structures. It provides the necessary information to include the contribution of nonstructural walls and components to the overall strength of both W1 and W1A (typically single and multi-family dwellings respectively). They offer an overstrength factor based on structural modelling for both bare structure, and structure + nonstructural + fitout, which vary with height (see Figure D.6).

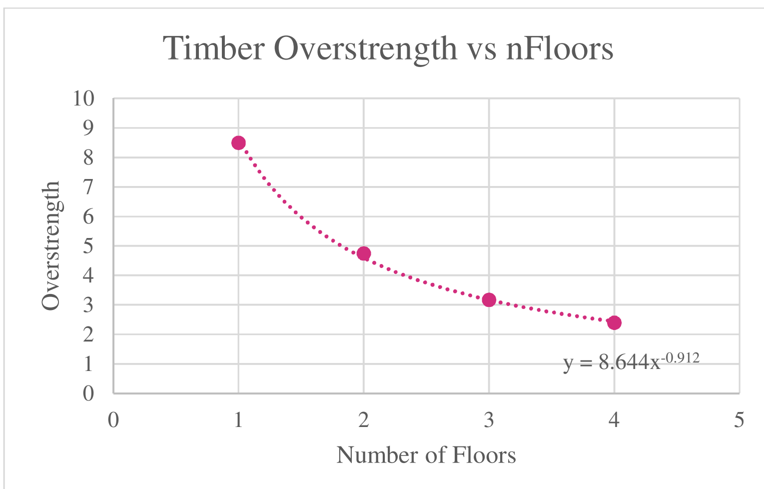

Figure D.6 Timber overstrength factor used showing dependence of number of floors (above ground)

In addition, this paper was useful to confirm the selection of prototype used for these buildings. The paper presents an analysis demonstrating that considering the global interaction between a typical mix of structural and nonstructural walls one could expect a behaviour consistent with that of the unblocked sheathing prototype (W-2 from SRG).

D3.2.5 Design Base Shear After Drawing Reviews

The above can be summarized in the following plot. This includes the results from each of the reviews above aggregated on top of the earlier code-based strength estimates. The resulting normalized design base shears have a general upward trend and increase in dispersion with time. This is both a consequence of evolving design codes and expectations, as well as better availability of high quality drawings from which to calculate more accurate design base shear values.

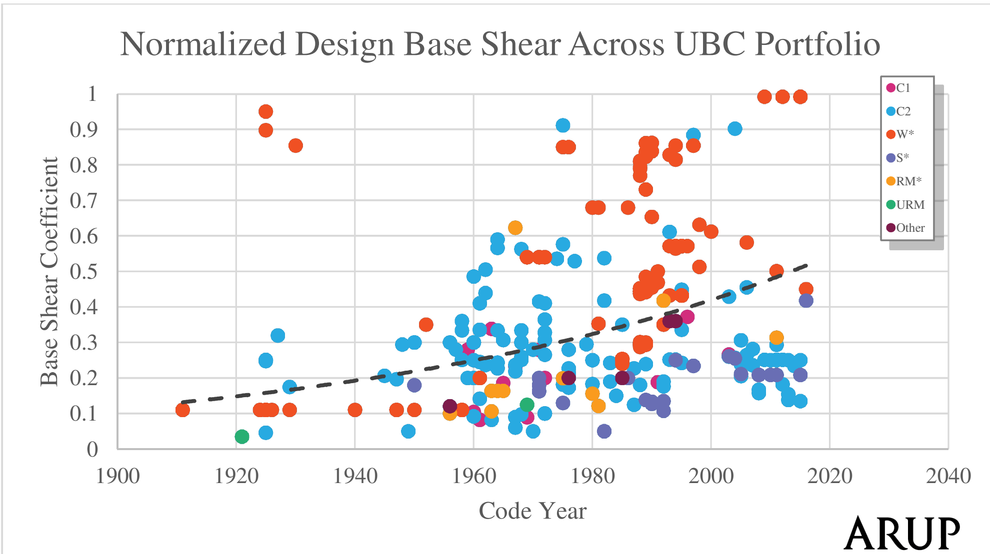

Figure D.7 Design base shear across the UBC portfolio, visualized by type and by year. Note that this represents the data used in the finalized PSRA, including the aforementioned overstrength effects, and all buildings that had individual calculations for strength conducted based on their drawings.

D3.3 Seismic Mass

To avoid the uncertainty that could be introduced by assumptions in deriving absolute values of mass, and noting that the strength input can be normalized to the seismic weight (Rm/Ws), both methodologies are based on deriving only a normalized seismic mass. This serves to understand how the normalized strength will vary up the height of the building, and is based on the assumption that the lateral system functionally remains the same on each floor (a generally typical condition for shorter buildings) while the seismic mass acting at each level decreases with height. This approach requires fewer assumptions, relating only to how mass is likely to be distributed within the building, and avoids the need to calculate each floor's mass explicitly. Distribution takes into account the following:

- Height (can reflect vertical irregularity, e.g. taller first story)
- Relative weight of each floor, i.e. lesser mass at the roof level (assumed as 60% of a typical floor)
- Area of each floor, assuming that relative mass will scale in proportion to the area of each floor

The normalized seismic mass at each floor level is used as input for the SRG Analyzer I dataset or the simplified DYNA approach.

For some of the SRG Analyzer I prototypes, an effective mass acting at some effective height is required. The effective mass is simply the total seismic mass.

D3.4 Height and Number of Floors

This data was based initially upon data received from UBC records. The incoming data was checked so that missing data and outliers could be flagged. A manual review process was then undertaken to correct for any missing data or errors. This involved checking against the drawings on file for each building, or if these were not available or did not provide the information required, satellite imagery/scans were used. Note that a number of buildings on campus take irregular forms and building heights and number of floors are not readily apparent. Some of these are flagged in our list of building tiers (Appendix H).

The individual story height was assumed to be constant up the building, unless a vertical irregularity (soft/weak story) was noted. In this case, the height of the ground floor was modified to reflect either an increase of 1/0.645 or 1/0.5 respectively for moderate or severe vertical irregularities. These values are in keeping with the FEMA P-154 guidelines (FEMA, 2002).

D3.5 Stiffness and Period Estimation

The stiffness of each structure is estimated across the portfolio, although it is only used in the EDP estimation for the simplified LS-DYNA method, where it is necessary to specify independent to the strength inputs. For the simplified LS-DYNA method, the stiffness is ascertained from a period estimate of the structure based on the construction typology and height. The methodology used is based on ASCE 7-10, with some modifications, which can be seen in the piecewise interpretation applied below in Figure D.8. These were also calibrated against results from modal analysis of detailed representations of Place Vanier, Frederic Lasserre, and Walter Gage tower.

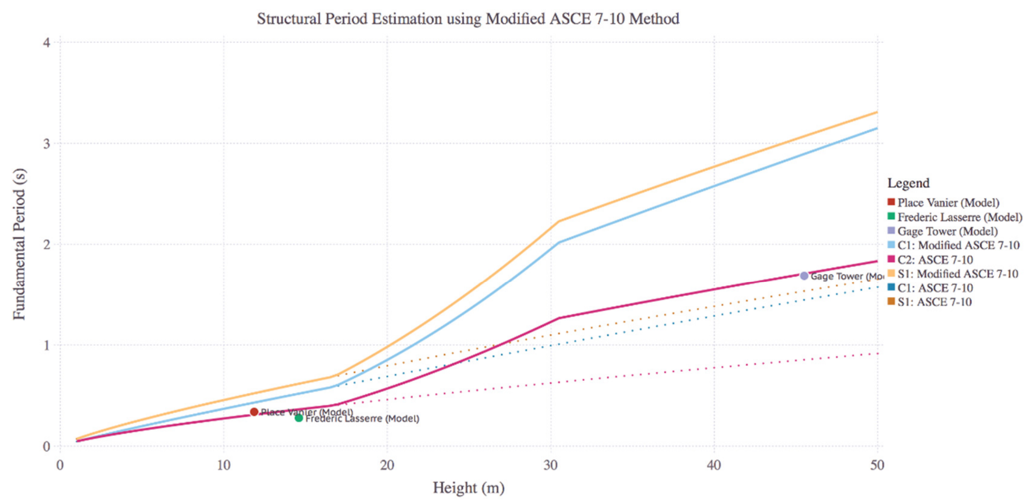

Figure D.8 Estimation of fundamental period across varying building height. A comparison with the results of the detailed models is included.

Additionally, the fundamental period was used for internal audits to the other buildings whose EDPs were estimated using the SRG methodology. A disaggregation of fundamental period across the portfolio can be seen below. As anticipated, the general tendency is for the taller buildings being analysed using the simplified LS-DYNA approach to have longer fundamental periods. While this trend is apparent, there is also considerable overlap in terms of period and consequently in relative dynamic stiffness due to the differences is construction typology. This also demonstrates that the selection of conditioning periods at T = 0.5 sec and 1.0 sec are reasonable.

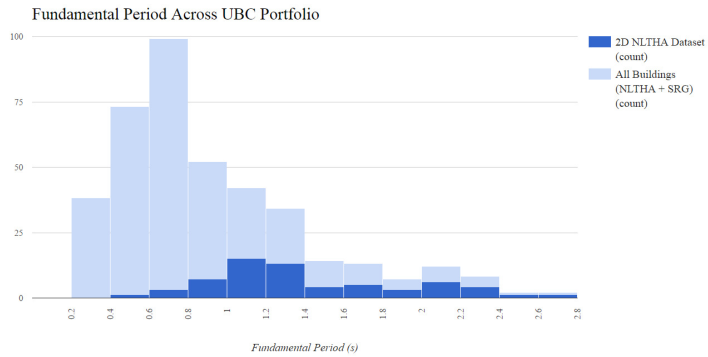

Figure D.9 Distribution of fundamental periods across the portfolio, showing a disaggregation (overlay) between the buildings whose fundamental period was used for modelling (2D NLTHA) and those where the fundamental period was used only for internal auditing purposes.

D3.6 Collapse Thresholds

In order to quantify collapse, the peak drift resulting from each simulated earthquake is compared with a collapse threshold, which is specific to the structure type of the buildings. This has already been done in the creation of the SRG dataset, with the majority of collapse thresholds being provided in SRG volume 4. However in the approach taken by this study, both the SRG and simplified DYNA methodologies require an internal awareness of the collapse threshold. The values used for these were the 99th and 99.9th percentile respectively of non-collapse data contained within SRG. This can be visualized as below, categorized by FEMA type and code year.

Table D.3 FEMA Type with assigned collapse threshold for each code era

FEMA Type	Pre-Code	First Code	Mod. Code	Benchmark
W1A	4.0%	4.3%	4.3%	4.3%
W1A	4.0%	4.0%	4.3%	4.3%
W2	3.7%	3.7%	3.7%	3.7%
S1	10.9%	10.9%	10.9%	10.9%
S2	9.8%	9.8%	9.8%	9.8%
S3	5.8%	5.8%	5.8%	5.8%
S4	7.8%	7.8%	7.8%	7.8%
S5	6.1%	6.1%	5.9%	5.9%
C1	1.0%	1.0%	3.3%	4.1%
C2	1.2%	1.2%	1.6%	2.0%
C3	1.2%	1.2%	1.2%	1.2%
PC1	1.2%	1.2%	1.2%	1.6%
PC2	1.0%	1.0%	1.0%	3.3%
RM1	3.1%	3.1%	5.1%	5.1%
RM2	3.1%	3.1%	5.1%	5.1%
URM	1.3%	1.3%	1.3%	1.3%
MH	4.0%	4.3%	4.3%	4.3%

Note that when these comparisons are made, the peak interstory drifts for buildings with noted torsional irregularities are increased by 30% to account for the fact that neither methodology mechanistically captures irregularities like torsional response.

Examining this at the SRG prototype level, we can disambiguate the different values used for the SRG and simplified DYNA methodologies:

Table D.4 SRG prototypes with assigned collapse drift threshold for each methodology

SRG Type	SRG	DYNA
W-1	3.7%	4.7%
W-2	4.0%	5.5%
W-3	4.6%	5.9%
W-4	11.3%	14.4%
S-1	8.5%	12.9%
S-2	8.5%	12.9%
S-3	8.5%	12.9%
S-4	5.8%	10.0%
S-5	5.8%	10.0%
S-6	5.8%	10.0%
S-7	9.8%	13.9%
S-8	10.9%	14.2%
S-9	10.9%	14.2%
S-10	11.3%	14.2%
C-1	4.1%	4.6%
C-2	3.3%	3.6%
C-3	1.0%	1.1%
C-4	4.7%	8.5%
C-5	5.2%	9.1%
C-6	1.6%	1.7%
C-7	1.2%	1.3%
C-8	2.0%	2.2%
M-1	1.6%	1.9%
M-2	4.6%	7.8%
M-3	5.1%	7.7%
M-4	1.4%	1.5%
M-5	1.0%	1.1%
M-6	0.6%	0.8%
B-1	1.3%	1.5%
F-1	8.6%	12.7%

D4 Consideration of Retrofitted Buildings

This section explores the approach to modelling EDPs for buildings that have already been retrofitted, and then extends this to consider proposed retrofits in the future.

D4.1 Existing Retrofitted Buildings

For structures that have already had some seismic upgrade, we gathered data on the type of structural system utilized for the retrofit and the year it was designed. These retrofits almost universally involve the addition of concrete shearwalls, although additional subtler actions were also undertaken in some cases, like structurally combining additions into a single structure, wrapping or reinforcing existing members, or replacing entire portions of a structure while keeping only the façade of the original building.

The buildings that were considered to have some kind of structural retrofit are summarized below, categorized by year of retrofit:

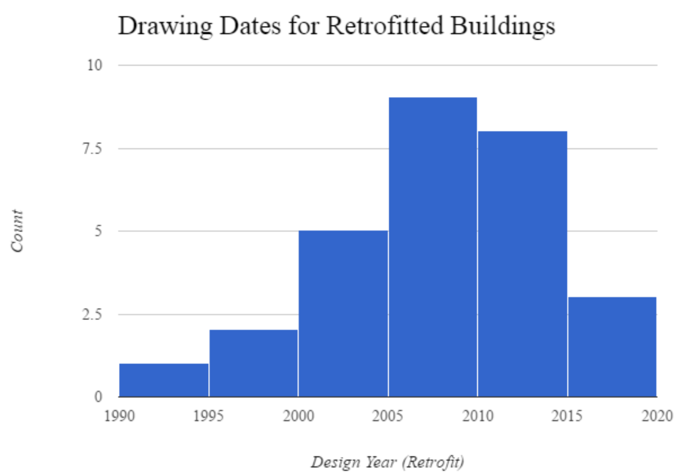

Figure D.10 Distribution of retrofit design year for buildings with structural retrofits in place.

Where possible, specific wall reviews were conducted to quantify the expected shear strength of these retrofitted buildings. Where this was not possible, the strength parameters utilized were based on the year of the retrofit and the designated proportion of code strength (75% or 100%). These assumptions are shown in Appendix H. This assumption is based on typical code practice and matches with the general notes for the retrofitted buildings that were available – no building had stated that the designer intended to achieve a higher level of performance than this, although wall reviews would suggest that some of these structures have.

D4.2 Proposed Retrofits

The performance of future, high performance proposed retrofits applied to each of the buildings in the portfolio was estimated in order to compare with the performance of the existing building stock for cost-benefit analysis (see Appendix G). The upgrades considered intend to meet or exceed 100% of modern code as shown in Table D.5 and described in Appendix F.

Table D.5Retrofit strategies for proposed retrofits by structure type

Structure Type (FEMA)	Retrofit Method	Target Strength Details
W1	Enhancing Shear Walls and Connections	Existing to 100% Code
W1A	Enhancing Shear Walls and Connections	Existing to 100% Code
W2	Adding BRB's	100% Code
S1	Adding BRB's	100% Code
S2	Adding BRB's	100% Code
S3	Adding BRB's	100% Code
S4	a) Adding new Shear Walls to 100% of Code, or, b) Enhacing Existing Shear Walls	a) New to 100% Code + Ductility to Existing, b) Existing to 100%
C1	a) Adding new Shear Walls to 100% of Code, or, b) Enhacing Existing Shear Walls	a) New to 100% Code + Ductility to Existing, b) Existing to 100%
C2	a) Adding new Shear Walls to 100% of Code, or, b) Enhacing Existing Shear Walls	a) New to 100% Code + Ductility to Existing, b) Existing to 100%
C3	Tearing out the infill and adding new shear walls	100% Code
PC1	Adding BRB's and Enhancing Diaphragm Connection	80% Code in PC1 + 40% in BRB
PC2	Enhancing Existing Shear Walls	100% Code
RM1	Adding BRB's and Enhancing Diaphragm Connection	80% Code in RM1 + 40% in BRB
RM2	Adding New Shear Walls	100% Code
URM	Adding New Shear Walls	100% Code

D5 Results

D5.1 Overview

Each of the EDPs is explored briefly below, with the addition of the probability of collapse implicit in these analyses.

Appendix E provides comparison of the EDPs from the simplified analysis to the advanced structural analysis for a few buildings.

D5.1.1 Interstory Drift

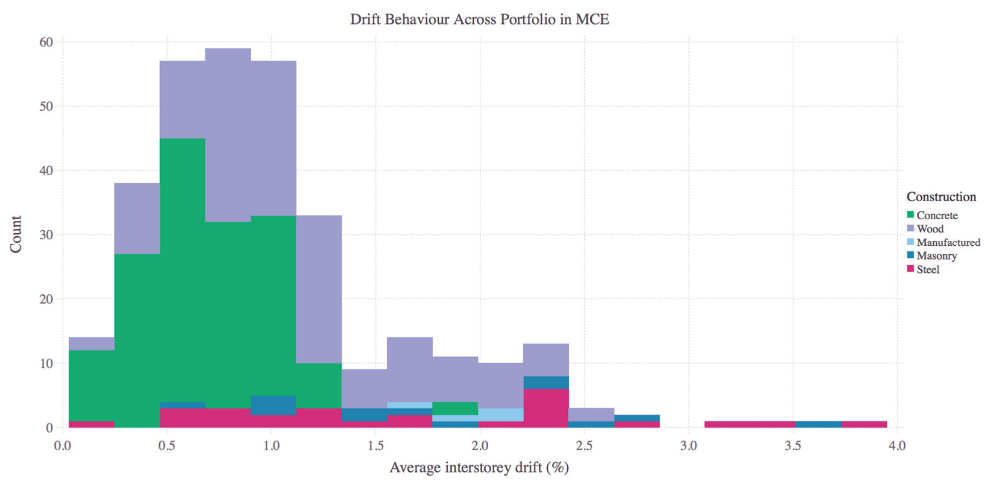

Figure D.11 Distribution of average interstory drift across the portfolio, each count represents a single building. Average drift is calculated across all above-ground floors and all ground motions at the MCE intensity.

Interstory drift predicted across the portfolio is summarized above, somewhat crudely considering the average across each building. Immediately notable is the clustering of wood structural types and concrete structural types, while the relatively less common steel structures have drift performance spanning the range of 1-4%. Even less common masonry types are similarly widely distributed, but this class includes both reinforced and unreinforced systems of varying age.

Note that collapse cases are not being included, i.e. drifts exceeding the collapse threshold for each structural type are not being included in this metric. One caveat to interpreting this data aggregated in this way is that the average drift for an individual building only considers the non-collapse cases. As a result, an individual building's average represented above may be the average of all 40 ground motions at MCE (i.e. no ground motions cause collapse), or could be the average of just 15 ground motions, with collapse occurring in the other 25 – this makes the data not strictly comparable point to point within the histogram in terms of structural performance, but it does provide an accurate view of how the data will be used subsequently by the PSRA.

D5.1.2 Residual Drift

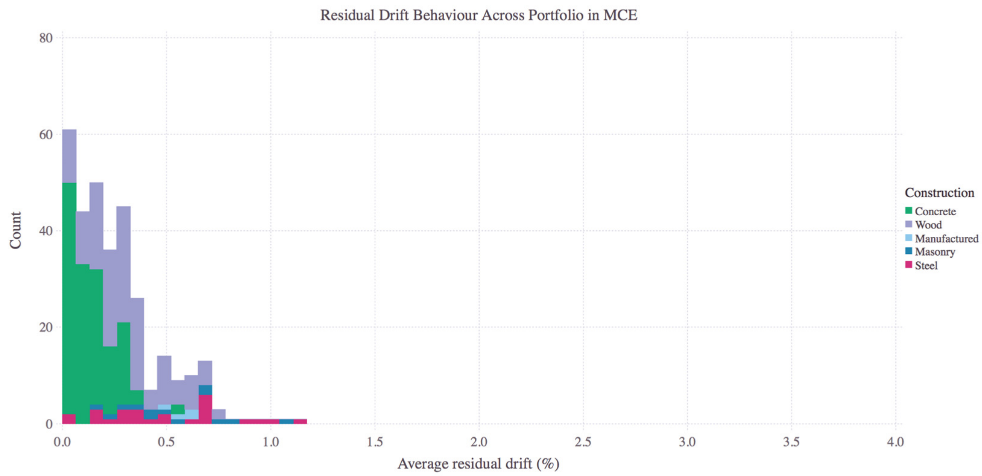

Figure D.12 Distribution of average residual drift across the portfolio, each count represents a single building. Average residual drift is calculated across all above-ground floors and all ground motions at the MCE intensity.

Residual drift behaviour, shown here on the same scale as interstory drift, is typically 1/4 to 1/10th as large as the peak drift. Performance is driven by exceeding yield drift on a ground motion by ground motion basis. Characteristically the distribution of performance for each of the broad construction type categories in MCE is similar to that of interstory drift.

This performance must be considered in concert with the consequences due to residual drift (see Appendix C). Considering concrete shearwall structures as an example, the above plot shows that concrete structures are generally performing better than other types with regard to residual drift in absolute terms, but these structures are also generally more sensitive to residual drift, with more severe damage states connected to lower levels of drift and residual drift. The interplay between these factors is not obvious when considering the residual drifts in isolation.

D5.1.3 Peak Floor Acceleration

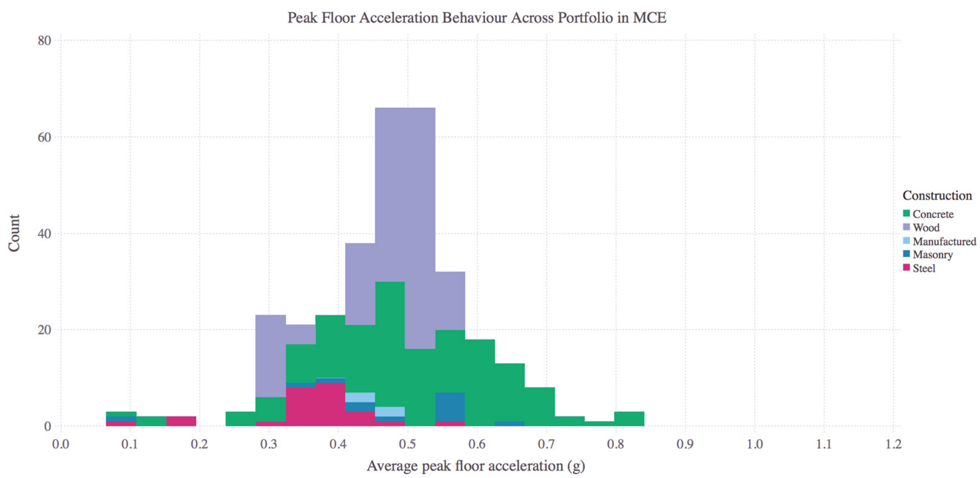

Figure D.13 Distribution of average peak floor acceleration across the portfolio, each count represents a single building. Average PFA is calculated across all above-ground floors and all ground motions at the MCE intensity.

The mean PGA across the ground motions considered at MCE is 0.33g, so the general tendency for amplification can be seen above this point. Noting a mix of heights being represented, the groupings of structural type again appear somewhat clustered. Note that the accelerations up the height of the building generally increase in a linear fashion such that the roof acceleration is the highest (see Appendix E).

D5.1.4 Probability of Collapse

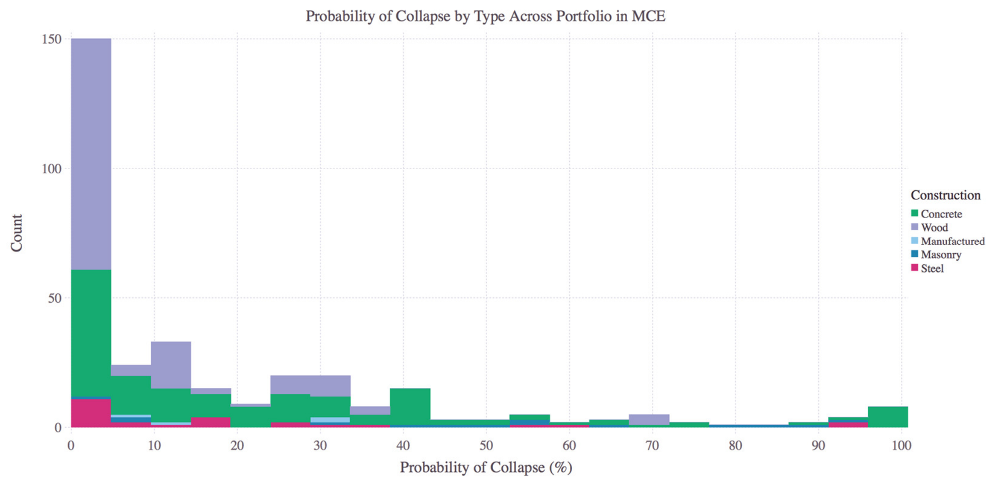

Figure D.14 Distribution of collapse probability across the portfolio, each count represents a single building. Collapse probability represents the percent of ground motions at the MCE intensity causing collapse for each structure.

Examining the probability of collapse for each building in the dataset we note that just under half of the population has a 0-5% probability of collapse in MCE, predicted on the basis of drift exceedance.

The poorest performing structures in terms of collapse are clearly concrete structures, which are overrepresented above 50% collapse, and account for all structures that show collapse in all 40 ground motions analysed at MCE. Conversely, steel and timber structures are clustered in the 0-30% probability of collapse range, with timber alone contributing the majority of structures in the 0-5% probability of collapse range.

D6 References

APEGBC. 2013. *Structural engineering guidelines for the performance-based seismic assessment and retrofit of low-rise British Columbia school buildings – 2nd Edition (SRG2).* BC, Canada: Association of Professional Engineers and Geoscientists of British Columbia

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Appendix E

Calibration of Building Movements using Advanced 3D Time-History Analysis

E1 Introduction

Three reinforced concrete shear wall buildings were selected for undertaking detailed 3D nonlinear time-history analysis for the purpose of calibrating the engineering demand parameters (EDPs) derived from the more simplified structural analysis methods (see Appendix D). The 3D analyses offer more accurate estimates of building behaviour and is able to capture localized damage throughout the structure. The main objective of the calibration is to increase the confidence in the EDP estimates from the simplified analyses, and thus the risk assessment results across the building portfolio. The time-history analysis was undertaken in the software package LS-DYNA, which accounts for nonlinear material and geometry.

While the detailed analysis described herein provides significantly more confidence in the actual building behavior in an earthquake for the three selected buildings, still further refinement would be required (e.g. including the assessment of bidirectional ground motions, and additional number of ground motions) to provide an absolute measure of collapse risk. Destructive material testing may also be warranted in some cases to better establish assumed material properties. We recommend refining the 3D analysis for Walter Gage Tower and the Frederic Lassere buildings, described herein, for the purposes of better understanding the absolute collapse risk of these buildings. We do not believe that further analysis of Place Vanier is a priority, but it could be undertaken for relatively less effort than other campus buildings because the model has already been built.

We also used the 3D detailed model to establish the building strength with more refinement (through pushover analysis), which was found to be significantly higher than the code base shear requirements. Thus, the higher strength resulted in better performance than originally anticipated for the buildings studied. The detailed strength assessment was also used to calibrate the strength of buildings with only the length of wall known (see Appendix D).This study underscored the importance of quantifying the correct building strength for the purposes of assessing a building’s capacity to resist collapse.

Sections E2 and E3 describe the construction of the buildings selected for detailed 3D analyses and the analytical inputs. Section E44 provides a high level summary of the 3D model results. It was found that the 3D analyses offered a more accurate and detailed picture of the building behavior, generally resulting in significant damage, but not collapse (in the few earthquakes modelled).

Finally, Sections 5 and 6 describe how the 3D models were used to calibrate the simplified models. For the low-rise buildings (which utilize SRG to predict EDPs), both pre and post-analysis adjustments were made using the 3D model results. For the high-rise buildings, the results directly from the simplified model matched relatively well with those from the 3D model, and no adjustment was necessary.

E2 Description of archetype buildings

The east tower of the Walter Gage complex was chosen as the archetype high-rise reinforced concrete shear wall building. Place Vanier (Cariboo and Tweedsmuir Houses) was chosen as the low-rise reinforced concrete shear wall buildings. Frederic Lasserre was originally selected as an archetype low-rise concrete moment frame building, but the presence of stair core walls suggested it would behave more like a shear wall building. Several other buildings on campus, originally designated as concrete moment frames, were also found to have stair core walls. This section covers the general configuration, typical details, and assumed material properties for each of the archetype buildings.

E2.1 Walter H. Gage Residence – East Tower (872-1)

Figure 1 Walter H. Gage Residence East Tower (left) vs. analytical model (right)

Walter Gage is a complex of student housing buildings containing three identical towers – the North Tower, South Tower, and East Tower. The analysis model was built based on the record drawings for the East Tower, which were the clearest of the three. This building is simply referred to as “Gage Tower” throughout this report.

Gage Tower, built in 1972, has 17 above-ground levels and 1 partially below-ground level. The building is a total of 164.4 ft above ground floor including the bulkhead. The floor plates are approximately 87 ft x 87 ft and the floor-to-floor height is typically 8.5 ft. The East Tower’s structural system is composed of 6” thick reinforced concrete flat slabs supported by reinforced concrete shear walls ranging in thickness between 6” and 12”, with 8” being the most common thickness.

Concrete strength is specified in the record drawings as 4 ksi up to the 5th floor for the 4 main 27.33 ft long shear walls in the center of the building, and 3 ksi for the remainder of the height. The concrete strength for the other concrete walls and for the slabs was not specified on the available structural record drawings, and has been assumed to be 3 ksi.

Steel reinforcement grade is also not specified on the available drawings, and has been assumed to be Grade 40 with the following properties:

- Expected Yield Stress = (40 ksi)(1.25 per ASCE 41-13) = 50 ksi
- Expected Tensile Stress = (70 ksi)(1.25 per ASCE 41-13) = 87.5 ksi
- Expected Rupture Strain = 15%

Figure 2 shows a typical shear wall boundary zone section near the base of the structure. The boundary zone vertical bars are typically #9’s near the base of the structure, and #8’s for the remainder of the building height. The ties are #3’s spaced at 18” vertically and have been assumed to be completely ineffectual in confining the concrete. The vertical reinforcement outside of the boundary zones and all of the horizontal reinforcement are not described on the available drawings. Therefore, the minimum reinforcement allowed by the code enforced when the building was designed was assumed for these areas.

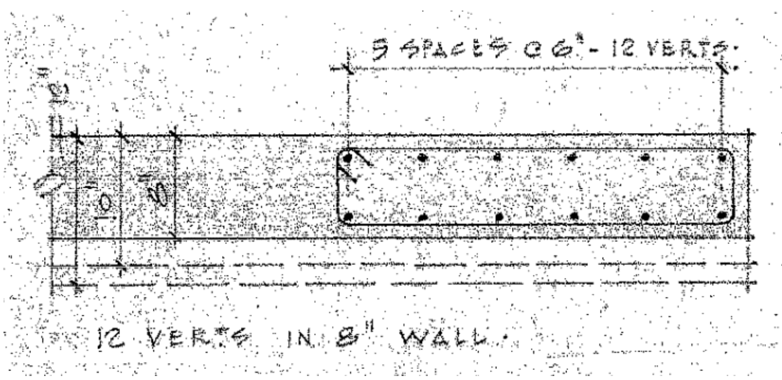


Figure 2 Walter H. Gage Residence typical section through main shear wall at first few floors of the building from the record structural drawings

E2.2 Place Vanier Residence - Cariboo House and Tweedsmuir House (545-1, 545-2)

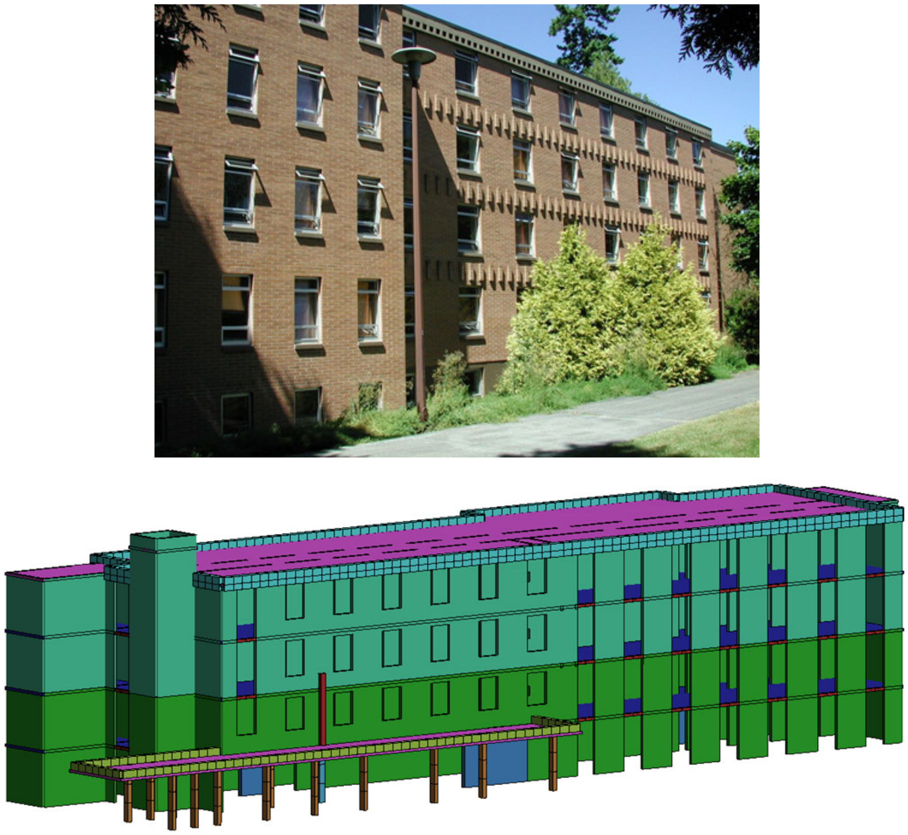


Figure 3 Place Vanier (top) vs. analytical model (bottom)

Place Vanier is a student housing complex containing 13 buildings – one common block and 12 houses. 10 of the houses - Cariboo, Tweedsmuir, Kootenay, Okanagan, Robson, Sherwood Lett, Dorothy Mawdsley, Margaret Mackenzie, Phyllis Ross, and Aldyen Hamber - are nearly identical. The analysis model was built based on the record drawings for the Cariboo and Tweedsmuir Houses, which were the clearest drawings available out of the 10 houses. These houses are simply referred to "Place Vanier" throughout this report.

Place Vanier, built in 1967, has 4 above-ground levels and 1 below-ground level. The building is a total of 40.6 ft above ground floor including elevator bulkhead and parapet. The floorplates are approximately 152 ft x 36 ft and the floor-to-floor height is typically 8.5 ft. Place Vanier's structural system is composed of 5" thick (typically) reinforced concrete flat slabs supported by 6" thick reinforced concrete shear walls.

Concrete strength is 3 ksi as specified on the record drawings.

Steel reinforcement grade, as with Gage Tower, is not specified on the available drawings, and has been assumed to be Grade 40 with the following properties:

- Expected Yield Stress = (40 ksi)(1.25 per ASCE 41-13) = 50 ksi
- Expected Tensile Stress = (70 ksi)(1.25 per ASCE 41-13) = 87.5 ksi
- Expected Rupture Strain = 15%

Figure 4 shows a typical shear wall reinforcement schematic from the record drawings. Wall reinforcement is typically a single curtain of #4's spaced at 12" each way for the exterior walls; a single curtain of #3's spaced at 18" each way for the interior walls. All walls have an additional #5 vertical bar at each edge of all openings. None of the walls have detailed boundary zones, making all the concrete unconfined.

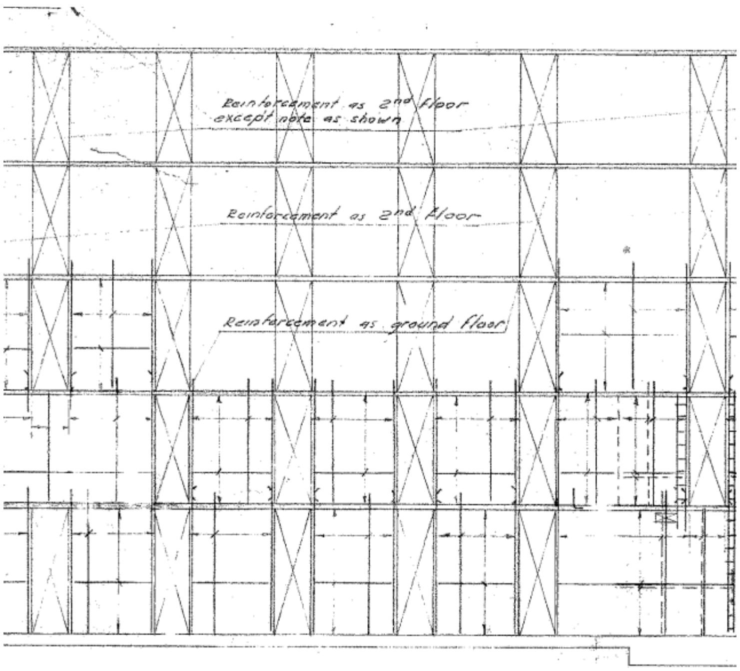
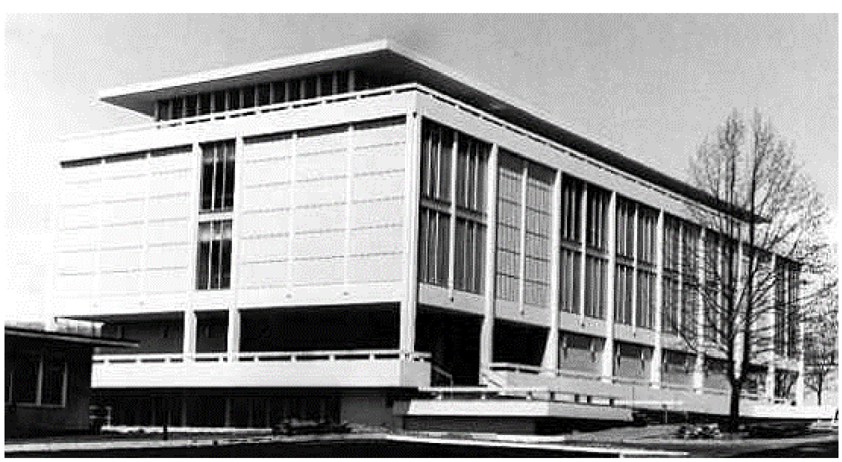


Figure 4 Place Vanier typical wall reinforcement schematic from record drawings

E2.3 Frederic Lasserre Building (028)



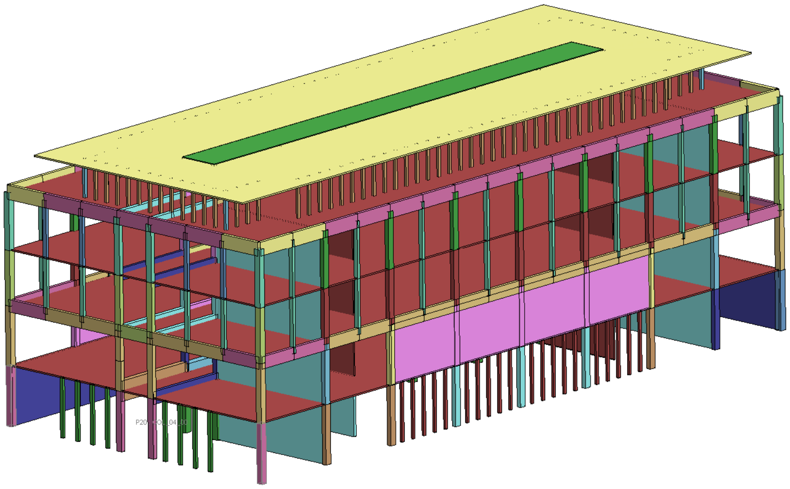


Figure 5 Lasserre (top) vs. analytical model (bottom)

Frederick Lasserre, built in 1962, is a single building containing classrooms and offices. It has 4 above-ground levels and 1 partially below-ground level. The building is a total of 46 ft above ground floor. The floorplates are approximately 160 ft x 71 ft and the floor-to-floor height is typically 13 ft. Lasserre's structural system is composed of a typical 12" thick reinforced concrete voided slab with closely spaced concrete ribs supported by a combination of reinforced concrete frames and 8" thick reinforced concrete shear walls. The dominant lateral force resisting system is the shear walls.

Concrete strength is not specified on the available structural drawings. 3 ksi nominal strength has been assumed for all concrete, which is believed to be typical for low-rise reinforce concrete construction from this time period.

Steel reinforcement grade, as with Gage Tower, is not specified on the available drawings, and has been assumed to be Grade 40 with an expected yield stress = (40 ksi)(1.25 per ASCE 41-13) = 50 ksi. The reinforcement ratio for walls and columns was estimated based on the drawings. See excerpt shown in Figure 6 as an example.

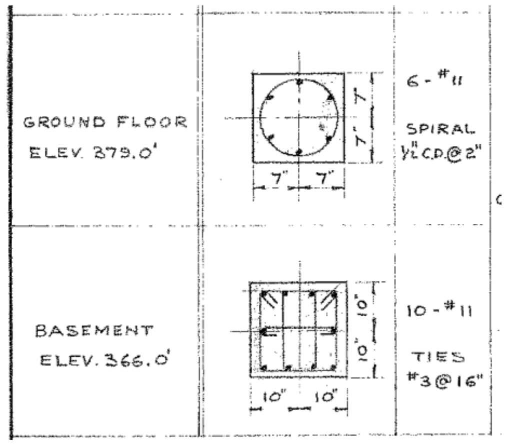


Figure 6 Example column reinforcement detailing shown in structural drawings

E3 Modeling assumptions

All three buildings were modeled and analysed in LS-DYNA, an advanced general-purpose multiphysics simulation software package developed by Livermore Software Technology Corporation (LSTC). A nonlinear time-history analysis, using an explicit solver which accounts for nonlinear geometry and nonlinear materials was undertaken with the ground motions shown in Section **Error! Reference source not found.** applied at the base of the model.

The buildings were modeled with the following element types:

- 2D nonlinear shell elements for the walls, with explicit layers representing steel reinforcement, unconfined concrete, and corresponding nonlinear material behavior. No "plane sections remain plane" assumption is invoked, and localized damaged at the end or corners of walls is explicitly captured.
- 1D lumped plasticity elements for the moment frame beams at Lasserre, which have been validated against testing at UCLA to reproduce the hysteretic behavior.
- 1D lumped plasticity elements for the moment frame columns at Lasserre.
- Floors:
    - Place Vanier: 2D elastic shell elements using stiffness modifiers.
    - Lasserre: 2D nonlinear shell elements, with explicit layers representing steel reinforcement, unconfined concrete, and corresponding nonlinear material behavior.

The models were subjected to the ground motions in conjunction with expected gravity loads, which includes self-weight, superimposed dead loads, and 25% of the unreduced live loads. Fixed supports were assumed at the base of the structure and soil-structure interaction was not considered. An inherent 5% was assumed for Place Vanier and Lasserre, while 2.5% critical damping was assumed for Gage (taller buildings are shown to have less inherent damping).

E4 Summary of 3D analyses results

This section provides a brief summary of general building damage for the earthquake scenarios considered. At Very Rare level, we analyzed 7 motions for Gage Tower, 2 for Place Vanier, and 2 for Lasserre. At the Rare level, we analyzed 2 motions for each building. Each of these motions were applied in one direction at a time only for consistency with SRG.

All three buildings studied experienced significant damage in the Very Rare earthquake, but we did not observe catastrophic collapse in the simulations considered. This does not mean that there is a zero probability of collapse as we did not analyse enough motions to assess collapse risk and only unidirectional motions were used (this is likely unconservative). The advantage of the simplified models is that a sufficient number of ground motions can be analysed to explicitly calculate collapse probability. For that reason, the EDPs from the simplified analysis were utilized for the risk assessment of the three building described herein.

While an insufficient number of ground motions were simulated to enable the explicit calculation of collapse risk, the fact that at least two of the buildings (Fred Lasserre and Place Vanier) did not exhibit catastrophic collapse indicates that the collapse risk is not as high as had originally been anticipated by Rapid Visual Screening per FEMA P-154. The RVS method assessed both Fred Lasserre and Place Vanier as high collapse risk (50% probability of collapse in Very Rare shaking). With the strength of each building derived explicitly from the detailed 3D models used as input to the SRG analysis, the probability of collapse of each building was estimated to be low. This was consistent with the results we observed from the limited number of ground motions studied in the detailed 3D analysis.

On the other hand, the RVS method originally assigned a very low probability of collapse to the Gage Tower (1% probability). Our analysis indicated severe damage to the walls. This level of damage does not explicitly meet the definition of collapse but it could be argued that gravity load carrying capacity was significantly diminished. In the end, we felt comfortable with the probability of collapse estimated by the simplified LS-DYNA analysis for Gage Towers (15% in the Very Rare earthquake).

E4.1 Gage Tower

Gage Tower experienced heavy wall damage during Very Rare shaking, as shown in Figure 7, but has a highly redundant lateral system which helps re-distribute the loads to multiple other walls. In the ground motions considered, the seismic load was transferred from the damaged shear walls to the concrete gravity walls. These walls were not originally designed to take seismic load, but in reality have substantial lateral capacity. The walls sustain significant crushing damage through the full wall thickness in some areas near the bottom of the building and a red-tag is almost certain. However, the analysis predicts that the tower is expected to remain standing during a Very Rare earthquake. Gage Tower performs better during a Rare earthquake, but is still expected to develop large cracks throughout. Again, the 3D analysis undertaken herein has limitations in that the ground motions are unidirectional, duration effects (particularly from Cascadia Subduction Zone earthquake) were not exhaustively studied, and only a limited number of ground motions were simulated.

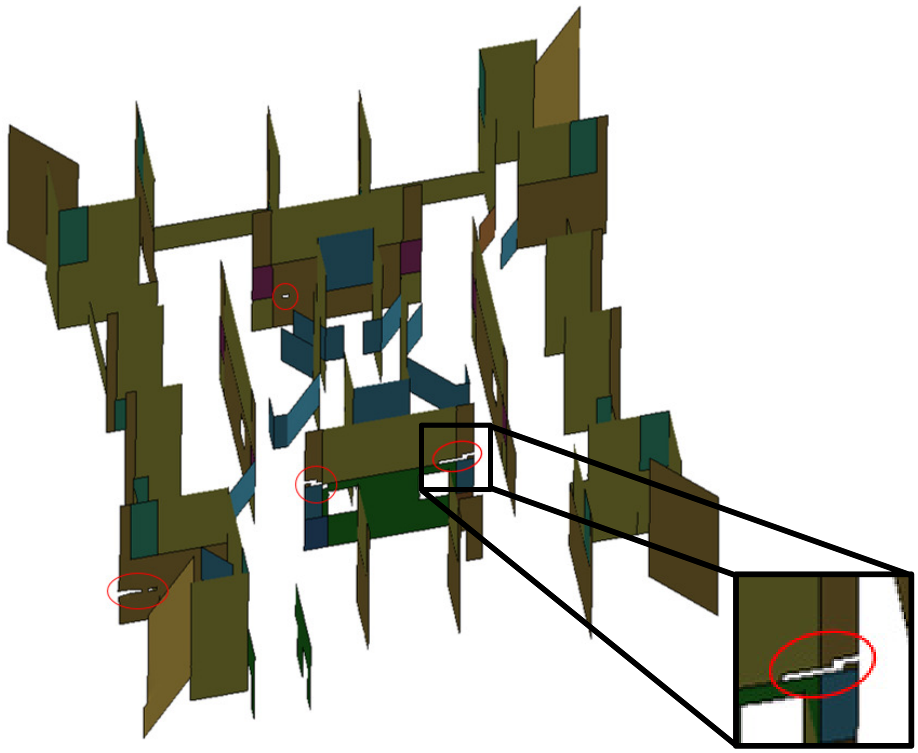


Figure 7 Failed (deleted) elements at end of Very Rare Subduction GM7, representing portions of wall which have seen concrete crushing through the whole section and rebar buckling. Failed areas circled in red. Only walls at first three levels shown.

E4.2 Place Vanier

Place Vanier also performed better than expected given the wide spacing of its shear walls in the short direction of the building. This is due in part to the kinematic effect in the slabs, an effect which is not captured in a simplified stick model, and to the flanging action provided by perpendicular walls. Place Vanier, like Gage, did not collapse in any of the 3D simulations, and it is expected to have a low probability of collapse in a Very Rare seismic event. Figure 8 shows the crack pattern in Place Vanier's walls at the end of a Very Rare ground motion. Under a Rare event, Place Vanier shows practically no crushing in the concrete walls, and moderate cracking in the resisting walls.

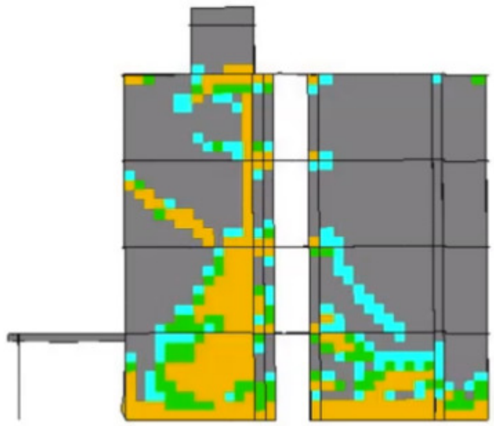


Figure 8 Crack pattern for Place Vanier at end of Very Rare ground motion (yellow = rebar yielding, but not rupture).

E4.3 Fred Lasserre

During a Very Rare seismic event, the building did not exhibit concrete crushing. It does, however, show extensive cracking and rebar yielding due to the low reinforcement ratio in the walls as shown in Figure 9. In addition, the penthouse sustained extensive damage and further detailed analysis is warranted to understand the risk of this portion of the building collapsing. A stair core tower that rises above the third floor and into the penthouse space appears to enhance the resistance of the penthouse. During a Rare event, Fred Lasserre show no crushing, no rebar yielding, and is expected to have smaller cracks.

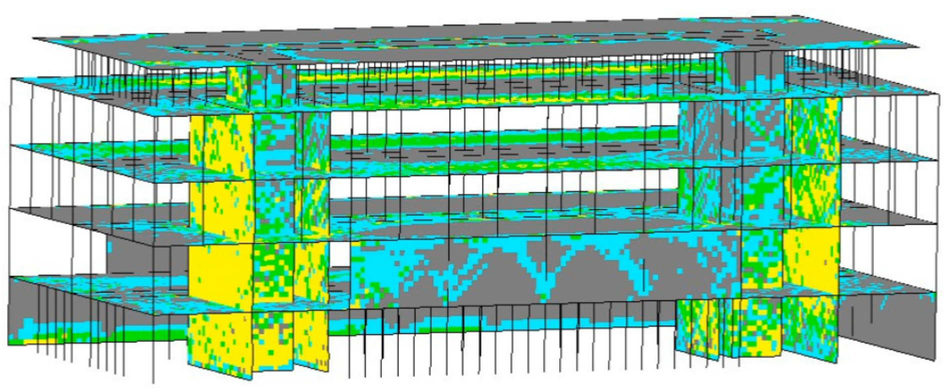


Figure 9 Crack pattern for Lassarre at end of Very Rare ground motion (yellow = rebar yielding, but not rupture).

E5 Calibration with SRG

The SRG method is used to estimate EDPs for low-rise buildings. To facilitate the calibration of the EDPs estimated by SRG (see Appendix D) for low-rise concrete shear wall buildings using the 3D DYNA results, we had to establish the common base shear strength to be used. This was defined as the strength derived from nonlinear pushover analysis of the 3D LS-DYNA model. This is represented as the plateau in Figure 11. The results from the SRG analyses, using the pushover-defined strengths, are referred to as "pushover-calibrated SRG results" herein.

E5.1 Adjustment of interstory drift

Figure 10 compares the pushover curve derived from the 3D LS-DYNA models of Fred Lasserre and Place Vanier, compared to that assumed by SRG for buildings of this type and age (C-7, see Appendix D for further detail). It is apparent that there is a discrepancy between the initial stiffness of the SRG backbone curve and that derived from LS-DYNA. The initial building stiffness assumed by SRG is much softer than LS-DYNA, which more likely resembles reality because the building components and material properties are explicitly modeled. The SRG backbone is bi-linear, meaning it is inherently limited in representing the full nonlinear behavior of concrete buildings, including cracking, up to the yield point. Due to this limitation, the SRG backbone will underestimate the initial stiffness. The LS-DYNA model may overestimate the initial stiffness as it does not account for foundation flexibility or other phenomena such as bond slip. The reality is that the pre-yield stiffness is somewhere in between.

The discrepancy in the initial building stiffness also led to a discrepancy in the interstory drift ratios (IDRs) between the 3D LS-DYNA results (which are likely better to resemble reality) and the pushover-calibrated SRG results (see Figure 11). We adjusted the IDRs for the low-rise concrete shear walls buildings, resulting from SRG methods, according to the dashed line shown in Figure 10. The dashed line represents the "IDR Adjustment Backbone," which was chosen as an approximate bilinearization of the pre-yield portion of the Lasserre and Place Vanier 3D LS-DYNA pushover curves. The new yield drift imposed by this curve is 0.25%, whereas the yield point assumed by the SRG backbone is 0.35%. The new "cracking drift" was set at 0.05% drift and the cracking strength as $0.45F_y$, where F_y is the yield strength. For drifts that are estimated by the SRG analysis to exceed 0.35% (the originally assumed yield-drift), these were reduced in post-processing by 0.1%. This is the difference in yield drift between the SRG backbone and the IDR Adjustment Backbone. For drifts that are estimated by the SRG analysis to be less than 0.35%, these are mapped horizontally back to the IDR Adjustment Backbone in post-processing. The resulting SRG drifts adjusted according to the above are shown in Figure 11. These show a much better match to the 3D LS-DYNA results. The upshot is that the resulting calibration reduces the drifts, particularly for moderate shaking (i.e. prior to yield), and the resulting risks across the portfolio.

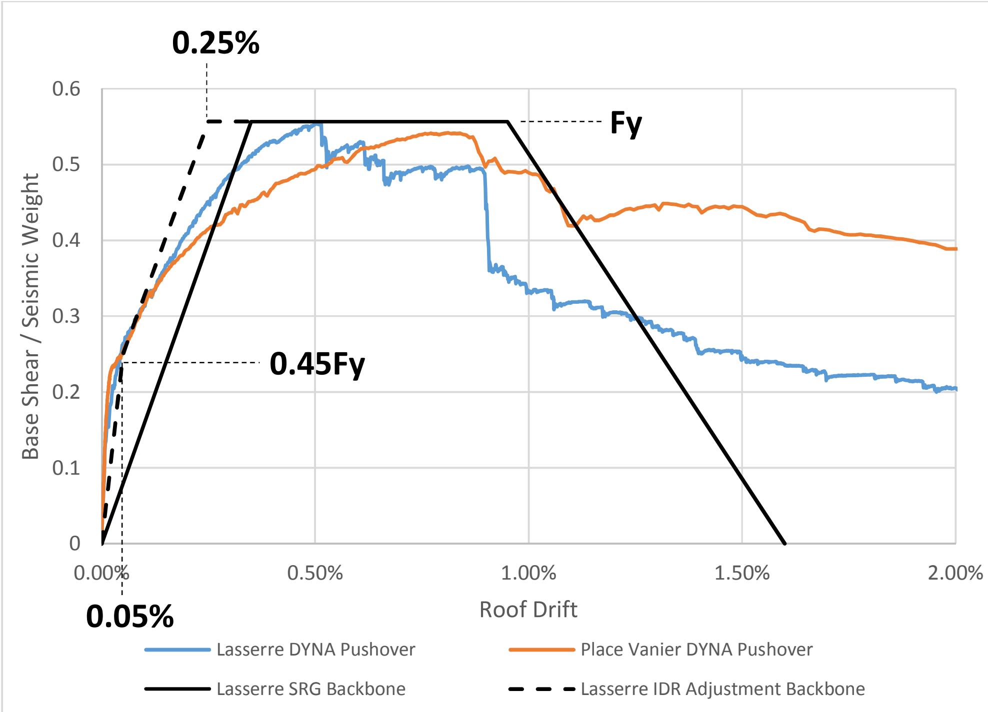
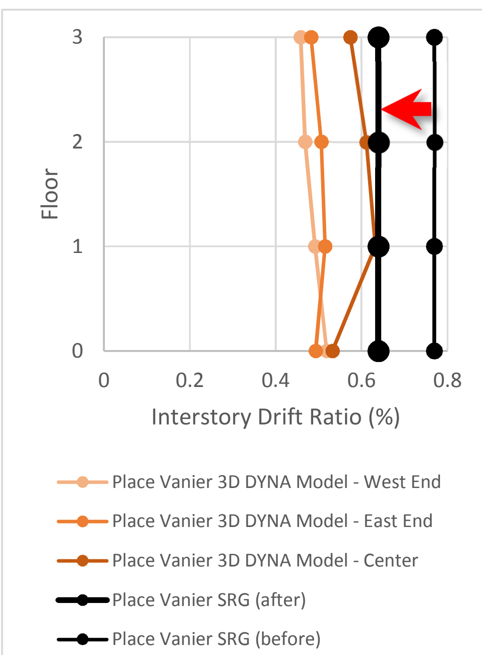


Figure 10 Lasserre C-7 SRG Backbone, Lasserre IDR Adjustment Backbone, and DYNA Pushover curves for Frederic Lasserre (bldg 028) and Place Vanier (bldg 545-1/2)



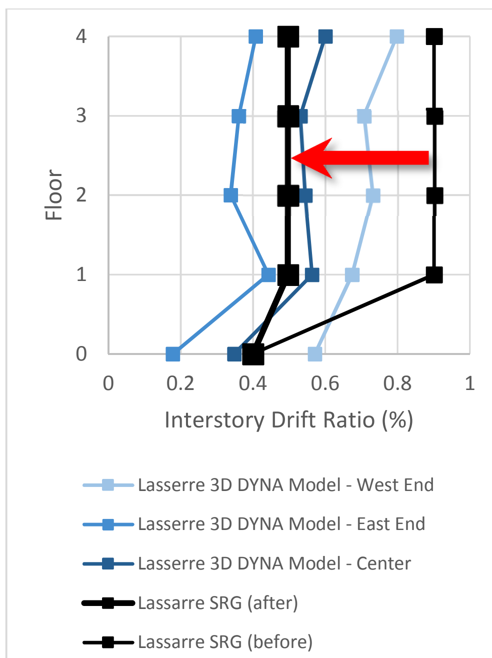


Figure 11 2475-yr IDRs: Pushover-Calibrated SRG results before and after IDR adjustment compared to 3D DYNA results for Place Vanier Bldg 545-1/2 (left) and Frederic Lasserre (right)

In Figure 11, the colored lines represent IDRs at different points on the floorplate. As both buildings are bar shaped (much longer in one direction than the other), three points are shown to adequately account for whole-building torsional effects and slab kinematic effects: west end, east end, and center. Place Vanier tends to have the highest IDR in the center due to slab kinematic effects – the shear walls are spaced far apart at only the ends of the building. Fred Lasserre tends to the highest IDR at the west end of the building due to whole building torsional effects caused by assymmetry in the basement walls – there is far more basement wall on the east end than the west end. The simplified SRG analyses are not able to capture these effects.

Figure 12 to Figure 15 show comparisons between the 3D DYNA and calibrated SRG model 2475-yr and 475-yr IDRs for Place Vanier and Lasserre. The results are in general agreement, although the limitations of the SRG analyses are apparent, as the 3D models capture the variance in EDPs up the height of the building.

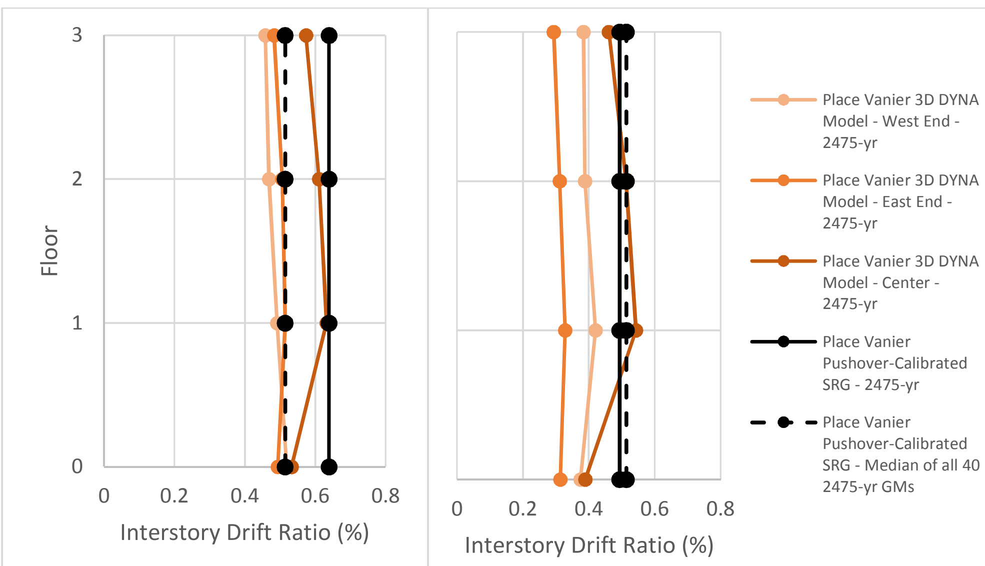


Figure 12 Bldg 545-1/2: 2475-yr Subcrustal GM10 (left) and Crustal GM2 (right) Interstory Drift Ratio (IDR) comparison between 3D DYNA results and SRG model

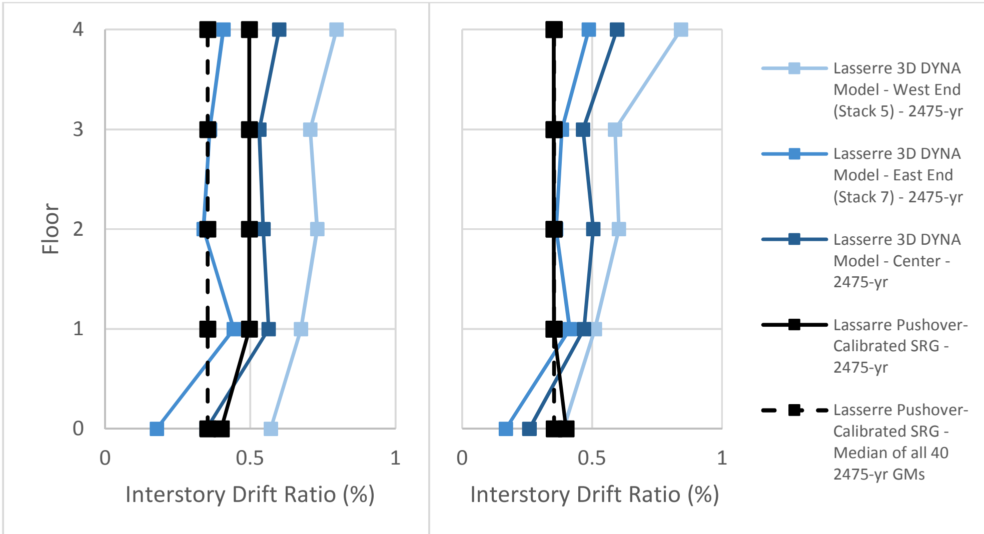


Figure 13 Bldg 028: 2475-yr Subcrustal GM10 (left) and Crustal GM2 (right) Interstory Drift Ratio (IDR) comparison between 3D DYNA results and SRG Model

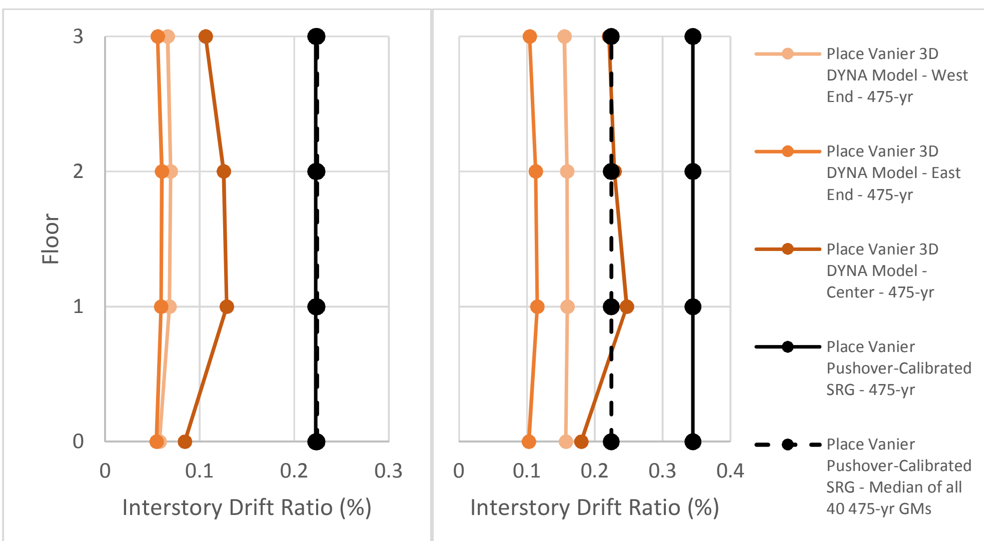


Figure 14 Bldg 545-1/2: 475-yr Subcrustal GM10 (left) and Crustal GM2 (right) Interstory Drift Ratio (IDR) comparison between 3D DYNA results and SRG model

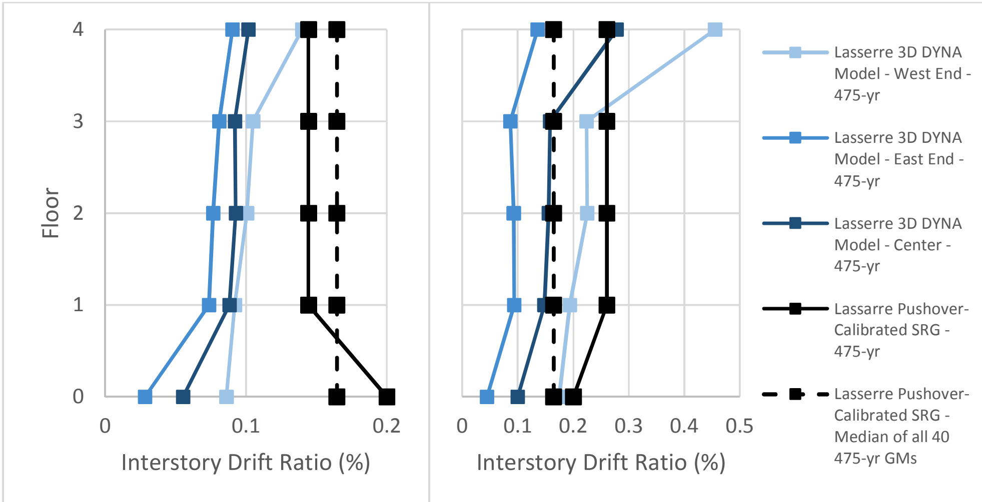


Figure 15 Bldg 028: 475-yr Subcrustal GM10 (left) and Crustal GM2 (right) Interstory Drift Ratio (IDR) comparison between 3D DYNA results and SRG Model

E5.2 Peak floor accelerations

The peak floor accelerations (PFAs) obtained using FEMA P-58 were a reasonable match to the 3D DYNA results, as shown in the figures below, and did not require any adjustment.

Figure 16 to Figure 19 below show comparisons between the 3D DYNA and calibrated SRG model 2475-yr and 475-yr PFAs for Place Vanier and Lasserre.

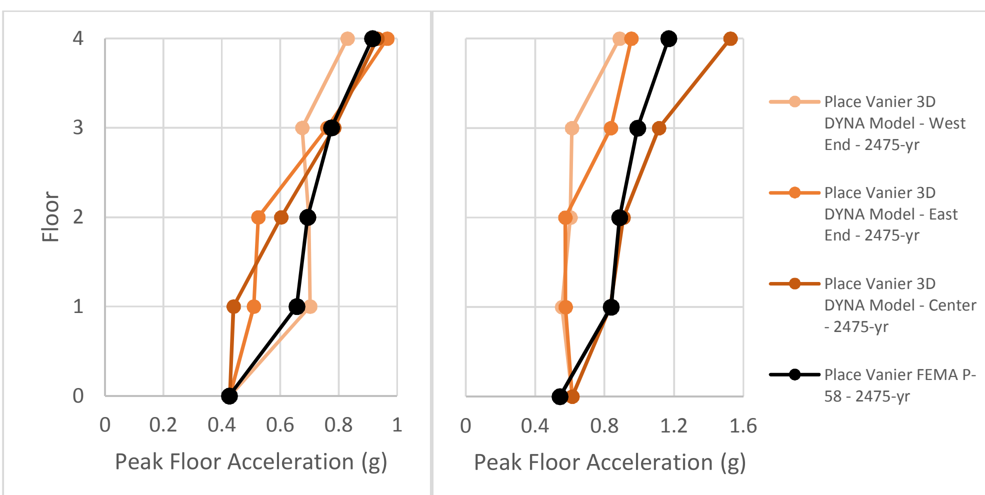


Figure 16 Bldg 545-1/2: 2475-yr Subcrustal GM10 (left) and Crustal GM2 (right) Peak Floor Acceleration (PFA) comparison between 3D DYNA results and FEMA P-58

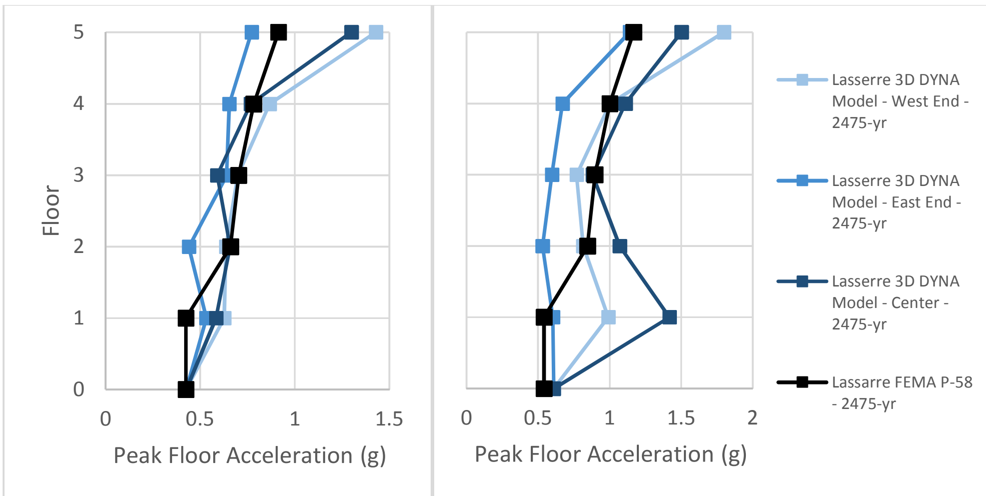


Figure 17 Bldg 028: 2475-yr Subcrustal GM10 (left) and Crustal GM2 (right) Peak Floor Acceleration (PFA) comparison between 3D DYNA results and FEMA P-58

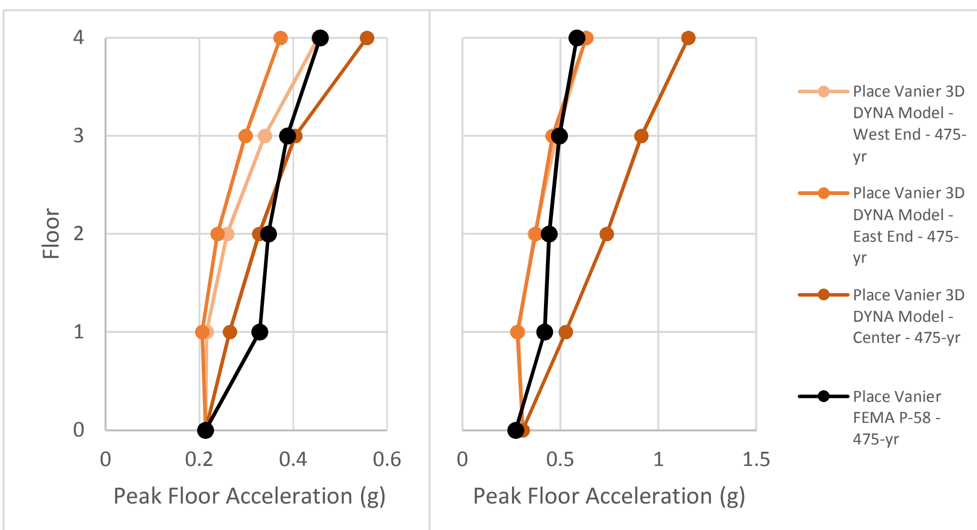


Figure 18 Bldg 545-1/2: 475-yr Subcrustal GM10 (left) and Crustal GM2 (right) Peak Floor Acceleration (PFA) comparison between 3D DYNA results and FEMA P-58

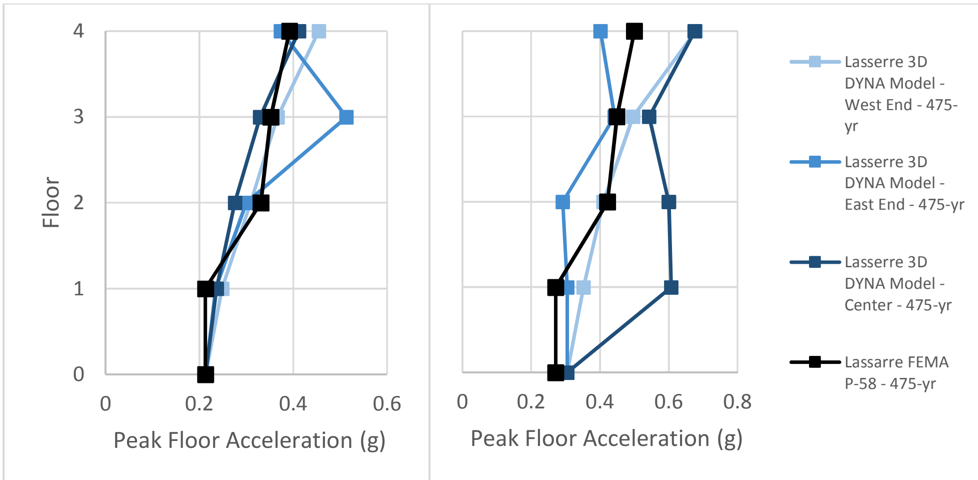


Figure 19 Bldg 545-1/2: 475-yr Subcrustal GM10 (left) and Crustal GM2 (right) Interstory Drift Ratio (IDR) comparison between 3D DYNA results and SRG model

E5.3 Residual interstory drifts

The residual interstory drifts (RIDRs) obtained using SRG had the least satisfactory match to the 3D LS-DYNA results. However, the RIDRs for Lasserre and Place Vanier were quite low in all runs, and are not expected to significantly contribute to the loss and downtime in the risk assessment. This generally holds true for all tall concrete shear wall buildings, which have a tendency to self-center due to self-weight, or those that do not sustain significant damage. The buildings we investigated all performed relatively well, owing to their large shear strength.

Figure 20 to Figure 21 below show comparisons between the 3D DYNA and calibrated SRG model 2475-yr RIDRs for Place Vanier and Lasserre.

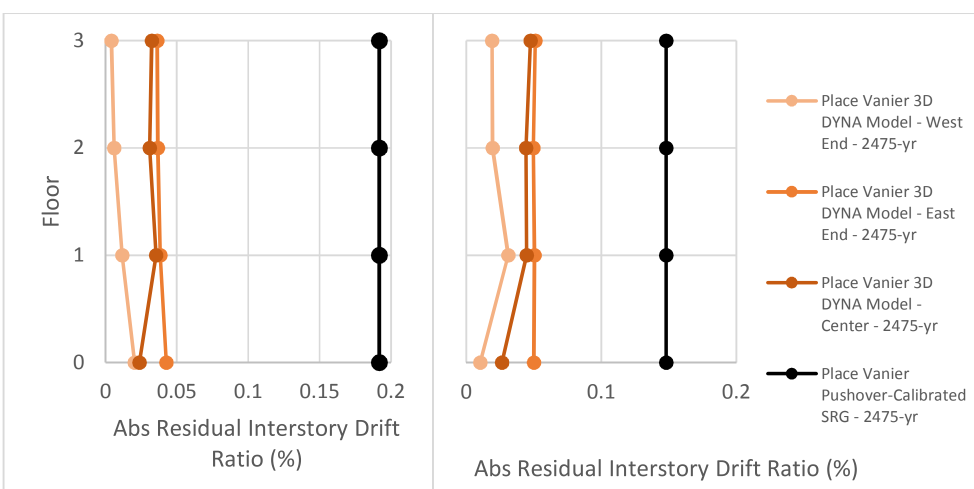


Figure 20 Bldg 545-1/2: 2475-yr Subcrustal GM10 (left) and Crustal GM2 (right) Residual Interstory Drift Ratio (RIDR) comparison between 3D DYNA results and SRG model

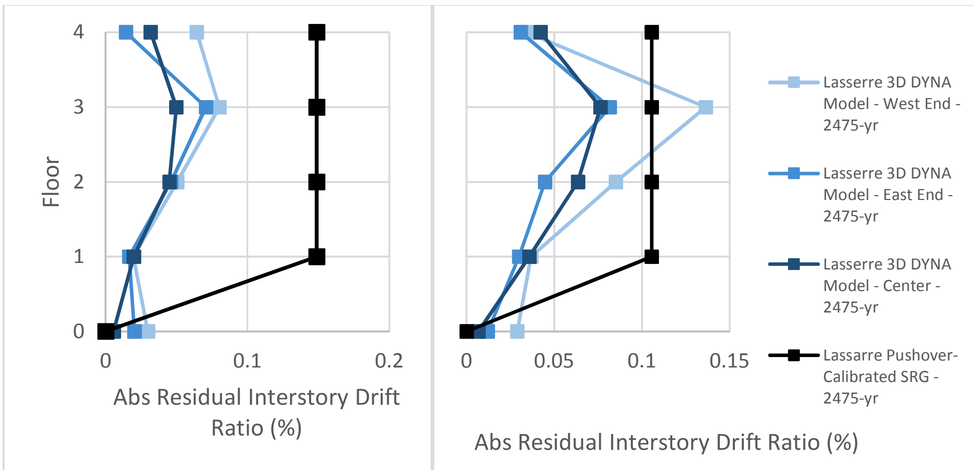


Figure 21 Bldg 028: 2475-yr Subcrustal GM10 (left) and Crustal GM2 (right) Residual Interstory Drift Ratio (RIDR) comparison between 3D DYNA results and SRG Model

E6 Calibration with simplified LS-DYNA analysis

Simplified LS-DYNA models are generally used to estimate EDPs for buildings taller than 4 stories. See Appendix D for further detail. For Gage Tower, 7 ground motions were run primarily to better detect collapse. 2 of the ground motions deemed to be representative of the hazard were chosen for the simplified model calibration. The IDRs and PFAs directly from the simplified model compared favorably with the IDRs and PFAs from the 3D LS-DYNA model, as shown in the figures below. The RIDRs did not match as well. However, the RIDRs from both models were very low, and are not expected to significantly contribute to the loss and downtime in the risk assessment. Therefore, no post-analysis adjustments were made to the EDPs from the simplified analysis. The simplified LS-DYNA model has some of the same limitations as the SRG model, in that it cannot capture the localized damage captured by the 3D model.

E6.1.1 Interstory drift

Figure 22 to Figure 23 show comparisons between the 3D DYNA and simplified DYNA 2475-yr and 475-yr IDRs for Gage Tower.

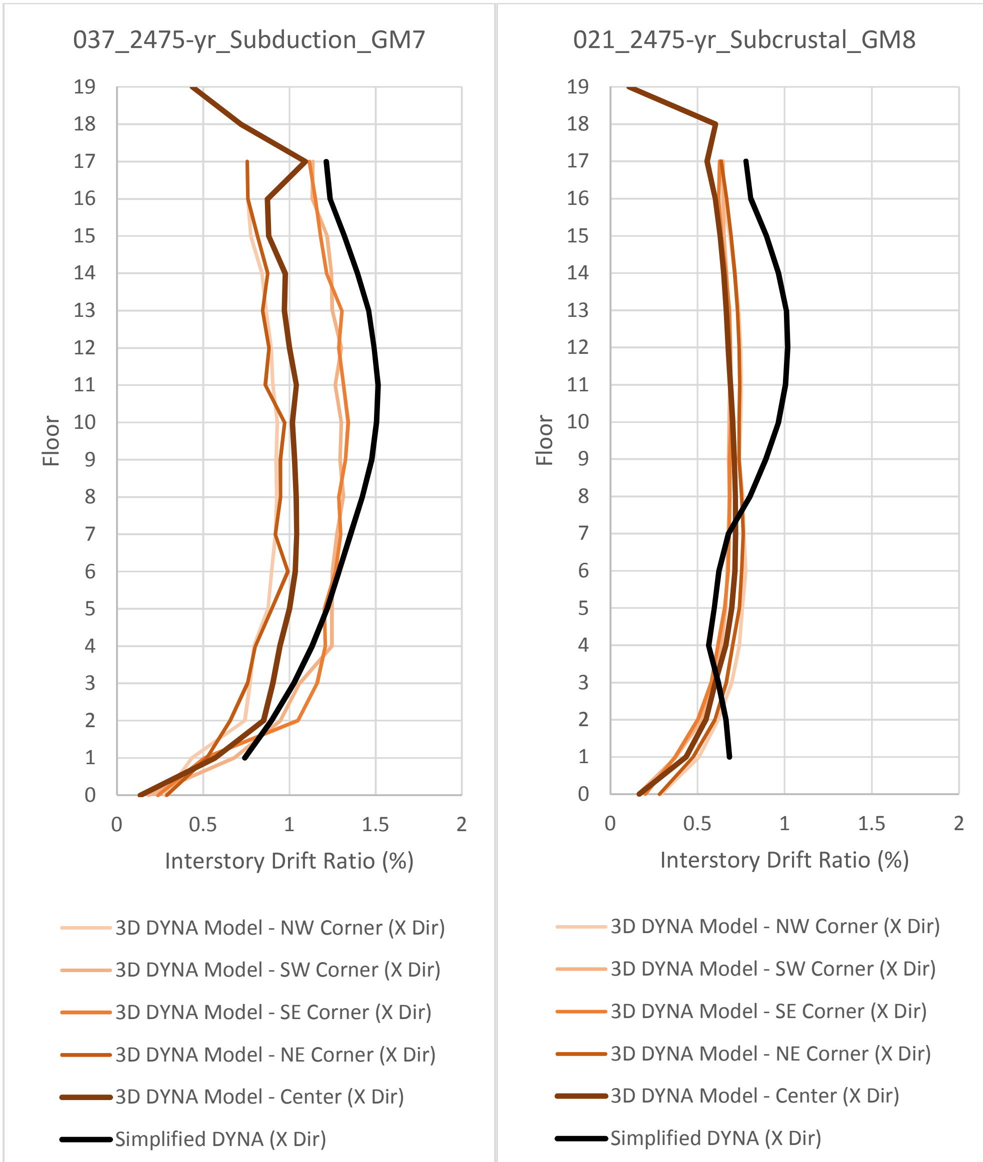


Figure 22 Bldg 872-1: 2475-yr Interstory Drift Ratio (IDR) comparison between 3D DYNA results and Simplified DYNA Results

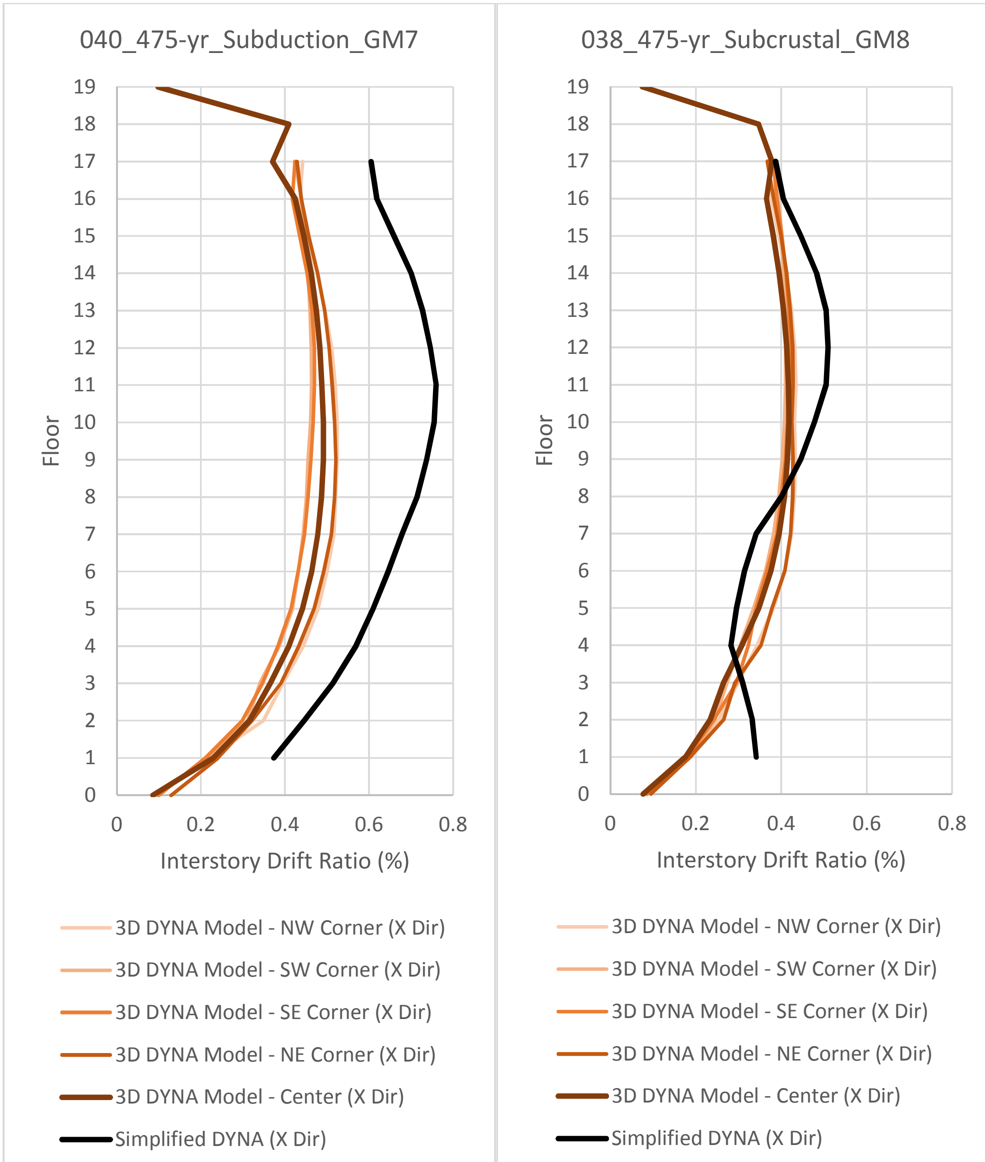


Figure 23 Bldg 872-1: 475-yr Interstory Drift Ratio (IDR) comparison between 3D DYNA results and Simplified DYNA Results

E6.1.2 Peak floor accelerations

Figure 24 to Figure 25 show comparisons between the 3D DYNA and simplified DYNA 2475-yr and 475-yr PFAs for Gage Tower.

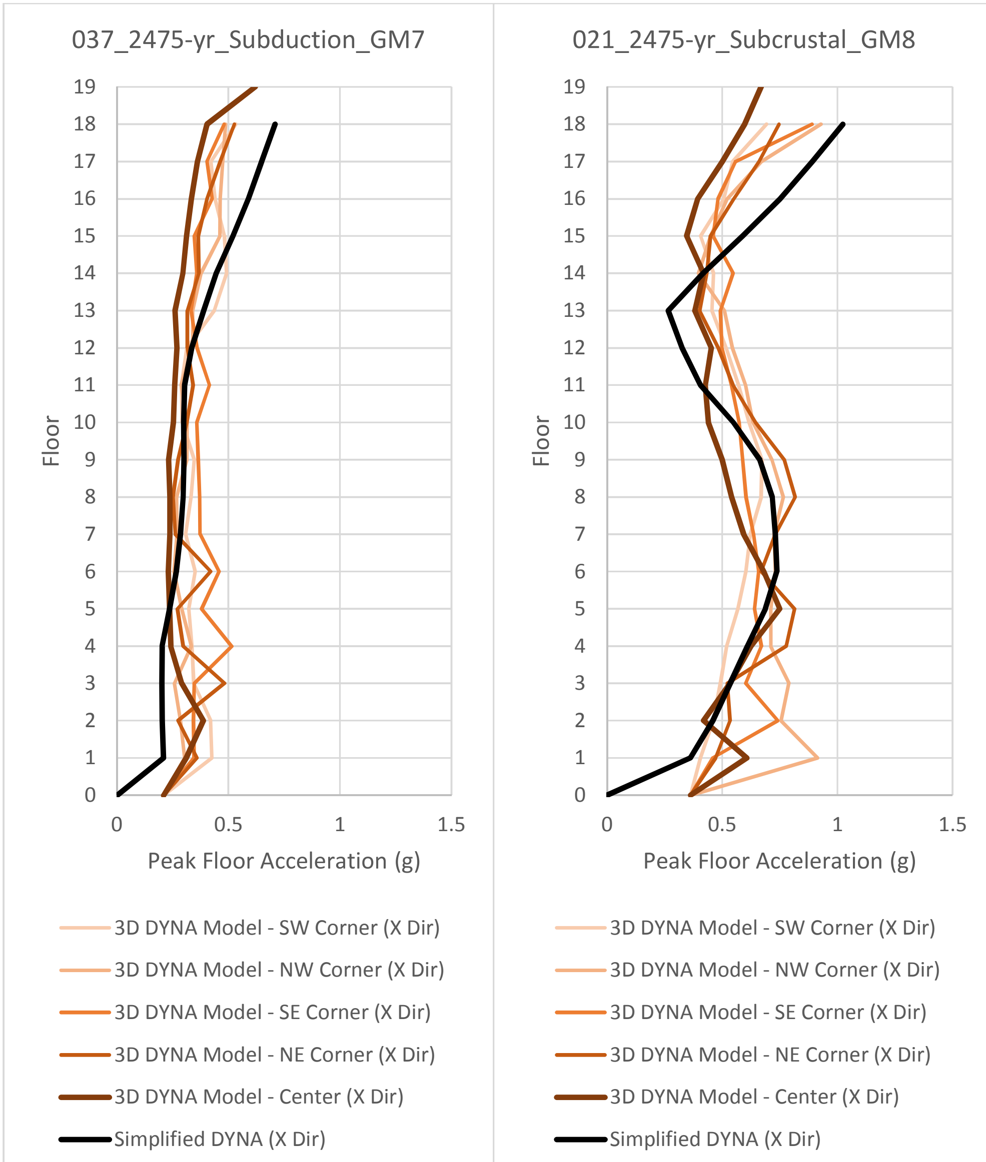


Figure 24 Bldg 872-1: 2475-yr Peak Floor Acceleration (PFA) comparison between 3D DYNA results and Simplified DYNA results

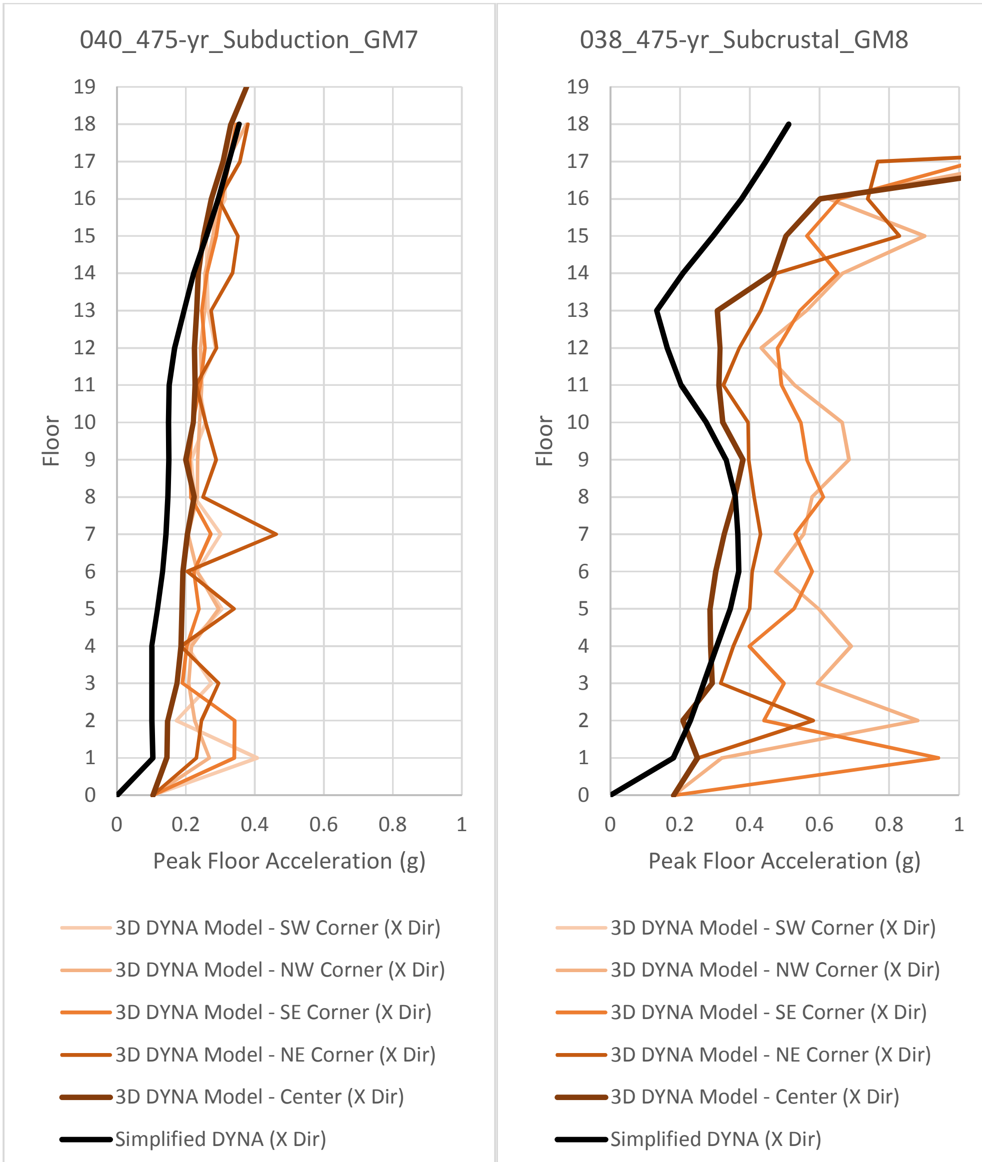


Figure 25 Bldg 872-1: 475-yr Peak Floor Acceleration (PFA) comparison between 3D DYNA results and Simplified DYNA Results

E6.1.3 Residual interstory drifts

Figure 26 shows a comparison between the 3D DYNA and simplified DYNA 2475-yr RIDRs for Gage Tower.

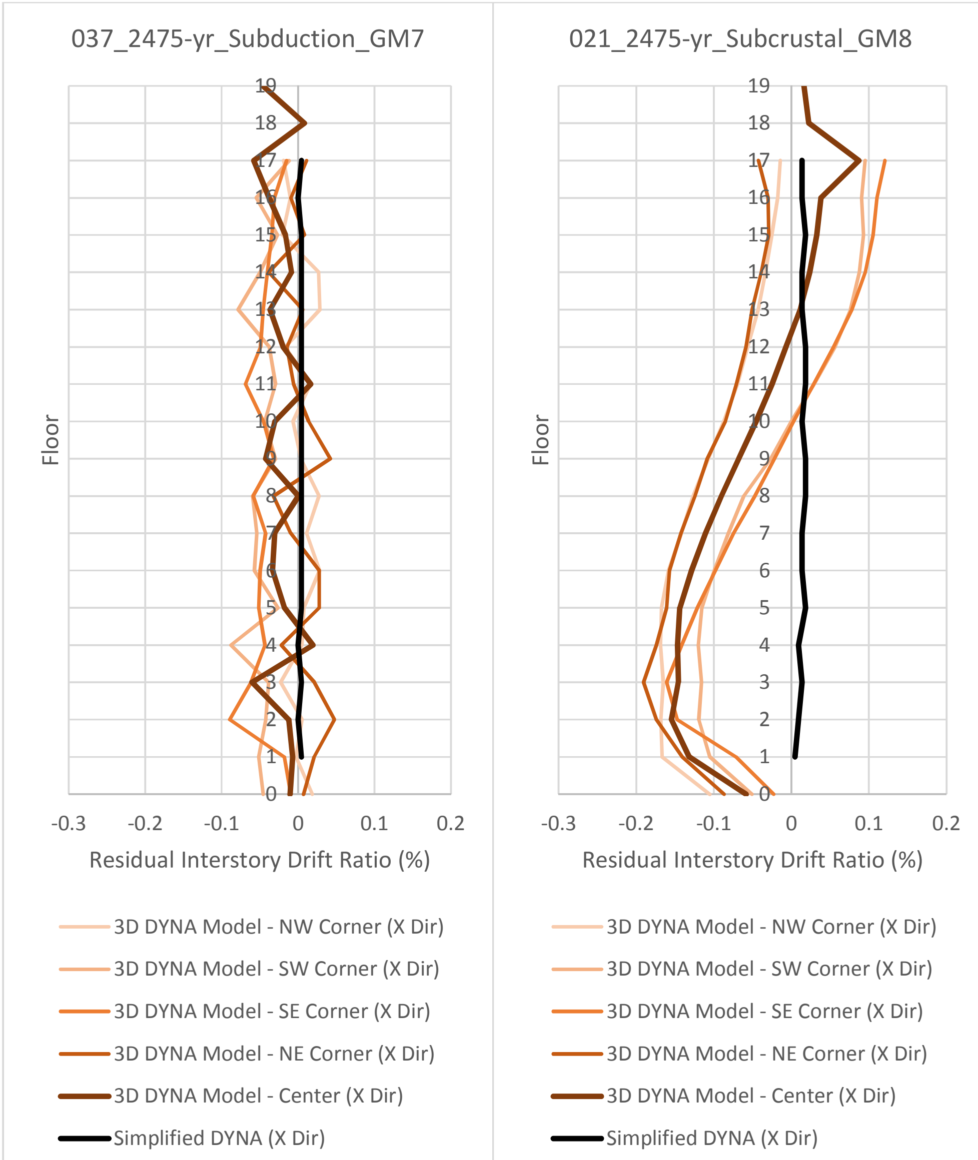


Figure 26 Bldg 872-1: 2475-yr Residual Interstory Drift Ratio (RIDR) comparison between 3D DYNA results and Simplified DYNA results

Appendix F

Conceptual Structural Mitigation Measures and Building Mitigation Costs

F1 Introduction

Arup develop conceptual level seismic retrofit strategies, described in further detail in section F2, in order to facilitate costing of each building. The conceptual structural retrofit packages are provided in section F3

Section F4 provides the costs to seismically retrofit, renew, demolish and replace each building on campus. These were developed by LEC Group. The costs were utilized in the cost-benefit analysis (see section 5.7).

F2 Seismic retrofit strategies

To inform the cost-benefit analysis, conceptual level seismic retrofit strategies were developed to allow costing for seismic retrofits of the buildings across the Point Grey Campus. For the purposes of this study, the conceptual level retrofits were designed to resist 100% of the current seismic forces per the 2012 British Columbia Building Code. A total of fifteen conceptual retrofit strategies were developed and used to represent the various types of retrofits applicable to the various UBC buildings based upon their construction typology (i.e. Light Wood, Steel Braced Frame, Concrete Shear wall, etc).

The types of retrofits proposed for each of the building typologies were influenced by a number of factors including: consultation with University staff, review of available best practice documentation such as the Seismic Retrofit Guidelines (SRG) and FEMA 547 (Techniques for the Seismic Rehabilitation of Existing buildings), and the consultants previous retrofit experience.

For each of the fifteen building typologies and retrofit strategies (listed below), the retrofits were developed for an example building meant to be representative of the average UBC building of that typology (averaging across area and number of floors). The application of the retrofits to these representative buildings was meant to aid in the development of retrofit costs on a $/m2 basis which could then be applied to the larger building stock across the UBC Campus.

Table F1 Building typology and retrofit measures

Building Typology		Description of Retrofit
W1	Light wood frame single- or multiple-family dwellings	Addition of new timber shear walls or enhancement of existing timber shear walls. Enhancement of existing connections for lateral shear and hold-down overturning forces. Enhancement of existing diaphragm shear and chord elements.
W1A	Light wood frame multi-unit, multi-story residential buildings	Addition of new timber shear walls or enhancement of existing timber shear walls. Enhancement of existing connection for lateral shear and hold-down overturning forces. Enhancement of existing diaphragm shear and chord elements.
W2	Wood frame commercial and industrial buildings	Addition of new Buckling Restrained Braces to provide ductile lateral resistance. Enhancement of existing connections for load path. Enhancement of existing diaphragm shear and chord elements.
S1	Steel moment-resisting frame	Addition of new Buckling Restrained Braces into steel moment frames to provide ductile lateral resistance. Enhancement of existing connections for load path. Enhancement of existing diaphragm shear and chord elements and retrofits to improve deformation capacity of gravity system.
S2	Braced steel frame	Replacement of existing braces with new Buckling Restrained Braces to provide ductile lateral resistance. Enhancement of existing connections for load path. Enhancement of existing diaphragm shear and chord elements and retrofits to improve deformation capacity of gravity system.
S3	Light metal frame	Addition of new Buckling Restrained Braces into steel moment frames to provide ductile lateral resistance. Enhancement of existing connections for load path. Enhancement of existing diaphragm shear and chord elements including the addition of in-plane bracing at the roof.
S4	Steel frame with cast-in-place concrete shear walls	Enhancement of existing diaphragm shear and chord elements and retrofits to improve deformation capacity of gravity system and either: a) Addition of new ductile shear walls to resist 100% of new code forces as well as the enhancement of existing shear walls to improve ductility, or, b) Strengthening of existing shear walls to resist 100% of new code forces as well as to add ductility.

C1	Concrete moment-resisting frame	Enhancement of existing diaphragm shear and chord elements and retrofits to improve deformation capacity of gravity system and either: a) Addition of new ductile shear walls to resist 100% of new code forces as well as the enhancement of existing shear walls to improve ductility, or, b) Strengthening of existing shear walls to resist 100% of new code forces as well as to add ductility.
C2	Concrete shear wall	Enhancement of existing diaphragm shear and chord elements and retrofits to improve deformation capacity of gravity system and either: a) Addition of new ductile shear walls to resist 100% of new code forces as well as the enhancement of existing shear walls to improve ductility, or, b) Strengthening of existing shear walls to resist 100% of new code forces as well as to add ductility.
C3	Concrete frame with unreinforced masonry infill walls	Removal of infill masonry walls. Enhancement of existing diaphragm shear and chord elements and retrofits to improve deformation capacity of gravity system and addition of new ductile shear walls to resist 100% of new code forces as well as the enhancement of existing shear walls to improve ductility
PC1	Tilt-up construction	Enhancement of Diaphragm as well as in-plane and out-of-plane connection of diaphragm and wall assemblies. Addition of new Buckling restrained braces to shorten diaphragm span and resist component of seismic load beyond that of current wall capacity
PC2	Precast concrete frame (with concrete shear walls)	Strengthening of existing shear walls to resist 100% of new code forces as well as to add ductility. Enhancement of existing diaphragm shear and chord elements and retrofits to improve deformation capacity of gravity system
RM1	Reinforced masonry with flexible floor and roof diaphragms	Enhancement of Diaphragm as well as in-plane and out-of-plane connection of diaphragm and wall assemblies. Addition of new Buckling restrained braces to shorten diaphragm span and resist component of seismic load beyond that of current wall capacity
RM2	Reinforced masonry with rigid floor and roof diaphragms	Addition of New shear walls to resist 100% of code forces and enhancement of existing diaphragm shear and chord elements

URM	Unreinforced masonry bearing-wall buildings	Addition of New shear walls to resist 100% of code forces and enhancement of existing diaphragm shear and chord elements including addition of new collectors. Restraining URM to new shear walls or new HSS strong-backs to prevent out of plane failure.

F3 Seismic retrofit drawing packages

F4 Mitigation costs

UBC BUILDINGS FOR COSTING CONSIDERATION											
INFORMATION FOR COST ESTIMATOR							FOR COST ESTIMATOR TO COMPLETE				
BUILDING ID		BUILDING NAME	YEAR	CONSTRUCTION TYPE	NUMBER OF ELEVATED STORIES	GROSS BUILDING AREA	STRUCTURAL RETROFIT COST	DEMOLITION COST	REPLACEMENT COST	RENEW	Ratio of Renewal to Replacement Cost
-	-	-	-	-	-	m2	$	$	$	$	
002-1	2.01	ACADIA PARK HIGHRISE	1967	C2	14	6,500	9,215,000	1,072,500	21,324,000	13,647,000	64%
007-01	7.01	FAIRVIEW CRESCENT STUDENT HOUSING - UNIT 1	1985	W1A	3	600	783,000	66,000	1,507,000	1,015,000	67%
007-11	7.11	Fairview Crescent Student Housing - Unit 11	1985	W1A	3	1,000	1,270,000	110,000	2,388,000	1,655,000	69%
007-14	7.14	Fairview Crescent Student Housing - Unit 14	1985	W1A	3	600	766,000	66,000	1,431,000	997,000	70%
007-19	7.19	Fairview Crescent Student Housing - Unit 19	1985	W1A	3	600	759,000	66,000	1,435,000	989,000	69%
007-23	7.23	Fairview Crescent Student Housing - Unit 23	1985	W1A	3	1,000	1,277,000	110,000	2,385,000	1,662,000	70%
007-26	7.26	Fairview Crescent Student Housing - Unit 26	1985	W1A	3	1,000	1,277,000	110,000	2,385,000	1,662,000	70%
009-01	9.01	ACADIA FAMILY HOUSING PHASE II - UNIT 1	1988	W1A	3	700	894,000	77,000	1,670,000	1,163,000	70%
009-02	9.02	ACADIA FAMILY HOUSING PHASE II - UNIT 2	1988	W1A	3	700	884,000	77,000	1,675,000	1,153,000	69%
009-03	9.03	ACADIA FAMILY HOUSING PHASE II - UNIT 3	1988	W1	1	200	240,000	22,000	360,000	287,000	80%
009-04	9.04	ACADIA FAMILY HOUSING PHASE II - UNIT 4	1988	W1A	3	700	894,000	77,000	1,670,000	1,163,000	70%
009-05	9.05	ACADIA FAMILY HOUSING PHASE II - UNIT 5	1988	W1A	2	600	766,000	66,000	1,431,000	997,000	70%
009-06	9.06	ACADIA FAMILY HOUSING PHASE II - UNIT 6	1988	W1	1	300	352,000	33,000	545,000	421,000	77%
009-07	9.07	ACADIA FAMILY HOUSING PHASE II - UNIT 7	1988	W1A	2	900	1,149,000	99,000	2,147,000	1,496,000	70%
009-08	9.08	ACADIA FAMILY HOUSING PHASE II - UNIT 8	1988	W1A	2	1,100	1,405,000	121,000	2,624,000	1,828,000	70%
009-09	9.09	ACADIA FAMILY HOUSING PHASE II - UNIT 9	1988	W1A	2	600	703,000	66,000	1,465,000	930,000	63%
009-10	9.1	Acadia Family Housing Phase II - Unit 10	1988	W1A	3	700	888,000	77,000	1,672,000	1,157,000	69%
009-11	9.11	Acadia Family Housing Phase II - Unit 11	1988	W1A	3	600	766,000	66,000	1,431,000	997,000	70%
009-12	9.12	Acadia Family Housing Phase II - Unit 12	1988	W1A	3	1,700	2,163,000	187,000	4,059,000	2,817,000	69%
009-13	9.13	Acadia Family Housing Phase II - Unit 13	1988	W1A	3	1,700	2,163,000	187,000	4,059,000	2,817,000	69%
009-14	9.14	Acadia Family Housing Phase II - Unit 14	1988	W1A	3	1,000	1,277,000	110,000	2,385,000	1,662,000	70%
009-15	9.15	Acadia Family Housing Phase II - Unit 15	1988	W1A	3	1,200	1,524,000	132,000	2,866,000	1,986,000	69%
009-16	9.16	Acadia Family Housing Phase II - Unit 16	1988	W1A	2	600	766,000	66,000	1,431,000	997,000	70%
009-17	9.17	Acadia Family Housing Phase II - Unit 17	1988	W1A	1	900	1,142,000	99,000	2,150,000	1,488,000	69%
009-18	9.18	Acadia Family Housing Phase II - Unit 18	1988	W1	1	400	481,000	44,000	721,000	574,000	80%
009-19	9.19	Acadia Family Housing Phase II - Unit 19	1988	W1A	1	1,300	1,656,000	143,000	3,103,000	2,156,000	69%
009-20	9.2	Acadia Family Housing Phase II - Unit 20	1988	W1	2	400	481,000	44,000	721,000	574,000	80%
009-21	9.21	Acadia Family Housing Phase II - Unit 21	1988	W1A	2	600	758,000	66,000	1,436,000	988,000	69%
009-22	9.22	Acadia Family Housing Phase II - Unit 22	1988	W1A	2	600	766,000	66,000	1,431,000	997,000	70%
009-23	9.23	Acadia Family Housing Phase II - Unit 23	1988	W1A	2	600	703,000	66,000	1,465,000	930,000	63%
009-24	9.24	Acadia Family Housing Phase II - Unit 24	1988	W1A	2	600	766,000	66,000	1,431,000	997,000	70%
009-25	9.25	Acadia Family Housing Phase II - Unit 25	1988	W1A	2	600	758,000	66,000	1,436,000	988,000	69%
009-26	9.26	Acadia Family Housing Phase II - Unit 26	1988	W1A	2	600	766,000	66,000	1,431,000	997,000	70%
010-01	10.01	ACADIA FAMILY HOUSING PHASE III - UNIT 1	1989	W1A	2	600	765,000	66,000	1,432,000	996,000	70%
010-02	10.02	ACADIA FAMILY HOUSING PHASE III - UNIT 2	1989	W1A	2	600	749,000	66,000	1,440,000	979,000	68%
010-03	10.03	ACADIA FAMILY HOUSING PHASE III - UNIT 3	1989	W1A	2	600	765,000	66,000	1,432,000	996,000	70%
010-04	10.04	ACADIA FAMILY HOUSING PHASE III - UNIT 4	1989	W1A	2	700	875,000	77,000	1,680,000	1,143,000	68%
010-05	10.05	ACADIA FAMILY HOUSING PHASE III - UNIT 5	1989	W1	1	300	360,000	33,000	541,000	429,000	79%
010-06	10.06	ACADIA FAMILY HOUSING PHASE III - UNIT 6	1989	W1A	3	1,300	1,575,000	143,000	3,146,000	2,071,000	66%
010-07	10.07	ACADIA FAMILY HOUSING PHASE III - UNIT 7	1989	W1A	3	1,300	1,645,000	143,000	3,109,000	2,144,000	69%
010-08	10.08	ACADIA FAMILY HOUSING PHASE III - UNIT 8	1989	W1A	3	1,200	1,528,000	132,000	2,865,000	1,989,000	69%
010-09	10.09	ACADIA FAMILY HOUSING PHASE III - UNIT 9	1989	W1A	3	1,200	1,522,000	132,000	2,868,000	1,983,000	69%
010-10	10.1	Acadia Family Housing Phase III - Unit 10	1989	W1A	2	600	765,000	66,000	1,432,000	996,000	70%
11	11	ACADIA COMMUNITY CENTRE	1989	W1A	2	900	1,149,000	99,000	2,147,000	1,496,000	70%
13	13	KIDS CLUB	1985	MH	1	1,000	n/a	65,000	919,000	n/a	n/a
014-1	14.01	ACADIA FACULTY ROW HOUSING - UNIT 1	1958	W1A	2	800	1,022,000	88,000	1,908,000	1,330,000	70%
014-2	14.02	ACADIA FACULTY ROW HOUSING - UNIT 2	1958	W1A	2	800	926,000	88,000	1,959,000	1,229,000	63%
014-3	14.03	ACADIA FACULTY ROW HOUSING - UNIT 3	1958	W1A	2	800	1,022,000	88,000	1,908,000	1,330,000	70%
17	17	OLD ADMINISTRATION BUILDING	1924	W2	2	3,200	5,160,000	352,000	10,582,000	7,087,000	67%
19	19	BIOENERGY RESEARCH AND DEMONSTRATION FACILITY	2012	W2	2	2,900	Benchmark	319,000	11,687,000	7,490,000	64%
20	20	THE BRIMACOMBE BUILDING	1995	C2	6	13,900	67,479,000	3,910,701	99,893,000	84,123,000	84%
21	21	LANDSCAPE ARCHITECTURE ANNEX	1921	URM	2	800	2,202,000	108,000	2,737,000	2,311,000	84%
22	22	LOWER MALL RESEARCH STATION	1960	C2	4	7,000	20,113,000	1,649,899	31,435,000	22,969,000	73%
23	23	HENRY ANGUS BUILDING	1965	C2	9	5,900	11,796,000	973,500	23,457,000	16,333,000	70%
024-3	24.03	RESEARCH STATION ANNEX 3	1965	RM1	1	600	921,000	99,000	1,641,000	1,182,000	72%
024-5	24.05	LOWER MALL HEADER HOUSE	1967	RM2	2	900	1,491,000	148,500	2,796,000	1,897,000	68%
26	26	HENRY ANGUS BUILDING ADDITION	1976	C2	5	17,100	29,463,000	2,821,500	51,300,000	36,440,000	71%
28	28	FREDERIC LASSERRE BUILDING	1962	C1	4	5,200	12,314,000	858,000	21,368,000	14,540,000	68%
29	29	CAMPUS COMMUNITY PLANNING 2	1947	W2	1	800	1,570,000	88,000	2,997,000	2,069,000	69%
34	34	AQUATIC CENTRE	1978	C2	2	6,500					
36	36	THEATRE-FILM PRODUCTION BUILDING	1925	W1A	3	1,000	2,153,000	110,000	3,575,000	2,591,000	72%
44	44	OLD AUDITORIUM	1925	URM	2	3,000	11,531,000	405,000	14,556,000	12,134,000	83%
45	45	AUDITORIUM ANNEX OFFICES A	1969	W1A	2	2,600	3,686,000	286,000	7,046,000	4,710,000	67%
46	46	ASIAN CENTRE	1975	C2	2	5,900	8,989,000	973,500	22,789,000	12,636,000	55%
48	48	ANTHROPOLOGY AND SOCIOLOGY BUILDING	1975	C2	3	6,700	13,681,000	1,508,249	23,815,000	16,414,000	69%
51	51	THE BARN	1925	W1	2	400	886,000	44,000	1,204,000	1,003,000	83%
52	52	FRASER RIVER PARKADE	1982	PC2	4	21,300	1,874,000	2,343,000	18,563,000	4,835,000	26%
57	57	CENTRE FOR COMPARATIVE MEDICINE	2011	RM1	2	11,900	Benchmark	1,963,500	74,476,000	63,706,000	86%
64	64	BIOLOGICAL SCIENCES BUILDING	1948	C2	3	7,600	24,374,000	1,999,026	37,652,000	27,475,000	73%
65	65	BIOLOGICAL SCIENCES BUILDING - WEST WING	1970	C2	4	8,700	27,902,000	2,288,358	43,101,000	31,452,000	73%
66	66	BIOLOGICAL SCIENCES BUILDING - NORTH WING	1976	C2	3	6,500	20,847,000	1,072,500	32,202,000	23,499,000	73%
68	68	BIOLOGICAL SCIENCES BUILDING - SOUTH WING	1957	C1	4	4,000	13,988,000	880,000	20,564,000	16,642,000	81%
69	69	BIOLOGICAL SCIENCES BUILDING - WORKSHOP	1976	C2	2	1,100	3,528,000	289,333	5,777,000	4,215,000	73%
70	70	BIOLOGICAL SCIENCES - PAPER RECYCLING/FLAMMABLE STORAGE FACILITY	1979	RM1	1	100	296,000	16,500	472,000	348,000	74%
071-1	71.01	BOTANY GREENHOUSE 1	1982	S3	1	200	155,000	27,000	334,000	206,000	62%
071-2	71.02	BOTANY GREENHOUSE 2	1982	S3	1	200	158,000	27,000	329,000	208,000	63%
75	75	UBC FARM YURT	2014	W1	1	100	Benchmark	11,000	201,000	165,000	82%
76	76	BOTANICAL GARDENS SCHOLARS' RETREAT	1986	W1	1	200	251,000	22,000	411,000	298,000	73%
78	78	BOTANICAL GARDENS - LUNCHROOM	1971	S3	1	100	259,000	13,500	365,000	295,000	81%
79	79	BOTANICAL GARDENS - GREENHOUSE AND WORKSHOP	1971	S3	1	100	439,000	13,500	546,000	486,000	89%
81	81	BOOKSTORE	1983	C2	6	10,200	18,666,000	1,683,000	39,667,000	26,251,000	66%
82	82	BOTANICAL GARDENS - GREENHOUSE, ALPINE GARDEN	1975	W1	1	100	430,000	11,000	546,000	483,000	88%
83	83	MICHAEL SMITH LABORATORIES	2004	C2	4	8,900	36,040,000	2,614,329	48,193,000	39,672,000	82%
90	90	BOTANICAL GARDENS - WORKSHOP	1980	W2	1	1,000	4,307,000	110,000	6,169,000	5,071,000	82%
91	91	BOTANICAL GARDEN - GARDEN PAVILION	1981	W1	2	400	1,227,000	44,000	1,591,000	1,364,000	86%
94	94	BOTANICAL GARDENS WORKSHOP (TRAILER)	1976	MH	1	200	n/a	13,000	150,000	n/a	n/a
97	97	BOTANICAL GARDEN CENTRE - GATE HOUSE AND SHOP-IN-THE-GARDEN	1990	W1	1	300	483,000	33,000	700,000	560,000	80%
98	98	BOTANICAL GARDEN CENTRE - CAMPBELL BUILDING	1990	W1A	2	900	1,258,000	99,000	2,356,000	1,611,000	68%
99	99	BOTANICAL GARDEN CENTRE - RECEPTION AND EDUCATION CENTRE	1990	W1	2	300	511,000	33,000	700,000	589,000	84%
100	100	BOTANICAL GARDEN CENTRE - LOOKOUT TOWER	1990	W1	1	100	170,000	11,000	233,000	196,000	84%
112	112	BROCK HALL - WEST WING	1940	W2	2	4,300	8,065,000	473,000	16,071,000	10,723,000	67%
112-1	112.01	BROCK HALL - EAST WING	1993	C2	2	8,100	15,451,000	1,336,500	27,750,000	18,756,000	68%
113	113	BROCK HALL ANNEX	1956	C3	2	2,700	5,142,000	445,500	9,232,000	6,435,000	70%
120	120	BUCHANAN TOWER	1972	C2	14	10,100	16,367,000	1,666,500	35,962,000	23,560,000	66%
121-1	121.01	BUCHANAN BUILDING BLOCK A	1958	C2	3	4,400	10,141,000	726,000	17,570,000	12,653,000	72%
121-2	121.02	BUCHANAN BUILDING BLOCK B	1958	C2	4	4,900	8,443,000	808,500	15,582,000	11,068,000	71%
121-3	121.03	BUCHANAN BUILDING BLOCK C	1958	C2	5	3,200	6,104,000	528,000	11,621,000	7,854,000	68%
122-1	122.01	BUCHANAN BUILDING BLOCK D	1960	C1	3	5,300	10,237,000	874,500	18,687,000	12,506,000	67%

UBC BUILDINGS FOR COSTING CONSIDERATION											
INFORMATION FOR COST ESTIMATOR							FOR COST ESTIMATOR TO COMPLETE				
BUILDING ID		BUILDING NAME	YEAR	CONSTRUCTION TYPE	NUMBER OF ELEVATED STORIES	GROSS BUILDING AREA	STRUCTURAL RETROFIT COST	DEMOLITION COST	REPLACEMENT COST	RENEW	Ratio of Renewal to Replacement Cost
-	-	-	-	-	-	m2	$	$	$	$	
122-2	122.02	BUCHANAN BUILDING BLOCK E	1960	C2	4	2,700	5,150,000	445,500	9,805,000	6,627,000	68%
130	130	CHAN CENTRE FOR THE PERFORMING ARTS	1997	C2	6	8,200	35,282,000	1,353,000	59,997,000	46,402,000	77%
132	132	CHEMISTRY D BLOCK, CENTRE WING	1925	C2	3	7,400	26,967,000	2,084,050	37,858,000	29,987,000	79%
136	136	CHEMISTRY E BLOCK, NORTH WING	1962	C2	4	2,600	12,103,000	815,134	16,848,000	13,953,000	83%
137	137	IN-VESSEL COMPOSTING FACILITY	2004	S3	1	400	619,000	54,000	766,000	668,000	87%
138	138	ENVIRONMENTAL SERVICES FACILITY - SOLVENT SILVER RECOVERY LAB	1994	MH	1	100	n/a	6,500	75,000	n/a	n/a
139	139	ENVIRONMENTAL SERVICES FACILITY - OFFICE	1993	MH	1	100	n/a	6,500	75,000	n/a	n/a
140	140	CHEMISTRY STORAGE	1956	RM2	0	100	432,000	16,500	572,000	493,000	86%
141	141	ENVIRONMENTAL SERVICES FACILITY - SOLVENT STORAGE AREA	1973	C2	1	400	449,000	88,000	1,018,000	649,000	64%
142	142	ENVIRONMENTAL SERVICES FACILITY - CHEMICAL WASTE PROCESSING STORAG	1986	C2	1	500	562,000	110,000	1,272,000	811,000	64%
143	143	ENVIRONMENTAL SERVICES FACILITY - PCB EQUIPMENT STORAGE CONTAINERS	1989	S3	1	300	267,000	57,000	350,000	292,000	83%
144	144	CHEMISTRY C BLOCK, EAST WING	1963	C2	5	3,500	14,071,000	1,056,158	20,471,000	16,429,000	80%
148	148	CHEMISTRY B BLOCK, SOUTH WING	1959	C2	3	6,800	24,169,000	1,837,253	35,070,000	26,943,000	77%
155	155	CHILD CARE SERVICES ADMINISTRATION BUILDING	1990	W1A	1	2,400	4,265,000	264,000	6,996,000	5,261,000	75%
160	160	CONTINUING STUDIES BUILDING	1997	S2	3	4,300	11,818,000	816,388	18,219,000	14,126,000	78%
164	164	HUGH DEMPSTER PAVILION	2004	C2	3	2,100	6,546,000	346,500	9,789,000	7,847,000	80%
165	165	INSTITUTE FOR COMPUTING, INFORMATION AND COGNITIVE SYSTEMS / COMPU	1993	C2	4	18,200	55,707,000	3,003,000	84,144,000	63,132,000	75%
166	166	INSTITUTE FOR COMPUTING, INFORMATION AND COGNITIVE SYSTEMS / COMPU	2005	C2	4	3,700	11,325,000	610,500	19,562,000	13,605,000	70%
180	180	RODNEY GRAHAM MILLENNIUM SCULPTURE PAVILLION	2003	C1	1	100	185,000	16,500	339,000	241,000	71%
182	182	LADNER CLOCK TOWER	1968	C2	1	100	172,000	16,500	318,000	226,000	71%
184	184	COAL AND MINERAL PROCESSING LABORATORY	1981	RM2	3	3,600	13,570,000	752,682	19,909,000	15,647,000	79%
198	198	J. B. MACDONALD BUILDING	1967	C2	3	9,200	24,448,000	2,232,886	38,301,000	28,202,000	74%
199	199	DAVID STRANGWAY BUILDING	2005	S1	6	12,300	37,826,000	2,721,547	69,994,000	49,087,000	70%
200	200	CHILD CARE SERVICES - BUILDING 1	1989	W1A	1	800	1,852,000	88,000	2,882,000	2,210,000	77%
201	201	CHILD CARE SERVICES - BUILDING 2	1989	W1A	1	800	1,851,000	88,000	2,881,000	2,208,000	77%
202	202	CHILD CARE SERVICES - BUILDING 3	1989	W1A	1	800	1,854,000	88,000	2,883,000	2,212,000	77%
203	203	CHILD CARE SERVICES - BUILDING 4	1989	W1A	1	600	1,252,000	66,000	2,115,000	1,512,000	71%
204	204	CHILD CARE SERVICES - BUILDING 5	1989	W1A	1	1,000	2,297,000	110,000	3,596,000	2,743,000	76%
205	205	CHILD CARE SERVICES BUILDING 1	2008	W1A	1	1,700	Benchmark	187,000	6,063,000	4,504,000	74%
206	206	CHILD CARE SERVICES BUILDING 2	2008	W1A	1	1,500	Benchmark	165,000	5,389,000	4,097,000	76%
207	207	CHILD CARE SERVICES BUILDING 3	2009	W1A	1	900	Benchmark	99,000	3,194,000	2,334,000	73%
212	212	SING TAO BUILDING	1997	C2	3	1,700	2,441,000	280,500	5,535,000	3,323,000	60%
225	225	EARTH SCIENCES BUILDING	2012	C2	5	17,500	Benchmark	4,213,127	74,331,000	53,238,000	72%
232	232	NEVILLE SCARFE BUILDING - LECTURE BLOCK	1962	C2	3	5,200	10,237,000	858,000	18,837,000	12,359,000	66%
234	234	NEVILLE SCARFE BUILDING - LIBRARY	1995	C2	3	3,900	6,539,000	643,500	12,805,000	8,618,000	67%
240-1	240.01	NEVILLE SCARFE BUILDING - CLASSROOM BLOCK	1965	C2	4	7,600	22,627,000	1,254,000	34,240,000	25,728,000	75%
240-2	240.02	NEVILLE SCARFE BUILDING - OFFICE BLOCK	1965	C2	4	2,800	4,297,000	462,000	9,044,000	5,765,000	64%
300	300	CHEMICAL BIOLOGICAL ENGINEERING BUILDING	2005	C2	7	13,300	41,295,000	3,096,465	72,314,000	53,730,000	74%
301	301	WAYNE AND WILLIAM WHITE ENGINEERING DESIGN CENTRE	2011	C2	4	2,600	Benchmark	429,000	14,953,000	11,804,000	79%
305	305	EARTHQUAKE ENGINEERING RESEARCH FACILITY	2003	S1	2	13,900	56,786,000	2,293,500	80,324,000	62,276,000	78%
306	306	CIVIL AND MECHANICAL ENGINEERING BUILDING	1976	C2	4	10,100	27,266,000	1,666,500	43,241,000	31,387,000	73%
307	307	CIVIL AND MECHANICAL ENGINEERING LABORATORIES	1971	S2	3	1,800	6,234,000	543,378	9,413,000	7,278,000	77%
308	308	THE LEONARD S. KLINCK BUILDING	1947	C2	5	10,300	20,360,000	1,699,500	37,237,000	24,563,000	66%
309	309	CIVIL AND MECHANICAL ENGINEERING STRUCTURES LAB	1969	C1	2	5,100	23,310,000	841,500	31,311,000	25,493,000	81%
310	310	ENGINEERING STUDENT CENTRE	2015	C2	2	1,300	Benchmark	214,500	4,318,000	2,794,000	65%
312	312	MACLEOD BUILDING	1963	C1	5	7,500	26,374,000	2,035,861	38,826,000	29,584,000	76%
313	313	THE FRED KAISER BUILDING	2005	C2	5	12,900	34,152,000	3,112,152	56,277,000	39,415,000	70%
314	314	BEATY BIODIVERSITY CENTRE	2009	C2	3	14,200	Benchmark	3,560,456	60,205,000	43,812,000	73%
316	316	AQUATIC ECOSYSTEMS RESEARCH LABORATORY	2005	C2	5	5,700	13,895,000	940,500	25,461,000	16,220,000	64%
320	320	DOROTHY SOMERSET STUDIOS	1925	W2	2	2,500	8,169,000	275,000	12,990,000	9,923,000	76%
324	324	B.C. BINNING STUDIOS	1925	W2	2	2,100	6,835,000	231,000	11,251,000	8,306,000	74%
337	337	FIRST NATIONS LONGHOUSE	1993	W2	3	2,400	4,111,000	264,000	10,216,000	6,029,000	59%
344	344	LEON AND THEA KOERNER UNIVERSITY CENTRE	1958	C1	3	4,500	10,517,000	742,500	19,182,000	13,190,000	69%
345	345	PETER WALL INSTITUTE FOR ADVANCED STUDIES	1987	C2	2	3,700	6,963,000	610,500	13,531,000	8,981,000	66%
353	353	FOREST SCIENCES CENTRE	1998	C2	5	22,800	61,479,000	5,188,093	101,388,000	70,781,000	70%
376	376	FREDERIC WOOD THEATRE	1963	C2	2	3,500	17,581,000	577,500	25,775,000	20,372,000	79%
377-1	377.01	MARINE DRIVE RESIDENCE - SIMON K.Y. LEE HKU-UBC HOUSE	2006	C2	16	11,700	16,815,000	1,930,500	38,251,000	24,827,000	65%
377-2	377.02	MARINE DRIVE RESIDENCE - BUILDING #2	2006	C2	5	6,800	9,128,000	1,122,000	19,654,000	11,903,000	61%
377-3	377.03	MARINE DRIVE RESIDENCE - BUILDING #3	2009	W1A	2	2,000	Benchmark	220,000	8,361,000	5,412,000	65%
377-4	377.04	MARINE DRIVE RESIDENCE - BUILDING #4	2008	C2	16	10,900	Benchmark	1,798,500	37,605,000	26,712,000	71%
377-5	377.05	MARINE DRIVE RESIDENCE - BUILDING #5	2008	C2	16	11,100	Benchmark	1,831,500	38,295,000	27,202,000	71%
377-6	377.06	MARINE DRIVE RESIDENCE - BUILDING #6	2007	C2	6	9,500	Benchmark	1,567,500	32,775,000	23,281,000	71%
380	380	OLD FIRE HALL	1926	W1A	2	500	976,000	55,000	1,672,000	1,188,000	71%
385	385	WOOD PRODUCTS LABORATORY	1990	S3	2	300	716,000	95,363	848,000	767,000	90%
386	386	H. R. MACMILLAN BUILDING	1967	C2	4	15,500	38,120,000	3,665,477	63,361,000	44,444,000	70%
387	387	FOREST SCIENCES GREENHOUSE	1990	S3	1	200	878,000	27,000	1,092,000	971,000	89%
389	389	FORESTRY FIELD HOUSE SOUTH CAMPUS	1980	RM1	1	400	1,990,000	66,000	2,544,000	2,246,000	88%
394	394	GAS GUN FACILITY	1989	C2	1	400	1,860,000	145,033	2,421,000	2,094,000	86%
401	401	GEOGRAPHY BUILDING	1925	W2	2	8,000	15,325,000	880,000	28,189,000	19,141,000	68%
402	402	EARTH AND OCEAN SCIENCES - MAIN	1971	C2	4	9,000	34,809,000	2,730,589	49,823,000	38,481,000	77%
403	403	EARTH AND OCEAN SCIENCES - SOUTH	1974	C2	4	1,700	2,861,000	280,500	5,424,000	3,768,000	69%
408	408	THEA KOERNER HOUSE	1961	C2	3	4,300	8,002,000	709,500	14,660,000	10,342,000	71%
409	409	THEA KOERNER HOUSE ADDITION	1971	C1	2	1,100	2,086,000	181,500	3,829,000	2,710,000	71%
412	412	GREEN COLLEGE - GRAHAM HOUSE, GREEN COMMONS, COACH HOUSE - BUILDI	1930	W1A	2	2,000	2,478,000	220,000	5,969,000	3,244,000	54%
413	413	GREEN COLLEGE - BUILDING A NORTH	1994	W1A	3	900	1,008,000	99,000	2,221,000	1,346,000	61%
414	414	GREEN COLLEGE - KITCHEN / LAUNDRY	1994	W1	1	100	120,000	11,000	180,000	143,000	79%
415	415	GREEN COLLEGE - BUILDING A SOUTH	1994	W1A	3	1,600	1,733,000	176,000	3,980,000	2,330,000	59%
416	416	GREEN COLLEGE - BUILDING B EAST	1994	W1A	3	1,500	1,875,000	165,000	3,599,000	2,451,000	68%
417	417	GREEN COLLEGE - BUILDING E	1994	W1	2	300	346,000	33,000	548,000	415,000	76%
418	418	GREEN COLLEGE - ADMINISTRATION -BUILDING F	1994	W1	2	300	373,000	33,000	617,000	443,000	72%
419	419	GREEN COLLEGE - PRINCIPAL's RESIDENCE - BUILDING C	1994	W1A	3	300	376,000	33,000	719,000	491,000	68%
420	420	CECIL GREEN PARK HOUSE	1911	W2	4	2,300	4,271,000	253,000	8,398,000	5,690,000	68%
421	421	CECIL GREEN PARK COACH HOUSE	1911	W1	2	400	729,000	44,000	995,000	837,000	84%
422	422	CECIL GREEN PARK SQUASH COURT	1929	W1	2	100	245,000	11,000	319,000	276,000	87%
428	428	WAR MEMORIAL GYMNASIUM	1950	C2	3	10,000	17,129,000	1,650,000	32,590,000	21,209,000	65%
430	430	ROBERT F. OSBORNE CENTRE - UNIT 1	1970	PC2	3	3,600	14,236,000	594,000	21,940,000	17,090,000	78%
431	431	ROBERT F. OSBORNE CENTRE - UNIT 2	1972	C2	2	3,000	12,438,000	495,000	17,728,000	14,482,000	82%
432	432	UBC TENNIS CENTRE	1997	S3	1	4,800	12,317,000	648,000	14,366,000	13,198,000	92%
433	433	UBC TENNIS CENTRE (NEW)	2011	S3	2	9,300	23,149,000	1,255,500	26,001,000	23,409,000	90%
434	434	GERALD MCGAVIN UBC RUGBY CENTRE	2013	C2	2	800	Benchmark	132,000	2,950,000	2,184,000	74%
436	436	HAIDA HOUSE	1961	W2	1	300	537,000	33,000	1,208,000	778,000	64%
437	437	UBC FOOTBALL ACADEMIC CENTRE	2016	W2	1	300	Benchmark	33,000	1,352,000	1,055,000	78%
440	440	MORTUARY HOUSE	1961	W2	1	100	157,000	11,000	343,000	217,000	63%
447	447	CHEMISTRY A BLOCK, CHEMISTRY PHYSICS BUILDING	1989	C2	4	7,100	29,837,000	2,158,141	39,175,000	32,734,000	84%
449	449	FOOD, NUTRITION AND HEALTH BUILDING	1982	C2	3	7,300	24,828,000	1,955,422	36,020,000	27,806,000	77%
450-1	450.01	ACADIA HOUSE - 2700	1991	W2	2	1,600	2,366,000	176,000	3,827,000	2,986,000	78%
451	451	SOPRON HOUSE	1991	W2	4	7,700	10,293,000	847,000	17,919,000	12,465,000	70%
456	456	HORTICULTURE BUILDING	1948	C2	1	3,300	13,902,000	544,500	19,728,000	16,164,000	82%

UBC BUILDINGS FOR COSTING CONSIDERATION											
INFORMATION FOR COST ESTIMATOR							FOR COST ESTIMATOR TO COMPLETE				
BUILDING ID		BUILDING NAME	YEAR	CONSTRUCTION TYPE	NUMBER OF ELEVATED STORIES	GROSS BUILDING AREA	STRUCTURAL RETROFIT COST	DEMOLITION COST	REPLACEMENT COST	RENEW	Ratio of Renewal to Replacement Cost
-	-	-	-	-	-	m2	$	$	$	$	
461	461	BIOMEDICAL RESEARCH CENTRE	1987	C2	5	4,900	21,570,000	1,414,090	30,858,000	24,983,000	81%
462	462	PURDY PAVILION	1977	C2	6	16,300	108,563,000	2,689,500	155,584,000	132,496,000	85%
463	463	KOERNER PAVILION	1980	C2	6	43,900	233,010,000	9,826,761	419,026,000	288,559,000	69%
465	465	DJAVAD MOWAFAGHIAN CENTRE FOR BRAIN HEALTH	2014	C2	6	14,500	Benchmark	2,758,461	73,104,000	44,591,000	61%
467	467	HEALTH SCIENCES PARKADE	1980	C2	4	38,400	17,357,000	4,224,000	33,351,000	8,717,000	26%
470	470	ENVIRONMENTAL SERVICES FACILITY - INCINERATOR	1969	URM	1	200	406,000	36,450	539,000	425,000	79%
472	472	INTERNATIONAL HOUSE	1958	C2	3	1,600	2,336,000	264,000	5,200,000	3,168,000	61%
473	473	P. A. WOODWARD INSTRUCTIONAL RESOURCES CENTRE	1972	C2	6	18,000	25,248,000	3,506,191	64,698,000	37,480,000	58%
476	476	JAPANESE TEA HOUSE - NITOBE GARDENS	1959	W1	1	200	254,000	22,000	432,000	301,000	70%
478	478	C. K. CHOI BUILDING FOR THE INSTITUTE OF ASIAN RESEARCH	1996	C2	3	3,500	5,399,000	577,500	12,039,000	7,459,000	62%
482	482	ALLARD HALL	2011	C2	5	14,600	Benchmark	2,409,000	51,517,000	32,480,000	63%
490	490	DAVID LAM MANAGEMENT RESEARCH CENTRE	1992	C2	5	6,800	14,179,000	1,122,000	24,128,000	16,953,000	70%
496	496	LIU INSTITUTE FOR GLOBAL ISSUES	2000	W2	3	2,100	3,523,000	231,000	6,908,000	4,797,000	69%
511	511	ENGINEERING HIGH HEAD ROOM LABORATORY	1992	RM2	1	400	1,206,000	124,373	1,792,000	1,419,000	79%
513	513	SCHOOL OF POPULATION PUBLIC HEALTH	1979	C2	4	9,900	17,648,000	2,092,894	32,611,000	21,687,000	67%
515	515	SEDGEWICK LIBRARY	1972	C2	0	19,300	34,625,000	4,222,375	59,916,000	42,500,000	71%
515-1	515.01	WALTER C. KOERNER LIBRARY	1996	C2	7	7,400	13,216,000	1,221,000	27,322,000	18,671,000	68%
516	516	IRVING K. BARBER LEARNING CENTRE	1927	C2	5	23,900	38,110,000	3,943,500	74,930,000	47,861,000	64%
518	518	MATHEMATICS BUILDING	1925	W2	2	6,000	14,345,000	976,860	23,157,000	17,207,000	74%
519	519	MATHEMATICS ANNEX	1924	W2	2	2,100	3,898,000	336,428	7,560,000	5,194,000	69%
521	521	CAMPUS ENERGY CENTRE	2016	W2	2	2,600	Benchmark	286,000	10,233,000	6,328,000	62%
523-1	523.01	D.H. COPP BUILDING	1961	C2	4	5,300	11,519,000	1,098,768	20,651,000	13,841,000	67%
523-2	523.02	FRIEDMAN BUILDING	1961	C1	5	4,300	14,577,000	709,500	22,703,000	17,402,000	77%
523-3	523.03	MEDICAL SCIENCES BLOCK C	1961	C1	5	4,000	13,845,000	1,092,326	21,399,000	16,490,000	77%
525-1	525.01	D.H. COPP BUILDING ADDITION	1967	C2	4	3,700	9,897,000	610,500	16,799,000	12,091,000	72%
525-2	525.02	FRIEDMAN BUILDING ADDITION	1967	C1	5	1,600	2,910,000	264,000	6,105,000	3,811,000	62%
526	526	D.H. COPP BUILDING ADDITION 2	1979	C2	4	3,900	6,592,000	643,500	13,335,000	8,674,000	65%
527	527	PHARMACEUTICAL SCIENCES CENTRE FOR DRUG RESEARCH AND DEVELOPMEN	2012	C2	9	30,200	Benchmark	6,507,966	193,861,000	148,735,000	77%
528	528	ROSE GARDEN PARKADE	1994	C2	5	26,300	24,746,000	2,893,000	48,580,000	37,081,000	76%
529	529	LIFE SCIENCES CENTRE	2004	C2	5	58,300	154,571,000	14,762,174	250,720,000	178,357,000	71%
536	536	WOODWARD BIOMEDICAL LIBRARY	1964	C2	3	9,100	16,100,000	1,981,319	28,285,000	19,813,000	70%
537	537	DETWILLER PAVILION 1	1968	C2	6	13,200	67,326,000	2,178,000	100,629,000	83,618,000	83%
540-1	540.01	TOTEM PARK RESIDENCE - COQUIHALA COMMON BLOCK/MAGDA's CONVENIEN	1964	C2	3	4,700	11,487,000	775,500	18,875,000	14,209,000	75%
540-2	540.02	TOTEM PARK RESIDENCE - HAIDA HOUSE/SALISH HOUSE	1964	C2	6	9,900	14,322,000	1,633,500	32,313,000	21,115,000	65%
540-3	540.03	TOTEM PARK RESIDENCE - DENE HOUSE/NOOTKA HOUSE	1964	C2	6	10,200	14,797,000	1,683,000	33,268,000	21,803,000	66%
543	543	VANIER PUMP STATION	1986	S3	1	0	n/a	n/a	10,000	n/a	n/a
544	544	PLACE VANIER RESIDENCE - GORDON SHRUM COMMON BLOCK	1960	C1	3	5,100	11,052,000	841,500	18,385,000	13,235,000	72%
545-1	545.01	PLACE VANIER RESIDENCE - CARIBOO HOUSE	1968	C2	4	2,600	3,801,000	429,000	7,801,000	5,154,000	66%
545-2	545.02	PLACE VANIER RESIDENCE - TWEEDSMUIR HOUSE	1968	C2	4	2,600	3,820,000	429,000	7,791,000	5,174,000	66%
548	548	PLACE VANIER RESIDENCE - KOOTENAY HOUSE	1961	C2	4	2,500	3,662,000	412,500	7,497,000	4,963,000	66%
551	551	THUNDERBIRD PARKADE	2007	PC2	6	69,200	Benchmark	7,612,000	69,171,000	18,065,000	26%
552	552	PLACE VANIER RESIDENCE - OKANAGAN HOUSE	1960	C2	4	2,500	3,662,000	412,500	7,497,000	4,963,000	66%
556	556	PLACE VANIER RESIDENCE - ROBSON HOUSE	1959	C2	4	2,500	3,671,000	412,500	7,492,000	4,973,000	66%
560	560	PLACE VANIER RESIDENCE - SHERWOOD LETT HOUSE	1960	C2	4	2,500	3,647,000	412,500	7,505,000	4,947,000	66%
562	562	FRANK FORWARD BUILDING	1968	C2	6	8,000	23,163,000	1,981,490	41,087,000	30,391,000	74%
565	565	TOTEM PARK RESIDENCE - KWAKIUTL HOUSE/SHUSWAP HOUSE	1968	C2	6	10,200	14,831,000	1,683,000	33,248,000	21,842,000	66%
566	566	TOTEM PARK RESIDENCE - QELEXEN HOUSE	2011	C2	8	6,800	Benchmark	1,122,000	22,121,000	14,650,000	66%
567	567	TOTEM PARK RESIDENCE - HEMLESEM HOUSE	2011	C2	8	9,900	Benchmark	1,633,500	32,201,000	21,339,000	66%
568	568	MORRIS AND HELEN BELKIN ART GALLERY	1995	C2	3	1,600	3,714,000	264,000	6,378,000	4,629,000	73%
570	570	MUSEUM OF ANTHROPOLOGY	1975	C2	3	11,400	38,902,000	2,398,629	64,423,000	45,947,000	71%
575	575	MUSIC BUILDING	1967	C2	5	6,900	16,712,000	1,138,500	26,898,000	19,527,000	73%
614	614	MARY BOLLERT HALL	1950	C2	2	1,800	2,676,000	297,000	5,837,000	3,615,000	62%
624	624	GEORGE CUNNINGHAM BUILDING ADDITION	1971	C2	4	2,000					
625	625	GEORGE CUNNINGHAM BUILDING	1960	C2	4	3,100					
633	633	CENTRE FOR INTERACTIVE RESEARCH IN SUSTAINABILITY	2011	C2	6	5,500	Benchmark	907,500	29,096,000	15,259,000	52%
635	635	ST. JOHN HOSPICE	2013	W1A	1	2,400	Benchmark	264,000	7,717,000	5,769,000	75%
638	638	SOUTH CAMPUS WAREHOUSE	1947	W2	2	3,500	5,679,000	385,000	11,778,000	7,789,000	66%
641	641	UNIVERSITY SERVICES BUILDING	1992	S2	2	16,300	19,079,000	1,793,000	46,652,000	24,800,000	53%
643	643	CAMPUS COMMUNITY PLANNING 1	1952	W1A	2	1,400	1,873,000	154,000	3,687,000	2,417,000	66%
646	646	BUILDING OPERATIONS EXTERIOR STORAGE SHED	1992	C2	1	1,000	1,823,000	165,000	2,120,000	2,015,000	95%
652	652	HENNINGS BUILDING	1945	C2	4	11,800	36,289,000	1,947,000	54,914,000	41,104,000	75%
654	654	ABDUL LADHA SCIENCE CENTRE	2006	C2	3	800	1,458,000	132,000	2,629,000	1,892,000	72%
656	656	HEBB BUILDING	1964	C2	6	6,200	23,391,000	1,761,044	37,305,000	29,809,000	80%
666	666	PLANT SCIENCE FIELD STATION	1991	C1	1	100	325,000	16,500	499,000	390,000	78%
667	667	PLANT SCIENCE GARAGE	1964	RM1	1	600	2,413,000	99,000	3,292,000	2,764,000	84%
668	668	TOTEM FIELD STUDIOS	1963	RM1	4	1,400	1,973,000	231,000	3,734,000	2,571,000	69%
669	669	STORES ROAD ANNEX	1925	W1	2	400	934,000	44,000	1,316,000	1,054,000	80%
670	670	PLANT SCIENCE FIELD BUILDING	1975	RM1	1	300	418,000	49,500	802,000	545,000	68%
674	674	LOGAN FIELD KIOSK	2016	C2	1	600	Benchmark	99,000	2,231,000	1,657,000	74%
724	724	POWER HOUSE	1925	C2	3	2,200					
725	725	POWER HOUSE - METER STATION	1961	C2	1	100	182,000	16,500	329,000	236,000	72%
728	728	NORMAN MACKENZIE HOUSE (PRESIDENT's RESIDENCE)	1950	W1A	2	1,300	4,175,000	143,000	5,811,000	4,826,000	83%
732	732	DOUGLAS KENNY BUILDING	1983	C2	5	9,200	20,129,000	2,255,102	35,682,000	23,882,000	67%
745	745	RITSUMEIKAN-UBC HOUSE	1992	W1A	4	6,900	8,145,000	759,000	15,858,000	10,153,000	64%
747	747	PULP AND PAPER CENTRE	1985	C2	4	3,700	12,463,000	999,263	18,854,000	14,811,000	79%
750	750	JACK BELL BUILDING FOR THE SCHOOL OF SOCIAL WORK	1992	S4	3	3,400	7,014,000	459,000	11,420,000	8,397,000	74%
760	760	RUGBY PAVILION	1963	RM1	1	700	1,590,000	115,500	2,614,000	1,926,000	74%
767	767	STAGING RESEARCH CENTRE	2010	S3	1	600	1,672,000	190,179	1,978,000	1,790,000	90%
768	768	BUILDING OPERATIONS - NURSERY	2009	W1A	1	2,600	Benchmark	286,000	3,360,000	2,462,000	73%
769	769	LIBRARY PARC@UBC	2015	S2	2	2,300	Benchmark	310,500	6,629,000	4,101,000	62%
770-1	770.01	SPIRIT PARK APARTMENTS - 2705	1993	W1A	2	1,800	2,132,000	198,000	4,382,000	2,815,000	64%
771	771	POINT GREY APARTMENTS (OSOYOOS HOUSING)	1993	W1A	4	8,800	9,997,000	968,000	20,420,000	12,558,000	61%
774	774	STUDENT RECREATION CENTRE	1995	C2	3	5,200	14,320,000	858,000	21,356,000	16,442,000	77%
780	780	THUNDERBIRD RESIDENCE - BUILDING A1	1995	W1A	4	20,900	26,164,000	2,299,000	52,381,000	32,246,000	62%
780-1	780.01	THUNDERBIRD RESIDENCE - BUILDING A4	1995	W1A	3	1,200	1,502,000	132,000	2,878,000	1,962,000	68%
781	781	THUNDERBIRD RESIDENCE - BUILDING A2	1995	W1A	4	5,000	6,314,000	550,000	11,963,000	8,235,000	69%
781-1	781.01	THUNDERBIRD RESIDENCE - BUILDING A3	1995	W1A	3	1,200	1,514,000	132,000	2,872,000	1,974,000	69%
782	782	THUNDERBIRD RESIDENCE - BUILDING B2	1995	W1A	4	4,900	5,659,000	539,000	12,004,000	7,510,000	63%
782-1	782.01	THUNDERBIRD RESIDENCE - BUILDING B3	1995	W1A	3	1,200	1,513,000	132,000	2,872,000	1,974,000	69%
783	783	THUNDERBIRD RESIDENCE - BUILDING B1	1995	W1A	4	5,000	6,320,000	550,000	11,959,000	8,242,000	69%
783-1	783.01	THUNDERBIRD RESIDENCE - BUILDING B4	1995	W1A	3	1,200	1,502,000	132,000	2,878,000	1,962,000	68%
784	784	THUNDERBIRD RESIDENCE - BUILDING C1	1995	W1A	4	5,000	6,331,000	550,000	11,954,000	8,253,000	69%
784-1	784.01	THUNDERBIRD RESIDENCE - BUILDING C2	1995	W1A	3	1,600	1,956,000	176,000	3,862,000	2,567,000	66%
785	785	THUNDERBIRD STADIUM	1967	C2	3	4,600	13,086,000	759,000	23,599,000	16,885,000	72%
789	789	MAIN SUBSTATION	1975	S3	1	700	1,042,000	94,500	1,261,000	1,126,000	89%
790	790	STUDENT UNION BUILDING (SUB)	1968	C2	3	19,400	40,088,000	3,201,000	69,464,000	48,003,000	69%
792	792	NORTH PARKADE	1988	C2	5	33,300	15,052,000	3,663,000	28,823,000	7,559,000	26%
795	795	AMS STUDENT NEST	2015	C2	6	21,400	Benchmark	3,531,000	77,403,000	47,679,000	62%

UBC BUILDINGS FOR COSTING CONSIDERATION

INFORMATION FOR COST ESTIMATOR							FOR COST ESTIMATOR TO COMPLETE				Ratio of Renewal to Replacement Cost
BUILDING ID		BUILDING NAME	YEAR	CONSTRUCTION TYPE	NUMBER OF ELEVATED STORIES	GROSS BUILDING AREA	STRUCTURAL RETROFIT COST	DEMOLITION COST	REPLACEMENT COST	RENEW	
-	-	-	-	-	-	m2	$	$	$	$	
822-1	822.01	ST. JOHN's COLLEGE	1997	W1A	2	4,100	4,432,000	451,000	10,204,000	5,963,000	58%
822-2	822.02	ST. JOHN's COLLEGE	1997	W1A	2	1,800	1,995,000	198,000	4,454,000	2,670,000	60%
822-3	822.03	ST. JOHN's COLLEGE	1998	W1A	3	9,000	11,156,000	990,000	20,419,000	13,775,000	67%
836	836	IONA BUILDING	1929	C2	7	8,800	17,570,000	1,452,000	43,028,000	26,460,000	61%
846	846	BIOLOGICAL ARCHIVE CENTRE	2008	S3	1	1,000	Benchmark	135,000	1,248,000	866,000	69%
858	858	BERWICK MEMORIAL CENTRE	1976	W2	1	3,200	6,371,000	528,000	11,533,000	8,371,000	73%
860	860	Athletics Washroom Facilities	2011	C2	1	1,700	Benchmark	280,500	6,502,000	4,749,000	73%
862	862	BASEBALL TRAINING FACILITY	2015	W2	2	1,400	Benchmark	154,000	6,180,000	4,573,000	74%
863-1	863.01	WEST MALL ANNEX	1969	W2	2	2,900	4,319,000	319,000	8,127,000	5,445,000	67%
863-2	863.02	AUDITORIUM ANNEX OFFICES B	1969	W1A	2	1,000	1,283,000	110,000	2,648,000	1,668,000	63%
864	864	WESBROOK BUILDING	1949	C2	5	10,900	36,960,000	2,736,742	54,729,000	41,408,000	76%
865-1	865.01	PONDEROSA OFFICE ANNEX A	1971	W1A	2	1,300	2,313,000	208,107	3,978,000	2,853,000	72%
865-2	865.02	PONDEROSA OFFICE ANNEX B	1971	W1A	2	1,500	2,270,000	230,465	4,445,000	2,869,000	65%
865-3	865.03	PONDEROSA OFFICE ANNEX C	1971	W1A	2	900	1,515,000	145,399	2,624,000	1,883,000	72%
867	867	WESBROOK BUILDING ANNEX	1983	C2	2	1,400	2,412,000	231,000	4,452,000	3,162,000	71%
868	868	DOUG MITCHELL THUNDERBIRD SPORTS CENTRE	2008	S2	3	31,700	Benchmark	5,927,859	117,405,000	86,470,000	74%
869-1	869.01	WALTER H. GAGE RESIDENCE - COMMON BLOCK	1972	C1	4	7,100	10,696,000	1,171,500	20,734,000	13,735,000	66%
869-2	869.02	WALTER H. GAGE RESIDENCE - SOUTH TOWER	1972	C2	17	9,600	14,188,000	1,584,000	31,161,000	20,821,000	67%
869-3	869.03	WALTER H. GAGE RESIDENCE - NORTH TOWER	1972	C2	17	9,600	14,192,000	1,584,000	31,159,000	20,825,000	67%
871-2	871.02	PONDEROSA OFFICE ANNEX E	1972	W1A	2	1,500	2,901,000	244,921	4,697,000	3,538,000	75%
871-3	871.03	PONDEROSA OFFICE ANNEX F	1972	W1A	2	1,200	1,526,000	186,699	3,182,000	1,988,000	62%
872-1	872.01	WALTER H. GAGE RESIDENCE - EAST TOWER	1972	C2	17	9,600	14,188,000	1,584,000	31,161,000	20,820,000	67%
872-2	872.02	WALTER H. GAGE RESIDENCE - COURT	1972	C2	3	4,700	8,164,000	775,500	16,441,000	10,686,000	65%
873	873	PONDEROSA OFFICE ANNEX G	1981	W2	1	1,200	2,029,000	198,000	3,943,000	2,758,000	70%
874	874	WALTER H. GAGE RESIDENCE - APARTMENTS	1984	C2	4	9,700	12,933,000	1,600,500	28,080,000	16,890,000	60%
876-1	876.01	ANTHROPOLOGY AND SOCIOLOGY BUILDING - ISABEL MACINNES HALL	1950	W1A	2	1,400	2,514,000	154,000	4,459,000	3,097,000	69%
876-2	876.02	ANTHROPOLOGY AND SOCIOLOGY BUILDING - ANNE WESBROOK HALL	1950	C2	3	1,400	2,859,000	231,000	5,275,000	3,636,000	69%
880	880	ANTHROPOLOGY AND SOCIOLOGY BUILDING - MARY MURRIN HALL	1956	C2	2	1,400	2,859,000	231,000	5,275,000	3,636,000	69%
896-1	896.01	PLACE VANIER RESIDENCE - DOROTHY MAWDSLEY HOUSE	1960	C2	4	2,600	3,853,000	429,000	7,774,000	5,208,000	67%
896-2	896.02	PLACE VANIER RESIDENCE - MARGARET MACKENZIE HOUSE	1960	C2	4	2,500	3,669,000	412,500	7,493,000	4,970,000	66%
896-3	896.03	PLACE VANIER RESIDENCE - PHYLLIS ROSS HOUSE	1960	C2	4	2,600	3,853,000	429,000	7,774,000	5,208,000	67%
896-4	896.04	PLACE VANIER RESIDENCE - ALDYEN HAMBER HOUSE	1960	C2	4	2,500	3,669,000	412,500	7,493,000	4,971,000	66%
898	898	PLACE VANIER RESIDENCE - KOREA UNIVERSITY - UBC HOUSE	2003	C2	6	5,600	8,213,000	924,000	18,214,000	12,072,000	66%
900	900	WEST PARKADE	1992	C2	6	40,000	18,080,000	4,400,000	40,047,000	10,442,000	26%
901	901	WEST MALL SWING SPACE BUILDING	2005	C2	5	5,500	14,515,000	907,500	23,074,000	16,759,000	73%
902	902	PLACE VANIER RESIDENCE - TEC DE MONTERREY - UBC HOUSE	2003	C2	6	5,200	7,609,000	858,000	16,923,000	11,190,000	66%
903	903	PONDEROSA COMMONS: AUDAIN ART CENTRE / SPRUCE HOUSE	2013	C2	17	10,600	Benchmark	1,749,000	43,906,000	29,216,000	67%
904	904	PONDEROSA COMMONS: MAPLE HOUSE / ARBUTUS HOUSE	2013	C2	16	18,000	Benchmark	2,970,000	59,546,000	36,799,000	62%
905	905	PONDEROSA COMMONS: CEDAR HOUSE / OAK HOUSE	2015	C2	19	26,500	Benchmark	4,372,500	87,876,000	53,755,000	61%

Appendix G

Cost-Benefit Analysis for Buildings

G1 Introduction

This appendix describes the cost-benefit analysis we conducted for the UBC building portfolio. In overview, the analysis integrates data from a wide range of sources to enable the identification and evaluation of different mitigation strategies. The appendix begins with a discussion of the cost-benefit methodology, including key inputs and limitations. It then provides a summary of results from the cost-benefit analysis and outlines several different mitigation strategies UBC could pursue to enhance the safety and resilience of its building portfolio.

G2 Cost-benefit methodology

The cost-benefit methodology utilized in this study is based on methodologies described in FEMA P-58 (ATC 2012), FEMA 366 (FEMA 2008), FEMA 227 (VSP Associates 1991), and other recent cost-benefit studies in the published literature (Liel and Deierlein 2013, Molina Hutt et al. 2015, Welch et al. 2014, Sullivan 2016). In overview, it uses results from the probabilistic seismic risk analysis (e.g., estimates of direct financial losses, injuries, fatalities, and downtime at each earthquake intensity; see Appendix C and Appendix I for additional information) to compute annualized measures of performance for an individual building, including average annual losses (AAL), average annual fatalities (AAF), and average annual downtime (AAD).

G2.1 Computation of annualized losses

Figure G.1 shows graphically how the AAL is computed. It is essentially the area under the loss curve, where the loss curve plots direct financial loss as a function of the annual exceedence probability for the four earthquake intensities evaluated. The process for computing other annualized quantities is similar.

For each building in the portfolio, annualized quantities are computed for the current building and three hypothetical design scenarios:

1. Current/existing
2. Renewal to 100% current code strength (façade is assumed not to be upgraded)
3. Replacement to current code
4. Replacement to REDi Gold, a beyond-code resilience standard

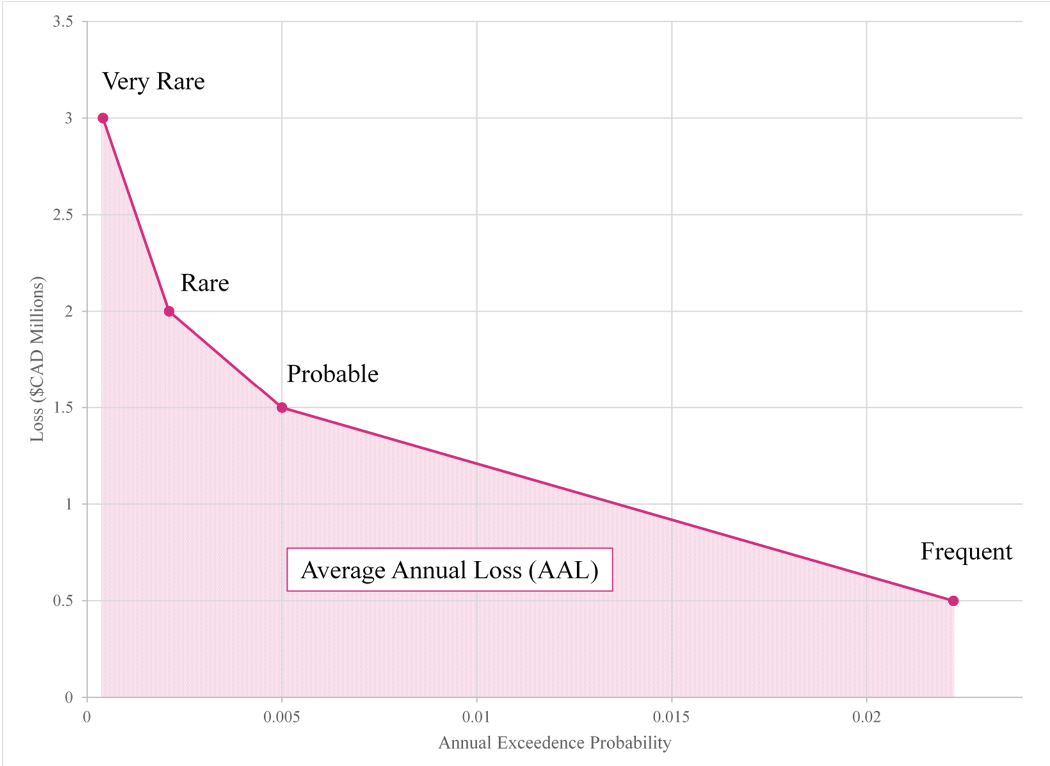


Figure G.1 Graphical depiction of the process for computing annualized performance measures (i.e., average annual loss)

G2.2 Computation of benefit-cost ratios

The last three hypothetical scenarios in the above list represent the three mitigation options considered in the cost-benefit analysis. The financial attractiveness of each option can be evaluated by computing the benefit-cost ratio (BCR) per the equation below. Note that BCR ≥ 1 indicates that a mitigation option is worth pursuing (i.e., the benefits outweigh the costs).

$$BCR = \frac{PV_{benefits}}{PV_{costs}} \qquad \text{Equation G.1}$$

$PV_{benefits}$ and PV_{costs} are the present value of the benefits and costs, respectively, of each mitigation option. In general, PV_{costs} is simply the cost of the mitigation option as determined by the cost estimator (see Section G2.3.3 and Appendix F), while $PV_{benefits}$ is computed using the equation below.

$$PV_{benefits} = A\left[\frac{1-\frac{1}{(1+i)^t}}{i}\right] \qquad \text{Equation G.2}$$

In the above equation, i is the discount rate, t is the investment time horizon (i.e., how long UBC plans to hold on to the building), and A is the stream of annualized avoided losses (e.g., reduced direct financial losses, and fatalities or downtime expressed in monetary terms) for a particular mitigation option relative to the estimated losses for the current building. Further detail about computing the stream of annualized avoided losses is provided in Sections G3.2 and G3.3.

G2.3 Inputs

The following subsections describe key inputs to the cost-benefit analysis.

G2.3.1 Results from probabilistic seismic risk assessment

One major input to the cost-benefit analysis is results from the probabilistic seismic risk assessment (PSRA). In overview, the PSRA predicts how each building in the portfolio is expected to perform at each earthquake intensity, in both its existing state and if it were renewed (refer to Appendix C for a full discussion of the PSRA methodology). Results from the PSRA are used to compute annualized quantities (e.g., AAL, AAF, AAD), BCRs, and CMFs for each building renewal mitigation option.

G2.3.2 Performance of replacement buildings

In order to compute similar quantities for the other two mitigation options (i.e., replacement to either current code or REDi Gold), the performance of replacement buildings needs to be determined. For the replacement to current code mitigation option, PSRA results for newer buildings in the portfolio (i.e., those constructed after 2008) were reviewed and averaged to establish the expected performance of code replacement buildings. For the replacement to REDi Gold mitigation option, the performance targets established in Almufti and Willford (2013) for the rare earthquake intensity were extrapolated to other intensities to establish the expected performance of REDi Gold buildings. Table G.1 summarizes the level of performance expected for each replacement building. Note that existing wood buildings are assumed to be replaced with wood, while all building types would be replaced with concrete shear wall.

G2.3.3 Mitigation costs

Another major input to the cost-benefit analysis is the costs associated with each of the three mitigation options (e.g., renewal, replacement to code, and replacement to REDi Gold). The costs of renewal and replacement to code were estimated directly by the cost estimator (see Appendix F), while the cost of replacement to REDi Gold was assumed to involve a 5% premium over the cost to replace to code, based on our experience that resilient design commands a 0 – 5% additional investment on hard costs. These values, in conjunction with the PSRA results, are used to compute BCRs and CMFs for each mitigation option.

Table G.1 Assumed performance of replacement buildings

Replacement Building	Fatalities (% population)				Financial Loss (% rpc value)				Downtime (days)			
	F	P	R	VR	F	P	R	VR	F	P	R	VR
Code (wood)	0	0	0	0	0	1	2	7	0	2	8	50
Code (concrete)	0	0	0	0	1	7	16	40	9	208	486	959
REDi Gold	0	0	0	0	0	4	8	10	2	14	90	180

F = frequent earthquake
P = probable earthquake
R = rare earthquake
VR = very rare earthquake

G2.3.4 Cost of downtime

In order to include downtime in the cost-benefit analysis, its impact needs to be monetized. Because some buildings are more important to campus operations than others, the cost of downtime needs to be computed for several different occupancies, including research, teaching, administrative, and residential. Table G.2 provides the downtime cost for each occupancy and a brief explanation of how it was estimated. With the exception of teaching space, the total area of each occupancy was computed by assigning a single primary occupancy to each building and then summing to get the total area.

G2.4 Consequently, the cost of downtime serves as an implicit measure of a building's importance. Limitations

Before discussing potential mitigation strategies, it is important to recognize several limitations associated with the cost-benefit methodology described in previous sections.

First, the methodology considers only a limited set of costs and benefits. On the cost side, only hard construction costs (including demolition costs) are considered for each mitigation option (see Appendix F for more information about how these costs were calculated); soft costs like engineering design fees and relocation expenses are not included. In general, inclusion of these costs would make each mitigation option less attractive. On the benefit side, only losses, fatalities, and downtime stemming from structural and nonstructural damage are considered when determining the benefits of each mitigation option. Losses from damage to building contents are not included; neither are indirect costs stemming from protracted downtime (e.g., relocation costs, damage to brand reputation, reduced student enrollment). These benefits, which are difficult to quantify, would generally make each mitigation option more attractive. Consequently, results from the cost-benefit analysis should be viewed as one of many different inputs into the decision-making process on which buildings to renew or replace, including architectural significance, fitness for intended use, and availability of swing space.

Table G.3 shows the buildings with the highest cost of downtime. Note that all buildings on the list are either critical research facilities, have significant classroom facilities, or both.

G2.4.1 Discount rate and investment time horizon

The choice of an appropriate discount rate, i, is one of the most challenging and impactful decisions in performing cost-benefit analyses (VSP Associates 1991). As Equation G.2 demonstrates, reducing the discount rate increases the BCR of a mitigation option, potentially making it more attractive to pursue. Per conversations with UBC staff, we have assumed a discount rate of 3.75% (which excludes inflation) in our cost-benefit analysis. Similarly, the time period over which the benefits of an investment accrue, t, can significantly impact the attractiveness of a mitigation option (see Equation G.2). Per conversations with UBC staff, we have assumed a 40 year investment period for building renewals and 75 year period for building replacements.

Table G.2 Downtime costs and sources for different building occupancies

Occupancy	Downtime cost (per day)	Source
Research	$4.63/m^2	Annual revenues from government grants and contracts[1] normalized by the total area of research space
Teaching	$73.49/seat	Annual revenues from tuition and student fees[1] normalized by the total number of classroom seats
Administrative	$1.84/m^2	Overhead from government grants and contracts (25%) normalized by the total area of administrative space [2]
Residential	$2.04/m^2	Rental data[3] and annual revenues from tuition and student fees[1] normalized by the total area of residential space

1. Consolidated Financial Statements for Year Ended March 31, 2016 (http://vpfinance.ubc.ca/files/2016/07/Mar_31_2016_Consolidated_Financial_Statements.pdf)
2. UBC policy on indirect costs of research (https://ors.ubc.ca/proposal-development/ubc-policy-indirect-costs-research)
3. Fees & Payments (http://vancouver.housing.ubc.ca/applications/fees-payments/)

G2.5 Limitations

Before discussing potential mitigation strategies, it is important to recognize several limitations associated with the cost-benefit methodology described in previous sections.

First, the methodology considers only a limited set of costs and benefits. On the cost side, only hard construction costs (including demolition costs) are considered for each mitigation option (see Appendix F for more information about how these costs were calculated); soft costs like engineering design fees and relocation expenses are not included. In general, inclusion of these costs would make each mitigation option less attractive. On the benefit side, only losses, fatalities, and downtime stemming from structural and nonstructural damage are considered when determining the benefits of each mitigation option. Losses from damage to building contents are not included; neither are indirect costs stemming from protracted downtime (e.g., relocation costs, damage to brand reputation, reduced student enrollment). These benefits, which are difficult to quantify, would generally make each mitigation option more attractive. Consequently, results from the cost-benefit analysis should be viewed as one of many different inputs into the decision-making process on which buildings to renew or replace, including architectural significance, fitness for intended use, and availability of swing space.

Table G.3 List of campus buildings with highest downtime cost

Building	Downtime cost (per day)	Critical research	Classroom seats
Life Sciences Centre	$269,910	Y	0
Koerner Pavilion	$203,242	Y	0
Pharmaceutical Sciences Centre For Drug Research And Development	$179,352	Y	538
Forest Sciences Centre	$151,192	Y	621
Earth Sciences Building	$123,642	Y	580

Henry Angus Building	$113,611	N	1546
H. R. Macmillan Building	$113,574	Y	569
West Mall Swing Space Building	$104,425	N	1421
P. A. Woodward Instructional Resources Centre	$95,313	N	1297
Chemical Biological Engineering Building	$87,589	Y	354

Second, the methodology does not include the impact of disruptions to campus utility systems. Please refer to Appendix L for a high-level discussion of the costs and benefits of different utility mitigation strategies. In general, utility mitigation is an attractive option because it can reduce downtime across the entire building portfolio, thus providing significant impact at relatively little cost.

G3 Mitigation strategies

We have developed three potential mitigation strategies for reducing the risks posed by earthquakes. All three strategies prioritize the protection of life safety. The second and third strategies rely on the cost-benefit analysis. The following subsections describe each strategy in more detail.

G3.1 Strategy #1

The first mitigation strategy involves prioritizing mitigation of buildings with the highest AAF (i.e., fatality risk), without regard to cost. In this strategy, the preferred mitigation option is renewal, primarily because renewed buildings are assumed to have performance (in terms of life safety) equivalent to a new code building at 60-70% of the cost. However, this strategy does not incorporate results from the cost-benefit analysis explicitly and, therefore, is not necessarily the most cost effective mitigation strategy.

Figure G.2 plots the reduction in portfolio-level AAF as a function of expenditure for Strategy #1. A vertical drop in the expenditure curve represents the decrease in AAF resulting from the renewal of a single building on campus, while the horizontal portion of the curve represents the cost required to renew the building. Because Strategy #1 prioritizes buildings with the highest AAF, the largest vertical drops in the expenditure curve occur initially. However, because the strategy does not explicitly consider mitigation costs, these vertical drops often require significant expenditure.

Similarly, Figure G.3 and
Figure G.4 plot the reduction in portfolio AAD and AAL, respectively, as a function of expenditure for the first mitigation strategy. Again, because the strategy only considers fatality risk (and not mitigation costs or the benefit of avoided losses and downtime), the expenditure curves for Strategy #1 in
Figure G.3 and

Figure G.4 do not show much reduction in portfolio-level AAD and AAL as the other strategies (described below).

G3.2 Strategy #2

The second mitigation strategy involves prioritizing mitigation of buildings that are most cost effective at saving lives. Note that this is not the same as dividing the cost of a retrofit by the number of lives that would be saved through retrofit in a Very Rare earthquake. It incorporates the annualized risk of fatalities, which is based on the likelihood of incurring fatalities for a range of earthquake intensity levels. The cost to mitigate a fatality can be computed using Equation G.1, Equation G.2, and the equations below.

$$A_{rnw} = C_{life} \cdot \Delta AAF_{rnw} \quad \text{Equation G.3}$$

$$\Delta AAF_{rnw} = AAF_{ext} - AAF_{rnw} \quad \text{Equation G.4}$$

A_{rnw} is the annualized avoided losses due to building renewal, AAF_{ext} is the average annual fatalities for the building in its existing configuration, AAF_{rnw} is the average annual fatalities for the building renewal, and C_{life} is the value assigned to life. The equations for annualized avoided losses for other mitigation options (e.g., code replacement, REDi replacement) are similar. The cost to mitigate fatalities (CMF) can be computed by assuming $BCR = 1.0$ and rearranging the above equations to solve for C_{life}. Subsequently, CMF can be interpreted as the value that must be assigned to life in order to produce a benefit-cost ratio equal to one, which is the threshold at which a mitigation option makes sense financially. Equation G.5 shows how to compute CMF for a building renewal; similar expressions can be developed for other mitigation options.

$$CMF_{rnw} = \frac{C_{rnw} \cdot \left[\frac{1 - \frac{1}{(1+i)^t}}{i}\right]^{-1}}{\Delta AAF_{rnw}} \quad \text{Equation G.5}$$

C_{rnw} is the cost to renew a building; see Section G2.3.3 for how these costs were determined.

Buildings with the lowest CMF are the most cost effective at saving lives and, consequently, would be the highest priority in Strategy #2. Similar to the first strategy, the preferred mitigation option in Strategy #2 is renewal, primarily because renewed buildings are assumed to have performance (in terms of life safety) equivalent to a new code building at 60-70% of the cost. This strategy does not consider the benefits of avoided financial losses and downtime.

Figure G.2, Figure G.3, and

Figure G.4 plot the reduction in portfolio-level AAF, AAD, and AAL, respectively, as a function of expenditure for Strategy #2. Unlike the first strategy, Strategy #2 considers mitigation costs in addition to fatality risk; therefore, the expenditure curve in Figure G.2 represents the most efficient allocation of money and resources in terms of reducing fatality risk. The trade-off, however, is that more buildings need to be mitigated to achieve the same drop in AAF as Strategy #1. The square footage requiring mitigation between the two strategies is likely to be similar though.

G3.3 Strategy #3

The third mitigation strategy involves prioritizing mitigation of buildings that are most cost effective at both saving lives and enhancing resilience. Similar to Strategy #2, the cost to mitigate fatalities and enhance resilience can be computed using Equation G.1, Equation G.2, and the equations below.

$$A_{rnw} = \Delta AAL_{rnw} + C_{dt} \cdot \Delta AAD_{rnw} + C_{life} \cdot \Delta AAF_{rnw} \qquad \text{Equation G.6}$$

$$\Delta AAL_{rnw} = AAL_{ext} - AAL_{rnw} \qquad \text{Equation G.7}$$

$$\Delta AAD_{rnw} = AAD_{ext} - AAD_{rnw} \qquad \text{Equation G.8}$$

$$\Delta AAF_{rnw} = AAF_{ext} - AAF_{rnw} \qquad \text{Equation G.9}$$

C_{dt} is the cost of downtime; refer to Section G2.3.4 for more information about how this quantity is calculated. Unlike Strategy #2, the equation for A_{rnw} includes the benefit of not only avoided fatalities but also avoided losses and downtime (i.e., enhanced resilience). Subsequently, the cost to mitigate fatalities and enhance resilience (CMF*) can be computed by assuming $BCR = 1.0$ and rearranging the above equations to solve for C_{life}. Equation G.10 shows how to compute CMF* for a building renewal, but similar expressions can be developed for other mitigation options (i.e., code replacement and REDi replacement).

$$CMF^{*} = \frac{C_{rnw} \cdot \left[\frac{1 - \frac{1}{(1+i)^{t}}}{i}\right]^{-1} - \Delta AAL_{rnw} - C_{dt} \cdot \Delta AAD_{rnw}}{\Delta AAF_{rnw}} \quad \text{Equation G.10}$$

Buildings with the lowest values of CMF^* are the most cost effective at both saving lives and enhancing resilience and, consequently, would be the highest priority in Strategy #3. As with the other strategies, building renewal is often the most effective mitigation option, though for a small number of buildings it is replacement to REDi Gold, primarily because of the significant reduction in downtime resulting from REDi Gold relative to other mitigation options.

Figure G.2, Figure G.3, and
Figure G.4 plot the reduction in portfolio-level AAF, AAD, and AAL, respectively, as a function of expenditure for the third mitigation strategy (labelled "Strategy #3"). Unlike previous strategies, Strategy #3 considers fatality risk, mitigation costs, and the benefit of avoided losses and downtime. As shown in Figure G.2, the reduction in portfolio-level AAF for Strategy #3 is similar to that of Strategy #2 (which is optimal). However, because the strategy also considers the benefit of avoided losses and downtime, the expenditure curves in Figure G.3 and

Figure G.4 are significantly better than the other strategies.

G3.4 Summary of mitigation strategies

Figure G.2, Figure G.3, and Figure G.4 show the relative reductions in AAF, AAD, and AAL, respectively, against the expenditures for the three mitigation strategies described in the previous sections.

Table G.4 provides key outputs from the cost-benefit analysis for each mitigation option for a representative sample of buildings, including average annual losses (AAL), average annual fatalities (AAF), and average annual downtime (AAD) for the current building configuration and CMF and CMF^* for each mitigation option (e.g., renewal, replacement to code, and replacement to REDi Gold).

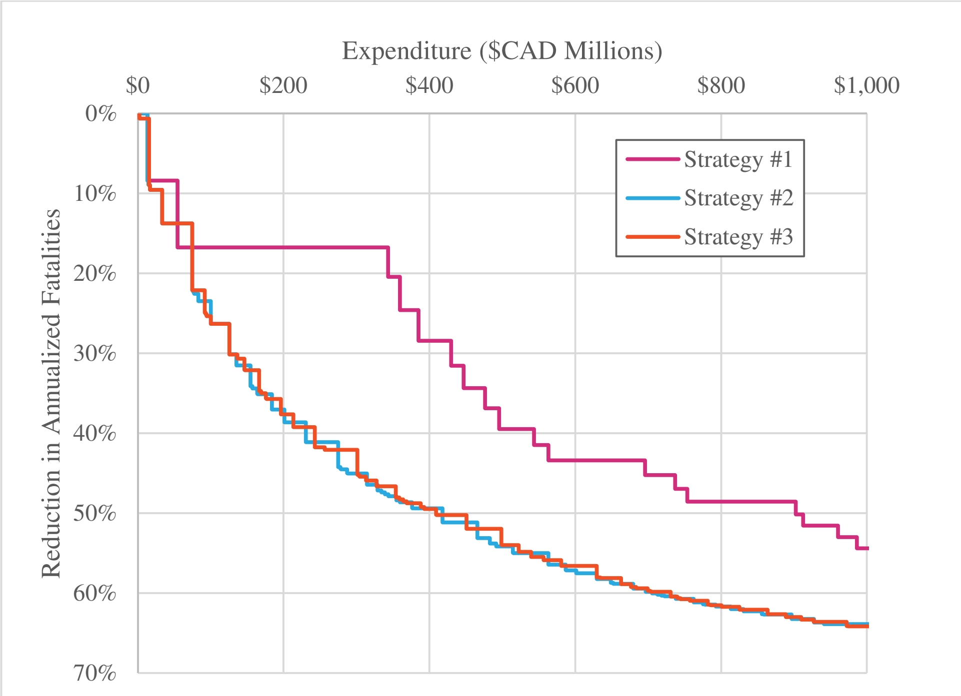


Figure G.2 Reduction in annualized fatalities (AAF) as a function of expenditure for each mitigation strategy

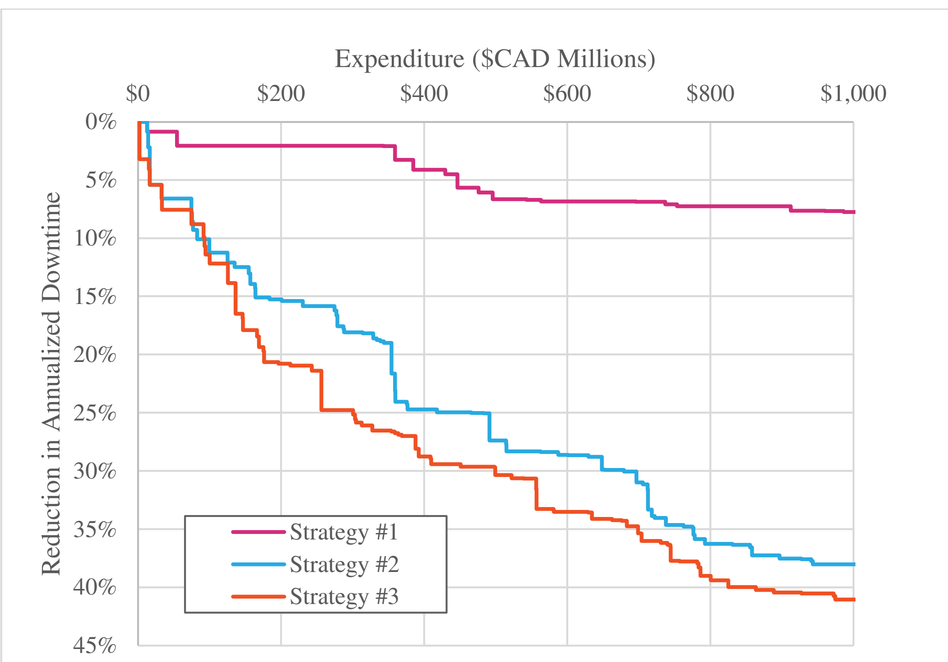


Figure G.3 Reduction in annualized downtime (AAD) as a function of expenditure for each mitigation strategy

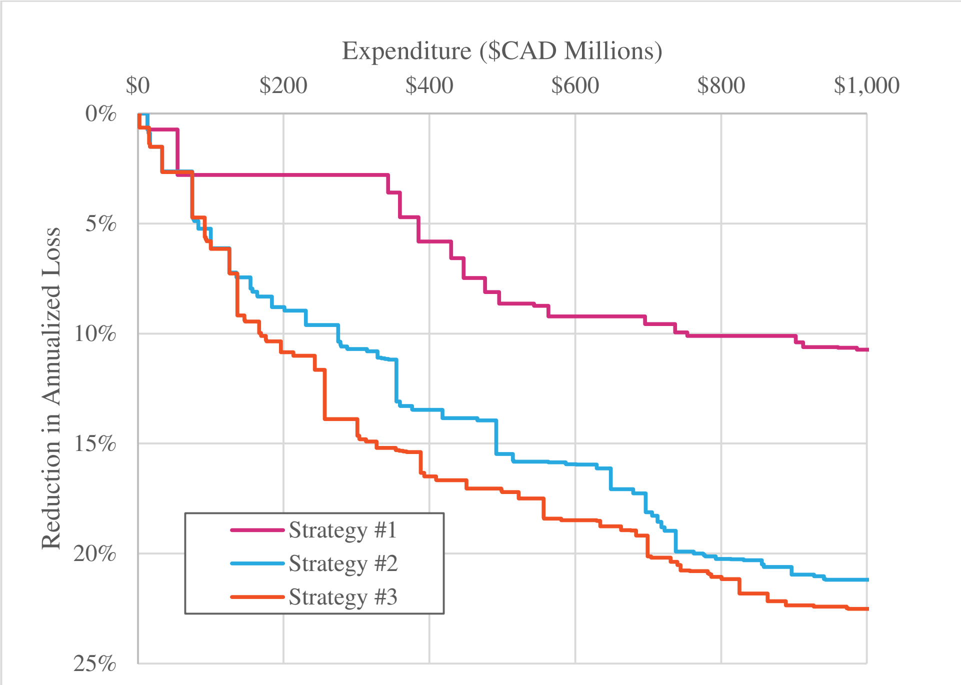


Figure G.4 Reduction in annualized losses (AAL) as a function of expenditure for each mitigation strategy

Table G.4 Outputs from the cost-benefit analysis for a representative sample of buildings

Building Name	**Current Performance**			**Renewal**		**Replacement to Code**		**Replacement to REDi**	
	AAL (10^3)	**AAF (10^{-3})**	**AAD**	**CMF (10^6)**	**CMF* (10^6)**	**CMF (10^6)**	**CMF* (10^6)**	**CMF (10^6)**	**CMF* (10^6)**
Medical Sciences Block C	$142	32.7	8.7	$24.6	$15.7	$28.5	$22.9	$28.8	$20.6
Wesbrook Building	$268	65.1	9.0	$31.0	$23.0	$37.2	$32.3	$37.0	$29.7
Macleod Building	$102	21.0	3.9	$73.9	$64.0	$86.9	$85.5	$81.7	$73.1

The numbers in

Table G.4 provide the foundations for the mitigation strategies described above. Note that the computed values of CMF and CMF^* are significantly larger than $15 million CAD, whereas in construction and engineering applications, previous research places a value on human life in the range of $2-5 million USD (Mitrani-Reiser 2007). From a strictly financial perspective, the cost-benefit analysis suggests that it may be cost prohibitive to retrofit buildings for the purpose of life safety, assuming that a value can be assigned to life. Liel (2013) came to a similar conclusion. However, we assume that will not dissuade UBC from continuing their retrofit program. For that purpose, the cost-benefit analysis provides a powerful basis for prioritizing buildings for renewal, based on the lowest relative CMF or CMF^*.

G4 Assignment of relative prioritization

Using outputs like those shown in Table G.4, we assigned relative prioritization rankings (e.g., Very High, High, Medium, or Low) for each of the three mitigation strategies. These rankings can be found in Appendix H. Please note the following:

- We have assigned rankings only for buildings within Structural Vulnerability Tiers IV, III, and a limited subset of II. Some Tier II buildings were observed to have casualty risks that potentially warranted further evaluation. These are primarily larger buildings with large population exposure.
- Prioritization rankings are relative in nature, meaning that a building ranked “low” should not necessarily be considered a low priority, in the absolute sense. Instead it means that, relative to other buildings, it is not the most impactful with respect to the selected mitigation strategy.
- For Strategy #1, buildings were ranked using their AAF (annual average fatalities); for Strategy #2, buildings were ranked using their CMF (cost to mitigate fatalities); for Strategy #3, buildings were ranked using their CMF^* (cost to mitigate fatalities and enhance resilience).
- For Strategy #1, the thresholds for ranking buildings were established by reviewing the anticipated performance of newer buildings in the campus portfolio. Buildings with values of AAF less than those of a new building (i.e., AAF < 0.002) were assigned a ranking of “Low.” Thresholds for the other rankings (i.e., Medium, High, and Very High) were determined by apportioning the remaining buildings among the three categories such that the “Medium” category had twice as many buildings as “High,” which in turn had twice as many as “Very High.”
- For Strategies #2 and 3, the thresholds for ranking buildings were established in such a way that the number of buildings in each category was roughly equivalent to Strategy #1 for consistency and to enable comparison across the various mitigation strategies.

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Appendix H

List of Individual Building Vulnerability, Risk, and Prioritization Rankings

H1 Summary of Contents

This appendix provides the list of buildings, their structural collapse vulnerabilities, prioritization rankings, and recommended next steps. A summary of the contents is provided below.

- Section H2 contains the following tables:
  - Table H1 provides a list of all unretrofitted campus buildings and their corresponding collapse vulnerability (designated by Tiers I, II, III, or IV).
  - Table H2 provides a list of all previously retrofitted campus buildings and their corresponding collapse vulnerability (designated by Tiers I, II, III, or IV).
  - Table H3 provides a condensed list of unretrofitted campus buildings with prioritization rankings for potential renewal (Very High, High, Medium, or Low) based on three mitigation strategies, enabled by cost-benefit analysis (see Section 5.7). Recommended next steps for each building are also provided.
  - Table H4 provides a condensed list of previously retrofitted campus buildings with prioritization rankings for potential renewal (Very High, High, Medium, or Low) based on three mitigation strategies, enabled by cost-benefit analysis (see Section 5.7). Recommended next steps for each building are also provided.
  - Table H5 provides a list of buildings which were identified to contain Very High nonstructural life safety hazards, including heavy cladding (including brick veneer), masonry partitions, parapets, and chimneys, is also provided.
- Section H3 provides the basis of the structural collapse vulnerability tiers.

Risks for individual buildings, including estimates of casualties, repair costs, and downtime, for the various earthquake intensity levels, are provided in an electronic addendum entitled “Building Risk Assessment Results.xlsx”.

H2 Building Lists

Table H1 Structural Vulnerability Collapse Tiers - Unretrofitted Buildings

Building ID	Building Name	Structural Vulnerability Tiers (Collapse Risk)
002-1	ACADIA PARK HIGHRISE	II
007-01	FAIRVIEW CRESCENT STUDENT HOUSING - UNIT 1	I
007-11	Fairview Crescent Student Housing - Unit 11	II
007-14	Fairview Crescent Student Housing - Unit 14	II
007-19	Fairview Crescent Student Housing - Unit 19	II
007-23	Fairview Crescent Student Housing - Unit 23	II
007-26	Fairview Crescent Student Housing - Unit 26	II
009-01	ACADIA FAMILY HOUSING PHASE II - UNIT 1	II
009-02	ACADIA FAMILY HOUSING PHASE II - UNIT 2	II
009-03	ACADIA FAMILY HOUSING PHASE II - UNIT 3	I
009-04	ACADIA FAMILY HOUSING PHASE II - UNIT 4	II
009-05	ACADIA FAMILY HOUSING PHASE II - UNIT 5	I
009-06	ACADIA FAMILY HOUSING PHASE II - UNIT 6	I
009-07	ACADIA FAMILY HOUSING PHASE II - UNIT 7	I
009-08	ACADIA FAMILY HOUSING PHASE II - UNIT 8	I
009-09	ACADIA FAMILY HOUSING PHASE II - UNIT 9	I
009-10	Acadia Family Housing Phase II - Unit 10	II
009-11	Acadia Family Housing Phase II - Unit 11	II
009-12	Acadia Family Housing Phase II - Unit 12	II
009-13	Acadia Family Housing Phase II - Unit 13	II
009-14	Acadia Family Housing Phase II - Unit 14	II
009-15	Acadia Family Housing Phase II - Unit 15	II
009-16	Acadia Family Housing Phase II - Unit 16	I
009-17	Acadia Family Housing Phase II - Unit 17	I
009-18	Acadia Family Housing Phase II - Unit 18	I
009-19	Acadia Family Housing Phase II - Unit 19	I
009-20	Acadia Family Housing Phase II - Unit 20	I
009-21	Acadia Family Housing Phase II - Unit 21	I
009-22	Acadia Family Housing Phase II - Unit 22	I
009-23	Acadia Family Housing Phase II - Unit 23	I
009-24	Acadia Family Housing Phase II - Unit 24	I
009-25	Acadia Family Housing Phase II - Unit 25	I
009-26	Acadia Family Housing Phase II - Unit 26	I
010-01	ACADIA FAMILY HOUSING PHASE III - UNIT 1	I
010-02	ACADIA FAMILY HOUSING PHASE III - UNIT 2	I
010-03	ACADIA FAMILY HOUSING PHASE III - UNIT 3	I
010-04	ACADIA FAMILY HOUSING PHASE III - UNIT 4	I
010-05	ACADIA FAMILY HOUSING PHASE III - UNIT 5	I
010-06	ACADIA FAMILY HOUSING PHASE III - UNIT 6	II
010-07	ACADIA FAMILY HOUSING PHASE III - UNIT 7	II
010-08	ACADIA FAMILY HOUSING PHASE III - UNIT 8	II
010-09	ACADIA FAMILY HOUSING PHASE III - UNIT 9	II
010-10	Acadia Family Housing Phase III - Unit 10	I
11	ACADIA COMMUNITY CENTRE	I
13	KIDS CLUB	II
014-1	ACADIA FACULTY ROW HOUSING - UNIT 1	III
014-2	ACADIA FACULTY ROW HOUSING - UNIT 2	III
014-3	ACADIA FACULTY ROW HOUSING - UNIT 3	III
17	OLD ADMINISTRATION BUILDING	III
19	BIOENERGY RESEARCH AND DEMONSTRATION FACILITY	I
20	THE BRIMACOMBE BUILDING	I
21	LANDSCAPE ARCHITECTURE ANNEX	IV
22	LOWER MALL RESEARCH STATION	III
023-1	HENRY ANGUS BUILDING CLASSROOM ADDITION	I
024-3	RESEARCH STATION ANNEX 3	IV
024-5	LOWER MALL HEADER HOUSE	I
28	FREDERIC LASSERRE BUILDING	II

29	CAMPUS COMMUNITY PLANNING 2	III
36	THEATRE-FILM PRODUCTION BUILDING	III
45	AUDITORIUM ANNEX OFFICES A	I
46	ASIAN CENTRE	II
48	ANTHROPOLOGY AND SOCIOLOGY BUILDING	IV
51	THE BARN	III
57	CENTRE FOR COMPARATIVE MEDICINE	I
69	BIOLOGICAL SCIENCES BUILDING - WORKSHOP	III
071-1	BOTANY GREENHOUSE 1	IV
071-2	BOTANY GREENHOUSE 2	IV
75	UBC FARM YURT	I
76	BOTANICAL GARDENS SCHOLARS' RETREAT	I
78	BOTANICAL GARDENS - LUNCHROOM	I
79	BOTANICAL GARDENS - GREENHOUSE AND WORKSHOP	I
81	BOOKSTORE	III
82	BOTANICAL GARDENS - GREENHOUSE, ALPINE GARDEN	I
83	MICHAEL SMITH LABORATORIES	I
90	BOTANICAL GARDENS - WORKSHOP	I
94	BOTANICAL GARDENS WORKSHOP (TRAILER)	II
97	BOTANICAL GARDEN CENTRE - GATE HOUSE AND SHOP-IN-THE-	I
98	BOTANICAL GARDEN CENTRE - CAMPBELL BUILDING	I
99	BOTANICAL GARDEN CENTRE - RECEPTION AND EDUCATION	I
100	BOTANICAL GARDEN CENTRE - LOOKOUT TOWER	I
112	BROCK HALL - WEST WING	III
112-1	BROCK HALL - EAST WING	I
113	BROCK HALL ANNEX	IV
120	BUCHANAN TOWER	II
122-2	BUCHANAN BUILDING BLOCK E	II
130	CHAN CENTRE FOR THE PERFORMING ARTS	I
137	IN-VESSEL COMPOSTING FACILITY	I
138	ENVIRONMENTAL SERVICES FACILITY - SOLVENT SILVER	I
139	ENVIRONMENTAL SERVICES FACILITY - OFFICE	I
140	CHEMISTRY STORAGE	IV
141	ENVIRONMENTAL SERVICES FACILITY - SOLVENT STORAGE AREA	I
142	ENVIRONMENTAL SERVICES FACILITY - CHEMICAL WASTE	I
143	ENVIRONMENTAL SERVICES FACILITY - PCB EQUIPMENT STORAGE	II
144	CHEMISTRY C BLOCK, EAST WING	III
148	CHEMISTRY B BLOCK, SOUTH WING	IV
155	CHILD CARE SERVICES ADMINISTRATION BUILDING	I
160	CONTINUING STUDIES BUILDING	I
164	HUGH DEMPSTER PAVILION	I
165	INSTITUTE FOR COMPUTING, INFORMATION AND COGNITIVE	I
166	INSTITUTE FOR COMPUTING, INFORMATION AND COGNITIVE	I
180	RODNEY GRAHAM MILLENNIUM SCULPTURE PAVILLION	I
182	LADNER CLOCK TOWER	III
184	COAL AND MINERAL PROCESSING LABORATORY	III
198	J. B. MACDONALD BUILDING	III
199	DAVID STRANGWAY BUILDING	II
200	CHILD CARE SERVICES - BUILDING 1	I
201	CHILD CARE SERVICES - BUILDING 2	I
202	CHILD CARE SERVICES - BUILDING 3	I
203	CHILD CARE SERVICES - BUILDING 4	I
204	CHILD CARE SERVICES - BUILDING 5	I
205	CHILD CARE SERVICES BUILDING 1	I
206	CHILD CARE SERVICES BUILDING 2	I
207	CHILD CARE SERVICES BUILDING 3	I
212	SING TAO BUILDING	I
225	EARTH SCIENCES BUILDING	I
233	NEVILLE SCARFE BUILDING - TEACHER EDUCATION OFFICE	II
234	NEVILLE SCARFE BUILDING - LIBRARY	I
300	CHEMICAL BIOLOGICAL ENGINEERING BUILDING	I
301	WAYNE AND WILLIAM WHITE ENGINEERING DESIGN CENTRE	I

305	EARTHQUAKE ENGINEERING RESEARCH FACILITY	I
306	CIVIL AND MECHANICAL ENGINEERING BUILDING	IV
307	CIVIL AND MECHANICAL ENGINEERING LABORATORIES	II
308	THE LEONARD S. KLINCK BUILDING	IV
309	CIVIL AND MECHANICAL ENGINEERING STRUCTURES LAB	IV
310	ENGINEERING STUDENT CENTRE	I
312	MACLEOD BUILDING	IV
313	THE FRED KAISER BUILDING	I
314	BEATY BIODIVERSITY CENTRE	I
316	AQUATIC ECOSYSTEMS RESEARCH LABORATORY	I
337	FIRST NATIONS LONGHOUSE	I
353	FOREST SCIENCES CENTRE	II
376	FREDERIC WOOD THEATRE	I
377-1	MARINE DRIVE RESIDENCE - SIMON K.Y. LEE HKU-UBC HOUSE	I
377-2	MARINE DRIVE RESIDENCE - BUILDING #2	I
377-3	MARINE DRIVE RESIDENCE - BUILDING #3	I
377-4	MARINE DRIVE RESIDENCE - BUILDING #4	II to III
377-5	MARINE DRIVE RESIDENCE - BUILDING #5	II to III
377-6	MARINE DRIVE RESIDENCE - BUILDING #6	I
380	OLD FIRE HALL	III
385	WOOD PRODUCTS LABORATORY	II
386	H. R. MACMILLAN BUILDING	IV
387	FOREST SCIENCES GREENHOUSE	IV
389	FORESTRY FIELD HOUSE SOUTH CAMPUS	IV
394	GAS GUN FACILITY	I
401	GEOGRAPHY BUILDING	III
402	EARTH AND OCEAN SCIENCES - MAIN	III
403	EARTH AND OCEAN SCIENCES - SOUTH	I
412	GREEN COLLEGE - GRAHAM HOUSE, GREEN COMMONS, COACH	I
413	GREEN COLLEGE - BUILDING A NORTH	I
414	GREEN COLLEGE - KITCHEN / LAUNDRY	I
415	GREEN COLLEGE - BUILDING A SOUTH	I
416	GREEN COLLEGE - BUILDING B EAST	I
417	GREEN COLLEGE - BUILDING E	I
418	GREEN COLLEGE - ADMINISTRATION -BUILDING F	I
419	GREEN COLLEGE - PRINCIPAL's RESIDENCE - BUILDING C	I
420	CECIL GREEN PARK HOUSE	III
421	CECIL GREEN PARK COACH HOUSE	III
422	CECIL GREEN PARK SQUASH COURT	III
428	WAR MEMORIAL GYMNASIUM	IV
430	ROBERT F. OSBORNE CENTRE - UNIT 1	IV
431	ROBERT F. OSBORNE CENTRE - UNIT 2	IV
432	UBC TENNIS CENTRE	I
433	UBC TENNIS CENTRE (NEW)	I
434	GERALD MCGAVIN UBC RUGBY CENTRE	I
436	HAIDA HOUSE	III
437	UBC FOOTBALL ACADEMIC CENTRE	I
440	MORTUARY HOUSE	III
447	CHEMISTRY A BLOCK, CHEMISTRY PHYSICS BUILDING	III
449	FOOD, NUTRITION AND HEALTH BUILDING	I
450-1	ACADIA HOUSE - 2700	I
451	SOPRON HOUSE	I
456	HORTICULTURE BUILDING	II
461	BIOMEDICAL RESEARCH CENTRE	III
462	PURDY PAVILION	III
463	KOERNER PAVILION	III
465	DJAVAD MOWAFAGHIAN CENTRE FOR BRAIN HEALTH	I
470	ENVIRONMENTAL SERVICES FACILITY - INCINERATOR	IV
473	P. A. WOODWARD INSTRUCTIONAL RESOURCES CENTRE	II
478	C. K. CHOI BUILDING FOR THE INSTITUTE OF ASIAN RESEARCH	I
482	ALLARD HALL	I
490	DAVID LAM MANAGEMENT RESEARCH CENTRE	II

496	LIU INSTITUTE FOR GLOBAL ISSUES	I
513	SCHOOL OF POPULATION PUBLIC HEALTH	I
515	SEDGEWICK LIBRARY	II
515-1	WALTER C. KOERNER LIBRARY	I
518	MATHEMATICS BUILDING	III
519	MATHEMATICS ANNEX	III
521	CAMPUS ENERGY CENTRE	I
523-3	MEDICAL SCIENCES BLOCK C	IV
527	PHARMACEUTICAL SCIENCES CENTRE FOR DRUG RESEARCH AND	II
528	ROSE GARDEN PARKADE	I
529	LIFE SCIENCES CENTRE	I
536	WOODWARD BIOMEDICAL LIBRARY	III
537	DETWILLER PAVILION 1	III
540-2	TOTEM PARK RESIDENCE - HAIDA HOUSE/SALISH HOUSE	I
540-3	TOTEM PARK RESIDENCE - DENE HOUSE/NOOTKA HOUSE	I
543	VANIER PUMP STATION	I
545-1	PLACE VANIER RESIDENCE - CARIBOO HOUSE	II
545-2	PLACE VANIER RESIDENCE - TWEEDSMUIR HOUSE	II
548	PLACE VANIER RESIDENCE - KOOTENAY HOUSE	II
551	THUNDERBIRD PARKADE	I
552	PLACE VANIER RESIDENCE - OKANAGAN HOUSE	III
556	PLACE VANIER RESIDENCE - ROBSON HOUSE	III
560	PLACE VANIER RESIDENCE - SHERWOOD LETT HOUSE	III
562	FRANK FORWARD BUILDING	III
565	TOTEM PARK RESIDENCE - KWAKIUTL HOUSE/SHUSWAP HOUSE	I
566	TOTEM PARK RESIDENCE - QELEXEN HOUSE	II
567	TOTEM PARK RESIDENCE - HEMLESEM HOUSE	II
568	MORRIS AND HELEN BELKIN ART GALLERY	I
570	MUSEUM OF ANTHROPOLOGY	I for Main Building, IV for Display Area
575	MUSIC BUILDING	IV
614	MARY BOLLERT HALL	I
624	GEORGE CUNNINGHAM BUILDING ADDITION	I
625	GEORGE CUNNINGHAM BUILDING	IV
633	CENTRE FOR INTERACTIVE RESEARCH IN SUSTAINABILITY	I
635	ST. JOHN HOSPICE	I
638	SOUTH CAMPUS WAREHOUSE	III
641	UNIVERSITY SERVICES BUILDING	III
643	CAMPUS COMMUNITY PLANNING 1	I
646	BUILDING OPERATIONS EXTERIOR STORAGE SHED	I
654	ABDUL LADHA SCIENCE CENTRE	I
666	PLANT SCIENCE FIELD STATION	II
667	PLANT SCIENCE GARAGE	III
668	TOTEM FIELD STUDIOS	IV
669	STORES ROAD ANNEX	III
670	PLANT SCIENCE FIELD BUILDING	III
674	LOGAN FIELD KIOSK	I
724	POWER HOUSE	IV
725	POWER HOUSE - METER STATION	III
728	NORMAN MACKENZIE HOUSE (PRESIDENT's RESIDENCE)	III
732	DOUGLAS KENNY BUILDING	III
745	RITSUMEIKAN-UBC HOUSE	I
747	PULP AND PAPER CENTRE	II
750	JACK BELL BUILDING FOR THE SCHOOL OF SOCIAL WORK	IV
760	RUGBY PAVILION	III
767	STAGING RESEARCH CENTRE	I
768	BUILDING OPERATIONS - NURSERY	I
769	LIBRARY PARC@UBC	I
770-1	SPIRIT PARK APARTMENTS - 2705	I
771	POINT GREY APARTMENTS (OSOYOOS HOUSING)	I
774	STUDENT RECREATION CENTRE	I

780	THUNDERBIRD RESIDENCE - BUILDING A1	I
780-1	THUNDERBIRD RESIDENCE - BUILDING A4	I
781	THUNDERBIRD RESIDENCE - BUILDING A2	I
781-1	THUNDERBIRD RESIDENCE - BUILDING A3	I
782	THUNDERBIRD RESIDENCE - BUILDING B2	I
782-1	THUNDERBIRD RESIDENCE - BUILDING B3	I
783	THUNDERBIRD RESIDENCE - BUILDING B1	I
783-1	THUNDERBIRD RESIDENCE - BUILDING B4	I
784	THUNDERBIRD RESIDENCE - BUILDING C1	I
784-1	THUNDERBIRD RESIDENCE - BUILDING C2	I
785	THUNDERBIRD STADIUM	IV
789	MAIN SUBSTATION	II
792	NORTH PARKADE	II
795	AMS STUDENT NEST	II
822-1	ST. JOHN's COLLEGE	I
822-2	ST. JOHN's COLLEGE	I
822-3	ST. JOHN's COLLEGE	I
846	BIOLOGICAL ARCHIVE CENTRE	I
858	BERWICK MEMORIAL CENTRE	I
860	Athletics Washroom Facilities	II
862	BASEBALL TRAINING FACILITY	I
863-1	WEST MALL ANNEX	I
863-2	AUDITORIUM ANNEX OFFICES B	I
864	WESBROOK BUILDING	IV
865-1	PONDEROSA OFFICE ANNEX A	I
865-2	PONDEROSA OFFICE ANNEX B	I
865-3	PONDEROSA OFFICE ANNEX C	I
867	WESBROOK BUILDING ANNEX	I
868	DOUG MITCHELL THUNDERBIRD SPORTS CENTRE	II
869-1	WALTER H. GAGE RESIDENCE - COMMON BLOCK	IV
869-2	WALTER H. GAGE RESIDENCE - SOUTH TOWER	II
869-3	WALTER H. GAGE RESIDENCE - NORTH TOWER	II
871-2	PONDEROSA OFFICE ANNEX E	I
871-3	PONDEROSA OFFICE ANNEX F	I
872-1	WALTER H. GAGE RESIDENCE - EAST TOWER	II
872-2	WALTER H. GAGE RESIDENCE - COURT	I
873	PONDEROSA OFFICE ANNEX G	I
874	WALTER H. GAGE RESIDENCE - APARTMENTS	II
876-1	ANTHROPOLOGY AND SOCIOLOGY BUILDING - ISABEL MACINNES HALL	II
876-2	ANTHROPOLOGY AND SOCIOLOGY BUILDING - ANNE WESBROOK HALL	II
880	ANTHROPOLOGY AND SOCIOLOGY BUILDING - MARY MURRIN HALL	II
896-1	PLACE VANIER RESIDENCE - DOROTHY MAWDSLEY HOUSE	II
896-2	PLACE VANIER RESIDENCE - MARGARET MACKENZIE HOUSE	II
896-3	PLACE VANIER RESIDENCE - PHYLLIS ROSS HOUSE	II
896-4	PLACE VANIER RESIDENCE - ALDYEN HAMBER HOUSE	II
898	PLACE VANIER RESIDENCE - KOREA UNIVERSITY - UBC HOUSE	I
900	WEST PARKADE	II
901	WEST MALL SWING SPACE BUILDING	I
902	PLACE VANIER RESIDENCE - TEC DE MONTERREY - UBC HOUSE	I
903	PONDEROSA COMMONS: AUDAIN ART CENTRE / SPRUCE HOUSE	II
904	PONDEROSA COMMONS: MAPLE HOUSE / ARBUTUS HOUSE	II
905	PONDEROSA COMMONS: CEDAR HOUSE / OAK HOUSE	II

Table H2 **Structural Vulnerability Collapse Tiers - Previously Retrofitted Buildings**

Building ID	Building Name	Structural Vulnerability Tiers (Collapse Risk)	Probability of Collapse in Very Rare Earthquake Shaking (2475 year Return Period)	Retrofit Code	% Strength of Retrofit Code
23	HENRY ANGUS BUILDING	I	0% to 10%	2012 BCBC	100%
26	HENRY ANGUS BUILDING ADDITION	II	11% to 19%	2006 BCBC	75%
44	OLD AUDITORIUM	II	11% to 19%	2006 BCBC	75%
52	FRASER RIVER PARKADE	I	0% to 10%	SRG	n/a
65	BIOLOGICAL SCIENCES BUILDING - WEST WING	II	11% to 19%	2006 BCBC	75%
66	BIOLOGICAL SCIENCES BUILDING - NORTH WING	I	0% to 10%	2012 BCBC	100%
68	BIOLOGICAL SCIENCES BUILDING - SOUTH WING	II	11% to 19%	2006 BCBC	75%
91	BOTANICAL GARDEN - GARDEN PAVILION	I	0% to 10%	SRG	n/a
121-1	BUCHANAN BUILDING BLOCK A	II	11% to 19%	2006 BCBC	75%
121-2	BUCHANAN BUILDING BLOCK B	I	0% to 10%	2006 BCBC	100%
121-3	BUCHANAN BUILDING BLOCK C	I	0% to 10%	2006 BCBC	100%
122-1	BUCHANAN BUILDING BLOCK D	III	20% to 49%	1998 BCBC	75%
132	CHEMISTRY D BLOCK, CENTRE WING	III	20% to 49%	1998 BCBC	75%
136	CHEMISTRY E BLOCK, NORTH WING	III	20% to 49%	1998 BCBC	75%
232	NEVILLE SCARFE BUILDING - LECTURE BLOCK	II	11% to 19%	1992 BCBC	100%
240-1	NEVILLE SCARFE BUILDING - CLASSROOM BLOCK	II	11% to 19%	1992 BCBC	100%
240-2	NEVILLE SCARFE BUILDING - OFFICE BLOCK	II	11% to 19%	1992 BCBC	100%
320	DOROTHY SOMERSET STUDIOS	II	11% to 19%	1998 BCBC	100%
324	B.C. BINNING STUDIOS	I	0% to 10%	1998 BCBC	75%
344	LEON AND THEA KOERNER UNIVERSITY CENTRE	II	11% to 19%	2006 BCBC	75%
345	PETER WALL INSTITUTE FOR ADVANCED STUDIES	III	20% to 49%	1998 BCBC	75%
408	THEA KOERNER HOUSE	II	11% to 19%	1992 BCBC	100%
409	THEA KOERNER HOUSE ADDITION	III	20% to 49%	1998 BCBC	75%
467	HEALTH SCIENCES PARKADE	II	11% to 19%	SRG	n/a
476	JAPANESE TEA HOUSE - NITOBE GARDENS	I	0% to 10%	1985 BCBC	100%
511	ENGINEERING HIGH HEAD ROOM LABORATORY	II	11% to 19%	2006 BCBC	75%
516	IRVING K. BARBER LEARNING CENTRE	II	11% to 19%	1998 BCBC	100%
523-2	FRIEDMAN BUILDING	III	20% to 49%	1998 BCBC	75%
525-2	FRIEDMAN BUILDING ADDITION	III	20% to 49%	1998 BCBC	75%
540-1	TOTEM PARK RESIDENCE - COQUIHALA COMMON BLOCK/MAGDA's CONVENIENCE STORE	II	11% to 19%	1998 BCBC	100%
544	PLACE VANIER RESIDENCE - GORDON SHRUM COMMON BLOCK	II	11% to 19%	1998 BCBC	100%
652	HENNINGS BUILDING	III	20% to 49%	1998 BCBC	75%
656	HEBB BUILDING	I	0% to 10%	2012 BCBC	100%
790	STUDENT UNION BUILDING (SUB)	I	0% to 10%	2012 BCBC	100%
836	IONA BUILDING	III	20% to 49%	1998 BCBC	75%

Table H3 Prioritization Rankings for Unretrofitted Buildings

Building ID	Building Name	Structural Vulnerability Tiers (Collapse Risk)	Mitigation Strategy #1 Priority	Mitigation Strategy #2 Priority	Mitigation Strategy #3 Priority	Explanation and/or Recommended Action if Mitigation is Pursued
002-1	ACADIA PARK HIGHRISE	II	medium	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
014-1	ACADIA FACULTY ROW HOUSING - UNIT 1	III	low	high	high	Assumed nominal code strength since no drawings. High also justified by concrete block walls. Perform further non-detailed on-site evaluation to establish input parameters, including strength, and re-run risk analysis.
014-2	ACADIA FACULTY ROW HOUSING - UNIT 2	III	low	high	high	Assumed nominal code strength since no drawings. High also justified by concrete block walls. Perform further non-detailed on-site evaluation to establish input parameters, including strength, and re-run risk analysis.
014-3	ACADIA FACULTY ROW HOUSING - UNIT 3	III	low	high	high	Assumed nominal code strength since no drawings. High also justified by concrete block walls. Perform further non-detailed on-site evaluation to establish input parameters, including strength, and re-run risk analysis.
17	OLD ADMINISTRATION BUILDING	III	medium	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures.
21	LANDSCAPE ARCHITECTURE ANNEX	IV	medium	very high	very high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures.
22	LOWER MALL RESEARCH STATION	III	high	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures.
024-3	RESEARCH STATION ANNEX 3	IV	low	low	low	We understand it will be demolished
29	CAMPUS COMMUNITY PLANNING 2	III	low	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
36	THEATRE-FILM PRODUCTION BUILDING	III	low	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
48	ANTHROPOLOGY AND SOCIOLOGY BUILDING	IV	high	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
51	THE BARN	III	medium	high	high	Assumed nominal code strength since no drawings. Perform further non-detailed on-site evaluation to establish input parameters, including strength, and re-run risk analysis.
69	BIOLOGICAL SCIENCES BUILDING - WORKSHOP	III	low	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
071-1	BOTANY GREENHOUSE 1	IV	low	low	low	
071-2	BOTANY GREENHOUSE 2	IV	low	low	low	
81	BOOKSTORE	III	high	high	high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures. Review impact of Michael Smith building and Bookstore.
112	BROCK HALL - WEST WING	III	medium	medium	very high	Insufficient drawings. Perform further on-site non-detailed evaluation to establish input parameters, including strength, and re-run risk analysis. Delcan also indicated external cast-in-place concrete shear walls which are highly vulnerable.
113	BROCK HALL ANNEX	IV	medium	high	high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
140	CHEMISTRY STORAGE	IV	low	medium	medium	The performance is highly dependent on the presence and properties of steel reinforcement. We have assumed that it is unreinforced. Verify internal steel reinforcement.
144	CHEMISTRY C BLOCK, EAST WING	III	medium	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
148	CHEMISTRY B BLOCK, SOUTH WING	IV	high	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
182	LADNER CLOCK TOWER	III	low	low	low	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
184	COAL AND MINERAL PROCESSING LABORATORY	III	medium	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
198	J. B. MACDONALD BUILDING	III	high	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
306	CIVIL AND MECHANICAL ENGINEERING BUILDING	IV	high	high	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
308	THE LEONARD S. KLINCK BUILDING	IV	high	high	high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
309	CIVIL AND MECHANICAL ENGINEERING STRUCTURES LAB	IV	very high	very high	very high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
312	MACLEOD BUILDING	IV	very high	high	high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
380	OLD FIRE HALL	III	low	medium	medium	Insufficient drawings. Perform further on-site non-detailed evaluation to establish input parameters, including strength, and re-run risk analysis.
386	H. R. MACMILLAN BUILDING	IV	very high	high	high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
387	FOREST SCIENCES GREENHOUSE	IV	low	low	low	
389	FORESTRY FIELD HOUSE SOUTH CAMPUS	IV	low	medium	low	The performance is highly dependent on the presence and properties of steel reinforcement. We have assumed that it is unreinforced. Verify internal steel reinforcement.
401	GEOGRAPHY BUILDING	III	medium	medium	high	No discernible lateral system from drawings. Perform further on-site non-detailed evaluation to establish input parameters, including strength, and re-run risk analysis.
402	EARTH AND OCEAN SCIENCES - MAIN	III	medium	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
420	CECIL GREEN PARK HOUSE	III	high	high	high	No structural drawings. Perform further on-site non-detailed evaluation to establish input parameters, including strength, and re-run risk analysis.
421	CECIL GREEN PARK COACH HOUSE	III	low	medium	medium	No structural drawings. Perform further on-site non-detailed evaluation to establish input parameters, including strength, and re-run risk analysis.
422	CECIL GREEN PARK SQUASH COURT	III	low	medium	medium	Assumed nominal strength as this is pre-code with no structural drawings. Perform further on-site non-detailed evaluation to establish input parameters, including strength, and re-run risk analysis.
428	WAR MEMORIAL GYMNASIUM	IV	medium	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
430	ROBERT F. OSBORNE CENTRE - UNIT 1	IV	very high	very high	very high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
431	ROBERT F. OSBORNE CENTRE - UNIT 2	IV	high	high	high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
436	HAIDA HOUSE	III	low	medium	medium	Perform further on-site non-detailed investigation to confirm construction details.
440	MORTUARY HOUSE	III	low	low	low	Perform further on-site non-detailed investigation to confirm construction details.
447	CHEMISTRY A BLOCK, CHEMISTRY PHYSICS BUILDING	III	high	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
461	BIOMEDICAL RESEARCH CENTRE	III	medium	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
462	PURDY PAVILION	III	high	medium	low	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures

463	KOERNER PAVILION	III	very high	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
470	ENVIRONMENTAL SERVICES FACILITY - INCINERATOR	IV	low	low	low	The performance is highly dependent on the presence and properties of steel reinforcement. Verify internal steel reinforcement.
473	P. A. WOODWARD INSTRUCTIONAL RESOURCES CENTRE	II	medium	low	low	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
490	DAVID LAM MANAGEMENT RESEARCH CENTRE	II	medium	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
518	MATHEMATICS BUILDING	III	medium	medium	medium	Insufficient drawings. Perform further on-site non-detailed evaluation to establish input parameters, including strength, and re-run risk analysis.
519	MATHEMATICS ANNEX	III	medium	medium	medium	Insufficient drawings. Perform further on-site non-detailed evaluation to establish input parameters, including strength, and re-run risk analysis.
523-3	MEDICAL SCIENCES BLOCK C	IV	very high	very high	very high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
527	PHARMACEUTICAL SCIENCES CENTRE FOR DRUG RESEARCH AND DEVELOPMENT	II	medium	low	low	Large diaphragm openings may increase vulnerability. Simplified structural analysis may be overly conservative for taller buildings.
536	WOODWARD BIOMEDICAL LIBRARY	III	high	high	high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
537	DETWILLER PAVILION 1	III	high	low	low	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
552	PLACE VANIER RESIDENCE - OKANAGAN HOUSE	III	medium	high	high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
556	PLACE VANIER RESIDENCE - ROBSON HOUSE	III	medium	high	high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
560	PLACE VANIER RESIDENCE - SHERWOOD LETT HOUSE	III	medium	high	high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
562	FRANK FORWARD BUILDING	III	high	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
570	MUSEUM OF ANTHROPOLOGY	IV	high	high	high	This ranking is for the Display Area. Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
575	MUSIC BUILDING	IV	very high	very high	high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
625	GEORGE CUNNINGHAM BUILDING	IV	high	very high	very high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
638	SOUTH CAMPUS WAREHOUSE	III	low	low	low	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
641	UNIVERSITY SERVICES BUILDING	III	medium	medium	high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
667	PLANT SCIENCE GARAGE	III	low	low	low	The performance is highly dependent on the presence and properties of steel reinforcement. We have assumed that it is unreinforced. Verify internal steel reinforcement.
668	TOTEM FIELD STUDIOS	IV	medium	medium	medium	The performance is highly dependent on the presence and properties of steel reinforcement. We have assumed that it is unreinforced. Verify internal steel reinforcement.
669	STORES ROAD ANNEX	III	low	medium	medium	Assumed nominal strength as this is pre-code with no drawings. Perform further on-site non-detailed evaluation to establish input parameters, including strength, and re-run risk analysis.
670	PLANT SCIENCE FIELD BUILDING	III	low	medium	medium	The performance is highly dependent on the presence and properties of steel reinforcement. We have assumed that it is unreinforced. Verify internal steel reinforcement.
724	POWER HOUSE	IV	medium	medium	very high	We understand it will be demolished
725	POWER HOUSE - METER STATION	III	low	low	low	We understand it will be demolished
728	NORMAN MACKENZIE HOUSE (PRESIDENT's RESIDENCE)	III	medium	medium	high	Insufficient structural drawings. Perform futher on-site non-detailed evaluation to establish input parameters, including strength, and re-run risk analysis.
732	DOUGLAS KENNY BUILDING	III	high	medium	medium	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
750	JACK BELL BUILDING FOR THE SCHOOL OF SOCIAL WORK	IV	medium	high	high	Appears there is only a lateral system in one direction. Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
760	RUGBY PAVILION	III	low	low	low	The performance is highly dependent on the presence and properties of steel reinforcement. We have assumed that it is unreinforced. Verify internal steel reinforcement.
795	AMS STUDENT NEST	II	medium	medium	medium	New building with severe vertical irregularity per rapid visual survey.
864	WESBROOK BUILDING	IV	very high	very high	very high	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
869-1	WALTER H. GAGE RESIDENCE - COMMON BLOCK	IV	medium	medium	low	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures
869-2	WALTER H. GAGE RESIDENCE - SOUTH TOWER	II	medium	medium	low	Advanced analysis demonstrates that while severe damage to walls likely, great amount of redundancy reduces collapse risk. Further detailed structural investigation warranted with bi-directional ground motions scaled appropriately to the period range of interest.
869-3	WALTER H. GAGE RESIDENCE - NORTH TOWER	II	medium	medium	low	Advanced analysis demonstrates that while severe damage to walls likely, great amount of redundancy reduces collapse risk. Further detailed structural investigation warranted with bi-directional ground motions scaled appropriately to the period range of interest.
872-1	WALTER H. GAGE RESIDENCE - EAST TOWER	II	medium	medium	low	Advanced analysis demonstrates that while severe damage to walls likely, great amount of redundancy reduces collapse risk. Further detailed structural investigation warranted with bi-directional ground motions scaled appropriately to the period range of interest.
874	WALTER H. GAGE RESIDENCE - APARTMENTS	III	medium	medium	low	Risk results indicate that more detailed structural evaluation is warranted to determine specific deficiencies and retrofit measures

Table H4 **Prioritization Rankings for Previously Retrofitted Buildings**

Building ID	Building Name	Structural Vulnerability Tiers (Collapse Risk)	Mitigation Strategy #1 Priority	Mitigation Strategy #2 Priority	Mitigation Strategy #3 Priority	Recommended Action
122-1	BUCHANAN BUILDING BLOCK D	III	medium	medium	medium	On-site structural evaluation and in-depth review of drawings, if available, to understand extent and nature of retrofit.
132	CHEMISTRY D BLOCK, CENTRE WING	III	medium	low	low	On-site structural evaluation and in-depth review of drawings, if available, to understand extent and nature of retrofit.
136	CHEMISTRY E BLOCK, NORTH WING	III	medium	low	low	On-site structural evaluation and in-depth review of drawings, if available, to understand extent and nature of retrofit.
345	PETER WALL INSTITUTE FOR ADVANCED STUDIES	III	medium	medium	medium	On-site structural evaluation and in-depth review of drawings, if available, to understand extent and nature of retrofit.
409	THEA KOERNER HOUSE ADDITION	III	low	medium	medium	On-site structural evaluation and in-depth review of drawings, if available, to understand extent and nature of retrofit.
516	IRVING K. BARBER LEARNING CENTRE	II	medium	medium	medium	On-site structural evaluation and in-depth review of drawings, if available, to understand extent and nature of retrofit.
523-2	FRIEDMAN BUILDING	III	medium	medium	low	On-site structural evaluation and in-depth review of drawings, if available, to understand extent and nature of retrofit.
525-2	FRIEDMAN BUILDING ADDITION	III	medium	medium	medium	On-site structural evaluation and in-depth review of drawings, if available, to understand extent and nature of retrofit.
652	HENNINGS BUILDING	III	medium	low	low	On-site structural evaluation and in-depth review of drawings, if available, to understand extent and nature of retrofit.
836	IONA BUILDING	III	medium	low	low	On-site structural evaluation and in-depth review of drawings, if available, to understand extent and nature of retrofit.

Table H5

BUILDING ID		BUILDING NAME	HEAVY CLADDING (1)	MASONRY PARTITIONS (2)	PARAPETS (3)	CHIMNEYS (4)
002-1	2.01	ACADIA PARK HIGHRISE	-	-	YES	-
007-01	7.01	FAIRVIEW CRESCENT STUDENT HOUSING - UNIT 1	YES	-	-	-
007-11	7.11	Fairview Crescent Student Housing - Unit 11	YES	-	-	-
007-14	7.14	Fairview Crescent Student Housing - Unit 14	YES	-	-	-
007-19	7.19	Fairview Crescent Student Housing - Unit 19	YES	-	-	-
007-23	7.23	Fairview Crescent Student Housing - Unit 23	YES	-	-	-
007-26	7.26	Fairview Crescent Student Housing - Unit 26	YES	-	-	-
009-01	9.01	ACADIA FAMILY HOUSING PHASE II - UNIT 1	YES	-	-	-
009-02	9.02	ACADIA FAMILY HOUSING PHASE II - UNIT 2	YES	-	-	-
009-03	9.03	ACADIA FAMILY HOUSING PHASE II - UNIT 3	YES	-	-	-
009-04	9.04	ACADIA FAMILY HOUSING PHASE II - UNIT 4	YES	-	-	-
009-05	9.05	ACADIA FAMILY HOUSING PHASE II - UNIT 5	YES	-	-	-
009-06	9.06	ACADIA FAMILY HOUSING PHASE II - UNIT 6	YES	-	-	-
009-07	9.07	ACADIA FAMILY HOUSING PHASE II - UNIT 7	YES	-	-	-
009-08	9.08	ACADIA FAMILY HOUSING PHASE II - UNIT 8	YES	-	-	-
009-09	9.09	ACADIA FAMILY HOUSING PHASE II - UNIT 9	YES	-	-	-
009-10	9.1	Acadia Family Housing Phase II - Unit 10	YES	-	-	-
009-11	9.11	Acadia Family Housing Phase II - Unit 11	YES	-	-	-
009-12	9.12	Acadia Family Housing Phase II - Unit 12	YES	-	-	-
009-13	9.13	Acadia Family Housing Phase II - Unit 13	YES	-	-	-
009-14	9.14	Acadia Family Housing Phase II - Unit 14	YES	-	-	-
009-15	9.15	Acadia Family Housing Phase II - Unit 15	YES	-	-	-
009-16	9.16	Acadia Family Housing Phase II - Unit 16	YES	-	-	-
009-17	9.17	Acadia Family Housing Phase II - Unit 17	YES	-	-	-
009-18	9.18	Acadia Family Housing Phase II - Unit 18	YES	-	-	-
009-19	9.19	Acadia Family Housing Phase II - Unit 19	YES	-	-	-
009-20	9.2	Acadia Family Housing Phase II - Unit 20	YES	-	-	-
009-21	9.21	Acadia Family Housing Phase II - Unit 21	YES	-	-	-
009-22	9.22	Acadia Family Housing Phase II - Unit 22	YES	-	-	-
009-23	9.23	Acadia Family Housing Phase II - Unit 23	YES	-	-	-
009-24	9.24	Acadia Family Housing Phase II - Unit 24	YES	-	-	-
009-25	9.25	Acadia Family Housing Phase II - Unit 25	YES	-	-	-
009-26	9.26	Acadia Family Housing Phase II - Unit 26	YES	-	-	-
010-01	10.01	ACADIA FAMILY HOUSING PHASE III - UNIT 1	YES	-	-	-
010-02	10.02	ACADIA FAMILY HOUSING PHASE III - UNIT 2	YES	-	-	-
010-03	10.03	ACADIA FAMILY HOUSING PHASE III - UNIT 3	YES	-	-	-
010-04	10.04	ACADIA FAMILY HOUSING PHASE III - UNIT 4	YES	-	-	-
010-05	10.05	ACADIA FAMILY HOUSING PHASE III - UNIT 5	YES	-	-	-
010-06	10.06	ACADIA FAMILY HOUSING PHASE III - UNIT 6	YES	-	-	-
010-07	10.07	ACADIA FAMILY HOUSING PHASE III - UNIT 7	YES	-	-	-
010-08	10.08	ACADIA FAMILY HOUSING PHASE III - UNIT 8	YES	-	-	-
010-09	10.09	ACADIA FAMILY HOUSING PHASE III - UNIT 9	YES	-	-	-
010-10	10.1	Acadia Family Housing Phase III - Unit 10	YES	-	-	-
11	11	ACADIA COMMUNITY CENTRE	YES	-	-	-
13	13	KIDS CLUB	-	-	YES	-
014-1	14.01	ACADIA FACULTY ROW HOUSING - UNIT 1	YES	-	-	-
014-2	14.02	ACADIA FACULTY ROW HOUSING - UNIT 2	YES	-	-	-
014-3	14.03	ACADIA FACULTY ROW HOUSING - UNIT 3	YES	-	-	-
17	17	OLD ADMINISTRATION BUILDING	-	-	-	-
19	19	BIOENERGY RESEARCH AND DEMONSTRATION FACILITY	YES	-	-	-
20	20	THE BRIMACOMBE BUILDING	-	-	-	-
21	21	LANDSCAPE ARCHITECTURE ANNEX	-	YES	-	-
22	22	LOWER MALL RESEARCH STATION	YES	-	-	-
23	23	HENRY ANGUS BUILDING	-	YES	-	-
023-1	23.1	HENRY ANGUS BUILDING CLASSROOM ADDITION	-	-	-	-
024-3	24.03	RESEARCH STATION ANNEX 3	YES	-	-	-
024-5	24.05	LOWER MALL HEADER HOUSE	YES	-	-	-
26	26	HENRY ANGUS BUILDING ADDITION	-	-	YES	-
28	28	FREDERIC LASSERRE BUILDING	YES	YES	-	-
29	29	CAMPUS COMMUNITY PLANNING 2	-	-	-	-
36	36	THEATRE-FILM PRODUCTION BUILDING	-	-	-	-
44	44	OLD AUDITORIUM	-	-	-	-
45	45	AUDITORIUM ANNEX OFFICES A	-	-	-	-
46	46	ASIAN CENTRE	-	-	-	-
48	48	ANTHROPOLOGY AND SOCIOLOGY BUILDING	-	-	-	-
51	51	THE BARN	-	-	-	-
52	52	FRASER RIVER PARKADE	-	-	-	-
57	57	CENTRE FOR COMPARATIVE MEDICINE	-	-	-	-
65	65	BIOLOGICAL SCIENCES BUILDING - WEST WING	-	YES	-	-

66	66	BIOLOGICAL SCIENCES BUILDING - NORTH WING	-	YES	-	-
68	68	BIOLOGICAL SCIENCES BUILDING - SOUTH WING	-	-	-	-
69	69	BIOLOGICAL SCIENCES BUILDING - WORKSHOP	-	YES	-	-
071-1	71.01	BOTANY GREENHOUSE 1	-	-	-	-
071-2	71.02	BOTANY GREENHOUSE 2	-	-	-	-
75	75	UBC FARM YURT	-	-	-	-
76	76	BOTANICAL GARDENS SCHOLARS' RETREAT	-	-	-	-
78	78	BOTANICAL GARDENS - LUNCHROOM	-	-	-	-
79	79	BOTANICAL GARDENS - GREENHOUSE AND WORKSHOP	-	-	-	-
81	81	BOOKSTORE	YES	-	YES	-
82	82	BOTANICAL GARDENS - GREENHOUSE, ALPINE GARDEN	-	-	-	-
83	83	MICHAEL SMITH LABORATORIES	YES	-	-	-
90	90	BOTANICAL GARDENS - WORKSHOP	-	-	-	-
91	91	BOTANICAL GARDEN - GARDEN PAVILION	-	-	YES	-
94	94	BOTANICAL GARDENS WORKSHOP (TRAILER)	-	-	-	-
97	97	BOTANICAL GARDEN CENTRE - GATE HOUSE AND SHOP-IN-THE-GARDEN	-	-	-	-
98	98	BOTANICAL GARDEN CENTRE - CAMPBELL BUILDING	-	-	-	-
99	99	BOTANICAL GARDEN CENTRE - RECEPTION AND EDUCATION CENTRE	-	-	-	-
100	100	BOTANICAL GARDEN CENTRE - LOOKOUT TOWER	-	-	-	-
112	112	BROCK HALL - WEST WING	-	-	-	YES
112-1	112.01	BROCK HALL - EAST WING	-	-	YES	YES
113	113	BROCK HALL ANNEX	YES	YES	-	-
120	120	BUCHANAN TOWER	-	YES	-	-
121-1	121.01	BUCHANAN BUILDING BLOCK A	YES	YES	-	-
121-2	121.02	BUCHANAN BUILDING BLOCK B	YES	YES	-	-
121-3	121.03	BUCHANAN BUILDING BLOCK C	YES	YES	-	-
122-1	122.01	BUCHANAN BUILDING BLOCK D	YES	YES	-	-
122-2	122.02	BUCHANAN BUILDING BLOCK E	YES	YES	-	-
130	130	CHAN CENTRE FOR THE PERFORMING ARTS	YES	-	-	-
132	132	CHEMISTRY D BLOCK, CENTRE WING	YES	YES	YES	-
136	136	CHEMISTRY E BLOCK, NORTH WING	YES	YES	YES	-
137	137	IN-VESSEL COMPOSTING FACILITY	YES	-	-	-
138	138	ENVIRONMENTAL SERVICES FACILITY - SOLVENT SILVER RECOVERY LAB	-	-	-	-
139	139	ENVIRONMENTAL SERVICES FACILITY - OFFICE	-	-	-	-
140	140	CHEMISTRY STORAGE	-	YES	YES	-
141	141	ENVIRONMENTAL SERVICES FACILITY - SOLVENT STORAGE AREA	-	-	-	-
142	142	ENVIRONMENTAL SERVICES FACILITY - CHEMICAL WASTE PROCESSING STORAGE BUI	-	-	-	-
143	143	ENVIRONMENTAL SERVICES FACILITY - PCB EQUIPMENT STORAGE CONTAINERS	-	-	-	-
144	144	CHEMISTRY C BLOCK, EAST WING	YES	-	YES	-
148	148	CHEMISTRY B BLOCK, SOUTH WING	YES	YES	-	-
155	155	CHILD CARE SERVICES ADMINISTRATION BUILDING	-	-	-	-
160	160	CONTINUING STUDIES BUILDING	YES	-	-	-
164	164	HUGH DEMPSTER PAVILION	-	-	-	-
165	165	INSTITUTE FOR COMPUTING, INFORMATION AND COGNITIVE SYSTEMS / COMPUTER	-	YES	-	-
166	166	INSTITUTE FOR COMPUTING, INFORMATION AND COGNITIVE SYSTEMS / COMPUTER	-	-	-	-
180	180	RODNEY GRAHAM MILLENNIUM SCULPTURE PAVILLION	-	-	-	-
182	182	LADNER CLOCK TOWER	-	-	-	-
184	184	COAL AND MINERAL PROCESSING LABORATORY	YES	YES	-	-
198	198	J. B. MACDONALD BUILDING	YES	YES	-	-
199	199	DAVID STRANGWAY BUILDING	YES	-	-	-
200	200	CHILD CARE SERVICES - BUILDING 1	YES	-	-	-
201	201	CHILD CARE SERVICES - BUILDING 2	YES	-	-	-
202	202	CHILD CARE SERVICES - BUILDING 3	YES	-	-	-
203	203	CHILD CARE SERVICES - BUILDING 4	YES	-	-	-
204	204	CHILD CARE SERVICES - BUILDING 5	YES	-	-	-
205	205	CHILD CARE SERVICES BUILDING 1	-	-	-	-
206	206	CHILD CARE SERVICES BUILDING 2	YES	-	-	-
207	207	CHILD CARE SERVICES BUILDING 3	-	-	-	-
212	212	SING TAO BUILDING	YES	-	-	-
225	225	EARTH SCIENCES BUILDING	YES	-	-	-
232	232	NEVILLE SCARFE BUILDING - LECTURE BLOCK	YES	YES	-	-
233	233	NEVILLE SCARFE BUILDING - TEACHER EDUCATION OFFICE	YES	-	-	-
234	234	NEVILLE SCARFE BUILDING - LIBRARY	YES	-	-	-
240-1	240.01	NEVILLE SCARFE BUILDING - CLASSROOM BLOCK	YES	YES	-	-
240-2	240.02	NEVILLE SCARFE BUILDING - OFFICE BLOCK	YES	-	-	-
300	300	CHEMICAL BIOLOGICAL ENGINEERING BUILDING	YES	-	-	-
301	301	WAYNE AND WILLIAM WHITE ENGINEERING DESIGN CENTRE	-	-	-	-
305	305	EARTHQUAKE ENGINEERING RESEARCH FACILITY	-	-	-	-
306	306	CIVIL AND MECHANICAL ENGINEERING BUILDING	YES	-	-	-
307	307	CIVIL AND MECHANICAL ENGINEERING LABORATORIES	YES	-	-	-
308	308	THE LEONARD S. KLINCK BUILDING	YES	-	-	-
309	309	CIVIL AND MECHANICAL ENGINEERING STRUCTURES LAB	YES	-	YES	-
310	310	ENGINEERING STUDENT CENTRE	-	-	-	-

312	312	MACLEOD BUILDING	YES	YES	-	-
313	313	THE FRED KAISER BUILDING	-	-	-	-
314	314	BEATY BIODIVERSITY CENTRE	YES	-	-	-
316	316	AQUATIC ECOSYSTEMS RESEARCH LABORATORY	YES	-	-	-
320	320	DOROTHY SOMERSET STUDIOS	YES	-	-	-
324	324	B.C. BINNING STUDIOS	YES	-	-	-
337	337	FIRST NATIONS LONGHOUSE	-	-	-	-
344	344	LEON AND THEA KOERNER UNIVERSITY CENTRE	-	-	-	-
345	345	PETER WALL INSTITUTE FOR ADVANCED STUDIES	-	-	-	-
353	353	FOREST SCIENCES CENTRE	YES	-	-	-
376	376	FREDERIC WOOD THEATRE	-	YES	YES	-
377-1	377.01	MARINE DRIVE RESIDENCE - SIMON K.Y. LEE HKU-UBC HOUSE	YES	-	-	-
377-2	377.02	MARINE DRIVE RESIDENCE - BUILDING #2	YES	-	-	-
377-3	377.03	MARINE DRIVE RESIDENCE - BUILDING #3	YES	-	-	-
377-4	377.04	MARINE DRIVE RESIDENCE - BUILDING #4	YES	-	-	-
377-5	377.05	MARINE DRIVE RESIDENCE - BUILDING #5	YES	-	-	-
377-6	377.06	MARINE DRIVE RESIDENCE - BUILDING #6	YES	-	-	-
380	380	OLD FIRE HALL	-	-	-	-
385	385	WOOD PRODUCTS LABORATORY	-	-	-	-
386	386	H. R. MACMILLAN BUILDING	YES	YES	YES	-
387	387	FOREST SCIENCES GREENHOUSE	-	-	-	-
389	389	FORESTRY FIELD HOUSE SOUTH CAMPUS	-	YES	-	-
394	394	GAS GUN FACILITY	-	-	-	-
401	401	GEOGRAPHY BUILDING	-	YES	-	-
402	402	EARTH AND OCEAN SCIENCES - MAIN	-	-	-	-
403	403	EARTH AND OCEAN SCIENCES - SOUTH	-	-	-	-
408	408	THEA KOERNER HOUSE	-	YES	YES	-
409	409	THEA KOERNER HOUSE ADDITION	-	YES	-	-
412	412	GREEN COLLEGE - GRAHAM HOUSE, GREEN COMMONS, COACH HOUSE - BUILDING D	-	-	-	-
413	413	GREEN COLLEGE - BUILDING A NORTH	-	-	-	-
414	414	GREEN COLLEGE - KITCHEN / LAUNDRY	-	-	-	-
415	415	GREEN COLLEGE - BUILDING A SOUTH	-	-	-	-
416	416	GREEN COLLEGE - BUILDING B EAST	-	-	-	-
417	417	GREEN COLLEGE - BUILDING E	-	-	-	-
418	418	GREEN COLLEGE - ADMINISTRATION -BUILDING F	-	-	-	-
419	419	GREEN COLLEGE - PRINCIPAL's RESIDENCE - BUILDING C	-	-	-	-
420	420	CECIL GREEN PARK HOUSE	YES	-	-	YES
421	421	CECIL GREEN PARK COACH HOUSE	YES	-	-	-
422	422	CECIL GREEN PARK SQUASH COURT	YES	-	-	-
428	428	WAR MEMORIAL GYMNASIUM	YES	-	-	-
430	430	ROBERT F. OSBORNE CENTRE - UNIT 1	YES	YES	-	-
431	431	ROBERT F. OSBORNE CENTRE - UNIT 2	YES	YES	-	-
432	432	UBC TENNIS CENTRE	-	-	-	-
433	433	UBC TENNIS CENTRE (NEW)	-	-	-	-
434	434	GERALD MCGAVIN UBC RUGBY CENTRE	-	-	-	-
436	436	HAIDA HOUSE	-	-	-	-
437	437	UBC FOOTBALL ACADEMIC CENTRE	-	-	-	-
440	440	MORTUARY HOUSE	-	-	-	-
447	447	CHEMISTRY A BLOCK, CHEMISTRY PHYSICS BUILDING	YES	YES	-	-
449	449	FOOD, NUTRITION AND HEALTH BUILDING	-	-	-	-
450-1	450.01	ACADIA HOUSE - 2700	YES	-	-	-
451	451	SOPRON HOUSE	-	-	-	-
456	456	HORTICULTURE BUILDING	-	-	-	-
461	461	BIOMEDICAL RESEARCH CENTRE	YES	-	-	-
462	462	PURDY PAVILION	-	-	-	-
463	463	KOERNER PAVILION	YES	-	-	-
465	465	DJAVAD MOWAFAGHIAN CENTRE FOR BRAIN HEALTH	YES	-	-	-
467	467	HEALTH SCIENCES PARKADE	-	-	-	-
470	470	ENVIRONMENTAL SERVICES FACILITY - INCINERATOR	-	YES	-	-
473	473	P. A. WOODWARD INSTRUCTIONAL RESOURCES CENTRE	-	-	-	-
476	476	JAPANESE TEA HOUSE - NITOBE GARDENS	-	-	-	-
478	478	C. K. CHOI BUILDING FOR THE INSTITUTE OF ASIAN RESEARCH	YES	-	-	-
482	482	ALLARD HALL	YES	-	-	-
490	490	DAVID LAM MANAGEMENT RESEARCH CENTRE	YES	-	-	-
496	496	LIU INSTITUTE FOR GLOBAL ISSUES	YES	-	-	-
511	511	ENGINEERING HIGH HEAD ROOM LABORATORY	-	-	-	-
513	513	SCHOOL OF POPULATION PUBLIC HEALTH	-	-	-	-
515	515	SEDGEWICK LIBRARY	YES	-	-	-
515-1	515.01	WALTER C. KOERNER LIBRARY	YES	-	-	-
516	516	IRVING K. BARBER LEARNING CENTRE	YES	YES	YES	-
518	518	MATHEMATICS BUILDING	-	-	-	-
519	519	MATHEMATICS ANNEX	-	-	-	-
521	521	CAMPUS ENERGY CENTRE	YES	-	-	-

523-2	523.02	FRIEDMAN BUILDING	YES	YES	-	-
523-3	523.03	MEDICAL SCIENCES BLOCK C	YES	YES	YES	-
525-2	525.02	FRIEDMAN BUILDING ADDITION	YES	YES	-	-
527	527	PHARMACEUTICAL SCIENCES CENTRE FOR DRUG RESEARCH AND DEVELOPMENT	-	-	-	-
528	528	ROSE GARDEN PARKADE	YES	-	-	-
529	529	LIFE SCIENCES CENTRE	YES	-	-	-
536	536	WOODWARD BIOMEDICAL LIBRARY	YES	YES	-	-
537	537	DETWILLER PAVILION 1	YES	-	-	-
540-1	540.01	TOTEM PARK RESIDENCE - COQUIHALA COMMON BLOCK/MAGDA's CONVENIENCE S	YES	-	YES	-
540-2	540.02	TOTEM PARK RESIDENCE - HAIDA HOUSE/SALISH HOUSE	YES	-	YES	-
540-3	540.03	TOTEM PARK RESIDENCE - DENE HOUSE/NOOTKA HOUSE	YES	-	YES	-
543	543	VANIER PUMP STATION	-	-	-	-
544	544	PLACE VANIER RESIDENCE - GORDON SHRUM COMMON BLOCK	YES	YES	YES	-
545-1	545.01	PLACE VANIER RESIDENCE - CARIBOO HOUSE	YES	YES	YES	-
545-2	545.02	PLACE VANIER RESIDENCE - TWEEDSMUIR HOUSE	YES	YES	YES	-
548	548	PLACE VANIER RESIDENCE - KOOTENAY HOUSE	YES	YES	YES	-
551	551	THUNDERBIRD PARKADE	YES	-	-	-
552	552	PLACE VANIER RESIDENCE - OKANAGAN HOUSE	YES	YES	YES	-
556	556	PLACE VANIER RESIDENCE - ROBSON HOUSE	YES	YES	YES	-
560	560	PLACE VANIER RESIDENCE - SHERWOOD LETT HOUSE	YES	YES	YES	-
562	562	FRANK FORWARD BUILDING	YES	YES	YES	-
565	565	TOTEM PARK RESIDENCE - KWAKIUTL HOUSE/SHUSWAP HOUSE	YES	-	YES	-
566	566	TOTEM PARK RESIDENCE - QELEXEN HOUSE	YES	-	-	-
567	567	TOTEM PARK RESIDENCE - HEMLESEM HOUSE	YES	-	-	-
568	568	MORRIS AND HELEN BELKIN ART GALLERY	YES	-	-	-
570	570	MUSEUM OF ANTHROPOLOGY	-	-	-	-
575	575	MUSIC BUILDING	YES	YES	-	-
614	614	MARY BOLLERT HALL	-	YES	-	-
624	624	GEORGE CUNNINGHAM BUILDING ADDITION	YES	YES	YES	-
625	625	GEORGE CUNNINGHAM BUILDING	YES	YES	-	-
633	633	CENTRE FOR INTERACTIVE RESEARCH IN SUSTAINABILITY	YES	-	-	-
635	635	ST. JOHN HOSPICE	YES	-	-	-
638	638	SOUTH CAMPUS WAREHOUSE	-	-	-	-
641	641	UNIVERSITY SERVICES BUILDING	YES	-	-	-
643	643	CAMPUS COMMUNITY PLANNING 1	-	-	-	-
646	646	BUILDING OPERATIONS EXTERIOR STORAGE SHED	-	-	-	-
652	652	HENNINGS BUILDING	YES	-	YES	-
654	654	ABDUL LADHA SCIENCE CENTRE	-	-	-	-
656	656	HEBB BUILDING	YES	-	YES	-
666	666	PLANT SCIENCE FIELD STATION	-	-	-	-
667	667	PLANT SCIENCE GARAGE	-	-	-	-
668	668	TOTEM FIELD STUDIOS	-	-	-	-
669	669	STORES ROAD ANNEX	-	-	-	-
670	670	PLANT SCIENCE FIELD BUILDING	-	-	-	-
674	674	LOGAN FIELD KIOSK	-	-	-	-
724	724	POWER HOUSE	-	-	YES	-
725	725	POWER HOUSE - METER STATION	-	-	-	-
728	728	NORMAN MACKENZIE HOUSE (PRESIDENT's RESIDENCE)	-	-	YES	YES
732	732	DOUGLAS KENNY BUILDING	YES	-	YES	-
745	745	RITSUMEIKAN-UBC HOUSE	YES	-	-	-
747	747	PULP AND PAPER CENTRE	YES	YES	-	-
750	750	JACK BELL BUILDING FOR THE SCHOOL OF SOCIAL WORK	-	-	-	-
760	760	RUGBY PAVILION	-	-	YES	YES
767	767	STAGING RESEARCH CENTRE	-	-	-	-
768	768	BUILDING OPERATIONS - NURSERY	-	-	-	-
769	769	LIBRARY PARC@UBC	YES	-	-	-
770-1	770.01	SPIRIT PARK APARTMENTS - 2705	YES	-	-	-
771	771	POINT GREY APARTMENTS (OSOYOOS HOUSING)	YES	-	YES	-
774	774	STUDENT RECREATION CENTRE	YES	-	-	-
780	780	THUNDERBIRD RESIDENCE - BUILDING A1	YES	-	-	-
780-1	780.01	THUNDERBIRD RESIDENCE - BUILDING A4	YES	-	-	-
781	781	THUNDERBIRD RESIDENCE - BUILDING A2	YES	-	-	-
781-1	781.01	THUNDERBIRD RESIDENCE - BUILDING A3	YES	-	-	-
782	782	THUNDERBIRD RESIDENCE - BUILDING B2	YES	-	-	-
782-1	782.01	THUNDERBIRD RESIDENCE - BUILDING B3	YES	-	-	-
783	783	THUNDERBIRD RESIDENCE - BUILDING B1	YES	-	-	-
783-1	783.01	THUNDERBIRD RESIDENCE - BUILDING B4	YES	-	-	-
784	784	THUNDERBIRD RESIDENCE - BUILDING C1	YES	-	-	-
784-1	784.01	THUNDERBIRD RESIDENCE - BUILDING C2	YES	-	-	-
785	785	THUNDERBIRD STADIUM	-	YES	YES	-
789	789	MAIN SUBSTATION	-	-	-	-
790	790	STUDENT UNION BUILDING (SUB)	-	YES	-	-
792	792	NORTH PARKADE	-	-	-	-

795	795	AMS STUDENT NEST	YES	-	-	-
822-1	822.01	ST. JOHN's COLLEGE	YES	-	-	-
822-2	822.02	ST. JOHN's COLLEGE	YES	-	-	-
822-3	822.03	ST. JOHN's COLLEGE	YES	-	-	-
836	836	IONA BUILDING	YES	-	-	-
846	846	BIOLOGICAL ARCHIVE CENTRE	-	-	-	-
858	858	BERWICK MEMORIAL CENTRE	-	-	-	-
860	860	Athletics Washroom Facilities	-	-	-	-
862	862	BASEBALL TRAINING FACILITY	-	-	-	-
863-1	863.01	WEST MALL ANNEX	-	-	-	-
863-2	863.02	AUDITORIUM ANNEX OFFICES B	-	-	-	-
864	864	WESBROOK BUILDING	YES	-	-	-
865-1	865.01	PONDEROSA OFFICE ANNEX A	-	-	-	-
865-2	865.02	PONDEROSA OFFICE ANNEX B	-	-	-	-
865-3	865.03	PONDEROSA OFFICE ANNEX C	-	-	-	-
867	867	WESBROOK BUILDING ANNEX	YES	YES	-	-
868	868	DOUG MITCHELL THUNDERBIRD SPORTS CENTRE	YES	YES	YES	-
869-1	869.01	WALTER H. GAGE RESIDENCE - COMMON BLOCK	YES	-	-	-
869-2	869.02	WALTER H. GAGE RESIDENCE - SOUTH TOWER	YES	-	-	-
869-3	869.03	WALTER H. GAGE RESIDENCE - NORTH TOWER	YES	-	-	-
871-2	871.02	PONDEROSA OFFICE ANNEX E	-	-	-	-
871-3	871.03	PONDEROSA OFFICE ANNEX F	-	-	-	-
872-1	872.01	WALTER H. GAGE RESIDENCE - EAST TOWER	YES	-	-	-
872-2	872.02	WALTER H. GAGE RESIDENCE - COURT	YES	-	-	-
873	873	PONDEROSA OFFICE ANNEX G	-	-	-	-
874	874	WALTER H. GAGE RESIDENCE - APARTMENTS	YES	-	-	-
876-1	876.01	ANTHROPOLOGY AND SOCIOLOGY BUILDING - ISABEL MACINNES HALL	-	YES	-	-
876-2	876.02	ANTHROPOLOGY AND SOCIOLOGY BUILDING - ANNE WESBROOK HALL	-	YES	-	-
880	880	ANTHROPOLOGY AND SOCIOLOGY BUILDING - MARY MURRIN HALL	-	-	-	-
896-1	896.01	PLACE VANIER RESIDENCE - DOROTHY MAWDSLEY HOUSE	YES	YES	YES	-
896-2	896.02	PLACE VANIER RESIDENCE - MARGARET MACKENZIE HOUSE	YES	YES	YES	-
896-3	896.03	PLACE VANIER RESIDENCE - PHYLLIS ROSS HOUSE	YES	YES	YES	-
896-4	896.04	PLACE VANIER RESIDENCE - ALDYEN HAMBER HOUSE	YES	YES	YES	-
898	898	PLACE VANIER RESIDENCE - KOREA UNIVERSITY - UBC HOUSE	YES	YES	-	-
900	900	WEST PARKADE	-	-	-	-
901	901	WEST MALL SWING SPACE BUILDING	YES	-	-	-
902	902	PLACE VANIER RESIDENCE - TEC DE MONTERREY - UBC HOUSE	YES	-	-	-
903	903	PONDEROSA COMMONS: AUDAIN ART CENTRE / SPRUCE HOUSE	YES	-	-	-
904	904	PONDEROSA COMMONS: MAPLE HOUSE / ARBUTUS HOUSE	YES	-	-	-
905	905	PONDEROSA COMMONS: CEDAR HOUSE / OAK HOUSE	YES	-	-	-

1. INCLUDES MASONRY VENEER, PRECAST, AND SIMILAR HEAVY CLADDING TYPES. DOES NOT INCLUDE EXPOSED STRUCTURAL CONCRETE. INCLUDES NEW BUILDINGS FOR COMPLETENESS.
2. INCLUDES MASONRY PARTITION WALLS THAT ARE UNREINFORCED, LIGHTLY REINFORCED, OR WHERE REINFORCING IS UNKNOWN.
3. ASSIGNED BASED ON ARUP'S ON-SITE EVALUATIONS AND IF PARAPETS DESIGNATED AS HIGH OR VERY HIGH BY DELCAN
4. BASED ON DELCAN'S OBSERVATIONS

H3 Basis of Building Collapse Vulnerability

H3.1 Tier designations

The qualitative descriptors utilized in previous studies (e.g. Very High, High, etc.) have been replaced with Roman numerals (the University of California system has also adopted the use of Roman numerals to designate expected seismic performance levels). This was done primarily to underscore that our methodology and criteria for assigning individual buildings into tiers differed from previous assessments.

H3.2 Basis of Tier levels and thresholds

We have assigned buildings into Structural Vulnerability Tiers based on their anticipated probability of structural collapse in Very Rare earthquake shaking (see table below). For Tier I, the threshold was based on the US building code implied minimum performance targets for new buildings (10% probability of collapse in Very Rare shaking). The Canadian codes do not provide explicit collapse objectives. The other thresholds were based on our judgment. The number of buildings which fall within each tier are also shown in the table. These are unretrofitted buildings (see below for previously retrofitted buildings).

Table H6 Count of unretrofitted buildings in each structural vulnerability tier

Structural Vulnerability Tiers (Collapse Risk)	Probability of Collapse in Very Rare Earthquake Shaking (2475 year Return Period)	Number of Buildings
I	0% to 10%	155
II	11% to 19%	63
III	20% to 49%	46
IV	50% to 100%	29
	TOTAL	293

In this study, the probability of collapse was explicitly quantified by performing structural analysis on a simplified representation of each building based on available data from on-site evaluations, building information supplied by UBC, Delcan's and GS/JM Engineering observations (which we note were generally thorough and helpful, particularly because Arup did not perform on-site evaluations of most of the older buildings at highest risk), and review of structural drawing (not always available). See Appendix D for further detail.

See Appendix A for definition of "collapse".

H3.3 Previously retrofitted buildings

The previously retrofitted buildings are separated from the un-retrofitted ones. This was done for clarity but also because our approach to ranking the retrofitted buildings differed slightly due to the following circumstances:

- The expected performance of a retrofitted building (relative to an un-retrofitted one) is more difficult to ascertain because the nature and extent of the retrofit can vary significantly and often the retrofits are undertaken nonconventionally (e.g. external buttresses). In other words, the expected performance depends on the retrofit and the outcomes can vary — in Napa, several retrofitted buildings performed poorly while others performed well. The ability to evaluate the expected performance of retrofitted buildings with simple methods is thus constrained. It can also be assumed that the retrofitted buildings on campus were previously identified as being the most highly vulnerable.

- Recall that Arup performed on-site evaluations on roughly 80 newer buildings (that Delcan had not assessed because they were generally constructed after 1994) and 30 older buildings (that Delcan had assessed, for auditing purposes). We relied on Delcan's observations for all other older buildings (constructed prior to 1994). Since the retrofitted buildings are all "older", they were not part of Arup's on-site evaluation and since the retrofits have generally been undertaken in the last 20 years, Delcan's observations did not include them. This means that on-site evaluations of retrofitted buildings on campus have not been undertaken by any party. Particular vulnerabilities noted by Delcan in 1994 could have been addressed by a subsequent retrofit but it would need to be confirmed by on-site evaluation. For the purposes of this study, we assumed that severe vertical irregularities were partially addressed.

- We reviewed structural retrofit drawings but many were unavailable or incomplete. Even with complete structural drawings, further detailed evaluation would be required to ensure that the retrofit addressed all identified deficiencies.

Thus, we rank retrofitted buildings based on the code year and the minimum level of strength that the retrofit adhered to (see table below). In several cases, we had to make assumptions on the code year and minimum level of strength because the drawings were unavailable. Retrofits adhering to 100% strength of 2006 or 2012 BCBC would be assigned to Tier I which is the same Tier that almost all new buildings on campus would achieve. This may be slightly unconservative as it is generally recognized that a retrofitted building would not perform as well as an equivalent new building, even if the retrofitted building satisfied 100% of the strength requirements of the same code used to design the equivalent new building. The minimum strength levels in 1985/1992 are roughly half those of 2006/2012, putting them at greater risk.

Table H7 Count of previously retrofitted buildings in each structural vulnerability tier

Structural Vulnerability Tiers (Collapse Risk)	Probability of Collapse in Very Rare Earthquake Shaking (2475 year Return Period)	Number of Buildings
I	0% to 10%	10
II	11% to 19%	16
III	20% to 49%	9
IV	50% to 100%	0
	TOTAL	35

Table H8 Tier designations of previously retrofitted buildings, based on retrofit code and proportion of code strength

% Strength of Retrofit Code	Retrofit Code Year				
	1985	1992	1998	2006	2012
100%	III	II	II	I	I
75%	IV	III	III	II	II

The main takeaways here are that 1) just because a building is retrofitted, it does not necessarily mean that it should fall into a lower Tier and 2) it is difficult to predict the expected performance levels of retrofitted buildings without detailed evaluation.

Appendix I

Portfolio Risk Results for Buildings

I1 Introduction

This appendix summarizes the portfolio-level seismic risk assessment results of the 328 existing buildings on University of British Columbia, Vancouver's campus. In particular, the risk metrics related to structural vulnerability (i.e. building demolition and collapse), casualty rate (i.e. injuries and fatalities of indoor populations), building repair costs, building recovery time (i.e. repair time and total downtime to achieve either re-occupancy or full functionality), content losses, and damaged components are presented. The methodology undertaken for the portfolio seismic risk assessment is documented in Appendix C.

I2 Existing Portfolio Risk Results

I2.1 Building Collapses and Demolitions

In a given earthquake, there is a probability that a building will be deemed irreparable. This could be due to a collapse or excessive damage resulting in building demolition. The number of buildings in each of those categories is summarized for each earthquake intensity level in Figure I1

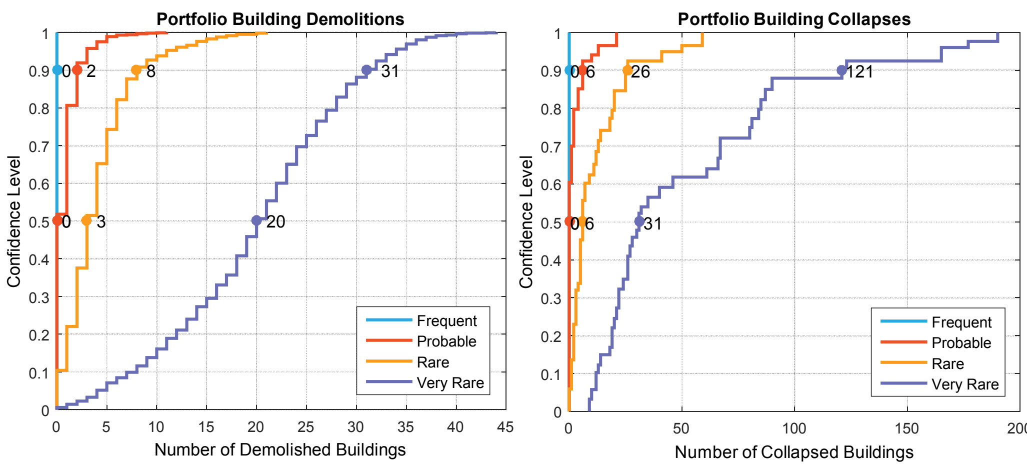

Figure I1 Number of buildings demolished and collapsed in each earthquake event

The best estimate for numbers of buildings that may collapse in the very rare earthquake is 31, or roughly 9.5% of the total building stock. See Appendix A for the definition of collapse.

I2.2 Indoor Casualty Rate

The indoor casualty rate due to building damage was typically driven by collapse-prone buildings. The campus-wide indoor casualty rates are shown in Figure I2. For a total 'equivalent continuous occupancy' indoor population of nearly 22,100 people, the best estimate for injuries and fatalities in the very rare earthquake event are 678 and 153, respectively.

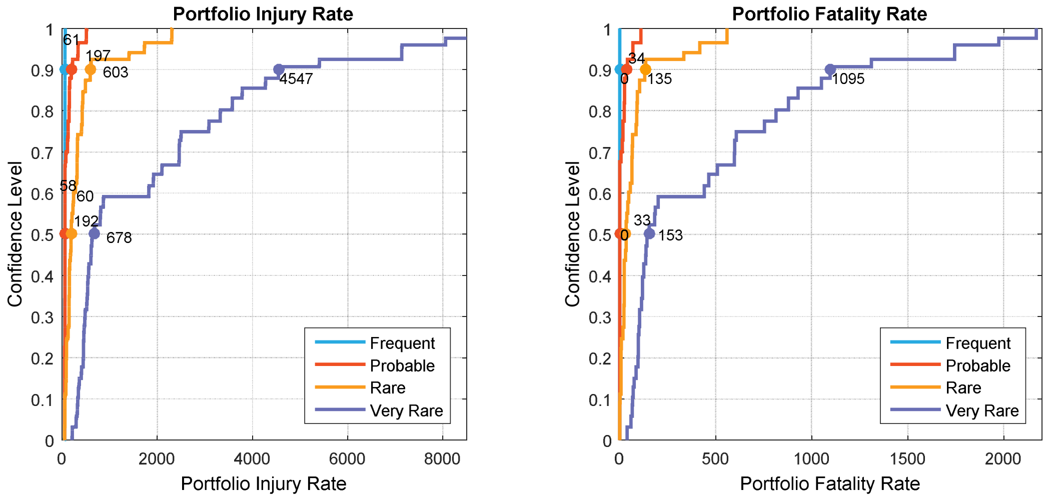

Figure I2 Indoor casualty rate in each earthquake event

It is important to note that there is a large degree of uncertainty in estimating casualties due to earthquake-related building damage. The range of casualties estimated for each return period earthquake is roughly an order of magnitude. See Appendix C for assumptions regarding casualty estimates.

I2.3 Repair Costs

The direct financial loss due to the cost of building repairs for the entire portfolio is shown in Figure I3. For reference, the total replacement cost considered for the building portfolio is just over $6.5 billion 2017 CAD. This corresponds to a best estimate percent loss of roughly 1%, 5%, 12%, and 40% for the Frequent, Probable, Rare, and Very Rare earthquakes respectively.

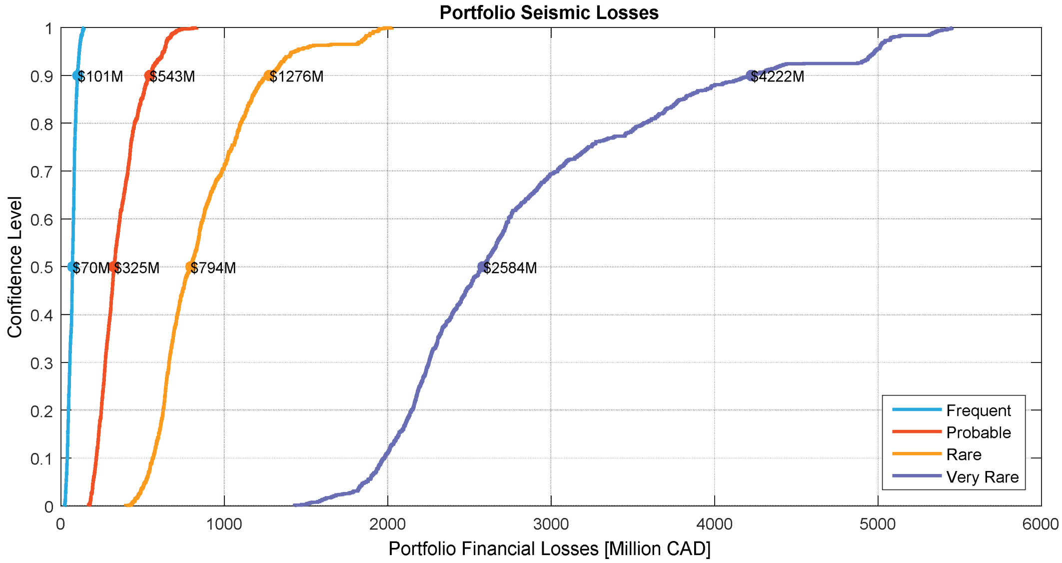

Figure I3 Portfolio direct financial loss due to building repairs in each earthquake event

The repair cost was also separated out for each of the insurance policies in Figure I4. For reference, the total replacement cost for 'core academic' buildings is about $4.8B 2017 CAD and for 'optional' buildings is about $1.8B 2017 CAD. The best estimate for percent loss of these building stocks is between 35-45% in the Very Rare earthquake.

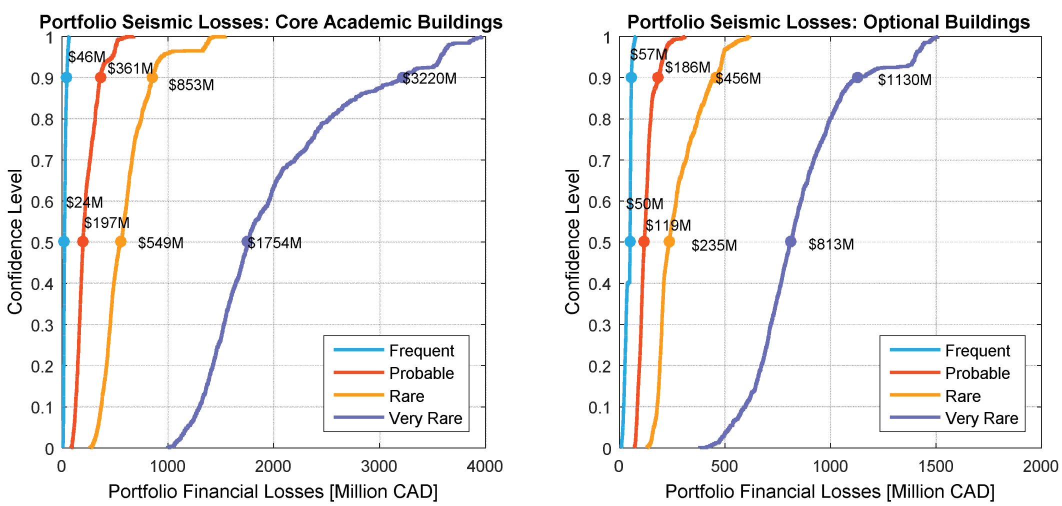

Figure I4 Portfolio direct financial loss in each earthquake event, separated by insurance policy

I2.4 Building Downtime

In this study, both "repair time" (i.e. duration of building repairs) and "downtime" (i.e. total duration of building recovery time due to both building repairs and delays to those repairs) is assessed. The median restoration times until functional recovery for various building occupancy categories on campus. For residential structures, the median restoration time is also reported to give an idea of when campus-residing students may shelter-in-place. These restoration curves are shown for each earthquake intensity level in Figure I5 through Figure I8. A cap of 48 months was assumed for all buildings. In addition, it was assumed that it would take typically 3-5 days for post-earthquake inspection regardless of damage in the building.

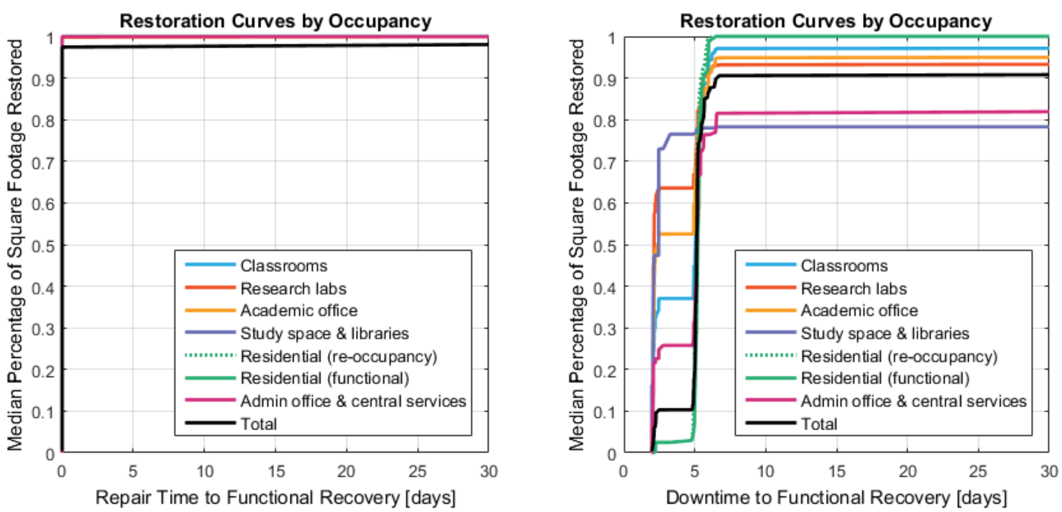

Figure I5 Median repair time and downtime following the frequent earthquake event

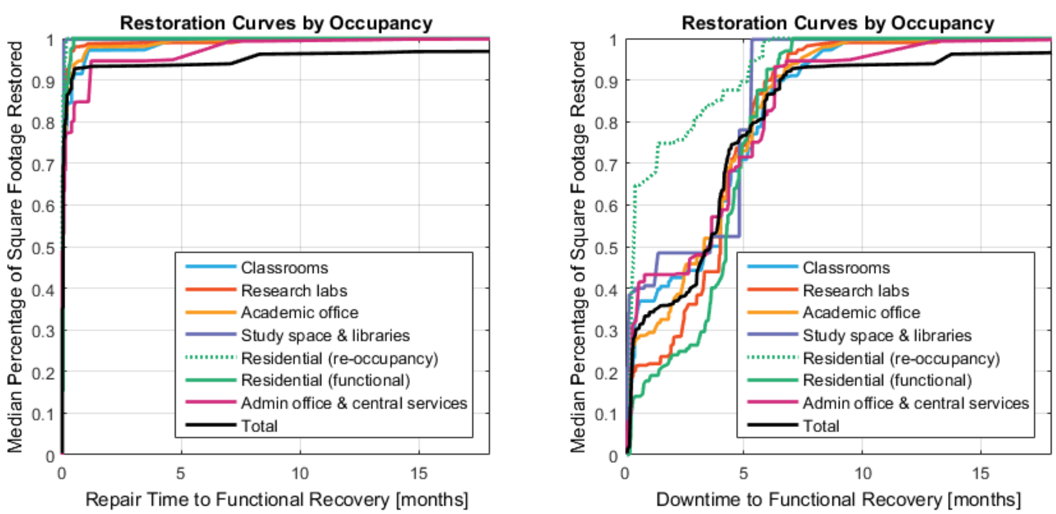

Figure I6 Median repair time and downtime following the probable earthquake event

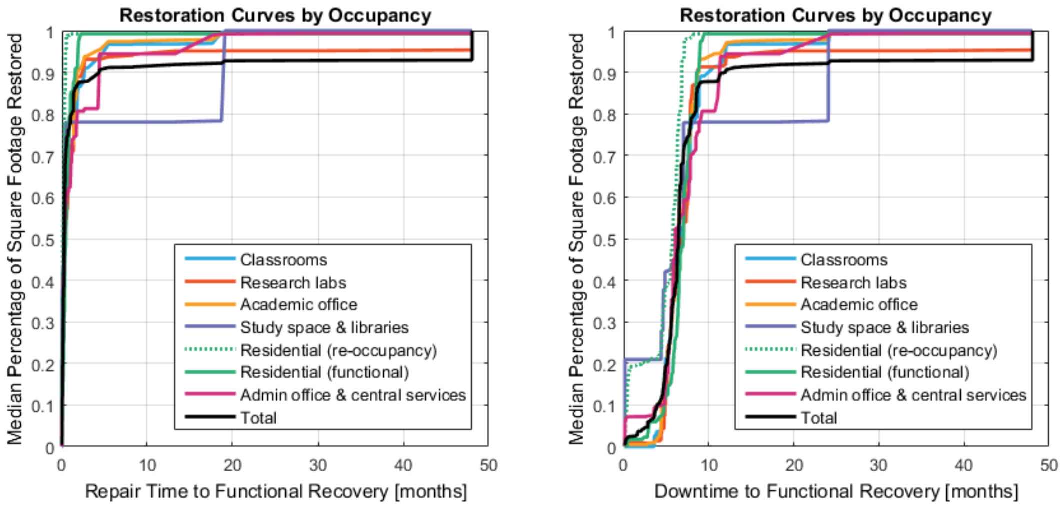

Figure I7 Median repair time and downtime following the rare earthquake event

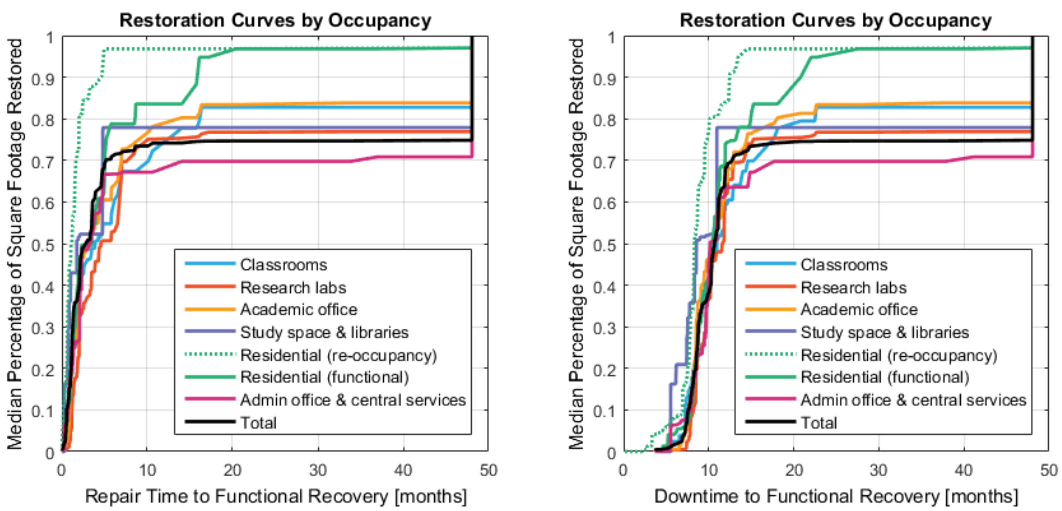

Figure I8 Median repair time and downtime following the very rare earthquake event

The repair time for each building in the Rare earthquake event is deaggregated in Figure I9 and Figure I20. From this, we see that although concrete wall structures are less collapse-prone, they can still result in significant recovery time. Even concrete wall structures designed to modern building codes can result in over 6 months of recovery time due to building repairs alone.

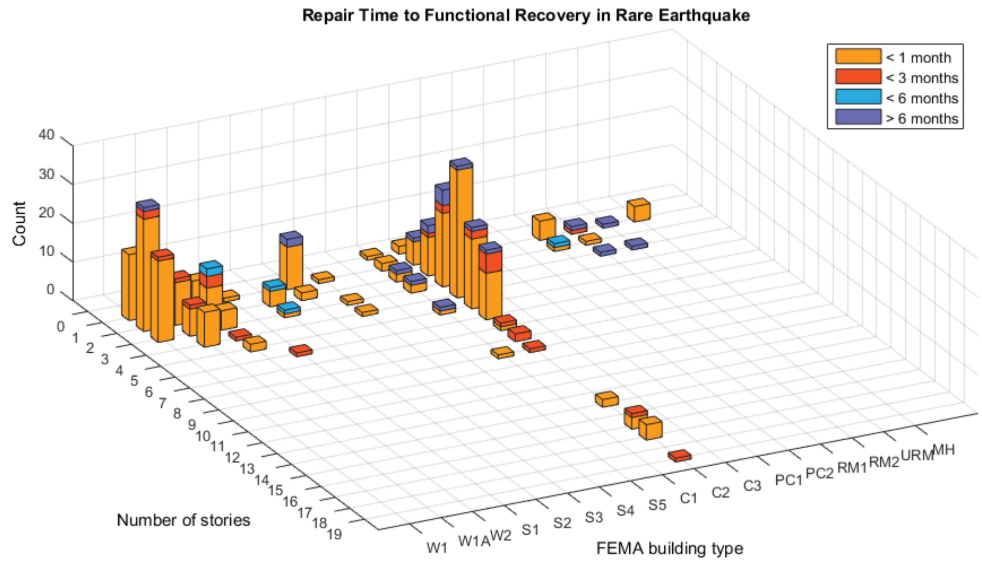

Figure I9 Deaggregation of repair time in the Rare earthquake by building height and structure type

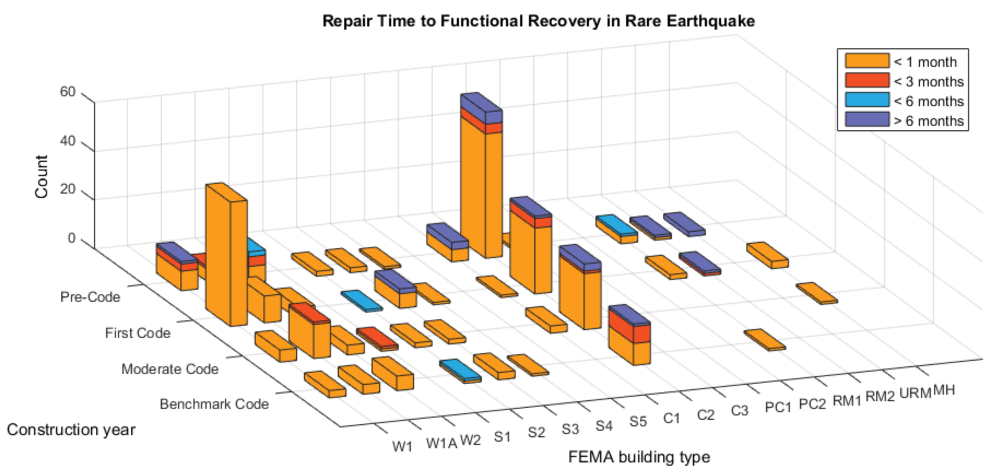

Figure I20 Deaggregation of repair time in the Rare earthquake by code year and structure type

I2.5 Component Damage

Since the risk assessment is performed at the component-level, the component damage can be deaggregated for a given earthquake intensity level. The components driving life safety and functionality concerns are shown in Figure I31 and Figure I42 for the Rare earthquake and in Figure I53 and Figure I64 for the Very Rare earthquake.

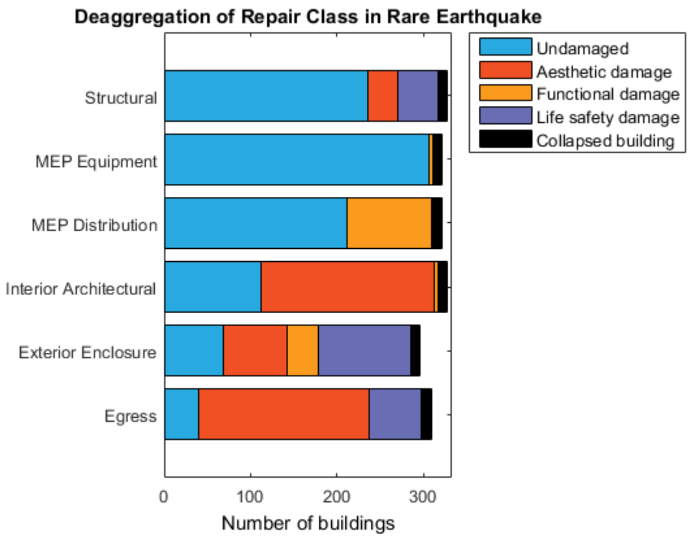

Figure I31 Coarse deaggregation of component damage in the rare earthquake event

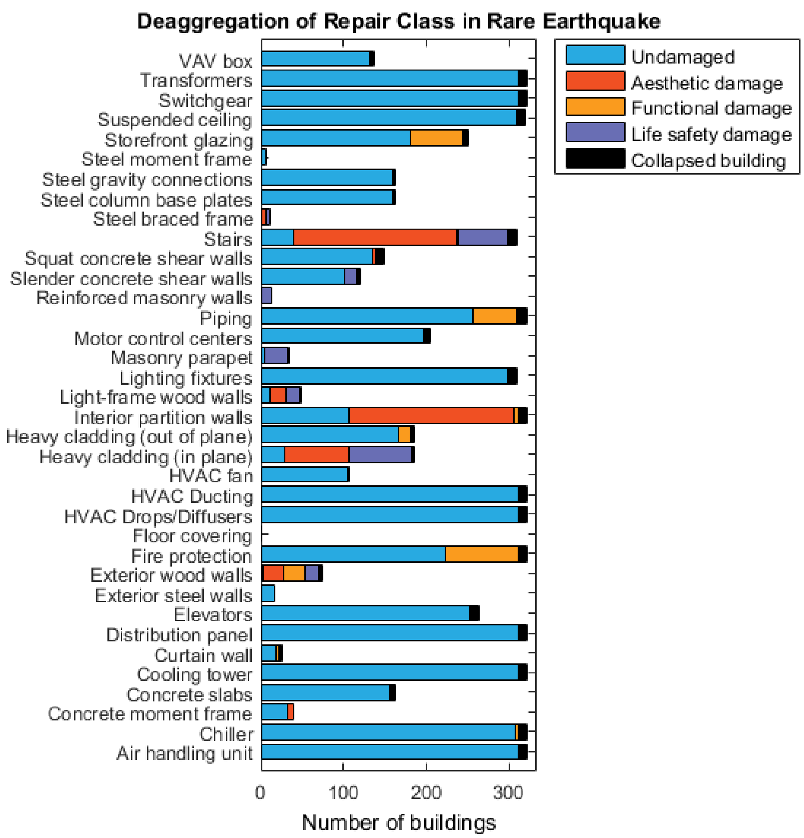

Figure I42 Detailed deaggregation of component damage in the rare earthquake event

In the Rare earthquake, heavy cladding and stairs are the most common cause of life safety concerns. Where it exists, masonry parapets or walls also cause frequent life safety issues. Functionality is commonly hindered by storefront glazing, exterior wood walls, and piping.

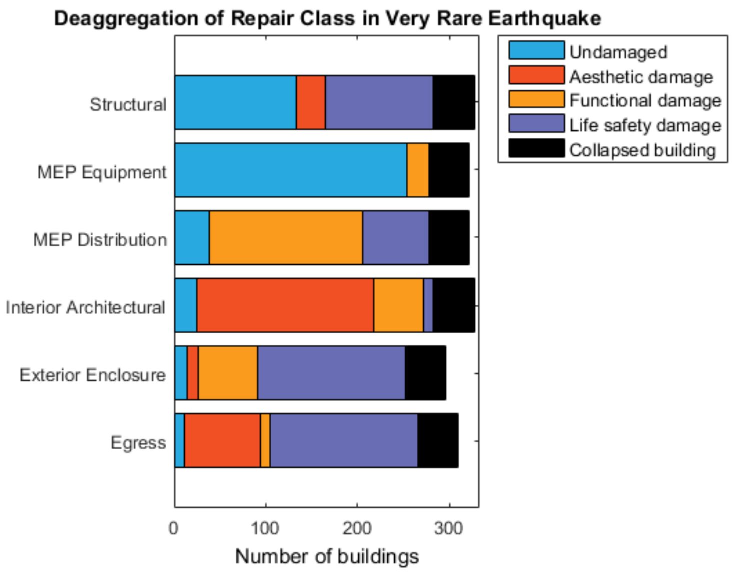

Figure I53 Coarse deaggregation of component damage in the very rare earthquake event

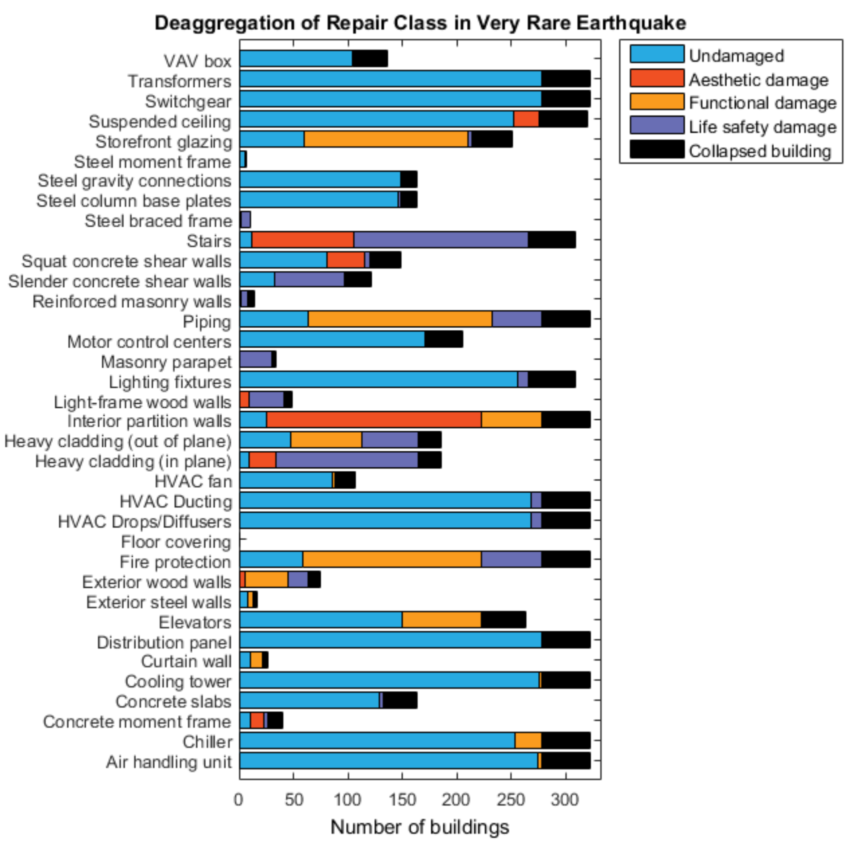

Figure I64 Detailed deaggregation of component damage in the very rare earthquake event

In the Very Rare earthquake, heavy cladding and stairs continue to drive life safety concerns. At this intensity level, slender concrete walls also frequently pose life safety risk. Functionality issues due to storefront glazing, piping, and elevators are also rampant.

I2.6 Contents Losses

The direct financial loss due to contents damage is assessed, although in a more qualitative manner than the cost due to building repairs. The results are presented in Figure I75. For low-intensity events, the contents losses are modest, but at higher intensity levels the contents losses can rival that of building repair losses. For structures that have highly valuable contents such as laboratories, the contents losses can be well beyond that of the building repairs.

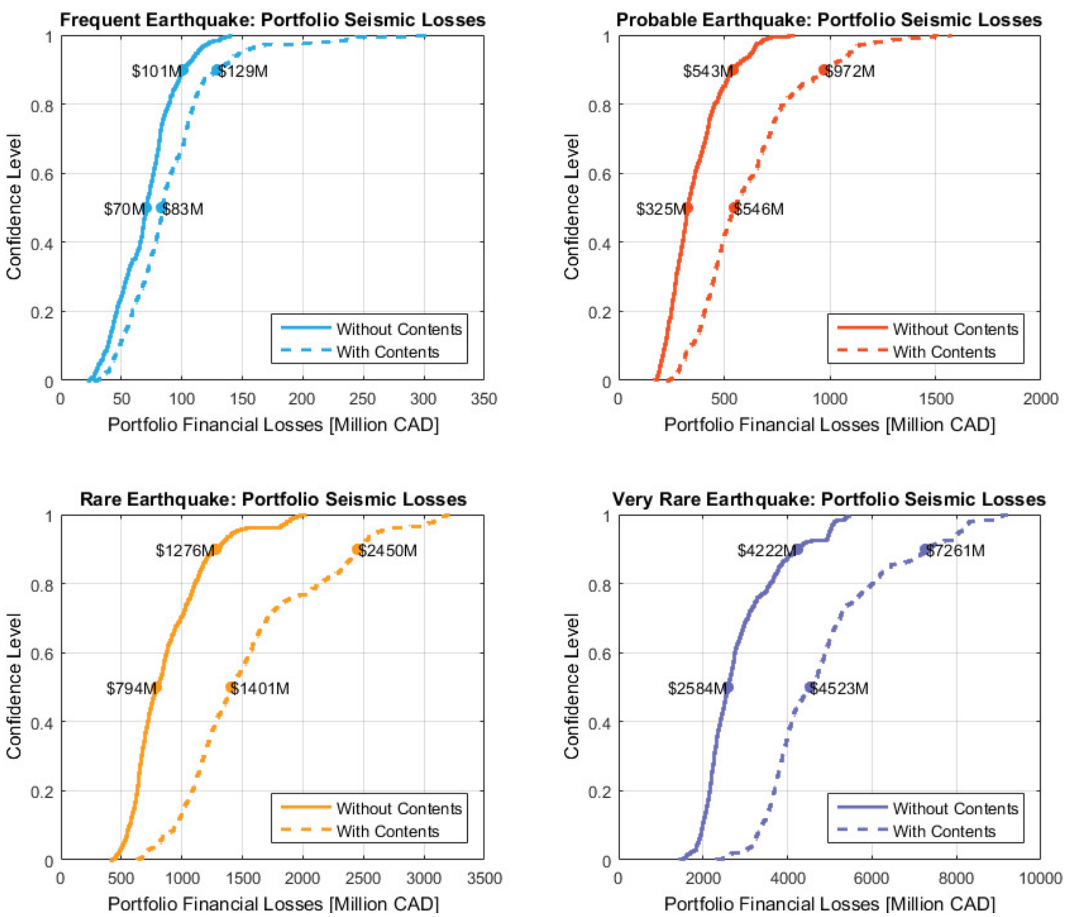

Figure I75 Portfolio direct financial loss with and without contents modeled in each earthquake event

Appendix K

Seismic Risk Assessment of Nonstructural Components and Contents, Conceptual Mitigations, and Costs

Appendix L

Seismic Risk Assessment of Utilities

L1 Introduction

In overview, this appendix presents an expanded seismic assessment of five utility systems on campus: electric power, water, natural gas, thermal energy, and sanitary sewer. It begins by providing an overview of each utility system. Next it describes the modeling framework developed for predicting utility restoration times after an earthquake and presents expected restoration times for each system in its current configuration. It then describes several conceptual mitigation strategies for improving the seismic performance of utility systems and the impact of each strategy on expected restoration times. Recommended mitigation measures for utilities are provided in section 8 of the main report.

L2 Description of Campus Utility Systems

The following subsections describe the current configuration of each utility system, including transmission to campus, critical facilities and equipment, distribution systems, dependence on other campus utility systems, and backup systems. It also identifies key vulnerabilities and ongoing mitigation activities, if any.

L2.1 Electric Power

Electric power is an especially critical utility system as it supports a large number of vital functions and services on campus. In particular, electric power supports other campus utility systems in the following ways:

- *Water*: At the Power House, electricity powers water pumps and other equipment that maintain adequate pressure for water service to most campus buildings for domestic and firefighting purposes.
- *Thermal Energy*: At the Campus Energy Centre, electricity powers water pumps, control systems, and other equipment that distribute hot water to most campus buildings for heating purposes.
- *Sanitary Sewer*: At several lift stations, electricity powers water pumps that move wastewater to collection points at the north and south ends of campus.

In addition, electric power supports the following functions in campus buildings:

- Lighting
- Elevators
- Emergency exit signage
- Heating, ventilation, and air conditioning (HVAC) equipment

- Plug loads, including refrigeration, laboratory equipment, computers, servers, etc.

L2.1.1 Current System Configuration

Figure L.1 provides an overview of the current electric power utility system on campus. The following subsections describe different aspects of the system, including:

- L2.1.1.1: How electricity is delivered to campus
- L2.1.1.2: Facilities and equipment on campus that have critical roles in supporting electric power service
- L2.1.1.3: Distribution systems that deliver electricity to end users
- L2.1.1.4: Dependence on other campus utility systems
- L2.1.1.5: Backup systems that can be called upon in case of disruption to normal service
- L2.1.1.6: Crew sizes and operational procedures for responding to disruptions

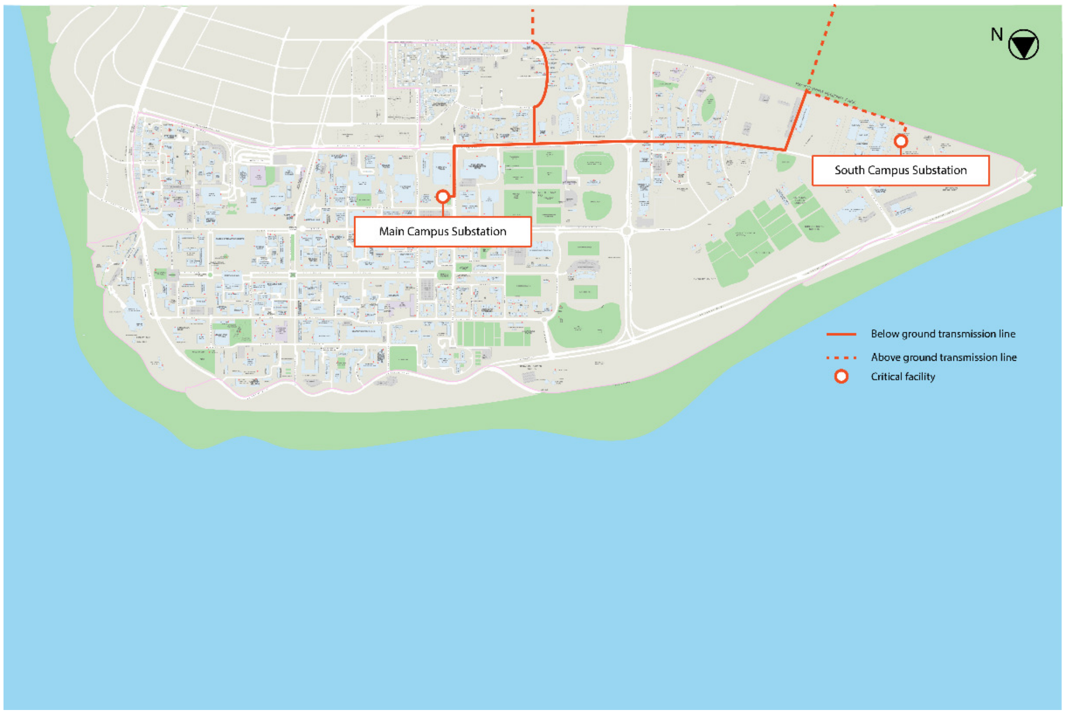

Figure L.1 Transmission lines, critical facilities, and interdependencies for the electric power system

L2.1.1.1 Transmission to Campus

UBC obtains electric power from BC Hydro via two 69 kV transmission lines that originate at the Sperling Substation approximately 7 km east of campus. From there, both lines run underground for 3.5 km to the Camosun Substation on the east side of Pacific Spirit Regional Park, where they split and go above ground through the park. Once they get to campus, both transmission lines go back underground (see Figure L.1). Together, both lines can deliver 55 MW of power.

L2.1.1.2 Critical Campus Facilities and Equipment

UBC owns and maintains two substations on campus, one next to the Campus Energy Centre (i.e., UNY, the main substation) and one at the southern edge of campus (i.e., UNS, the south campus substation) (see Figure L.1). The main substation powers a significant portion of campus buildings, while the south campus substation powers TRIUMF and other south campus buildings. UBC plans to connect all south campus buildings except TRIUMF to the main substation and has begun putting the necessary infrastructure in place. When complete, the south campus substation will power only TRIUMF. Because these research facilities are beyond the project scope, the remainder of this section focuses on the main substation.

The main substation can be powered by either of the two transmission lines from BC Hydro, so there is redundancy if one of the transmission lines were to fail.

However, if there is a failure at Camosun Substation or somewhere further upstream, UBC likely will lose complete service.

In terms of equipment, there are two 46.7 MVA transformers in the main substation yard (see Figure L.2). Given current campus energy demands, one transformer can power the entire campus, meaning there is redundancy in the system if one were to fail or needed to be serviced. The transformers were installed in 1983 and have a typical operating life of 30-40 years, but are expected to have a longer service life due to their light operating load. The transformers are anchored to a concrete pad; however, we were unable to observe anchorage details because the transformers were in operation. If one of the transformers were damaged in an earthquake, it is unlikely that it could be fixed onsite by campus staff. Staff anticipate it could take 6-24 months to service a damaged transformer, and $1-2 million CAD to replace.

Figure L.2 One of the two 46.7 MVA transformer at the main campus substation

Also in the yard is various protective equipment (insulators, breakers, switches, etc.) that is vulnerable to earthquake shaking, though some overhead lines have flexible detailing to accommodate differential displacement. These flexible connections were installed in 1999. Any protective equipment that gets damaged would likely take time to repair and/or replace as the parts typically cannot be obtained off the shelf by UBC staff. However, staff indicated that damage to protective equipment would not necessarily render the electrical system nonfunctional (i.e., they would still keep the power on at the risk of damaging the transformers).

There is a single story building at the main substation that houses switchgear for 14 feeders (distribution circuits) that deliver power to clusters of buildings throughout campus. There are also three standby feeders that provide secondary pathways to deliver power to all campus buildings (i.e., there are two different lines to every building). The electrical switchgear is welded to steel rails in the floor; however, the weld capacity was not checked. The switchgear was installed in 1972 and will likely be replaced in the next 5 years. If one of the 14 normal feeders was damaged staff could use parts from the standby feeders as a temporary fix.

L2.1.1.3 Campus Distribution System

The main substation distribution network is a dual redundant system that distributes power to campus buildings at 12.5 kV via 10 km of underground duct banks, which are PVC pipes encased in concrete to protect them from accidental damage caused by excavation equipment. Typically, there are between six and nine PVC pipes in a duct bank; approximately 50% of them are empty in anticipation of future cabling needs. A network of regularly spaced manholes (typically 2m x 3m in plan) allow two workers to perform maintenance and/or install new cables.

As mention previously, the main substation distribution network comprises 14 normal feeders that support different clusters of buildings on campus. There are also three standby feeders that can be used to deliver power to buildings if a normal feeder were to fail. Each standby feeder supports approximately 6 normal feeders; however, in the event that two normal feeders need to be connected to a single standby feeder, a detailed load analysis would need to be performed.

L2.1.1.4 Dependence on Other Campus Utility Systems

Electrical power does not rely on other campus utilities to provide service.

L2.1.1.5 Backup Systems

Currently, UBC has limited onsite power generating capabilities in the event of a loss of supply from BC Hydro. The Bioenergy Research Demonstration Facility (BRDF) can generate 2 MW of electricity, but it is not supposed to run if BC Hydro is down. The typical campus load is 35 MW, so the BRDF would be not be able to meet the demand even if it were able to run.

UBC also maintains and operates an extensive network of backup generators on campus. There are approximately 65 generators, most of which are diesel, though a few are gasoline or propane. These generators support approximately 50 buildings, providing electricity to power emergency exit signage and lighting in the event of an outage. Certain facilities, however, support critical research that could be impacted significantly in the event of a power outage. UBC has identified 14 such facilities. For these buildings, the backup generator supports additional loads (e.g., freezers, etc.).

L2.1.1.6 Operational Procedures and Crew Size

There are six high voltage workers capable of making repairs to the distribution network who are on site Monday through Friday. BC Hydro performs routine maintenance on the transmission lines that feed into campus 4-5 times per year, so campus staff have relatively frequent experience dealing with rerouting issues.

L2.1.2 Key Vulnerabilities

Our review of the current configuration of the electric power system has identified the following vulnerabilities.

- Transmission lines through Pacific Spirit Regional Park are aboveground and are vulnerable to falling trees and wildfire from dry brush beneath the lines.
- Though campus electrical infrastructure has redundancy, the two main transmission lines through Pacific Spirit Regional Park originate from the same substation off campus, which makes the university vulnerable to complete loss of power if there is an issue at the substation.
- Important electrical equipment at the main substation, including the two 46.7 MVA transformers in the yard and switchgear in the substation building, were installed 30-40 years ago, meaning they are not likely to be seismically qualified. Therefore, they could be more vulnerable to damage in an earthquake than newer equipment. Furthermore, the anchorage of electrical equipment was likely upgraded to satisfy the 1995 National Building Code of Canada; however, anchorage requirements have changed significantly since then. Consequently, the electrical equipment is more vulnerable to anchorage failure and toppling than newer equipment. This is especially important given the long lead times in repairing and/or replacing equipment.
- Though campus has an extensive network of backup generators, UBC has limited onsite diesel fuel storage capabilities. In the aftermath of a major earthquake, transportation systems are likely to be disrupted, meaning that diesel fuel resupply might not be possible.

L2.1.3 Ongoing Mitigation

In addition to maintaining standard inventories of parts and performing routine maintenance of electrical equipment and backup generators, UBC is pursuing or planning to pursue the following mitigation activities. Unless explicitly stated otherwise, these activities have not been considered in our model of the electric power system (described in Section L3).

- UBC is currently switching all south campus buildings except TRIUMF from the south campus substation to the main substation, which might increase the reliability of power service at those buildings. This activity has been accounted for in our model of the electric power system.
- UBC is planning to purchase a third transformer for the main substation to address future power needs. While this transformer will not increase the redundancy of the system per se, if the equipment is seismically rated with anchorage that meets current seismic standards, it will decrease the likelihood a power outage after an earthquake.
- UBC is considering constructing an 18 MW cogeneration facility adjacent to the Campus Energy Centre to increase its onsite generating capabilities.
- UBC is considering constructing a 400,000 L diesel tank farm in south campus to provide 2-4 days of fuel for backup generators. The anticipated cost of this measure is $750,000 CAD.

L2.2 Water

UBC requires water for a variety of important uses, including drinking, cleaning, sanitation, cooking, firefighting, irrigation, equipment cooling, and research applications. It is important to note upfront that there is no auxiliary water distribution system for firefighting purposes.

L2.2.1 Current System Configuration

Figure L.3 provides an overview of the current electric power utility system on campus. The following subsections describe different aspects of the system, including:

- L2.2.1.1: How water is delivered to campus
- L2.2.1.2: Facilities and equipment on campus that have critical roles in supporting water service
- L2.2.1.3: Distribution systems that deliver water to end users
- L2.2.1.4: Dependence on other campus utility systems
- L2.2.1.5: Backup systems that can be called upon in case of disruption to normal service
- L2.2.1.6: Crew sizes and operational procedures for responding to disruptions

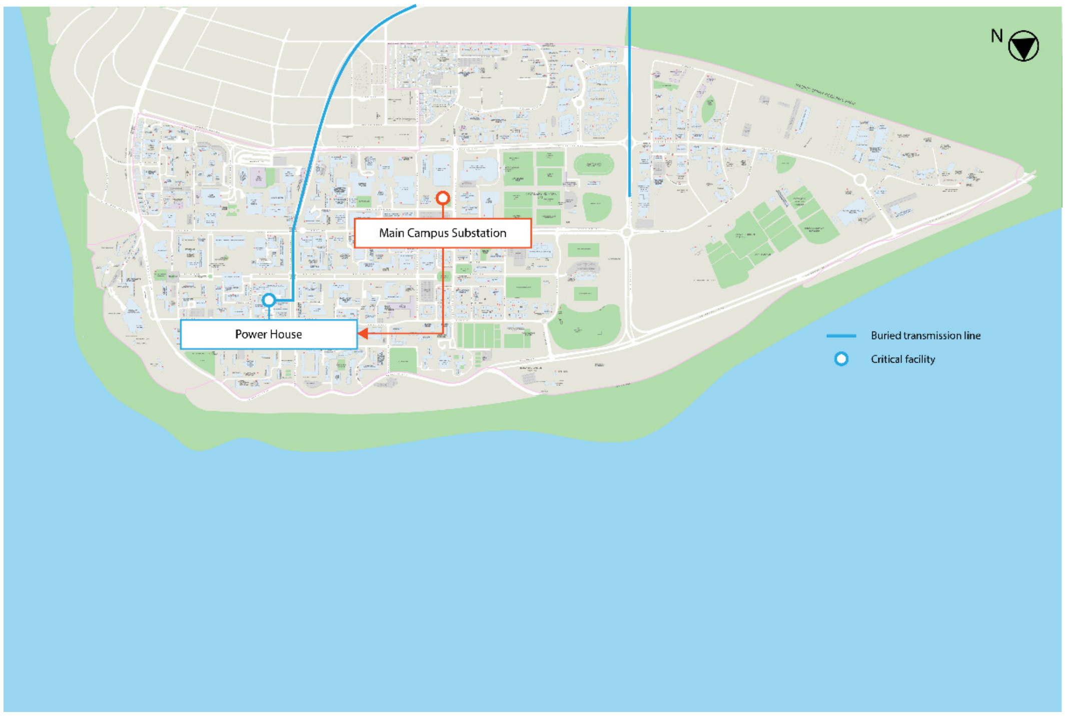

Figure L.3 Transmission lines, critical facilities, and interdependencies for the water system

L2.2.1.1 Transmission to Campus

UBC obtains water from Metro Vancouver via two underground transmission lines that both originate at the Sasamat Reservoir, an underground concrete storage tank approximately 1.5 km east of campus in Pacific Spirit Regional Park. The Sasamat Reservoir is fed primarily by the Capilano and Seymour reservoirs to the north of Vancouver. From the Sasamat Reservoir, a single transmission line runs towards campus along West 16th Avenue before splitting into two separate lines. One branch, a 24-inch ductile steel main, enters campus at University Boulevard, while the second, a 16-inch asbestos cement main, enters at West 16th Avenue.

L2.2.1.2 Critical Campus Facilities and Equipment

The 24-inch water main runs directly to the Power House, where a set of pumps pressurize the water and distribute it to all academic buildings and student residences. This high pressure zone covers approximately 80% of campus. Consequently, the pumping station at the Power House plays a critical role in distributing water to campus buildings. It increases the pressure to 100 psi, primarily for the purposes of firefighting and to provide water in tall buildings. The 24-inch water main enters the facility below grade and splits before flowing into two sets of parallel pumps. The first set comprises three electric pumps at the north end of the Power House in a side room near grade (referred to as the “concrete bunker”). The second set comprises two diesel pumps in the basement adjacent to (but not inside) the “concrete bunker.” Typically, only one of the three electric pumps is in service, meaning there is redundancy if one were to fail. In the event of a fire on campus, additional pumps can be switched on to maintain adequate pressure for firefighting. In the event of a power outage, the diesel pumps can be used as backup, drawing fuel from a three nearby underground diesel tanks that currently hold approximately 300,000L.

Electrical equipment (e.g., transformers, switchgear, distribution panels, etc.) is housed in a room at the south end of the Power House in the basement. There is also some electrical equipment in the “concrete bunker.”

L2.2.1.3 Campus Distribution System

Campus distribution systems are divided into two zones: a high pressure zone fed by the pumping station at the Power House and a low pressure zone fed directly by the 16-inch main under West 16th Avenue. The high pressure zone supplies water to all academic buildings and student residences, while the low pressure zone supplies water to residential buildings in the University neighborhoods and the Lower Mall. There are seven pressure reducing stations on campus that allow water to pass from the high pressure to the low pressure zone, meaning there is some redundancy in the system in the low pressure zone if the 16-inch main were to go down. Pressure reducing stations are inspected every month and do not require electricity to function.

There is approximately 54 km of underground water distribution mains on campus. These pipes are a mix of different materials, including ductile iron, steel, PVC, cast iron, and asbestos cement. Staff estimates that approximately 20% of distribution pipes are cast iron, which tend to be clustered near older buildings. Furthermore, most building services pipes (i.e., the lines from the main to the building) are cast iron. Cast iron pipes are problematic because they have performed poorly in recent earthquakes.

The distribution system features a network of valves that allow damaged sections of pipe to be quickly isolated, helping limit the extent of service disruptions while repairs are made. There is also a campus wide backflow prevention program that protects the water supply from potential contamination.

Water for firefighting is delivered via the same distribution network as potable water, with 420 hydrants located throughout campus.

L2.2.1.4 Dependence on Other Campus Utility Systems

The pumping station at the Power House has a critical dependence on electric power, as the three primary water pumps require electricity to operate. This dependence is captured in Figure L.3. In the event of an outage, backup water pumps that run on diesel can maintain water pressure until the 300,000 L diesel tank is depleted. Once the diesel reserves are depleted, however, water service to

80% of campus buildings will be disrupted, which will also hamper the ability to fight fires.

L2.2.1.5 Backup Systems

Currently, UBC has limited ability to mitigate the impact of a loss of municipal water supply. In terms of onsite water storage, UBC lacks the necessary infrastructure for storing water on campus in quantities sufficient to meet normal demand. In terms of alternative sources of water, the university recently implemented an emergency water purification system near the Botanical Gardens that is capable of producing up to 100,000 L of water a day. UBC is currently developing a strategy for distributing water pumped at this facility to other parts of campus. Normal campus water consumption is approximately 12 million liters per day, so the emergency purification system would be able to meet less than 1% of normal campus demand.

L2.2.1.6 Operational Procedures and Crew Size

There is a crew of six workers for responding to leaks in the water distribution network. This crew is also responsible for making repairs to natural gas and sanitary sewer distribution networks. Currently there is no welder on staff, so any such work is contracted out to specialists. Similarly, UBC contracts its excavation work out to third party companies. Consequently, after a major earthquake, UBC may be unable to restore water service without the assistance of third party contractors.

L2.2.2 Key Vulnerabilities

Our review of the current configuration of the water system has identified the following vulnerabilities.

- Following a major earthquake, the municipal water supply could be disrupted for several weeks (possibly due to the vulnerabilities described in the next two paragraphs, or possibly due to issues further upstream). Currently, UBC has limited capability to mitigate a protracted disruption of municipal water supply. Immediately after an earthquake, loss of offsite supply would seriously hamper firefighting capabilities. In the longer term, lack of water could impact student housing, critical research, and other day-to-day operations.
- UBC obtains its water from Sasamat Reservoir, a buried concrete tank in Pacific Spirit Regional Park. While details of the reservoir are unknown, a conversation between UBC staff and Metro Vancouver revealed that it has never been seismically upgraded. If the reservoir were to fail it could disrupt the campus water supply.
- The two main transmission lines from the Sasamat Reservoir pass through land maintained by University Endowment Lands, a jurisdiction that has

limited resources and may struggle to repair damaged sections of water main after an earthquake.

- Critical water pumping infrastructure is located within the Power House, a building that is a significant collapse hazard in an earthquake. Even if it does not collapse, extensive structural damage could damage critical equipment and/or trigger a red tag, which would restrict access to the building and likely disrupt water service to most of campus and also hamper firefighting capabilities.
- When the 24-inch water main enters the Power House, it splits and flows to two sets of pumps (as described previously). The section of pipe that feeds the diesel pumps is brittle cast iron, which will likely perform poorly in an earthquake. Because there are no valves for isolating this section of pipe, a break in the cast iron section would depressurize the electric pumps, rendering the entire system nonfunctional.
- The Power House "substation" (i.e., transformers and switchgear that distribute power to electrical equipment in the Power House) is located in the basement, making it vulnerable to water damage in the event of a pipe break that causes a flood. In addition, there is also sensitive electrical equipment in the "concrete bunker" that could be damaged if a leak developed in one of the electric water pumps.
- Significant portions of the water distribution system are cast iron or asbestos cement pipe, which in recent earthquakes have proven to be more vulnerable to breaking than ductile iron, steel, and PVC pipes. While these breaks can be isolated to minimize their impact, they will take time to repair.
- Though it has been mentioned in previous paragraphs, it is worth repeating that UBC's firefighting infrastructure is especially vulnerable to earthquakes. Because there is no auxiliary water system on campus, a loss of municipal supply or damage to the Power House would render firefighting infrastructure nonfunctional. While there is a fire station on campus with two trucks, they will respond to calls as needed, meaning they could potentially be called off campus to deal with large fires after an earthquake. Even if they are available to respond to fires on campus, it is uncertain that hydrants would be functional.

L2.2.3 Ongoing Mitigation

UBC staff is acutely aware of the vulnerabilities described in the previous section and are currently pursuing or planning to pursue the following mitigation activities. Unless explicitly stated otherwise, these activities have not been considered in our model of the campus water system (described in Section L3).

- UBC is currently replacing approximately 200-500 m of cast iron pipe per year at a cost of approximately $1,000 CAD per meter.

- UBC plans to decommission the diesel water pumps in the Power House by June 2017. This task will involve installing a new backup diesel generator to power the three electric water pumps in the event of an electrical outage. It will also involve removing the brittle sections of cast iron pipe that feed the backup diesel water pumps. We have included this mitigation activity in our network model.
- UBC is currently formulating a broader mitigation strategy for the Power House (i.e., demolition or renewal).
- Metro Vancouver is planning to conduct an assessment of the Sasamat Reservoir in 2019 and perform seismic upgrades afterwards.

L2.3 Natural Gas

UBC requires natural gas for a variety of uses, the most important of which is the boilers at the Campus Energy Centre that produce hot water for the thermal energy system. See Section L2.4 for a detailed discussion of the thermal energy system. The UBC Hospital is another critical user of natural gas, primarily for heating because the hospital is not tied into the thermal energy system. UBC also uses natural gas for cooking, research applications, and building equipment.

L2.3.1 Current System Configuration

Figure L.4 provides an overview of the current natural gas utility system on campus. The following subsections describe different aspects of the system, including:

- L2.3.1.1: How natural gas is delivered to campus
- L2.3.1.2: Facilities and equipment on campus that have critical roles in supporting natural gas service
- L2.3.1.3: Distribution systems that deliver natural gas to end users
- L2.3.1.4: Dependence on other campus utility systems
- L2.3.1.5: Backup systems that can be called upon in case of disruption to normal service
- L2.3.1.6: Crew sizes and operational procedures for responding to disruptions

Figure L.4 Transmission lines, critical facilities, and interdependencies for the natural gas system

L2.3.1.1 Transmission to Campus

UBC receives natural gas from Fortis BC via three uninterruptible transmission lines (see Figure L.4). The primary line is a 12-inch main that runs under University Boulevard to a pressure reducing station outside the Power House. Branches from this 12-inch main feed the hospital, the University Endowment Lands housing areas, and the Campus Energy Centre. The branch to the Energy Centre is interruptible, meaning that in exchange for a lower gas price the supply can be disrupted periodically. The second transmission line is in the southern part of campus under West 16th Avenue, while the third line runs along Chancellor Boulevard in the northern part of campus. While all three of these mains are cross-connected, loss of the 12-inch main would disrupt the thermal energy system and impact service throughout most of campus. Loss of the other two lines, on the other hand, would have no visible impact on gas service.

L2.3.1.2 Critical Campus Facilities and Equipment

There are four pressure reducing stations on campus, including one adjacent to the Power House that handles 50% of UBC’s gas supply and one outside the Campus Energy Centre (see Figure L.5). These stations on campus are outdoors and consist of a series of pipes, valves, gauges, and regulators that reduce the incoming transmission line pressure from 100 to 15 PSIG for distribution purposes. These stations do not depend on electricity to remain functional and have proven in recent earthquakes to be rugged.

Figure L.5 Pressure reducing station at the Campus Energy Centre

L2.3.1.3 Campus Distribution System

The gas distribution system on campus comprises approximately 43 km of buried pipe, of which half is steel and half is high density polyethylene (HDPE). The distribution system features a network of valves that allow damaged sections of pipe to be quickly isolated, helping limit the extent of service disruptions while repairs are made. All campus buildings have been retrofitted with an automatic seismic shutoff valve, which will trip if the peak ground acceleration exceeds 0.11g during an earthquake. These devices help prevent fires caused by broken gas lines within damaged buildings. After an earthquake, the shut off valves would need to be reset manually, but not before pressure testing the gas lines in the building for leaks, which would take between 2 and 4 hours per building (assuming no leaks are detected).

In addition to the distribution network owned and maintained by UBC, Fortis BC also owns, services, and maintains an independent distribution system that supplies the Wesbrook neighborhood in the South Campus area. Relighting this neighborhood could be more challenging because of Fortis BC's larger service area. This distribution system, however, is beyond the scope of this assessment.

L2.3.1.4 Dependence on Other Campus Utility Systems

Natural gas does not rely on other campus utilities to provide service.

L2.3.1.5 Backup Systems

Currently, UBC has limited capability to mitigate the impact of a loss of municipal gas supply. In terms of onsite storage, UBC lacks the necessary infrastructure for storing natural gas on campus in quantities sufficient to meet normal demand. In terms of alternative sources of gas, UBC can substitute diesel fuel for natural gas in certain instances. For example, the boilers at the Campus Energy Centre are dual fuel, meaning they can run on either natural gas or diesel.

L2.3.1.6 Operational Procedures and Crew Size

UBC has a crew of six workers to maintain the natural gas system, however, this crew is also responsible for maintaining the water and sanitary sewer systems. Currently there is no welder on staff, so any such work is contracted out to specialists. Similarly, UBC contracts its excavation work out to third party companies. Consequently, after a major earthquake, UBC may be unable to restore water service without the assistance of third party contractors.

L2.3.2 Key Vulnerabilities

Our review of the current configuration of the natural gas system has identified the following vulnerabilities.

- Following a major earthquake, the municipal gas supply could be disrupted for several weeks. Currently, UBC has limited capability to mitigate a protracted disruption of municipal gas supply, which could significantly impact the functionality of the thermal energy system, which can run for approximately 12 hours on its current supply of diesel.
- While the automatic seismic shutoff values decrease the likelihood of earthquake induced fires, the process for restoring gas service to an individual building is expected to take at least 2-4 hours if no leaks are detected. When this number is aggregated across the entire building stock, it could take several weeks to restore gas service to all buildings on campus.

L2.3.3 Ongoing Mitigation

Aside from routine testing of valves and pipes for leaks, we are unaware of any additional mitigation activities that UBC is currently pursuing or planning to pursue.

L2.4 Thermal Energy

UBC requires thermal energy primarily for the purposes of heating campus buildings and producing domestic hot water. In the winter, adequate heating is critical for continued occupancy of buildings.

L2.4.1 Current System Configuration

Figure L.6 provides an overview of the current thermal energy utility system on campus. The following subsections describe different aspects of the system, including:

- L2.4.1.1: How thermal energy is delivered to campus
- L2.4.1.2: Facilities and equipment on campus that have critical roles in supporting thermal energy service
- L2.4.1.3: Distribution systems that deliver thermal energy to end users
- L2.4.1.4: Dependence on other campus utility systems
- L2.4.1.5: Backup systems that can be called upon in case of disruption to normal service
- L2.4.1.6: Crew sizes and operational procedures for responding to disruptions

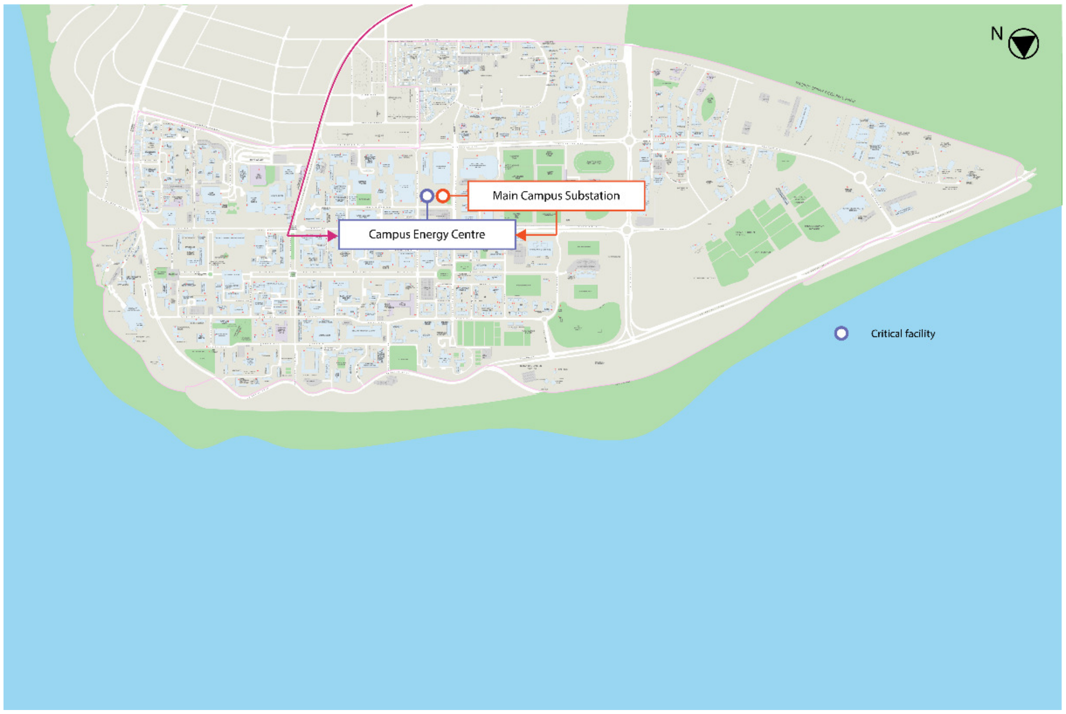

Figure L.6 Transmission lines, critical facilities, and interdependencies for the thermal energy system

L2.4.1.1 Transmission to Campus

The thermal energy system is a closed loop system, meaning that hot water supplied to buildings via buried distribution pipelines returns to the Campus Energy Centre to be reheated and redistributed. Therefore, unlike electric power, water, and natural gas, there are no transmission lines that feed campus.

L2.4.1.2 Critical Campus Facilities and Equipment

The Campus Energy Centre (CEC), which opened in November of 2015, is a state-of-the-art facility that provides thermal energy to approximately 115 buildings on campus. In overview, three 15 MW boilers produce hot water that is then pumped via an underground distribution system to individual buildings for the purposes of heating and domestic hot water. Buildings that are not connected to the thermal energy system have their own equipment for heating air and water.

The CEC is fed by a 10-inch steel gas line that branches directly from the 12-inch main under University Boulevard. The gas supply on this branch is interruptible, meaning that UBC pays a discounted unit rate for gas but there can be periodic service disruptions. The 10-inch line enters the CEC a few feet above grade through an oversized opening in the perimeter wall, meaning the connection can accommodate some differential displacement in an earthquake (note: the adequacy of the opening was not checked). There is also an automatic seismic shutoff valve.

Currently there are three 15 MW boilers on the ground floor of the CEC that heat water, with space to install a fourth to accommodate future campus needs (see Figure L.7). Because of the interruptible gas supply, the boilers are dual fuel, meaning they can be powered by either natural gas during normal operation or diesel fuel if natural gas is unavailable. Anchorage for the boilers and all equipment at the CEC has been designed for seismic forces; however, not all anchorage was readily visible during inspection and not all equipment anchorage was thoroughly inspected. In general, all new equipment installed on campus has anchorage designed for seismic forces, while equipment installed prior to 1970 is likely to be unanchored.

There are three electric distribution pumps adjacent to the boilers that provide the pressure necessary to deliver hot water to individual buildings (see Figure L.8). These distribution pumps do not need water for cooling. Typically only two pumps are running at any given time, one at 100% and the second at 50%, so there is redundancy in the system if a single pump failed. The pumps are anchored to a concrete pad that is vertically isolated from the ground floor. Drawings indicate that pipe connections to/from the distribution pumps (and also the boilers) are flexibly detailed. However, the pumps (and other equipment) have not been seismically qualified, meaning that their internal components could be damaged by strong earthquake shaking.

Figure L.7 15 MW boilers at the Campus Energy Centre

The operating temperature of the system ranges from 80-100°C, with temperature-related volume changes in water accommodated by four expansion tanks on the second floor of the CEC. These four tanks are pressurized by an adjacent air compressor. It is unclear, however, whether loss of the expansion tanks and/or air compressor would compromise the functionality of the system.

There is a room of electrical equipment adjacent to the distribution pumps. Equipment includes motor control systems equipment, plant control systems, distribution panels, and transformers. Outside the CEC there is a primary transformer that converts the 12 kV distribution line to 600 V. The CEC also has heat exchangers and other equipment that support HVAC and plumbing systems; however, failure of this equipment is unlikely to impact the functionality of the thermal energy system.

The Campus Energy Centre is staffed 24 hours a day, 7 days a week with at least one employee. There is a control room on the second floor with a bank of computers and monitors that monitor and control system performance, including real-time energy intake at individual buildings, though staff cannot remotely control the thermal intake of individual buildings.

Figure L.8 Distribution pumps at the Campus Energy Centre

L2.4.1.3 Campus Distribution System

The thermal energy distribution system comprises approximately 12 km of supply pipe and 12 km of return pipe, which is typically steel pipe laid on a bed of gravel before being buried. The distribution system features a network of valves that allow damaged sections of pipe to be quickly isolated, helping limit the extent of service disruptions while repairs are made. There is also a leak detection system that can remotely detect and locate leaks, placing it within one of seven different zones.

L2.4.1.4 Dependence on Other Campus Utility Systems

In general, the thermal energy system depends on electric power and natural gas to operate successfully. Electricity is required for water pumps, motor control systems, and computers at the CEC, while natural gas is required for the boilers. In the event of an electrical outage, however, the CEC has a 1 MW backup diesel generator that can power critical equipment, including one distribution pump, one boiler, and their control systems. Similarly, if there is a disruption to the supply of natural gas, the boilers at the CEC can run on diesel fuel. There is a 42,000 L above-ground diesel tank adjacent to the CEC that can provide fuel for both the boilers and the backup diesel generator. The above-ground tank has a flexible connection to an underground pipe that feeds the boilers and generator. Staff estimates that this supply of diesel fuel can power the thermal energy system for a minimum of 12 hours at full load.

While communication infrastructure is outside the scope of this assessment, it is important to note that the CEC does not require an internet connection to monitor and control system performance. However, loss of intranet would result in staff being unable to monitor the thermal intake of buildings.

L2.4.1.5 Backup Systems

While there is no backup to the thermal energy system per se, the CEC is highly redundant. In addition to the aforementioned backup supplies of electric power and natural gas, the closed loop nature of the system means that latent heat can provide thermal energy to buildings without significant degradation of service for a couple hours in the case of an outage at the CEC. However, if there were a protracted disruption to natural gas and/or electric power after an earthquake, a significant number of buildings on campus would be without heating, which in the winter could render them uninhabitable.

L2.4.1.6 Operational Procedures and Crew Size

UBC has a crew of three workers and an apprentice to maintain the thermal energy system. Currently there is no welder on staff, so any such work is contracted out to specialists. Similarly, UBC contracts its excavation work out to third party companies. Consequently, after a major earthquake, UBC may be unable to restore thermal energy service without the assistance of third party contractors

The CEC is required to be staffed with at least one worker at all times to monitor the status of the boilers and other equipment. If the CEC were red-tagged after an earthquake, staff would be unable to enter the facility and thus would have to shut down the thermal energy system.

L2.4.2 Key Vulnerabilities

Our review of the current configuration of the thermal energy system has identified the following vulnerabilities.

- Limited onsite diesel storage capabilities make the system vulnerable to protracted natural gas disruptions. Furthermore, diesel fuel is delivered via trucks from a supplier in Burnaby. In normal circumstances, it can arrive in approximately 4 hours. The ultimate source of the fuel, however, is the United States, which involves bridge crossings that could be compromised in an earthquake.
- While the CEC is expected to perform well in an earthquake, if it is red tagged due to nonstructural damage (e.g., fallen ceiling tiles or lights), staff would be unable to enter the facility to monitor plant operations. Because the CEC

requires 24-hour staffing, the system would need to be shut down until the red tag is removed from the facility.

L2.4.3 Ongoing Mitigation

In addition to performing routine inspection and maintenance of boilers, valves, and other critical equipment, UBC is pursuing or planning to pursue the following mitigation activities. Unless explicitly stated otherwise, these activities have not been considered in our model of the thermal energy system (described in Section L3).

- UBC is planning to add more equipment at the CEC to the backup generator. Currently, only one boiler and electric pump are on the backup power circuit, but there is additional capacity in the diesel generator, so staff plans to add an additional boiler and pump to the circuit in the coming months.
- UBC is planning to add "black start" capabilities in the next few months, which will allow the boilers to be restarted on diesel fuel in the event of loss of electric power.
- UBC is considering different options for increasing its onsite diesel storage capabilities, including setting up service contracts with diesel providers or constructing a 400,000 L diesel tank farm in south campus to provide 2-4 days of fuel for backup generators.

L2.5 Sanitary Sewer

The sanitary sewer system collects and transports wastewater generated in buildings to collection points at the north and south ends of campus where it enters the Metro Vancouver sewer system. UBC has separate infrastructure for its sanitary and storm sewer systems. The consequences of damage to the sanitary sewer system are different than the other utilities in that the primary risk is to the environment. In other words, damage to the sewer system would not render buildings uninhabitable; however, continued use of toilets and sinks would result in raw sewage leaking from damaged pipes and contaminating parts of campus. For certain buildings, flooding of basements due to inoperability of wastewater pumps and/or adjacent lift stations (due to disruption of electricity) is also a concern.

L2.5.1 Current System Configuration

Figure L.9 provides an overview of the current sanitary sewer utility system on campus. The following subsections describe different aspects of the system, including:

Figure L.10

- L2.5.1.1: How wastewater is transported from campus

- L2.5.1.2: Facilities and equipment on campus that have critical roles in supporting sanitary sewer service
- L2.5.1.3: Distribution systems that deliver electricity to end users
- L2.5.1.4: Dependence on other campus utility systems
- L2.5.1.5: Backup systems that can be called upon in case of disruption to normal service
- L2.5.1.6: Crew sizes and operational procedures for responding to disruptions

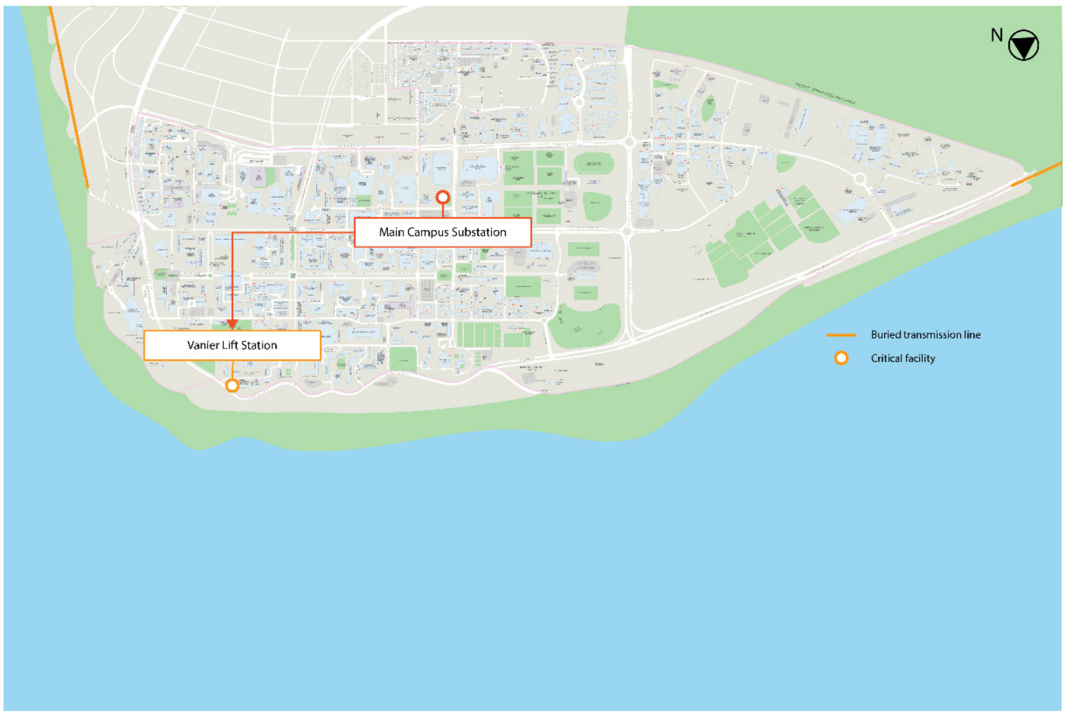

Figure L.9 Transmission lines, critical facilities, and interdependencies for the sanitary sewer system

L2.5.1.1 Transmission to Campus

There are two main catchment areas on campus at the north and south ends, each with a separate connection to the Metro Vancouver sewer system. In the south the connection is at Southwest Marine Drive, while in the north the connection is near the intersection of Chancellor Boulevard and Northwest Marine Drive (see Figure L.9).

L2.5.1.2 Critical Campus Facilities and Equipment

While most of the sanitary sewer system is gravity fed, parts of it require pumping. There are four major lift stations on campus, each with its own backup diesel generator. The biggest one is the Vanier pump station at the northwest edge of campus, which handles approximate 20% of campus wastewater. The station has three underground electric pumps in two vertical shafts and a backup diesel generator in a nearby shed with diesel fuel reserves for approximately 4-6 hours of operation. There is a remote alarm at the Power House that goes off if there is an issue at the Vanier lift station. This alarm will be moved to the Campus Energy Centre when the Power House is decommissioned.

In addition to the four main lift stations, there are also 20 smaller pumping stations at individual buildings to lift wastewater from below-grade floors to adjacent sewer mains. For example, there is a lift station at the Life Sciences Building that has full backup for 24 hours. If the lift station were to fail, sewage could back up and flood the basement.

L2.5.1.3 Campus Distribution System

The sanitary sewer distribution system comprises approximately 52 km of underground pipe composed of a wide range of materials, including vitrified clay, asbestos cement, concrete, and PVC. Approximately 15-20% of pipes are vitrified clay, which is brittle and likely to perform poorly in an earthquake. Whenever possible, overflows have been added to allow alternate drainage routes in the event of a sewer backup.

L2.5.1.4 Dependence on Other Campus Utility Systems

Lift stations have a critical dependence on electric power, which is partly mitigated by backup diesel generators at each station. However, these generators have limited fuel reserves, so in the event of a protracted power disruption, they will need to be refueled regularly to prevent failure of the sanitary sewer system.

L2.5.1.5 Backup Systems

There is no backup for the sanitary sewer system, as UBC lacks the ability to treat or store wastewater in the event of a pipe break or protracted power outage. However, UBC may be able to discharge untreated effluent directly into the storm sewer system and/or the Strait of Georgia in accordance with its spill response and discharge procedures.

L2.5.1.6 Operational Procedures and Crew Size

UBC has a crew of six workers to make repairs to the sanitary sewer system; however, this crew is also responsible for repairs to the water and natural gas systems. If vitrified clay pipes were damaged in an earthquake, campus staff would need to contract out the repair work to a third party company. However, staff noted that there are only three contractors in area that do this type work.

L2.5.2 Key Vulnerabilities

Our review of the current configuration of the sanitary sewer system has identified the following vulnerabilities.

- Campus lift stations have diesel backup generators with limited fuel reserves, making them vulnerable to prolonged power outages.
- The municipal sewer line at the north end of campus is close to the edge of a rapidly eroding cliff. While UBC is aware of this vulnerability, jurisdictional issues are making it challenging to mitigate because the university does not own the pipe or the cliff.
- From the north and south catchment points on campus, wastewater flows to Iona Island treatment plant. If this facility were to go down, the municipal system could backup, which in turn could backup campus systems.

L2.5.3 Ongoing Mitigation

Aside from routine inspection and maintenance of lift stations and pipes, we are unaware of any additional mitigation activities that UBC is currently pursuing or planning to pursue with respect to the sanitary sewer system. However, staff mentioned that some sections of vitrified clay pipe have been retrofitted with fiberglass liners, though it is unclear whether these retrofits were part of a broader mitigation strategy or were simply a response to pipe breaks.

L3 Network Risk Analysis

In order to assess the expected seismic performance of campus utility systems, a simplified network model was developed for each system. This section provides details on both the modeling framework (Section L3.1) and the network models for each utility system (Section L3.2).

L3.1 Modeling Framework Overview

This section summarizes the network risk modeling architecture and calculation process. A high level overview is shown in Figure L.10.

The first input is the seismic hazard. The uniform hazard spectra is used as the basis for the utilities risk analysis, and there are four return periods (i.e. earthquake scenarios) being considered. Main ground motion parameters of interest include the peak ground acceleration and peak ground velocity. See Appendix A for complete details on the seismic hazard at the site.

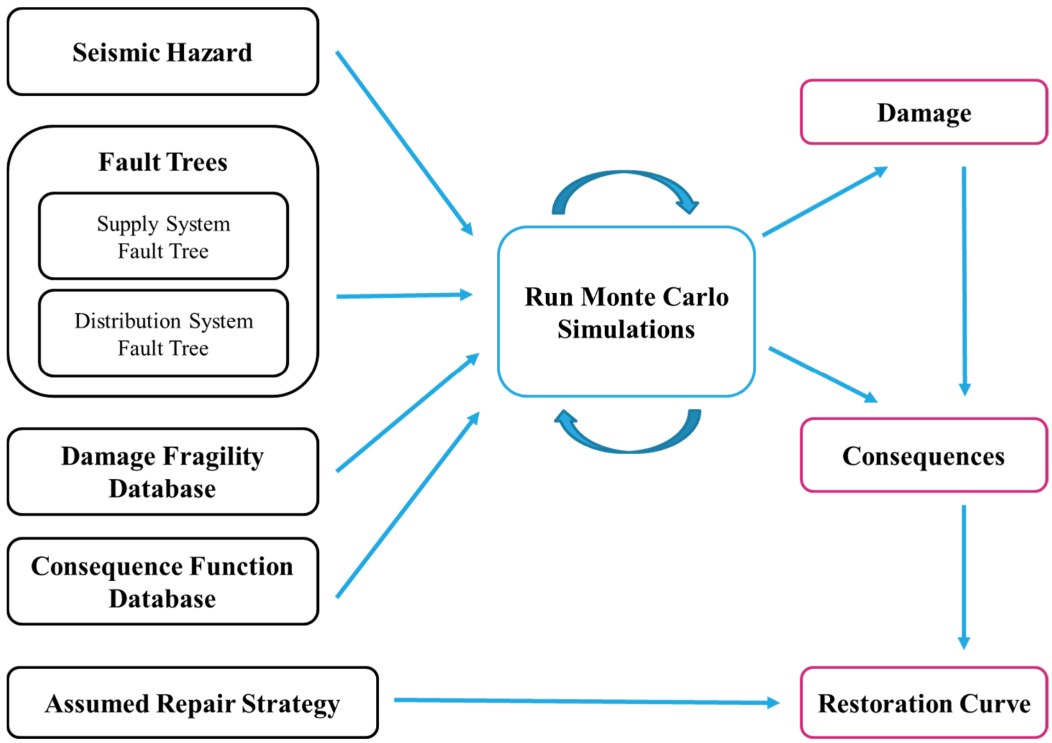

Figure L.10 Modeling Framework Overview

The configuration of each utility service (electric power, water, natural gas, thermal energy, and sanitary sewer) are separated into two primary modules: (1) supply system module and (2) distribution system module (2). Fault trees are created for each of these modules in order to conduct the probabilistic Monte Carlo simulations.

The supply system includes components whose failure would compromise the functionality of the entire utility service on campus (e.g., critical equipment and facilities, campus transmission lines, interdependencies, and loss of municipal supply), while the distribution system includes pipes and conduits that deliver the utility to end users on campus. Unlike failures in the supply system, failures in the distribution system would disrupt utility service to only localized parts of campus.

Taken together, these two modules enable an understanding of how each utility system is likely to perform in different earthquake scenarios. Table L.1 documents which modules were developed for each utility system.

Table L.1 Utility systems and modules developed

Utility	Supply Module	Distribution Module
Electric power	Yes	Yes

Water	Yes	Yes
Thermal energy	Yes	Yes
Natural gas	Yes	Yes
Sanitary sewer	No	Yes

The probability of damage (fragility curves) are stored in a damage fragility database, and the expected restoration times and associated uncertainty values are stored in a consequence function database. These databases are accessed in each Monte Carlo iteration to determine which components of the fault trees have incurred damage.

Once damage has been predicted in each realization, the consequence (i.e. restoration times) are calculated for the broken components and a critical path to recovery is constructed based on the fault tree and restoration times. The restoration times calculated for a critical path are combined with the assumed repair strategies for each service to predict:

1) Time of total service disruption
2) Time to 100% service recovery

The following sections describe each component of the modeling framework in further detail.

L3.1.1 Supply system module

The supply system module involves developing a simplified network model of a particular utility service that can predict whether the system is functional after an earthquake. More specifically, the supply module involves developing a custom fault tree that captures how different combinations of failures (e.g., equipment, buildings, transmission lines, municipal supply, and utility interdependencies) impact the overall functionality of the utility service. It uses fault trees in conjunction with fragility curves and consequence functions to predict damage, loss of functionality, and restoration times for the entire supply system.

A sample fault tree is shown below in Figure L.11. Fault tree structures use Boolean logic to combine a set of events and determine the binary state of a system. The events are combined using “or” and “and” gates. “Or” gates occur if any of the input events occur. “And” gates occur only if all of the input events occur.

For example, the topmost gate in the fault tree shown in Figure L.11 is an “Or” gate. The supply system fails if there is either a loss of municipal supply, the equipment group fails, the pipe group fails, the facility building is damaged, or the equipment is damaged. However, the equipment group fails only if both equipment 1 and 2 are damaged. Similarly, the pipe group fails only if both pipe 1 and 2 are broken. Thus, “and” gates represent redundancies in a utilities network because all the components below the gate must fail in order for the gate to fail. On the other hand, “or” gates represent a series system, meaning that failure of a single component will trigger failure of the gate.

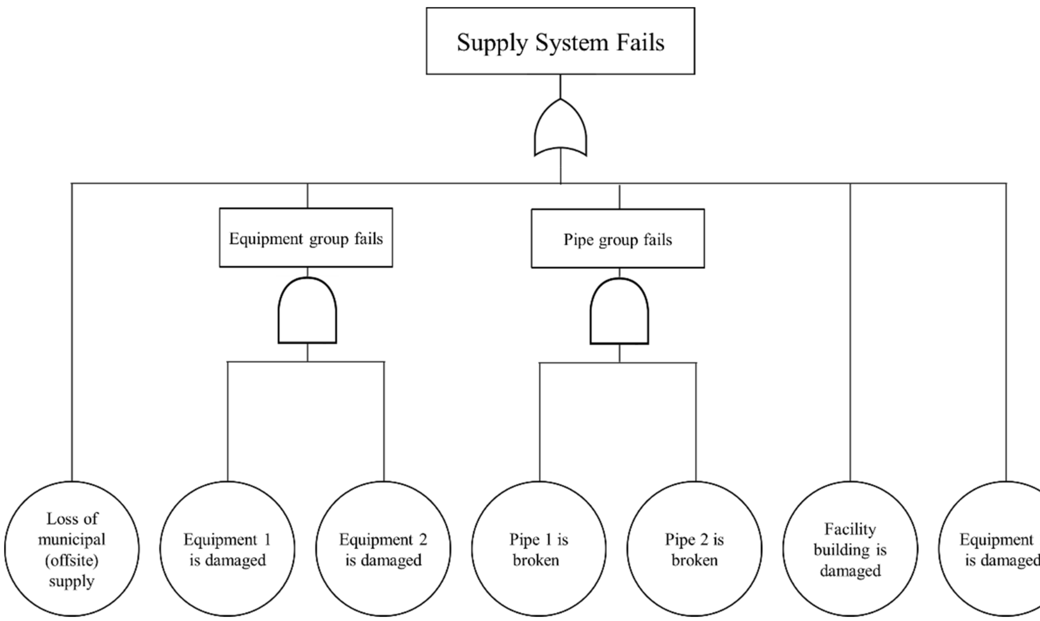

Figure L.11 Sample fault tree

The occurrence of an event—such as damage to a pipe, equipment, or building—is decided based on the event’s damage fragility curve(s) and consequence functions. Damage fragility curves provide the probability of exceeding certain damage states given a ground motion parameter (e.g. peak ground acceleration). Consequence functions are a probabilistic distribution of restoration times for a given damage state. In using probabilistic functions, the network risk analysis incorporates the inherent uncertainty in approximating the damage and losses sustained by utility systems in an earthquake scenario.

Fault trees have been constructed for the electric power, water, thermal energy, and natural gas supplies using information obtained from campus personnel, site visits, reports, and drawings. In general, given the critical nature of these supply systems, if the fault tree predicts failure, the entire utility system is assumed to be unavailable.

The following sections summarize how the damage and restoration times of equipment, utility interdependencies, offsite supplies, and transmission pipes were calculated within the modeling framework.

L3.1.1.1 Equipment

Equipment that contributes to the functionality of the utility service include items such as pumps, boilers, electric transformers, and switchgear. To predict the damage and restoration time, a database of damage fragility curves and consequence functions was created based on literature review and information provided by campus personnel. These databases are presented in the Network Model section (Section L3.2).

L3.1.1.2 Anchorage for Equipment

High-risk equipment with either poor anchorage conditions, high aspect ratios, or extraordinarily high restoration times were modeled using both anchored and unanchored damage fragility curves and consequence functions. Given that specific anchorage details were not available, a general anchorage damage fragility curve was calculated following the methodology presented in Section 3.8.4 of FEMA-P-58 (FEMA, 2012), as shown in Table L.2. This general fragility curve was used for all equipment in which anchorage was included in the modeling.

Table L.2 Anchorage Damage Fragility Curve Parameters

Type	**Value**
Median PGA	0.5g
Dispersion	0.5
Distribution type	Lognormal

Within each simulation, the anchored equipment's damage state is determined by the following procedure:

1. Use the general anchorage fragility curve in Table L.2 to see if the anchorage has failed.
2. If the anchorage has failed:
    a. Use the *unanchored* damage fragility curves and the consequence functions associated with those damage states.
3. If the anchorage has not failed:
    a. Use the *anchored* damage fragility curves and the consequence functions associated with those damage states.

L3.1.1.3 Building Damage

A portion of the equipment within a supply system may be located inside a building. For example, the Power House contains much of the equipment that supports water service to campus. In the event of a major earthquake, the building could sustain a significant amount of damage and be deemed a life safety hazard, or collapse altogether. In either scenario, most or all of the critical equipment within the building would likely also be damaged and become nonfunctional. Repair crews would not be allowed inside the building.

To incorporate this relationship between critical facility buildings and the utility equipment housed inside these buildings, the building damage states from the portfolio seismic risk assessment (PSRA) are used as inputs to the utility network risk analysis. More specifically, for each system that is dependent on a critical facility building performance, the building's PSRA results are used to interpret whether or not the equipment is functional and, if not, how long it would take to repair and/or replace the relevant components.

If the PSRA predicts a nonzero re-occupancy time, the building is considered a life safety hazard for some period of time after the earthquake. This means that the equipment inside may be damaged due to falling debris and/or that crews would not be allowed to enter the building to repair critical equipment and restore utility service.

L3.1.1.4 Utility Interdependencies

The water and thermal energy supply systems depend on the availability of the electricity supply system. To maintain consistency within each simulation, the electricity supply system state is calculated for a given earthquake scenario. Then, the resulting system state and associated restoration times are directly fed into the water and thermal energy supply systems for the same earthquake scenario.

L3.1.1.5 Offsite Supply

Supply systems depend on the availability of municipal, offsite supplies of the associated utility service. The restoration time of the offsite supplies are a function of earthquake intensity (i.e. return period) and, for each realization, are calculated using a lognormal distribution with a dispersion value of 0.4. The median restoration times are provided below in Table L.3.

Table L.3 Median restoration times of municipal utility supplies, adapted from (Arup, 2014)

Utility	**Frequent**	**Probable**	**Rare**	**Very Rare**
Electric power	6 hours	1 day	2 days	7 days

Water	1 day	3 days	14 days	21 days
Natural gas	12 hours	2 days	7 days	14 days

L3.1.1.6 **Pipes**

Transmission pipes play an important role in delivering utility services to campus supply systems. Transmission pipes are included in the fault tree models of the water, natural gas, thermal energy, and electric power supply systems.

The probability of pipe damage in an earthquake depend on the ductility of the pipe material, total length of pipe, and pipe diameter. More specifically, repair rate equations that are a function of pipe material, length, diameter, and ground motion parameter (i.e. peak ground velocity) predict the expected number of breaks per unit length of pipe, or the repair rate (RR). The expected number of breaks is as the product of the repair rate and the total length of that pipe segment. Then, the number of breaks in each simulation is calculated using a Poisson distribution centered on the expected number of breaks.

The repair rate equation for pipe breaks (American Lifelines Alliance, 2001) is:

$$RR = K_1(0.00187)(PGV)$$

where K_1 represents the fragility curve modification factors for different materials and PGV is the peak ground velocity in inches/second. Materials that are more likely to be damaged in a seismic event tend to have higher K_1 values. RR is the expected number of breaks per unit length of pipe.

Then, the expected number of breaks is:

$$\lambda = RR * (L)$$

where *L* represents the length of that pipe segment.

The Poisson distribution probability mass distribution (PMF) uses the expected number of breaks to calculate the probability of *k* number of breaks. The PMF is given as:

$$p(k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

where *k* is the number of breaks, λ is the expected number of breaks, and p(k) is the probability of obtaining *k* breaks. The probabilities of obtaining 0 through 5 breaks is calculated, and these probabilities are used as the basis for the Monte Carlo simulation to determine the number of breaks in each realization.

Table L.4 categorizes the pipe materials and corresponding fragility curve modification factors for the different transmission pipes on campus. The median restoration time per break is also included. The restoration time per break is estimated based on information from UBC utilities staff, and does not include the time required to obtain a hydrovac, which is discussed in more detail below.

Table L.4 Pipe materials, fragility curve modification factors, and median restoration times for the transmission pipes on campus. All fragility modification factors (unless otherwise noted) are from the American Lifelines Alliance Seismic Fragility Formulations for Water Systems (American Lifelines Alliance, 2001).

Supply system	Pipe material	Type	K_1	Length (km)	Median restoration time per break (days)
Electric power, transmission line 1	Electrical conduit (PVC encased in concrete)	Brittle	1.0*	1.9 km	7
Electric power, transmission line 2	Electrical conduit (PVC encased in concrete)	Brittle	1.0	1.0 km	7
Water	Welded steel (large diameter)	Ductile	0.15	0.8 km	1
Natural Gas	Welded steel (small diameter)	Ductile	0.6	0.8 km	1
Thermal Energy	Welded steel (small diameter)	Ductile	0.6	0.8 km	1
Sanitary Sewer	N/A				

*The electrical conduit fragility modification factor is from (Eidinger, 2017).

In repairing buried pipelines, the first step is to acquire a hydrovac, which acts as an impeding factor on the restoration time calculations. The availability of a hydrovac depends on the location of local hydrovac companies, their internal resources, and their ability to access campus. Thus, for each simulation in which there is at least one buried pipe break across all utility systems, additional time for acquiring the hydrovac is added to the required service restoration time. This time is calculated using a lognormal distribution with a median of 3 days and dispersion value of 0.5.

L3.1.2 Distribution system module

Similar to the pipe damage calculation process introduced in the previous section, the distribution network module uses repair rate equations to compute the number of breaks expected in an earthquake scenario. Because UBC's distribution systems tend to be redundant and configured in a way that allows damaged parts to be isolated, breaks are not assumed to cause total failure of the utility system (i.e., breaks will only affect limited portions of campus). Because of limited available information and the complexity of the distribution networks, the module cannot predict which parts of campus will lose service due to a break. Instead, it simply predicts the number of breaks expected in an earthquake scenario and the amount of time it would take to repair, which can be useful in scenario planning.

Table L.5 categorizes the pipe materials and corresponding fragility curve modification factors for the different distribution systems on campus. The median restoration time per break is also included. The restoration time per break is estimated based on information from UBC utilities staff, and does not include the time required to obtain a hydrovac.

Table L.5 Pipe materials, fragility curve modifications factors, and median restoration times for the distribution systems on campus. All fragility modification factors (unless otherwise noted) are from the American Lifelines Alliance Seismic Fragility Formulations for Water Systems (American Lifelines Alliance, 2001).

Distribution system	Pipe material	Type	K_1	Length (km)	Median restoration time per break (days)
Electric Power	Electrical conduit (PVC encased in concrete)	Brittle	1.0*	10.1	7
Water	Ductile iron	Ductile	0.5	36.6	1
	Cast iron	Brittle	1.0	16.8	1

Thermal Energy	Welded steel (large diameter)	Ductile	0.15	23.8	1
Natural Gas	Welded steel (large diameter)	Ductile	0.15	20.4	1
	PVC	Ductile	0.5	23.2	1
Sanitary Sewer	Asbestos cement	Brittle	1.0	23.5	1
	PVC	Ductile	0.5	28.7	1

*The electrical conduit fragility modification factor is from (Eidinger, 2017)

L3.1.3 Assumed repair strategies for downtime calculation

For each utility service, three different service recovery times are calculated for each of the four earthquake scenarios:

1. Municipal/offsite supply downtime
2. Estimated time of total service disruption time on campus (100% outage), which includes the municipal supply downtime and time required to restore the supply system
3. Estimated time to 100% service, in which all repairs to the distribution system have been completed in addition to repairs to the supply system and the municipal supply downtime

The calculation procedure for each utility service is outlined below in Table L.6. The times are calculated from assumed repair strategies based on communications with UBC utilities staff and engineering judgment.

Table L.6 Assumed repair strategies and downtime calculation procedures for the five utility services

Service	Assumed repair strategy	Municipal/offsite supply downtime	Total service disruption time	Time to 100% service recovery

Electric Power	Issues in the electrical system can be detected in the absence of offsite supply. Thus, assume both supply and distribution systems can be repaired in the absence of offsite supply	Median offsite supply downtime	Maximum of offsite supply downtime and time to repair campus supply systems	Maximum of offsite supply downtime, and the time to repair both campus supply and distribution systems
Water	Assume that the supply system can be repaired in absence of offsite supply, but distribution systems cannot.	Median offsite supply downtime	Maximum of offsite supply downtime and time to repair campus supply systems	Sum of total service disruption time and time to repair campus distribution systems
Natural Gas	Assume that neither supply nor distribution systems can be repaired in the absence of offsite supply.	Median offsite supply downtime	Sum of offsite supply downtime and time to repair campus supply systems	Sum of total service disruption time and time to repair campus distribution systems
Thermal Energy	Supply system depends on the availability of natural gas offsite supply. Restoration times for the thermal energy supply system assumes sufficient diesel reserves to mitigate a natural gas offsite supply disruption.	N/A	Time required to make repairs to the supply system	Time required to make repairs to the supply and distribution systems
Sanitary Sewer	The supply system has not been modeled, and 100% service outage is not expected for the sewer system.	N/A	N/A	Time required to make repairs to the distribution system

L3.2 Network Models

The following sections describe the network models developed for each utility system. Each section includes a diagram of the fault tree model for the supply system (if applicable) and tables listing damage fragility and consequence functions used in the analysis. Each section will also highlight any high-risk items or single-point failures.

L3.2.1 Electric power

The campus electric power supply system fault tree is shown below in Figure L.12. Single point failures include loss of municipal electric power supply, damage to the main substation, and the main switchgear. In a very rare earthquake, the median disruption time for the municipal supply is 7 days, as shown in Table L.3. The main substation building is not expected to sustain significant damage in a very rare earthquake and the components inside should not cause disruption to the campus electric power supply. Damage to the main switchgear can lead to an average downtime of 20 days for the entire supply system.

Transformers have an especially high restoration time. If there is damage to the transformer itself, it can take more than six months to repair/replace the equipment as it may have to be shipped out for servicing. This kind of damage is expected to occur at very high peak ground acceleration values, if the equipment is well-anchored. However, our analysis did not explicitly include the correlation between the transformers. If they are identical and co-located, there is some probability that if one of them were to fail, the other would fail as well.

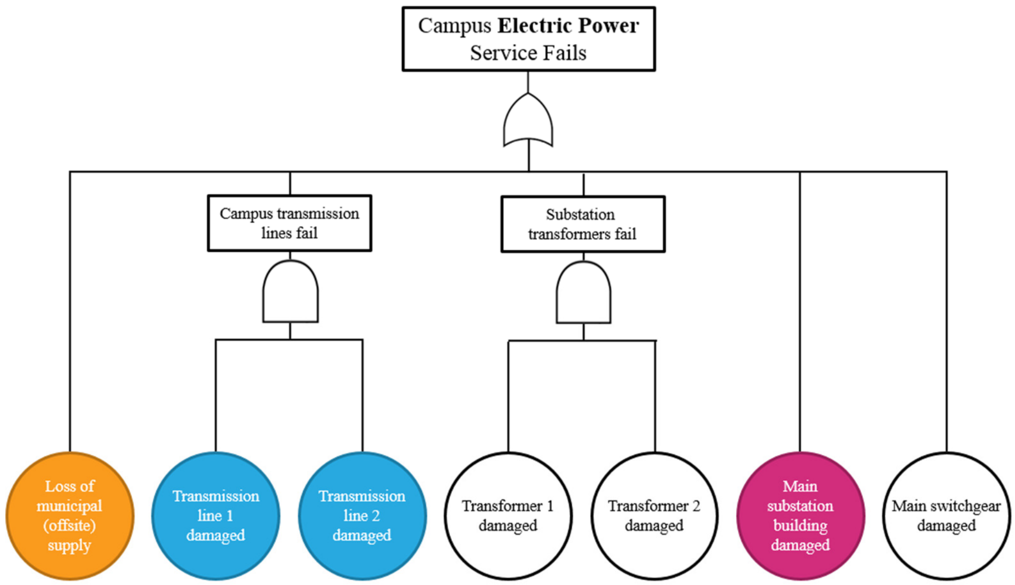

Figure L.12 Electric power supply system fault tree

The fragility and consequence database is shown in Table L.7. Unless otherwise noted, all equipment fragility and consequence functions are based on the Seismic Performance Assessment of Buildings – Performance Assessment Calculation Tool (PACT), Version 3.0 (FEMA, 2016).

Table L.7 Damage fragility curves and consequence functions for components of the electric power supply system

Event	**Type**	**Damage function parameters**		**Consequence function parameters**		
		Median ground motion parameter	Dispersion	Median restoration time (days)	Dispersion	Distribution type
Loss of municipal (offsite) supply	Offsite supply	Assume this event always occurs with a nonzero restoration time.		See Table L.3		
Transmission line 1 damaged	Pipe	See Table L.4		7.0	0.4	Lognormal

Transmission line 2 damaged	Pipe	See Table L.4		7.0	0.4	Lognormal
Transformers	Anchorage	PGA = 0.5g	0.50	N/A	N/A	N/A
	Anchored Equipment*	PGA = 2.0g	0.5	240	0.4	Lognormal
	Unanchored Equipment*	PGA = 0.8g	0.5	240	0.4	Lognormal
Main substation building damaged	Building Damage	PSRA results (see Appendix I)				
Main switchgear damaged	Anchorage	PGA = 0.5g	0.50	N/A	N/A	N/A
	Anchored Equipment	PGA = 2.4g	0.40	20.230	5.244	Normal
	Unanchored Equipment	PGA = 1.28g	0.40	20.230	5.244	Normal

*Damage fragility functions and consequence functions for these components are based on PACT but have been modified to reflect the condition of the specific equipment on UBC campus and the expected disruptions to utility service based on information from UBC personnel. The available literature focuses primarily on establishing fragility functions, and thus some engineering judgment was used to approximate reasonable consequence functions for the highlighted components

The electric power distribution system includes 10.1km of buried electrical conduit, whose concrete casing is a brittle material. As the pipelines are buried, a hydrovac would be required before beginning repairs.

L3.2.2 Water

The campus water service supply system fault tree is shown below in Figure L.13.

Single point failures include loss of municipal water supply, damage to the campus transmission lines, and damage to the Power House building. In a very rare earthquake, there is a 50% probability that the municipal supply will have a downtime of at least 21 days, as shown in Table L.3.

The Power House building is a vulnerable building, and access to it is crucial in restoring water service on campus, as many of the equipment that operate as part of the water supply system are contained within the Power House. As such, the model assumes that if the building PSRA results show a nonzero re-occupancy time, then UBC would devise a temporary workaround to restore water service as soon as possible, without relying on demolition of the facility and/or construction of a new facility. Thus, if the PSRA predicts nonzero re-occupancy time, the restoration time for the Power House is calculated using a lognormal distribution with a median of 60 days and a dispersion value of 0.5.

The campus transmission line consists of 800 meters of large-diameter welded steel piping, which is one of the more rugged and ductile materials. It is not expected that the transmission line would sustain significant damage and add to water supply downtime.

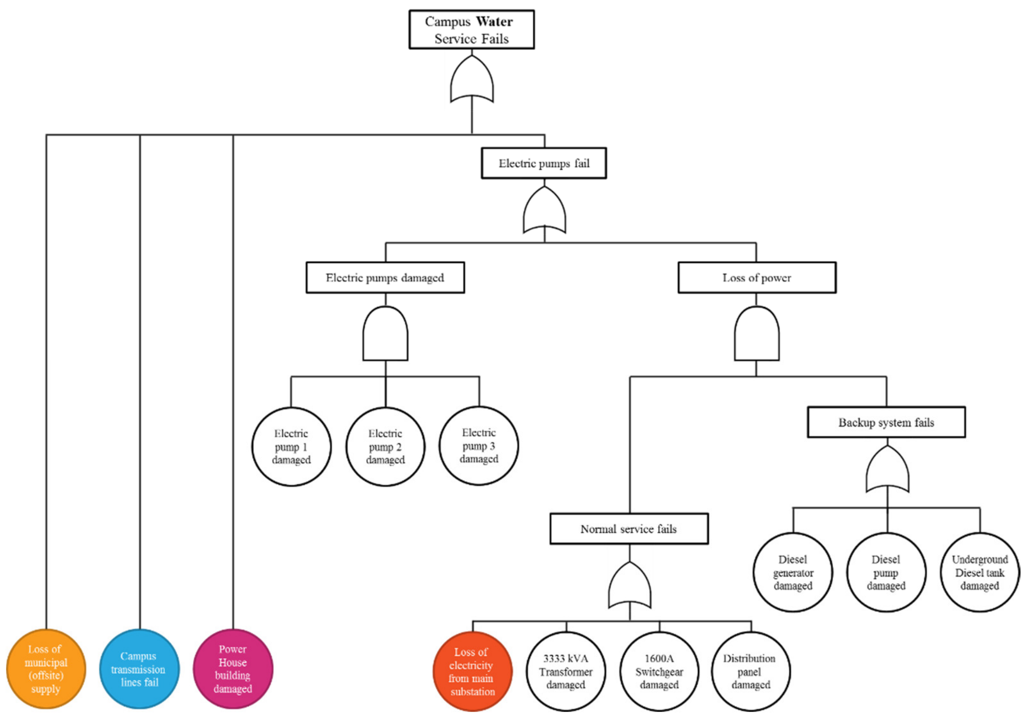

Figure L.13 Water supply system fault tree

The water system is also dependent on the functionality of the campus electric power supply system. However, UBC has a diesel backup system in place, whose components are not expected to be significantly damaged in a very rare earthquake. Thus, the utility interdependency does not play a key role in determining availability of water service on campus.

Damage fragility curves and consequence functions for all components in the water supply system are shown in Table L.8. Unless otherwise noted, all equipment fragility and consequence functions are based on the Seismic

Performance Assessment of Buildings – Performance Assessment Calculation Tool (PACT), Version 3.0 (FEMA, 2016).

Table L.8 Damage fragility curves and consequence functions for components in the water supply system

Event	Type	Damage function parameters		Consequence function parameters		
		Median ground motion parameter	Dispersion	Median restoration time (days)	Dispersion	Distribution type
Loss of municipal (offsite) supply	Offsite supply	Assume this event always occurs with a nonzero restoration time.		See Table L.3		
Transmission line fails	Pipe	See Table L.4		1.0	0.5	Lognormal
Power House building damage	Building Damage	PSRA results (see Appendix I)				
Electric pump (1, 2, or 3) damaged*	Equipment	PGA = 1.1g	0.5	4.0	0.4	Lognormal
Loss of electricity form campus electric supply system	Utility Interdependency	Fault tree analysis				
3333 kVA transformer damaged	Equipment	PGA = 3.05g	0.5	14.390	0.310	Lognormal

1600A switchgear damaged	Equipment	PGA = 2.4g	0.4	10.28	2.665	Normal
Distribution panel damaged	Equipment	PGA = 3.05g	0.4	11.753	3.060	Normal
Diesel generator damaged	Equipment	PGA = 2.0g	0.2	8.603	0.303	Lognormal
Diesel pump damaged*	Equipment	PGA = 1.5g	0.5	2.0	0.3	Lognormal

*Damage fragility functions for these components are from Seismic Reliability Assessment of Critical Facilities Handbook, a technical report published by the Multidisciplinary Center for Earthquake Engineering Research (MCEER) (Johnson, Sheppard, Quilici, Eder, & Scawthorn, 1999). Consequence functions of these components are derived based on a comparison of consequence functions available in the PACT database as well as information from UBC personnel. The available literature focuses primarily on establishing fragility functions, and thus some engineering judgment was used to approximate reasonable consequence functions for the highlighted components

The water distribution network consists of 36.6 km of ductile iron and 16.8 km of cast iron, meaning that the majority of the water distribution system is composed of ductile piping. There is an ongoing program to replace the cast iron piping with ductile piping.

L3.2.3 Natural Gas

Figure L.14 shows the fault tree diagram for the campus gas supply system. The loss of municipal supply and damage to the campus transmission line govern the availability of natural gas service on campus. While pressure reducing stations play a role in providing natural gas service, they are not typically vulnerable components in earthquakes (EERI, 2014) and thus are neglected in the analysis.

The campus gas transmission line is a small-diameter welded steel pipe, 800 meters in length. Due to the ductility of the material and the relatively short pipe length, the transmission is not expected to sustain significant damage during a very rare earthquake.

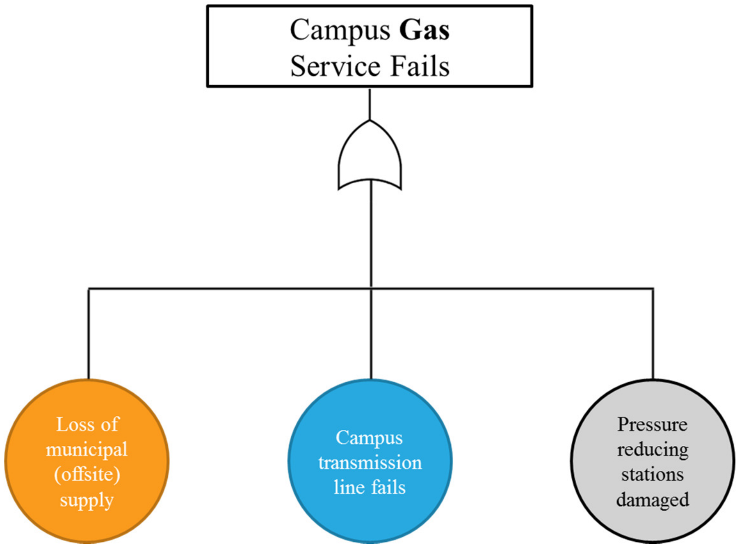

Figure L.14 Campus gas supply system fault tree

Table L.9 Damage fragility curves and consequence functions for components in the natural gas supply system

Event	**Type**	**Damage function parameters**		**Consequence function parameters**		
		Median ground motion parameter	Dispersion	Median restoration time (days)	Dispersion	Distribution type
Loss of municipal (offsite) supply	Offsite supply	Assume this event always occurs with a nonzero restoration time.		See Table L.3		
Transmission line fails	Pipe	See Table L.4		1.0	0.5	Lognormal
Pressure reducing stations damaged	Equipment	This event is not considered in our analysis.		N/A		

The distribution module of the natural gas service on campus includes 20.4 km of large-diameter welded steel piping, 23.2 km of PVC piping, and a shutoff valve that is triggered at an acceleration of 0.3g. If the shutoff valve is triggered, it could take several weeks to restore natural gas service to all buildings on campus. Each building would need to be pressure tested, which would require 2-4 hours per building apart from fixing any pipe leaks. Within each building, all appliances must be re-lighted manually.

For this analysis, the shutoff valve restoration time is calculated from a lognormal distribution with a median of 21 days and a dispersion value of 0.5. Because the network risk analysis is conducted at the portfolio-level, the shutoff valve restoration time does not include time required to manually re-light appliances within the building.

To calculate the restoration time of the natural gas distribution module, the shutoff valve restoration time is added to the time required to fix any buried pipelines.

L3.2.4 Thermal Energy

Figure L.15 shows the fault tree diagram for the campus thermal energy supply system.

The thermal energy supply system contains many redundancies with mostly rugged components. Single-point failures include damage to the Campus Energy Centre building, which was built recently and has a low probability of collapse in a very rare earthquake scenario, as per the PSRA results (see Appendix I).

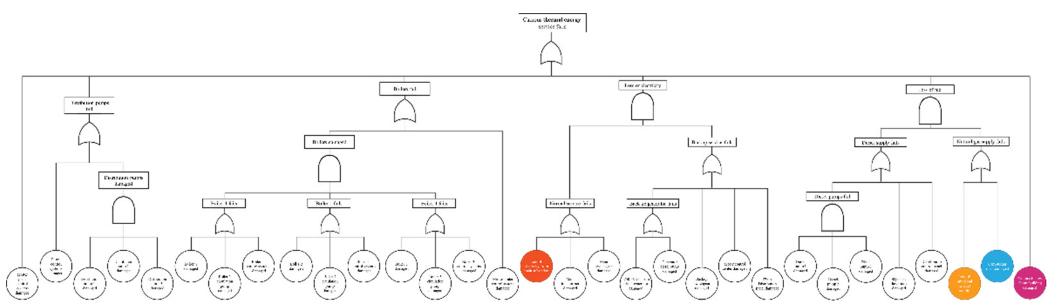

Figure L.15 Campus thermal energy supply system fault tree diagram

The distribution model for thermal energy includes 23.8 km of large-diameter, welded steel piping, which is a rugged, ductile material and thus does not contribute significantly to downtime. The expected number of pipe breaks for very rare earthquake is 0.5 breaks.

The damage fragility curves and consequence functions for all components in the thermal energy supply system are listed below in Table L.10. Unless otherwise noted, all equipment fragility and consequence functions are based on the Seismic Performance Assessment of Buildings – Performance Assessment Calculation Tool (PACT), Version 3.0 (FEMA, 2016).

Table L.10 Damage fragility curves and consequence functions for components in the thermal energy supply system

Event	Type	Damage function parameters		Consequence function parameters		
		Median ground motion parameter	**Dispersi on**	**Median restorati on time (days)**	**Dispersi on**	**Distribution type**
Loss of municipal (offsite) supply	Offsite supply	Assume this event always occurs with a nonzero restoration time.		See Table L.3		
Master plant control systems damaged	Equipment	PGA = 3.0g	0.4	1.953	0.605	Normal
Pump control systems damaged	Equipment	PGA = 3.0g	0.4	1.953	0.605	Normal
Distributio n pump 1, 2, or 3 damaged*	Equipment	PGA = 2.6g	0.6	7.0	0.4	Lognormal
Boiler 1, 2, or 3 damaged*	Equipment	PGA = 3.0g	0.5	30	0.5	Lognormal
Boiler circulation pump 1, 2, or 3 damaged*	Equipment	PGA = 2.6g	0.6	4.0	0.4	Lognormal
Boiler control panel 1, 2,	Equipment	PGA = 3.0g	0.4	1.953	0.605	Normal

Event	**Type**	**Damage function parameters**		**Consequence function parameters**		
		Median ground motion parameter	**Dispersion**	**Median restoration time (days)**	**Dispersion**	**Distribution type**
or 3 damaged						
Master boiler control system damaged	Equipment	PGA = 3.0g	0.4	1.953	0.605	Normal
Loss of electricity from the main substation	Utility Interdependency	Fault tree analysis				
Main transformer damaged	Equipment	PGA = 3.05g	0.5	13.660	0.310	Lognormal
Main switchgear damaged	Equipment	PGA = 2.4g	0.4	16.08	4.168	Normal
1250 kVA backup diesel generator damaged	Equipment	PGA = 2.0g	0.2	16.177	0.303	Lognormal
Generator diesel pump damaged*	Equipment	PGA = 1.5g	0.5	2.0	0.3	Lognormal
Backup switchgear damaged	Equipment	PGA = 2.4g	0.4	16.08	4.168	Normal

Event	Type	Damage function parameters		Consequence function parameters		
		Median ground motion parameter	Dispersion	Median restoration time (days)	Dispersion	Distribution type
Motor control center damaged	Equipment	PGA = 2.5g	0.4	5.371	0.310	Lognormal
225 A distribution panel damaged	Equipment	PGA = 3.05g	0.4	4.910	0.295	Lognormal
Diesel 1, 2, or 3 *pump damaged	Equipment	PGA = 1.5g	0.5	2.0	0.3	Lognormal
42,000L diesel tank damaged*	Equipment	PGA = 1.9g	0.5	7.0	0.5	Lognormal
Diesel pump control panel damaged	Equipment	PGA = 3.0g	0.4	1.953	0.605	Normal
Campus gas main transmission line damaged	Pipe	See Table L.4		1	0.5	Lognormal
Campus energy center building damaged	Building Damage	PSRA results (see Appendix I)				

*Damage fragility functions for these components are from Seismic Reliability Assessment of Critical Facilities Handbook, a technical report published by the Multidisciplinary Center for Earthquake Engineering Research (MCEER) (Johnson, Sheppard, Quilici, Eder, & Scawthorn, 1999). Consequence functions of these components are derived based on a comparison of consequence functions available in the PACT database as well as information from UBC personnel. The available literature focuses primarily on establishing fragility functions, and thus some engineering judgment was used to approximate reasonable consequence functions for the highlighted components

L3.2.5 Sanitary Sewer

A distribution system model was created for the sanitary sewer, consisting of 23.5 km of asbestos cement (a brittle material) and 28.7 km of PVC (a ductile material). The buried sewer pipelines also require a hydrovac to be available before beginning any repairs.

No supply system module was created for the sanitary sewer, as the distribution module was sufficient for describing the performance of the sanitary sewer in the event of an earthquake.

L4 Expected Restoration Times for Existing Utility Systems

This section presents results from simplified network analyses of the five utility services in their current configurations.

Table L.11 presents best estimates of the campus service downtimes for each of the utility services and corresponding earthquake scenarios. The campus service downtime represents the range between duration of total service disruption and time to 90% service recovery. Table L.12 provides a summary of the best estimate and 90th percentile confidence level restoration times for each utility.

Table L.11 Best estimate of disruption and recovery times for existing utility systems

Earthquake	**Electric Power**		**Water**		**Natural Gas**	
	Municipal downtime	Campus service downtime	Municipal downtime	Campus service downtime	Municipal downtime	Campus service downtime
Frequent	6 hours	6 hours	1 day	1 day	12 hours	12 hours
Probable	1 day	1 day	3 days	61-65 days	2 days	2-6 days
Rare	2 days	2.5 days	14 days	65-70 days	7 days	7-13 days
Very Rare	7 days	7-12.5 days	21 days	68-76 days	14 days	14-40 days

The following sections include details on items that contribute most to downtime of each utility service and any other notable items.

Table L.12 Summary of restoration times for the five utility services for UBC campus

Service	Module for On-Campus Systems	Rare Earthquake		Very Rare Earthquake	
		Median restoration time (days)	90th percentile restoration time (days)	Median restoration time (days)	90th percentile restoration time (days)
Electric Power	Supply	12 hours	2 days	1.5 days	4.5 days
	Distribution	0 days	18 days	11 days	36.5 days
Water	Supply	65 days	112 days	68 days	113 days
	Distribution	5 days	10 days	8 days	15 days
Natural Gas	Supply	0 days	6 hours	6 hours	12 hours
	Distribution	6 days	27 days	26 days	33 days
Thermal Energy	Supply	0* days	0* days	0* days	0* days
	Distribution	0* days	4 days	0 days	5 days
Sanitary Sewer	Distribution	6 days	10 days	8 days	15 days

*Systems in which the median restoration time is zero have a probability of system failure less than 50%. Systems in which the 90th percentile restoration time is zero have a probability of system failure less than 10%.

L4.1 Electric Power

Table L.13 shows the best estimate times for service recovery, along with the main contributors to downtime, for the electric power system. Only rare and very rare intensity levels are shown because only municipal supply is anticipated to be disrupted in smaller earthquakes. Figure L.16 and Figure L.17 show the restoration curves for the electric power system.

Table L.13 Best estimate of service recovery times for the campus electric power service. All times are expressed in units of days.

Electric Power					
Rare Earthquake					
Best estimate of on-campus supply system restoration time	Best estimate of on-campus distribution system restoration time	Best estimate of offsite supply downtime	Best estimate of total service disruption time	Best estimate of time to 90% service recovery	Main contributors to downtime
12 hours	0 days	2 days	2.5 days	2.5 days	Offsite supply
Very Rare Earthquake					
Best estimate of on-campus supply system restoration time	Best estimate of on-campus distribution system restoration time	Best estimate of offsite supply downtime	Best estimate of total service disruption time	Best estimate of time to 90% service recovery	Main contributors to downtime
1.5 days	11 days	7 days	7 days	12.5 days	Offsite supply

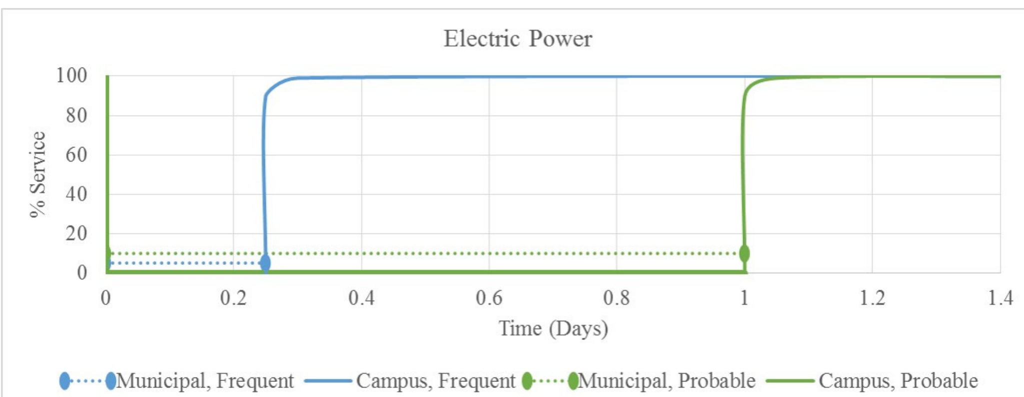

Figure L.16 Restoration curves for the electric power system (frequent and probable earthquakes)

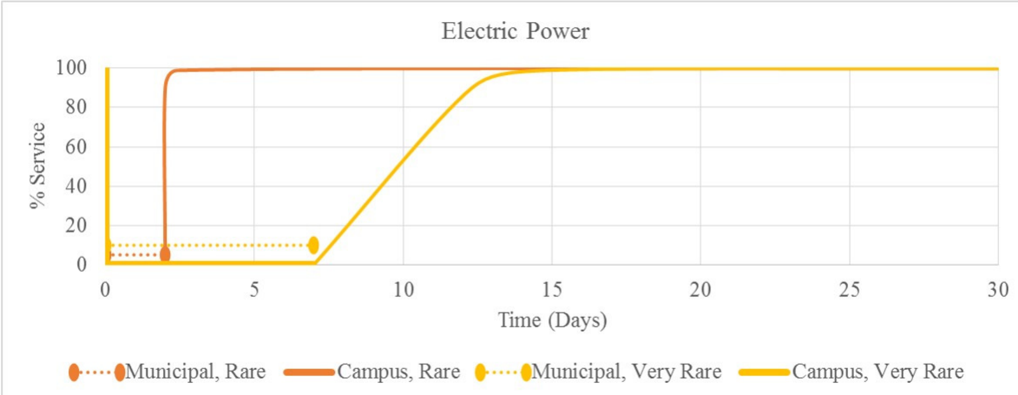

Figure L.17 Restoration curves for the electric power system (rare and very rare earthquakes)

Much of the time for which electric power experiences total service disruption can be attributed to loss of municipal supply. For all earthquake scenarios except the very rare return period, electric power is expected to recover to 90% service recovery a short time after the municipal supply is restored.

In the probable and frequent earthquakes, the time required to reach 90% service recovery after total service disruption is short, because no pipes are expected to break in that scenario. However, as the restoration time for each break in the electrical conduit is 7 days and the rare and very rare earthquake scenarios are expected to cause at least one break, the rate of recovery for those return periods is much slower.

L4.2 Water

Table L.14 shows the best estimate times for service recovery, along with the main contributors to downtime, for the water system in the rare and very rare earthquakes. Figure L.18 and Figure L.19 show the restoration curves for the water system.

Table L.14 Best estimate of service recovery times for the campus water service. All times are expressed in units of days.

Water					
Rare Earthquake					
Best estimate of on-campus supply system restoration time	Best estimate of on-campus distribution system restoration time	Best estimate of offsite supply downtime	Best estimate of total service disruption time	Best estimate of time to 90% service recovery	Main contributors to downtime
65 days	5 days	14 days	65 days	70 days	Offsite supply, damage to the Power House building
Very Rare Earthquake					
Best estimate of on-campus supply system restoration time	Best estimate of on-campus distribution system restoration time	Best estimate of offsite supply downtime	Best estimate of total service disruption time	Best estimate of time to 90% service recovery	Main contributors to downtime
68 days	8 days	21 days	68 days	76 days	Offsite supply, damage to the Power House building

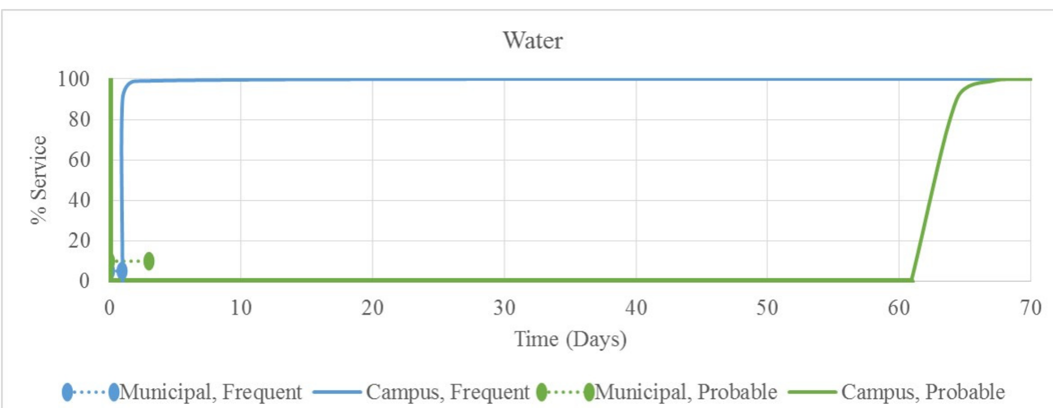

Figure L.18 Restoration curves for the water system (frequent and probable earthquakes)

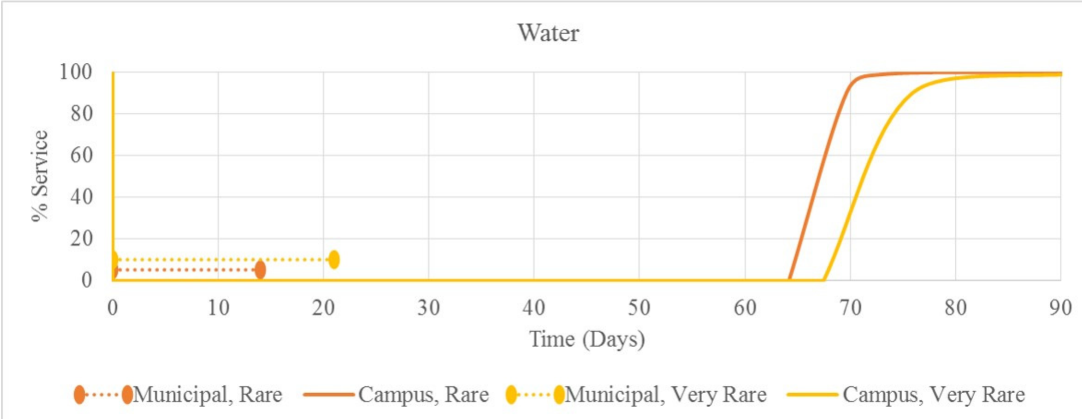

Figure L.19 Restoration curves for the water system (rare and very rare earthquakes)

Disruption to the water supply is dominated by the poor earthquake performance of the Power House building, in the probable, rare, and very rare earthquakes. The Power House has a high probability of collapse in rare and very rare earthquakes and has a high probability of being red-tagged in a probable earthquake. In these scenarios, we assume that water will be restored before the Power House is re-built, by UBC taking extraordinary measures to re-locate the water supply lines and pumps to an alternate location. We assume that this will take roughly 60 days for the purposes of the risk assessment. The Power House is the key vulnerability in the entire utility network.

L4.3 Natural Gas

Table L.15 shows the best estimate of times to service recovery, along with the main contributors to downtime, for the natural gas system in the rare and very rare earthquakes. Figure L.20 and Figure L.21 show the restoration curves for the natural gas system for all earthquake scenarios.

Table L.15 Best estimate of service recovery times for the campus natural gas service. All times are expressed in units of days.

Natural Gas					
Rare Earthquake					
Best estimate of on-campus supply system restoration time	Best estimate of on-campus distribution system restoration time	Best estimate of offsite supply downtime	Best estimate of total service disruption time	Median time to 90% service recovery	Main contributors to downtime
0 days	6 days	7 days	7 days	13 days	Offsite supply
Very Rare Earthquake					
Best estimate of on-campus supply system restoration time	Best estimate of on-campus distribution system restoration time	Best estimate of downtime of offsite supply	Best estimate of total service disruption time	Median time to 90% service recovery	Main contributors to downtime
6 hours	26 days	14 days	14 days	40 days	Offsite supply, shutoff valve

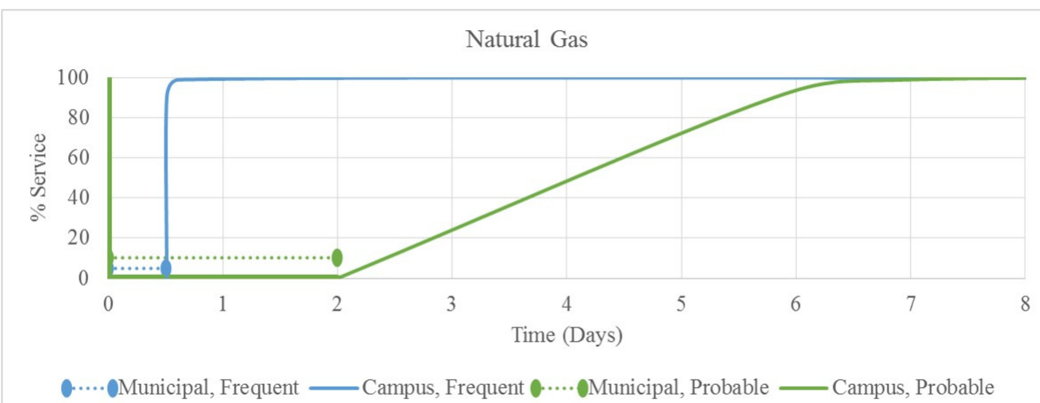

Figure L.20 Restoration curves for the natural gas system (frequent and probable earthquakes)

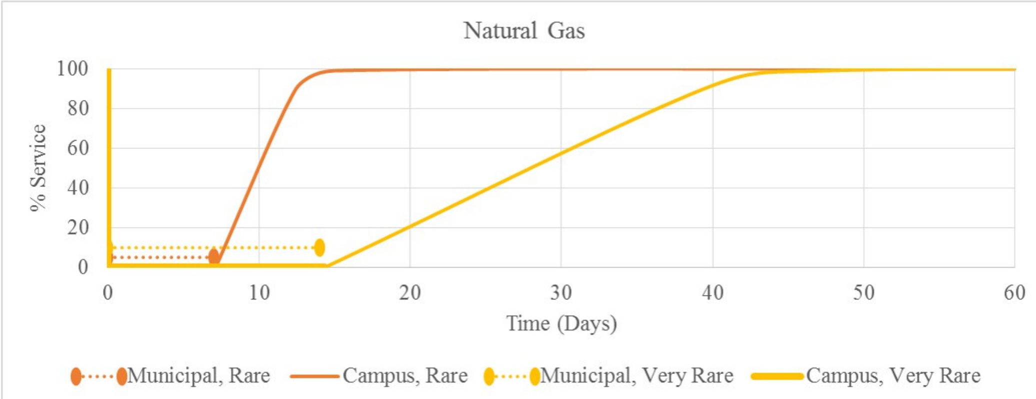

Figure L.21 Restoration curves for the natural gas system (rare and very rare earthquakes)

Natural gas is disrupted in rare and less intense earthquake shaking by the municipal supply. In very rare earthquake shaking, the shutoff valves are likely to be triggered. A major contributor to natural gas service recovery is re-lighting and re-pressurizing the distribution system which is anticipated to take a significant amount of time (hence the gradual curve towards 90% service recovery). An effective mitigation measure would be to implement operational preparedness measures that dedicate more manpower to priority buildings for re-lighting after an earthquake, particularly for sensitive research specimens that require constant access to natural gas supply.

L4.4 Thermal Energy

Although the best estimate of supply system restoration times in our analysis is zero days, the natural gas offsite supply is expected to be unavailable for more than the 12 hours that can be mitigated by the backup diesel fuel. Thus, in order to maintain the functionality of the thermal energy service after an earthquake, UBC should prepare for a larger supply of diesel fuel to be used while the offsite gas supply is unavailable.

L4.5 Sanitary Sewer

Table L.16 shows the best estimate of service recovery times, along with the main contributors to downtime, for the sanitary sewer system. Note that the analysis does not include a separate model/fault tree developed for the sanitary sewer supply system, and thus only restoration times for the distribution system have been calculated. In addition, water supply would be required to utilize the sewer system. Often, this is disrupted for a longer period of time than the sewer system. While sanitary sewer is not expected to experience total service disruption due to an earthquake, other damages to the sewer distribution network could result in health hazards for UBC's campus.

Table L.16 Best estimate of service recovery times for the campus sanitary sewer service. All times are expressed in units of days.

Sanitary Sewer					
Rare Earthquake					
Best estimate of on-campus supply system restoration time	Best estimate of on-campus distribution system restoration time	Best estimate of offsite supply downtime	Best estimate of total service disruption time	Best estimate of time to 90% service recovery	Main contributors to downtime
N/A	6 days	N/A	0 days	6 days	Distribution pipelines
Very Rare Earthquake					
Best estimate of on-campus supply system restoration time	Best estimate of on-campus distribution system restoration time	Best estimate of offsite supply downtime	Best estimate of total service disruption time	Best estimate of time to 90% service recovery	Main contributors to downtime
N/A	8 days	N/A	0 days	8 days	Distribution pipelines

L5 Conceptual Mitigation Strategies

This section presents several conceptual mitigation strategies to address critical vulnerabilities and reduce expected restoration times. It also estimates expected costs for each strategy. The mitigation strategies considered include:

- Continue replacing brittle piping in the distribution systems
- Establish a protocol/retainer contract for obtaining a hydrovac within one day after the earthquake
- Ensure that there is a readily available supply of diesel fuel capable of supporting the thermal energy supply service in the event of loss of offsite natural gas supply
- Establish a protocol for implementing a temporary facility in the event that the Power House is red-tagged and thus would not be accessible to repair crews for an extended period of time
- Replace the Power House to improve structural integrity and vulnerability of equipment stationed inside. If the replacement process would take a long time, an interim facility to which equipment could be moved may also be recommended.

These mitigation options are within UBC's control. Unfortunately, the municipal supply outages tend to dominate many of the scenarios considered and mitigation of some on-campus systems will not significantly reduce the risks. However, there is a possibility that the municipal supply outages have been overestimated. In that case, the on-campus mitigations will have a larger impact.

L5.1 Expected restoration times for conceptual mitigation strategies

Three mitigation measures were explicitly modeled in the risk analysis to quantify their benefits. Brittle pipe replacement, hydrovac retainer contract, and Power House replacement were explored as potential mitigation measures as these were expected to have the most impact on expected service disruption times and were the most likely to be pursued. The results of modeling these mitigation measures are described in the following section.

L5.1.1 Brittle pipe replacement

The water distribution pipelines are composed of either cast iron or ductile iron. The former is a brittle material and has a higher probability of breaking in a seismic event. This section describes the results of modeling a water distribution system with all of the cast iron piping replaced with ductile iron piping.

Figure L.22 shows the water service restoration curves before and after replacing the brittle pipes in the distribution system. Although the total service disruption time remains the same, the rate of recovery to 90% service is faster for the system with only ductile piping. Table L.17 presents the best estimate of number of water distribution pipe breaks for the four earthquake scenarios being considered, as well as the 90^{th} percentile estimate of breaks. A brittle pipe replacement program would reduce the time to 90% service recovery by only one day, as it would reduce the best estimate of number of breaks by 1 and each break has an expected restoration time of 1 day. In summary, our analysis demonstrates that it may not be cost-effective to replace the brittle pipe, at least from a seismic perspective.

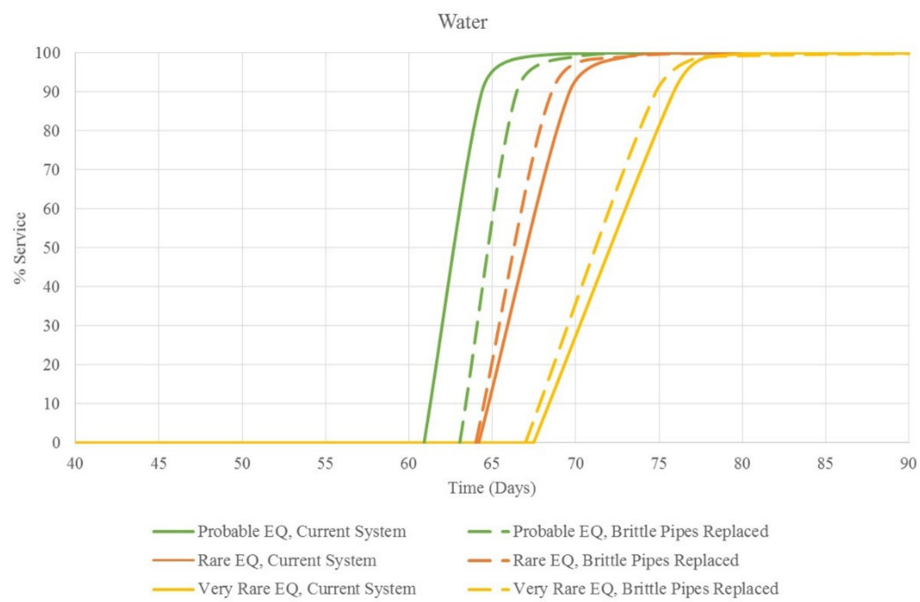

Figure L.22 Restoration curves of the water system before and after the brittle pipe replacement

Table L.17: Number of pipe breaks anticipated for the current water distribution system and the system with only ductile piping

Earthquake scenario/return period	**Current System**		**Brittle Pipes Replaced with Ductile Pipes**	
	Best estimate of number of breaks	90th percentile estimate of number of breaks	Best estimate of number of breaks	90th percentile estimate of number of breaks
Frequent	0	2	0	1
Probable	1	3	0	2
Rare	3	6	2	5
Very Rare	5	12	4	9

L5.2 Hydrovac Retainer Contract

All buried pipelines require a hydrovac to begin repair work. Currently, UBC does not own a hydrovac and must acquire one from an external source. The model of the existing utility systems assumes a median time of 3 days (this may be unconservative) to acquire a hydrovac, and this time is added to the total restoration time whenever there is at least one underground pipe break.

If UBC were to establish a retainer contract with a local company and guarantee that a hydrovac could be acquired within 1 day after a seismic event, the time estimated for distribution pipe repairs would decrease significantly. Relative to the estimated municipal supply outages, the estimated time to repair pipes is not significant. However, if the municipal supply happens to perform well, the restoration of piping would be critical path and the hydrovac appears to be an attractive option.

Figure L.22, Figure L.23, and Figure L.24 show the restoration curves of electric power, water, and natural gas with and without the hydrovac retainer contract. The restoration curves consistently reach 90% service recovery approximately two days earlier with the hydrovac retainer contract in place. Only the earthquake scenarios in which there is at least one underground pipe break are shown in the following figures.

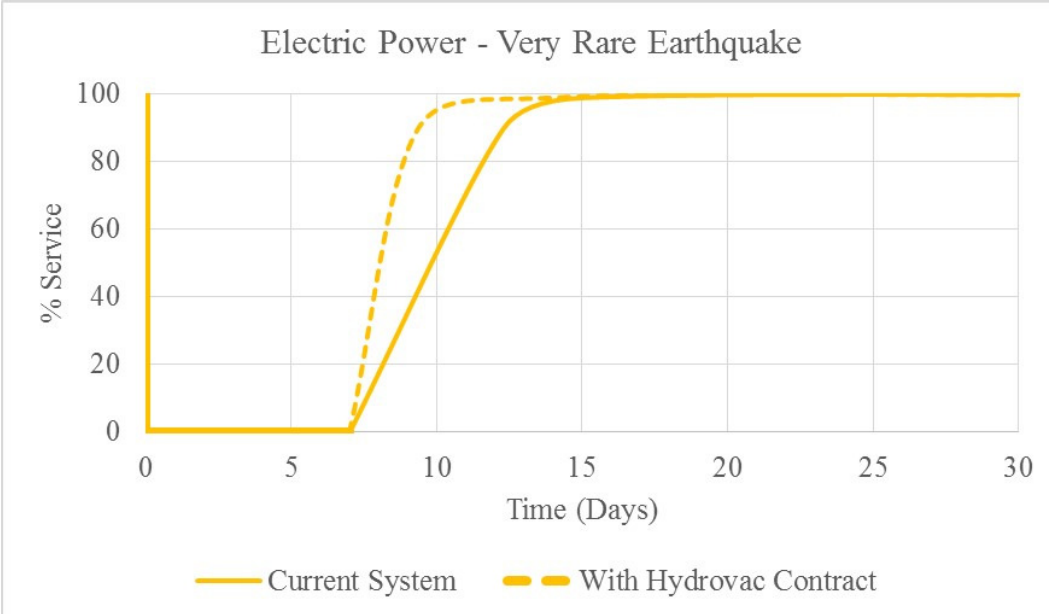

Figure L.22 Electric Power system - restoration curve comparison for the very rare earthquake scenario

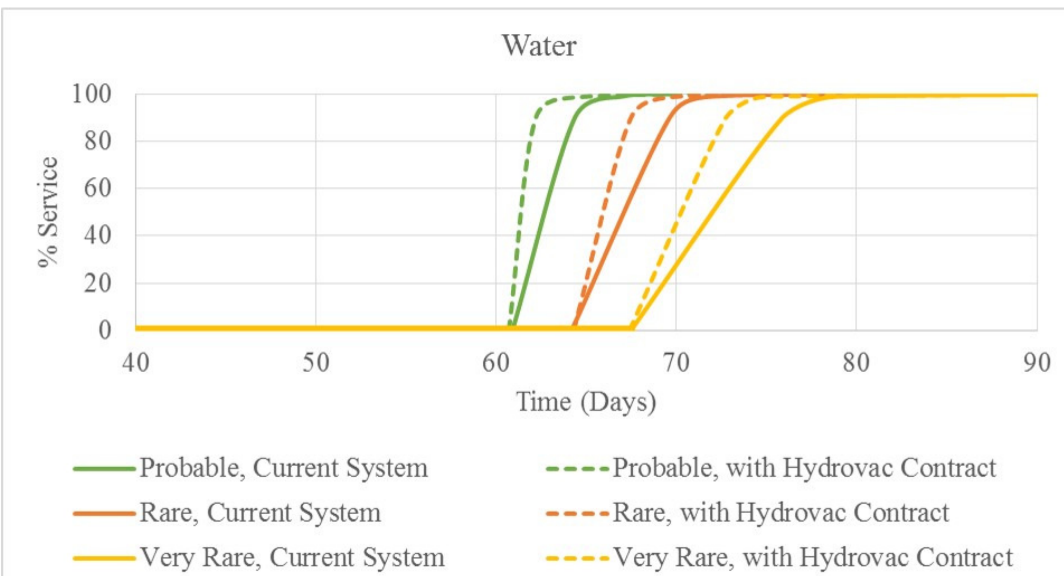

Figure L.23 Water system - restoration curve comparisons for the probable, rare, and very rare earthquake scenarios

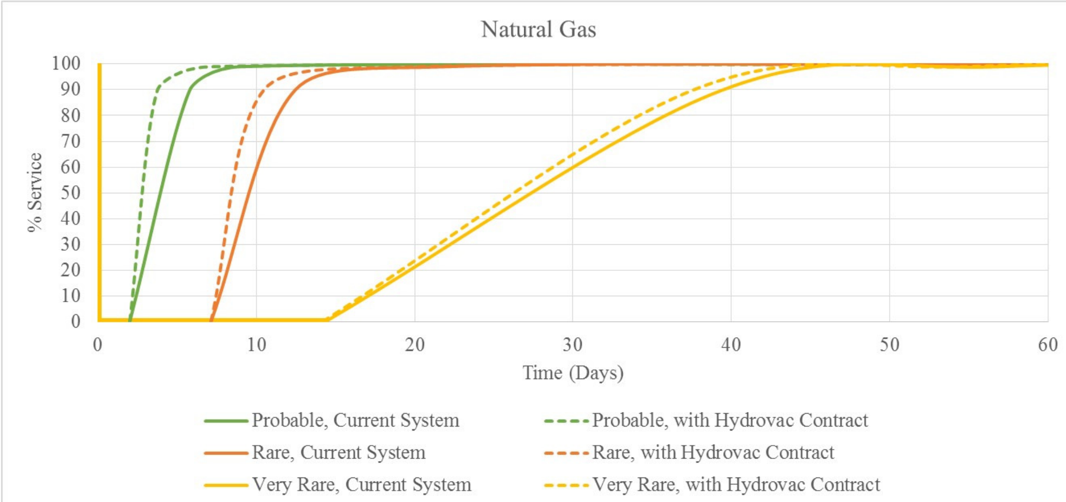

Figure L.24 Natural gas system - restoration curve comparisons for the probable, rare, and very rare earthquake scenarios

L5.3 Power House Replacement

A key contributor to water disruption is the Power House facility that houses the water pumps. In all earthquake scenarios greater than the frequent intensity level, there is at least a 50% probability of the Power House being demolished, collapsed, or otherwise red-tagged (not safe for entry). In these scenarios, the water pumps and piping within the Power House are likely to be damaged and inaccessible for repairs. We assume it would take at least two months to install temporary mitigation measures to allow for water service on campus. Replacing the Power House with a new building or shelter for the water pumps —one that would perform in a capacity similar to the Campus Energy Centre in a seismic event—would greatly reduce the downtime associated with the water supply system and remove the single greatest vulnerability on the campus.

Figure L.25 shows the expected restoration curves for the current water system configuration, as well as the expected restoration curves for the water system after replacing the Power House.

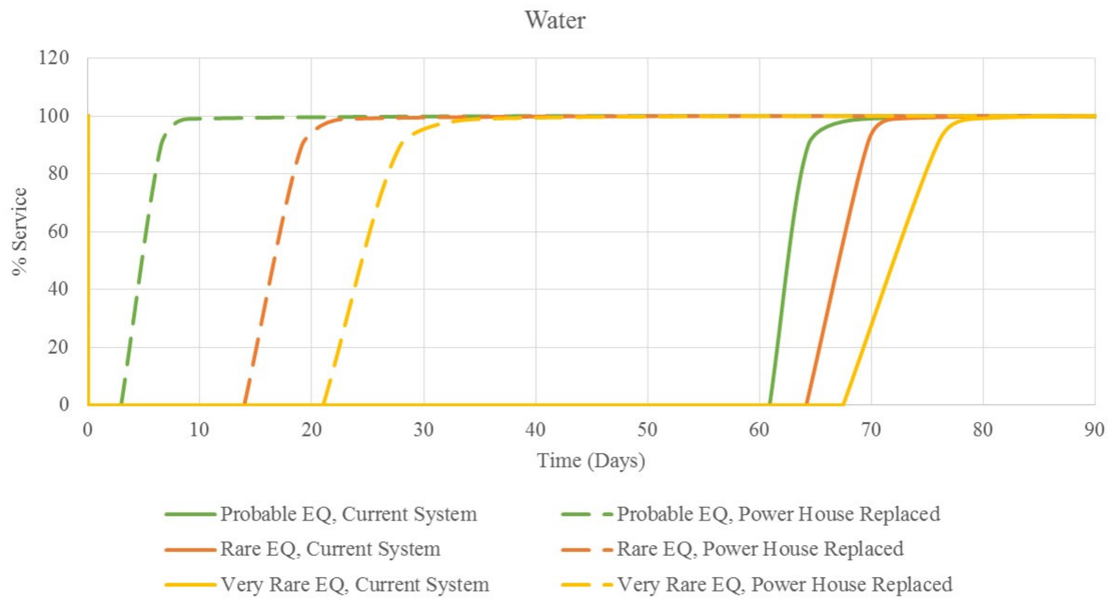

Figure L.25 Comparison of water service restoration curves with the current system and with the Power House building replaced

Replacing the Power House with a building that has a low probability of collapsing or sustaining significant structural damage in an earthquake dramatically reduces the estimated time of total service disruption. Thus, this action is expected to be a worthwhile investment to prevent long-term outage of water service on campus.

L6 References

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Appendix M

Resilience Assessment of
Campus Operations

M1 Introduction

This appendix provides detailed documentation of the operational risk assessment Arup conducted for the Point Grey campus. This assessment used the Campus Resilience Index as a guide. The four main resilience dimensions are people, business, assets, and organization. Within each dimension there are three drivers, which in turn comprise 4-5 indicators, resulting in a set of 51 indicators that address different aspects of resilience.

The appendix is organized into four main sections, one for each of the four resilience dimensions. Each section features a table that documents the assessment process for each indicator. More specifically, the tables provide background information for each indicator in the Campus Resilience Index, including a description of the indicator, why it is important, and criteria for assigning different resilience scores. The tables also document information we compiled for each indicator from various sources, including documents shared by UBC staff or available publicly and notes from workshops, interviews, and personal communications with UBC staff. Based on this information, we assigned a score for each indicator, including a discussion of progress and remaining gaps. Despite efforts to be as comprehensive as possible, we were unable to gather sufficient information to assign scores for a small number of indicators.

The assessment informed our recommendations contained in section 8 of the main body of the report.

M2 People

	Goal	No.	Indicator	Prompt	Why is this Important	Best (5)	Medium (3)	Worst (1)	Notes from EMP and annexes	Notes from workshops/meetings	Score	Progress	Gaps
1	Basic Needs	1.1	Food Supply	To what extent does the University have access to an affordable, reliable, nutritious, and locally-sourced food supply?	Accessible food sources are critical following an event as normal delivery services may not be running. Vending machines and grocery chains may be emptied out even prior to an event. Food planning by campus facilities or nearby access to farms reduces dependencies on the intermediate links that could break.	The University has excellent onsite food production facilities that provide locally-sourced, nutritious, affordable meals to all students and staff, and has contingency plans for obtaining food during emergencies. In addition, surrounding communities have a wide range of food options (e.g., grocery stores, restaurants, farmers markets, etc.).	The University has capacity to provide meals to some students, faculty, and staff, but meals might not be not locally-sourced, nutritious, or affordable. Some surrounding communities are "food deserts."	The University has no onsite food production capabilities and no contingency plans. Surrounding communities are "food deserts."	-- EMP: UBC will "use existing agreements with private sector providers of accommodation, food, fuel and sanitation facilities for reinforcement or augmentation of existing UBC emergency response and recovery activities" -- EMP: specifies a goal of having sufficient food to feed 72,000 people for three days -- Annex F: identifies core task of building operations task force as "Being prepared to provide support to logistics task force warehousing operation" -- Annex J: logistics task force responsible for acquiring food for mass care task force (3-5 days of supply typical, though unclear for how many people) -- Annex J: logistics task force to coordinate distribution of propane for cooking (7 days of supply)	-- UBC recently purchased 6 food trucks, which in an emergency can function as mobile kitchens. -- There is also a small farm on campus. -- UBC is currently working on an MOU with a south campus grocery store. -- Dorms do not have emergency food rations. -- Rockefeller Study to understand resilient food crops to grow in campus farm. -- Standard food delivery from Sysco is expected to feed staff and students for 72 hours.	3	-- EMP specifies goal of having food for 72,000 people for 3 days -- Annex J mentions a stockpile of food for medical task force and propane for cooking, but unclear where food is stored and how many people it can feed -- Have assets that could be useful in an emergency, including: o six food trucks o small farm with farmers market o several restaurants -- Grocery store near campus (currently working on an MOU)	-- UBC likely to be well short of specified food goal -- Lack of emergency food rations in dorms -- Limited warehousing capabilities -- Lack of coordination of existing resources -- Food rationing strategy not developed
		1.2	Water Supply	To what extent does the University have access to a clean, reliable supply of drinking water?	Shocks can often result in water supply being cut off due to damaged infrastructure and/or contamination. Water that is controlled internally by the campus is exposed to less potential failure simply because there are less dependencies.	The University has its own source of water, onsite treatment facilities with backup power, and storage capacity of several days for the entire campus. In addition, the University has contingency plans for obtaining potable water during emergencies and has enacted water-conservation technologies and policies.	Water is supplied by a municipal provider that has taken steps to reduce system vulnerabilities. The campus has some onsite water storage capacity for essential functions.	Water is supplied by municipal system through vulnerable area. The University has no onsite storage facilities and no contingency plans.	-- EMP: mentions "planning and pre-positioning of materials and supplies required for future emergencies" (e.g., stockpiling of water) as an action in the prevention and mitigation phase. -- EMP: specifies a goal of having sufficient potable water for 72,000 people for three days. --Annex F: states that UBC expects to be without full water service for up to 12 weeks after a M7.3 earthquake in the Strait of Georgia -- Annex F: identifies core task of building operations task force as "Establish water pumping station at alternate water point (Botanical Gardens) and be prepared to commence water distribution plan in accordance with logistics task force" -- Annex J: logistics task force responsible for provision of potable water but quantities are not specified	-- UBC has a portable trailer with filtration capabilities that can pump from a campus creek, though there are potential issues with the flow in the creek. -- UBC is still developing a strategy (with the help of students) for distributing water pumped by the mobile trailer. -- New aquatic center has capacity to store 1 million liters of rain water. -- 2014 Water action plan looks at governance issues and strives to reduce dependency on regional water sources. Explores redundant water service, building scale systems and rainwater recovery.	3	-- EMP specifies goal of having potable water for 72,000 people for 3 days -- Portable water pumping and filtration capabilities; distribution strategy currently under development -- Potential emergency supply of water at new aquatic centre (though unlikely to be potable) -- Some water mains have been replaced	-- UBC likely to be well short of specified water goal -- Critical water equipment at Power House is highly vulnerable to earthquake damage, which will disrupt water distribution on campus -- Portable water pumping and filtration capabilities likely insufficient for demand -- Water rationing strategy not developed -- Limited water storage capabilities -- Some water mains old and brittle
		1.3	Sanitation Systems	To what extent does the University have a robust, reliable sanitation system?	Broken or nonfunctioning sanitation systems can lead to disease outbreak and fatalities after an event. When large populations become sick at the same time this can become overwhelming for health facilities to treat.	Onsite waste water collection and treatment facilities are robust and protected against threat.	The campus relies on a regional/offsite sanitation system and maintains no control.	The sanitation system is frequently overloaded.	-- EMP: UBC will "use existing agreements with private sector providers of accommodation, food, fuel and sanitation facilities for reinforcement or augmentation of existing UBC emergency response and recovery activities" -- EMP: specifies a goal of having sanitation for 72,000 people for three days -- Annex F: identifies core task of building operations task force as "Be prepared to provide support to logistics task force in the provision of non-potable water for ablution requirements."		3	-- EMP specifies goal of providing sanitation to 72,000 people for 3 days after an emergency -- Most of sewer system is gravity fed and thus not dependent on power -- Some sewer mains have been retrofitted -- Lift stations have backup diesel generators	-- Unclear how UBC plans to achieve specified sanitation goal -- North collection point highly vulnerable to cliff erosion (but have approximately 10 years to mitigate) -- Lift stations have limited supply of fuel (typically 4-6 hours); unclear how UBC plans to refill them -- Unclear if UBC has plans for preventing and/or responding to sewer overflows -- Some sewer mains old and brittle
		1.4	Waste Management	To what extent does the University have an adequate waste management program? To what extent has the University protected students, staff, and property from hazardous materials?	Containment of toxic waste materials is as important as containing sewage. Poor waste management or lack thereof can also lead to sickness and fatalities. It is important that waste is removed prior to decomposition.	Collection and disposal service is internal to campus to protect against failed external service and strikes. There is containment of onsite hazardous materials such as bio research animal waste and protection against upstream offsite contamination.	Campus relies on regional/external waste collection service. On site containment of hazmat but campus is exposed to external contamination.	Waste collection service is provided by the city or region often experiencing failure. Unsanitary, dirty, exposed or unsafe areas on site.		-- Currently UBC has no plan for post-disaster clean up and debris removal, but does have at least a dozen cranes on campus for various construction projects (maybe also use for USAR). -- Campus maintains a 75% diversion goal by 2015 but have managed to meet 67% in 2016 so are doing well. -- Solid waste is collected by university fleet and taken to offsite disposal at the municipal landfill	3	-- UBC has waste management department that "provides both waste management services and waste reduction education to the UBC campus community through the coordination of recycling, composting, e-waste, and litter reduction initiatives" -- UBC has established waste diversion goals	-- No plan for post-disaster clean up and/or debris removal
		1.5	Climate Control	To what extent has the University implemented strategies for reducing external temperatures caused by urban heat island effect? Have buildings on campus been designed to maximize occupant thermal comfort? Poor cooling at night may lead to heat exhaustion and loss of function.	Very high or very low outside air temperatures limit the use of outdoor space and confine people to indoor activities which can reduce overall capacity and ability to have redundancy. Lack of proper cooling and heating can effect human sleep patterns reducing rest, ability to concentrate, learning capability and functionality.	Ample well shaded areas reduce exposure to heat and protect against dehydration and fatigue from lack of sleep. Cool roofs, green roofs, green spaces, trees, cool pavements, permeable surfaces, and other strategies have been implemented to reduce urban heat island effect. All buildings on campus are designed for passive comfort and have state-of-the-art control systems to monitor and adjust internal air quality and temperature.	Some strategies to mitigate urban heat island effect have been implemented or are being considered. Some buildings have air conditioning and only a few are designed for passive comfort or include advanced control systems to monitor occupant comfort.	Campus is located in a very hot area with no shade protection. The university has taken no actions to mitigate urban heat island effect. Few buildings have air conditioning or passive comfort designs.			3	-- The Vancouver climate is pretty moderate, so unless an emergency occurs in the winter, people should be able to remain comfortable outside for several hours -- EMP specifies mass care reception centres at UBC Tennis Centre, Student Rec Centre, and UNA community centre -- Most campus buildings get their heat from the district energy system, which was constructed in 2015 and appears to be highly reliable and redundant -- New buildings designed for LEED Gold	-- Unclear whether UBC has a strategy for providing temporary shelter from the cold to the campus population -- Highly centralized nature of the district energy system means that if the energy centre goes offline it will impact a significant portion of campus buildings -- Unclear whether LEED Gold buildings are designed for passive survivability

	Goal	No.	Indicator	Prompt	Why is this Important	Best (5)	Medium (3)	Worst (1)	Notes from EMP and annexes	Notes from workshops/meetings	Score	Progress	Gaps
2	Healthcare	2.1	Medical Services	To what extent does the University have access to reliable, affordable health care? To what extent are important medications available to students and staff?	On site health care or close access from campus is critical after a shock as dependency on an external facility will come with competition for service that may result in students having deprioritized attendance or no service at all.	Primary care services with sufficient bed capacity are on site or within close proximity to be dependable during an emergency event.	Medical facilities on site include a clinic or day use office unable to house patients over night during an event.	There are no medical facilities on site.	-- EMP: UBC Hospital is expected to provide a larger spectrum of medical treatment options during an emergency -- EMP: a Mobile Emergency Care Centre (MECC)/Triage Facility is to be located at the entrance to the UBC Hospital -- Annex I: "UBC hospital will respond to the direction of the Vancouver General Hospital (VGH)/Vancouver Acute (VA) and Vancouver Coastal Health (VCH); therefore, may be unable to provide direct support to UBCV casualties or those UBCV residents which self-present in hopes of receiving medical treatment." -- Annex I: "UBC Hospital may not be available for casualty treatment due to influx of casualties from other locations sent by Vancouver General Hospital/Vancouver Acute/Vancouver Coastal Health Agency"	-- The campus hospital is an urgent care facility (not a trauma center) with 150-200 inpatient beds. The primary trauma receiving center is VGH. The UBC hospital is almost an inpatient department of VGH. There has been some nonstructural mitigation at the hospital but the building is old and its seismic performance is questionable.	4	-- UBC Hospital is located on campus and is likely to play a significant role in an emergency -- UBC also has a mobile triage facility that can provide emergency medical treatment -- There is an ambulance station on campus with two parking spots	-- Coordination with UBC Hospital appears to be lacking; hospital may have different priorities than campus -- UBC Hospital vulnerable to damage in an earthquake and may be rendered unusable (note: an assessment of the UBC Hospital is outside the scope of this study) -- Ambulances are not dedicated to UBC -- Capacities of medical facilities unknown
		2.2	Medication Availability	To what extent are important medications available to students and staff?	Deliveries following an event may not be reliable. If there are students or staff who depend on any type of medication refills, this service is critical.	72 hours of predicted medication needs on site for use during and after hazard events. Provides flu shots and vaccines to students free of charge.	Medications are available on site but no calculations have been run to understand minimal 72 hour needs.	No medications are housed on site.	-- EMP: identifies "planning and pre-positioning of materials and supplies required for future emergencies" (e.g., stockpiling of first aid supplies) as an action in the prevention and mitigation phase. -- Annex J: logistics task force will "liaise with UBC departments and private sector pharmacies for the acquisition of additional emergency medical supplies" -- Annex I: "UBCV does not hold a large stock of medical supplies; therefore, the Provincially controlled National Emergency Stockpile System (NESS) will be expected to provide medical logistic support after the first 24 hours" -- Annex I: "During Phase 1 (i.e., before an emergency), Student Health Services, Faculty of Medicine, logistics task force, and Risk Management Services will coordinate the development of a baseline medical supplies inventory and identify how these requirements can be sourced" but the status of this task is unclear.		2	-- Recognition of need to coordinate with different groups and departments to determine medicine needs -- Identification of National Emergency Stockpile System as potential supply of medicine in first 24 hours -- Annex I specifies maintaining a minimum of 5 days of medical supplies	-- Unclear whether the medical supply needs assessment has been performed and where such supplies would be stored -- Unclear how UBC will access the national stockpile in an emergency (i.e., no MOUs in place)
		2.3	Mental Health Counseling	To what extent do students and staff have adequate, affordable access to mental health counseling?	If an event occurs there will be an increase in stress which can lead to students and staff requiring increased mental health services.	Well-advertised free counseling services are available to all students and staff before and after shocks.	Mental health services are available on site but are limited by cost or quantity.	There are no mental health services on site			NR		
		2.4	Emergency Response	To what extent does the University have mechanisms in place to mobilize critical emergency response services after a disaster event?	In the case of a major event, local emergency services will likely be overwhelmed. Independent services allow the university to maintain internal control of student emergency transport.	The university has an onsite ambulance service or other medical transport system with trained EMT staff.	The local emergency response service is within reach of the campus but does not maintain exclusive contracts for use during an event which could result in overloading.	Minimal access to Emergency Medical Services with the immediate area.	-- EMP: identifies "mass care" and "medical" as two Emergency Support Functions and establishes respective task forces with responsibility for coordinating and executing actions -- EMP: identifies the Commonsblock Building #6 as the mass care task force HQ, and UBC Hospital and Koerner Pavilion as medical task force HQs -- EMP: specifies the following locations for mass care receptions centres: UBC Tennis Centre, Student Rec Centre, UNA community centre -- Annex F: Building Operations task force will coordinate with Facilities Planning task force to undertake search and rescue operations -- Annex I: "UBCV's student population has an Emergency Medical Assistance Team (EMAT) construct which will be included in the emergency medical treatment concept"	-- UBC has a mobile medical unit for first aid and a large number of students with first aid training. -- There is an ambulance station on campus with two parking spots but the trucks are not dedicated to UBC (i.e., they can be deployed anywhere). -- Task Force Mass Care (TFMC) is responsible for activation of Emergency Response teams	3	-- EMP establishes medical task force for coordinating emergency medical services -- Annex I specifies "patient care continuums" (i.e., protocols) for responding to different types of emergencies -- Annex I identifies students with first aid training as a potential resource in responding to an emergency	-- Lacks regular training exercises -- Leadership structure of medical task force is unclear -- Patient care continuums make assumptions about availability of UBC Hospital and other facilities in an emergency
3	Safety	3.1	Campus Guidelines	To what extent has the University enacted guidelines that enhance campus safety and security?	Without guidelines or rules there can be no legal enforcement and nothing for police to uphold if the campus were to see rioting or unrest.	Campus Policies, Rules and Laws exist to mitigate crime and confusion following shocks.	Campus has minimal rules or guidelines	There are no campus rules or guidelines to prevent crime and confusion.			NR		
		3.2	Security	To what extent are police adequately trained and resourced to effectively respond to call-outs?	Police should be available to help and protect students and staff if there is any form of unrest following a major event.	Campus Police Department is visible and able to protect occupant safety against post shock situations, including civil disturbances.	Campus has small police department with poor track record of preventing crime.	No campus police department. Campus utilizes local city police department for security.	-- EMP: recognizes the threat of cyber attacks aimed at University research and intellectual property -- EMP: identifies "public safety" as an Emergency Support Function and establishes a task force with responsibility for coordinating and executing actions -- EMP: identifies the Campus Security building and UBC Bookstore as task force HQs		3	-- Have emergency "blue phones" throughout campus and late night "safewalk" services -- EMP recognizes the threat of cyber attack -- EMP establishes a public safety task force -- In general, crime on campus appears to be pretty rare	-- Unclear what cyber security protections have been implemented
		3.3	Safe Environments	What is the safety level of the campus?	Are there dark poorly lit areas or zones that have a history of attack?	The campus is well lit and there are no secluded areas know for attacks.	The campus has some history of attacks but events are minimal.	The campus is in a dangerous area with high crime statistics that include attacks on campus.			NR		
		3.4	Fire Response	To what extent are the fire services adequately trained and resourced to effectively respond to call-outs?	Fire service response is typically the first response to a disaster even if it is not a fire. They are likely to include EMTs.	On campus Fire Department with quick response times.	Regional fire department supports campus but is located near site. Will share coverage with city during an event.	Campus relies on City or Regional fire department and is situated in congested urban area.		-- Training exercises and threat assessment around forest fires	3	-- Has fire hall on campus with two crew and three fire apparatus that can quickly respond to a small fire -- Fire hall is operated and staffed by Vancouver Fire and Rescue Service, who is well prepared for a major earthquake	-- Fire hall is not dedicated to serving UBC, so after an earthquake crews may be deployed to other locations -- Water supply for firefighting is vulnerable to seismic damage and disruption; campus has limited onsite water storage capabilities

M3 Business

	Goal	No.	Indicator	Prompt	Why is this Important	Best (5)	Medium (3)	Worst (1)	Notes from EMP and annexes	Notes from workshops/meetings	Score	Progress	Gaps
4	Finance	4.1	Insurance	To what level has the university insured their critical assets and processes?	Insurance is one potential stream of funding after an event.	All assets and processes have high levels of coverage with guaranteed speedy payout following an event	The campus portfolio is fully insured but many assets may have poor coverage due to inaccurate assessment of value and content	Most assets on site are underinsured or self-insured.			3	-- UBC has core academic insurance through the province and optional insurance with $175 million seismic sub limit	-- Uncertainty around payout timing -- Some buildings of considerable value are not included in the core academic coverage -- Optional coverage may be inadequate
		4.2	Funding	To what extent does the University have adequate funding mechanisms secured for emergencies and other unforeseen events?	If the campus does not have funding set aside for potential repairs they may have to wait long periods of time to receive funding approval from FEMA or other sources.	Funding and financing mechanisms (including insurance, cash reserves, lines of credit) in place to repair damaged systems following a shock.	There is some operational cash available on hand but many repairs would need financing.	Funding is subject to grants and insurance applied for after events potentially taking months or years to become available.	-- EMP: Board of Governors has approved a Strategic Emergency Resolution of up to $20 million for response and up to $60 million for recovery operations	-- $2.5 Billion budget $600M in annual research grants, $600M in student fees, $600M government funding -- $0.5B in cash reserves on hand and $100 M line of credit	3	-- Board of Governors has allocated $20 and $60 million for response and recovery activities -- Could possibly receive federal/regional aid	-- Unclear what the allocated funding is for, or if it's adequate for a major earthquake -- Uncertainty around the when federal disaster funds would be available
		4.3	Student Financing	To what extent do students have adequate access to financial resources for tuition and other expenses?	Students may experience financial loss during an event due to damaged assets (computers, clothing, cars). The ability to get loans allows students that have no financial cushion to take out loans to repair or replace their essential items.	Students maintain a broad ability to finance fees and educational costs.	Funding is available to most students requiring assistance with educational costs.	Only basic support provided for student fee and educational needs		-- International and domestic students pay different fees for attendance	NR		
		4.4	Managed Expenditures	To what extent does the university manage annual expenditures?	High levels of expenditures in areas that are beyond standard operating costs could lead to low or negative funds.	The campus has well managed capital projects and finance departments.		The finance department is poorly organized and audits may come back with poor results.		-- Organized investment plan	NR		
5	Revenue	5.1	Services	To what extent has the University protected important research equipment and materials from threat? To what extent is the university prepared with backup educational resources?	Loss of research could set the university back years and negatively impact their ability to publish notable work. Access to additional seating, computers, books, specimens, test materials, printers, projectors and lights will allow classes to resume more quickly even after there has been damage.	All specimens and test materials are protected from threat with shock resistant systems. Appropriate tools and materials are available to continue educational services.	Specimens are generally protected in "safe" areas but have not been uniquely accounted for. Materials are resourced as needed.	There has been no special protection of specimens identified. Equipment is basic and not well maintained.	-- Annex J: logistics task force responsible for identifying the number and types of alternative facilities required for the continuation or resumption of university operations, including research -- Annex H: facilities planning task force to "lead the development of contingency plans relating to temporary accommodation, academic, or research facilities"		2	-- Business continuity plans distinguish between high priority and normal courses -- Business continuity plans identify critical functions for campus departments, which might include research activities -- EMP annexes assign responsibility for temporary research facilities to logistics management and facilities planning task forces	-- Unclear whether UBC has developed list of high priority courses -- Lack of teaching recovery plan, including thresholds for maximum amount of space that can be lost before campus operations are significantly impacted -- Lack of centralized research continuity plan for departments and faculty to follow -- Unclear who is responsible for protecting lab equipment and materials
		5.2	Investment	To what extent does the university maintain reliable revenue streams?	Universities often provide medical services or real-estate leasing as part of revenue generating business investments.	University has planned for continuation of external business services offered to the public such as medical and real-estate leasing.	Continuation of external medical services are planned for but there is no planning for additional business	There is no BCM planning for business services			NR		
		5.3	Market	What is the demand for services on site? To what extent has the University cultivated a reputation for excellence in teaching or is the university strategically located?	School rankings play directly into to the attractiveness and retention of enrollment at a school.	Students are provided high quality education by world class staff	Education is medium and staff has high turnover.	Education is basic and equivalent can be found elsewhere			NR		
		5.4	Business Impact Assessment	Has the university performed a business impact assessment for critical functions subject to expected shocks?	In order to maintain continuity of services it is important to know the potential impact of major events, both positive and negative.	The University has conducted a business impact assessment and has taken steps to mitigate critical vulnerabilities, and updates the assessment regularly.	The University has conducted a business impact assessment but has not mitigated critical vulnerabilities.	The University has not conducted a business impact assessment.		-- UBC currently lacks campus wide business impact assessment, but staff recognize this as a gap.	2		-- Lack of campus wide business impact assessment -- Unclear if UBC has developed protection plans for its various revenue streams (e.g., rent, merchandise, sports, etc.)
6	Operations	6.1	Business Continuity Planning	To what extent has the University developed adequate business continuity plans?	A business continuity plan is an important first step in identifying how to continue teaching, feeding, housing and generally taking care of students following a shock. If this hasn't been considered, there is often a lack of direction on how to achieve the tasks. (especially under adverse conditions)	Business Continuity Management plans are in place to ensure events do not impact operation of the university including teaching and research.	BCM Planning is in place to ensure essential services such as housing, heating and elevators operate but does not include academics.	There is no BCM planning for campus operation	-- EMP: mentions implementing continuity plans during the recovery phase of a disaster. -- EMP: mentions using continuity plans as a guide in determining the remaining capability and capacity of UBC after a major emergency, including the number and type of academic or research facilities required	-- UBC has a platform for conducting business continuity planning (Kuali Ready) at the unit level (e.g., dept. of sociology), but it is not very flexible and does not enable prioritization of critical processes across different units.	3	-- Some groups and departments on campus have completed business continuity plans through online portal (Kuali Ready) -- EMP mentions using business continuity plans to guide recovery (i.e., determine capacity and needs)	-- Not all departments/groups have completed continuity plans, and completed plans are of varying quality -- Staff mentioned the online continuity tool is not flexible enough -- Lack of framework for aggregating and prioritizing critical functions identified in continuity plans -- Unclear how business continuity plans will be used to guide recovery

	Goal	No.	Indicator	Prompt	Why is this Important	Best (5)	Medium (3)	Worst (1)	Notes from EMP and annexes	Notes from workshops/meetings	Score	Progress	Gaps
		6.2	Emergency Operations Center	To what extent does the University have adequate and redundant emergency operations controls (EOC) during and after an event?	This will allow the university to continue organized command even if the primary control area is not functional.	There is a backup EOC location and systems to maintain key business functions during and after an event.	There is no identified backup EOC but planning has been performed as to how to manage operations if the primary EOC center was damaged.	There is no identified backup plan for operations.	-- EMP: uses a "modified Incident Command System structure in the establishment of its EOC" and specifies an EOC and task force structure -- EMP: establishes a Crisis Management Team for emergencies that do not require an EOC -- EMP: specifies discrete levels of EOC implementation depending primarily on the duration of the emergency -- EMP: specifies the EOC should be staffed and operational within one hour of notification during work hours and within two hours during non-work hours -- EMP: identifies the University Services Building as the primary EOC location, 2389 Health Services Mall as alternate EOC location, and the ICICS building as the spare EOC location -- Annex C: "provides the detail necessary for the effective operations of the EOC, its core components and the subordinate task forces." -- Annex C: specifies an alternate EOC location that differs from the EMP -- Annex C: specifies additional roles and responsibilities but it is unclear whether they have been assigned to individuals on campus	-- UBC has an Emergency Operations Centre (EOC) in University Services Bldg but is planning to move it to better space in Ponderosa (?). -- UBC also has a virtual EOC (i.e., DisasterLAN) that enables staff to log tickets after an emergency, but no one knows their passwords or how to use it. -- UBC anticipates it will take 24-48 hours to launch the EOC -- UBC has not developed procedures for operating at reduced capacity. -- If the incident takes place during the silent hours, TFBO workforce is expected to be reduced during the initial 48-72 hours of an emergency due to inability of TFBO personal to reach campus	4	-- EMP and Annex C outline protocols for establishing and running the EOC, including primary, alternate, and spare locations -- Have virtual EOC -- EMP appears to be very thorough	-- EMP has not been validated -- Unclear if staff knows how to use virtual EOC -- Unclear if training exercises conducted regularly -- Some roles and responsibilities not clearly assigned
		6.3	Logistics	To what extent have backup supplies of essential goods and services been identified and secured?	If the event results in shut down of typical operation for 24 hours or more, onsite supply stores will likely be exhausted before new supplies can be shipped in.	Delivery of essential goods such as food and backup generator fuels is ensured through contracts.	There are contracts in place for delivery of fuel but not for food or other services.	There are few logistics contracts and deliveries are performed by independent goods providers.	-- EMP: identifies "logistics management" as an Emergency Support Function and establishes a task force with responsibility for coordinating and executing actions -- EMP: identifies the EOC as the task force HQ -- Annex J: "Many of the services provided by UBC Vancouver campus departments utilize the 'just-in-time'"; "It is impractical in today's economic climate to stockpile great quantities of material for possible or potential emergency situations" -- Annex J: logistics task force assigned the following responsibilities: 1. identify commodities that could be in high demand in an emergency and are impractical to stockpile beforehand 2. develop working relationships, MOAs, and/or contracts with local suppliers and service providers (potentially outside of the Lower Mainland or British Columbia)	-- Task Force Logistics (TFLOG) should be prepared for fuel distribution, water operation and warehouse operation	3	-- EMP establishes logistics management task force to identify high-demand commodities and develop agreements with local suppliers (among other things)	-- Unclear if high-demand commodities have been identified -- Unclear if locations for stockpiles have been identified -- Unclear if agreements/MOAs have been established
		6.4	Asset Management	To what extent does the university use a building management system or other asset management tools?	It is important to have thorough calculation of building and infrastructure operations usages.	The campus has a fully automated BMS with dynamic digital displays in the control center.	There are some automated building information systems in place but they do not extend throughout the campus.	There is no BMS on campus		-- There is a list of the 65 generator locations on campus but these are not dynamically connected. Fuel storage does not meet 72 hours	NR		

M4 Assets

	Goal	No.	Indicator	Prompt	Why is this Important	Best (5)	Medium (3)	Worst (1)	Notes from EMP and annexes	Notes from workshops/meetings	Score	Progress	Gaps
7	Facilities	7.1	Housing Capacity	To what extent is the University able to house students on campus after an emergency?	Housing can include actual units plus emergency shelters for off campus students. This is important even in commuter schools because if students cannot commute after an event disrupts an area, they will be forced to stay home and this will delay class resumption or lead to dropped classes.	There are sufficient dormitories or temporary facilities to house student for 3 to 6 months after an event if large numbers of local housing are damaged.	There is some on site housing but not enough to house all students and staff.	The site is a commuter campus with little on site housing and no temporary emergency shelter location	-- EMP: UBC will "use existing agreements with private sector providers of accommodation, food, fuel and sanitation facilities for reinforcement or augmentation of existing UBC emergency response and recovery activities"	-- 12,000 students live on campus -- Dorms do not have emergency kits or food rations -- 11,000 student beds in Vancouver and 4,000 on waitlist	3	-- UBC houses approximately 10,000 students on campus (54,000 students enrolled as of 01-Nov-2016) -- Emergency kits available for purchase -- Might be able to double up students in dorms in an emergency (but at this stage it's just an idea)	-- Some student housing is vulnerable to earthquake damage -- Do not have plan for accommodating displaced students
		7.2	Codes, Standards, and Enforcement	To what extent do buildings on campus meet or exceed current building codes?	Old buildings that are not retrofitted to code are typically the first to fail in a shock event. These should be upgraded as quickly as possible.	All campus facilities are designed to remain functional after a hazard event.	Some campus buildings have been retrofitted to meet code.	Campus facilities are old and have not been retrofitted to meet current building codes		-- No campus buildings have been designed as post disaster facilities.	3	-- New buildings designed to current code and LEED Gold -- Renewals achieve LEED Gold -- Some older buildings have been retrofitted or replaced	-- No buildings designed as post-disaster facilities -- A large number of buildings are old and in need of retrofit or replacement -- Code compliant buildings achieve life safety in design earthquake and may be unusable for long period of time after earthquake
		7.3	Instruction Space	To what extent does the University have additional instruction space?	Additional space allows the university to keep functioning even if some rooms have been temporarily closed.	Lab and Classroom space have extra capacity to allow for reduction during repair work.	Lab and classroom space are just at capacity	There is not sufficient lab or classroom space		-- Swing space is in short supply -- Level 3 Laboratories are to be protected after an event	3	-- Campus has permanent swing space for use during renewals and/or building replacements	-- Supply of swing space is likely inadequate for demand after a major earthquake
		7.4	Emergency Shelter	To what extent have emergency shelter options been identified on campus?	Emergency shelters are where the off campus students may need to stay if access to the campus was shut down or if power in the local area resulted in students not having functional homes.	Sufficient public buildings are constructed and prepared to provide emergency shelter for all campus occupants with basic power and water for 72 hours.	There are minimal shelter zones on campus without water or power.	There is no safe shelter after an event and occupants have no ability to remain in place	-- EMP: mentions "planning and pre-positioning of materials and supplies required for future emergencies" (e.g., pre-positioning of temporary shelters) as an action in the prevention and mitigation phase. -- EMP: specifies a goal of having emergency accommodation for 10,000 people -- EMP: UBC has "identified specific areas for the development and establishment of temporary accommodation areas" which will be provisioned with "power, water and sanitation facilities" -- Annex H: facilities planning task force to determine best site for emergency accommodation	-- The tennis centre is the primary emergency social services reception centre and houses 1,000 beds from BC Housing, an agency with extensive infrastructure and staff. However, it is located near the Thunderbird Centre, which uses ammonia to cool its ice and could affect the usability of the tennis centre if there were a release. -- The student rec centre is a secondary facility with showers -- During the meeting, UBC suggested they could double up students in dorms after an emergency, but it seems like they haven't given this idea much prior thought. -- Annex F specifies that TFBO is responsible for development of ad hoc temporary shelters	4	-- Have open space that could potentially be used for temporary shelter (assuming the weather is good) -- Have a goal in the EMP of providing emergency accommodation to 10,000 people -- Have 1,000 beds from BC Housing at the Tennis Centre -- Have identified Tennis Centre and Student Rec Centre as reception centres	-- Currently unlikely to achieve specified accommodation goal -- Unclear where temporary accommodation areas are located and what the accommodations will look like
8	Utilities	8.1	Energy Supply	To what extent does the University have an adequate and reliable primary energy source (including backup power)?	Energy is a vulnerable asset that is often the cause of operational downtime. The ability to control its own power and/or have onsite backup power allows the university to not be victim to the community at large.	There are robust primary power systems which include renewable power sources. There are automated secondary power systems which include smart start programming.	Campus meets basic power and backup power requirements but has not implemented renewable generation or planned for long term recovery.	Power is supplied by external provider with poor reliability. Backup systems require manual turn on and will last only a few hours.	-- EMP: UBC will "use existing agreements with private sector providers of accommodation, food, fuel and sanitation facilities for reinforcement or augmentation of existing UBC emergency response and recovery activities" -- Annex F: UBC anticipates being without electricity and natural gas for up to 3 and 4 weeks, respectively (full service restoration), in a M7.3 earthquake in the Strait of Georgia. -- EMP: specifies a goal of having sufficient fuel for emergency vehicles, support equipment, and generators for 96 hours. -- Annex F: identifies core task of building operations task force as "Be prepared to provide emergency generator support to Level 3 Laboratory, EOC and task force locations; be prepared to provide support to logistics task force fuel distribution actions." -- Annex J: logistics task force responsible for non-leaded gas (5 days of service) and, in the event of a major emergency, diesel fuel (7 days of service)	-- Fuel storage volume could be sufficient for 5 days but stored in a singular tank which is used for fleet fueling as well	3	-- Electric power distribution system is redundant (two transmission lines from BC Hydro through Pacific Spirit Park; two transformers at main substation, each of which can power the entire campus; two feeds for most campus buildings; breaks can be isolated to minimize impact) -- Have stockpile of electrical equipment and components -- Anchorage of electrical equipment at main substation meets 1995 provisions -- Have extensive network of diesel backup generators (most permanently installed but also a few portable ones) -- Gas distribution network is redundant (several cross-connected mains from Fortis BC; breaks can be isolated to minimize impact) -- Have installed automatic seismic gas shut off valves -- W37Perform regular maintenance of electric, diesel generators, and gas systems	-- Have very limited onsite power generation capabilities -- Plans for responding to major incident are not fully developed (small crews likely to be overwhelmed) -- Most diesel generators intended to provide power for egress, not occupancy -- Limited onsite reserves of diesel fuel -- Strategy for refilling generators not fully developed
		8.2	Energy Dependence	To what extent has the Campus implemented practices to reduce power dependency?	Reduced dependency on power enables the campus to survive for longer on backup systems and on site renewable energy.	There are concerted efforts to increase conservation of energy in all areas possible and many facilities use passive comfort.	The campus has limited ability to reduce energy consumption following an event.	The campus has not implemented energy conservation or planned for long term survivability.			NR		
		8.3	Communication Systems	To what extent does the University have reliability and redundancy in communication systems (including emergency announcement systems)?	Communication systems are important for normal operations and, in the event of an emergency, to let students and staff know how to most safely respond. Redundancies in the system allow students and staff to access important information as long as one system is still working.	There are redundant systems in place to prevent communication downtime. Emergency announcement system uses redundant forms of communication (loud speakers, personal emails, cell phones, etc.)	Communication systems have limited redundancies. Emergency announcements are communicated via audio announcement only.	Communication networks are old and have no redundancies. There is no emergency communication announcement system.	-- EMP: "Coordination within task force elements is through a combination of data, cellphone and radio communications. Should existing communication facilities become inoperable, satellite communications will be used to establish and maintain communications with UBC Vancouver Policy Group and other jurisdiction's EOCs" -- EMP: identifies an "Information Management" component of the EOC responsible for "developing, coordinating, and disseminating a common operating picture (situational awareness) throughout the EOC and to other jurisdiction's EOCs" -- EMP: "the UBC emergency website (www.emergency.ubc.ca) will be the primary channel to disseminate information to faculty, staff and students"	-- Staff noted that an emergency plan for IT services needs to be developed further. -- UBC has earthquake preparedness materials/training online (i.e., ShakeOut drop, cover, and hold).	3	-- Have redundant means of communication in an emergency (landline, cell, internet, radio, satellite) -- EMP identifies UBC emergency website as primary channel to communicate with students and staff -- Website has detailed procedures for various emergencies -- Have online training for active shooter	-- Reliability of each communication system is unclear, especially cellular network, which often gets overloaded and backup batteries for cell towers get depleted -- Communication infrastructure may be inadequate for mass communication -- Level of awareness among students and staff about website is unclear -- Unclear if there are designated individuals on campus with training to help people in an emergency -- Unclear if students will be able to access website in an emergency (esp if network down or overloaded)
		8.4	Maintenance Programs	To what extent does the campus perform adequate facility maintenance to protect against stresses and shocks?	Poorly maintained systems may lead to unplanned risk exposure	Highly active maintenance program ensures systems function as originally programed and designed.	Maintenance is behind schedule and some essential systems are beginning to age.	There is little or no maintenance budget.	-- Annex F: provides overview of maintenance activities for each utility system, which appear to be thorough -- Annex H: facilities planning task force to provide advice on repair and replacement of infrastructure after an earthquake	-- Monthly inspections are to be provided by the Preventative Maintenance (PM) program operated by Powertech Labs. -- Semiannual maintenance to be performed by third party Finning	4	-- Annex F documents maintenance plans for each utility system on campus, which appear to be fairly regular and comprehensive -- Have program that replaces 150-200m of water mains each year	-- Unclear how the locations of water main replacement are determined

	Goal	No.	Indicator	Prompt	Why is this Important	Best (5)	Medium (3)	Worst (1)	Notes from EMP and annexes	Notes from workshops/meetings	Score	Progress	Gaps
		8.5	Data Storage	To what extent is important data protected from loss or damage during an event? Data storage is essential as it often controls all electronic and mechanical functions.	Data storage is data centers or where information found on the internet resides. They are very sensitive to movement and temperatures so important websites may be down if these centers have not been designed to handle shocks.	All campus data is protected in backup locations that are located to minimize hazard exposure.	There is one on site data storage location.	Data is stored off site and not backed up.		-- Currently, UBC backs up all its data to the University of Okanagan but it could take a year to sort through the archives (Danny said it was the equivalent of copying the pages of all the books in a library and then throwing the copies into a giant pile). -- UBC has a cold backup site but needs both hot and warm sites.	2	-- Currently backup all data to Okanagan (cold site)	-- Lack warm and hot sites -- Data stored at cold site would take a year to sort through -- Unclear if individual departments and researchers have backups of data
9	Mobility	9.1	Accessibility	Are campus facilities accessible by roadways, bridges and pathways following an event? To what extent have pedestrian and bicycle routes been established on campus?	The greater number of pathways that enter a campus the better as it improves redundancy and helps to ensure safe exits to emergency services if needed. Walking/biking should be possible even if all other forms of access are diminished.	Roads, Bridges and pathways are not impinged during emergency events due to robust construction and avoidance of hazard areas. Walkways and bikeways designed to assure alternative mobility options.	Some roadways exposed to threat but there are redundant access points into the site. Partial design and construction of walkway and bicycle networks.	Access points are limited and exposed to major threat zones such as low lying roads or bridges. There are no bicycle routes and fee pedestrian ways on site.		-- Campus security is tasked with traffic control in an emergency but they are not trained in emergency response.	3	-- Have snow removal plans that could potentially guide the response to other emergencies -- Campus security is tasked with traffic control in an emergency -- Have plans for staff accessing the EOC in an emergency -- Have weekly online map of road closures	-- Limited number of routes to/from campus -- Unclear whether procedures exist for cordoning off damaged facilities in an emergency (and enforcing the cordon) -- Debris management plans not fully developed
		9.2	Transportation	To what extent are transportation systems reliable and affordable?	Will there be mechanisms for students to leave the campus after an event? Will this be useable for weeks to come if the shock is great? This can include bus systems.	Bus, Train and shuttle services are reliable during and after events.	Transit options exist but are limited in quantity, unreliable and run for minimal hours a day.	There are few or no transportation options in the area.	-- Annex J: in the event of large-scale movement of people, logistics task force will coordinate with Coast Mountain Bus Company	-- 2014 Strategic Transport Plan: Focuses on Mode Split, Land use (mixed use hubs & minimizing trips), Reduced Parking Spaces. -- Public Transit is pretty much maxed out based on bus line locations (50% usage) waiting for extension of rapid transit which is in regional plan	3	-- Annex J mentions that UBC will coordinate with Coast Mountain Bus Company on large-scale movement of people -- UBC offers transit card to students for monthly fee -- 15 bus routes to campus plus 2 campus shuttles -- Public transit is most popular way of getting to campus	-- Plans for large-scale movement of people from campus not fully developed -- Unclear if UBC has MOU with TransLInk to maintain minimum level of service in an emergency
		9.3	Land Use Planning	To what extent has the university planned development around accessibility to multiple transport modes?	The proximity of essential campus facilities to transport pathways will enable greater accessibility and use.	The campus is laid out such that housing and classrooms are easily accessible from transit stops and bike trails.	The campus is laid out such that some housing and classrooms are easily accessible from transit stops and bike trails.	The campus is laid out such that little housing and classrooms are easily accessible from transit stops and bike trails.		-- 20 year sustainability Plan focused on energy, sustainability, transport, water, engagement and green building. -- No SLR risk but concern over coastal erosion	NR		
		9.4	Way Finding	To what extent has the University mapped important evacuation and emergency routes on campus?	This will be of assistance to determine meeting places and provide directions when google maps does not function after an event.	Key locations and essential pathways are clearly labeled and shown on maps. This is important for emergency preparedness/ evacuation.	There is some major location labeling and way finding on site but in limited areas.	There is no way finding or mapping.			3	-- Have various way finding maps online and signage (including digital) throughout campus	-- Unclear whether procedures have been developed for way finding in an emergency

M5 Organization

	Goal	No.	Indicator	Prompt	Why is this Important	Best (5)	Medium (3)	Worst (1)	Notes from EMP and annexes	Notes from workshops/meetings	Score	Progress	Gaps
10	Strategy	10.1	Policy	To what extent is the Campus committed to an internal mission or public vision?	This is what bonds a group together and makes them want to be part of something. If students/staff don't care strongly for the university they will not be deterred from departing for an alternate institution.	Students and staff maintain strong passion for educational goals	The campus maintains a mission but there is not large student endorsement	There is no campus mission outside of class credit completion		-- Index of university policies is on line and inclusive #5 Sustainable Development, #8 Disaster Management, #9 Hazardous Materials Management, #68 Snow Disruption,	NR		
		10.2	Mission	Does the campus maintain a strong sense of identity? To what extent does the University provide services that distinguish itself from other academic institutions?	Highly regarded or Unique programs and courses help to set an institution apart and increase the appeal to those seeking these services. Being proud of the school or city is part of why students choose a campus. Wanting to wear the shirt or hat and attend the sporting events are what bring students back, cause their children to attend, and result in continued success of an institution.	University offers highly desirable educational and extracurricular services. The University is highly desirable to students and staff, preventing departure during downtime scenarios.	The university is well acclaimed but similar to many other equivalent universities. Students form sub identities within campus but may not be part of campus wide collective.	University offers minimal classes and no additional services. The University maintains little draw and students may transition to alternate institutions if not available.		-- The university is the #2 rated in Canada and has a very selective admissions program	NR		
		10.3	Emergency Planning	To what extent has the University developed and disseminated emergency response plans?	Preparing, training for and simulating an event are the best ways to ensure readiness during a shock.	Detailed emergency response plans have been communicated and are well understood by all staff and students.	Emergency Response plans are generic and known only by operations staff.	There is no campus wide awareness of Emergency Response plans.	-- EMP: the purpose of the EMP is to "develop a flexible, scalable and robust (plan) through which a safe and secure learning and research environment can be maintained." -- EMP: specifies the following response priorities: a. provide for the safety and health of all responders b. save lives c. reduce suffering d. protect public health e. protect critical infrastructure f. protect property g. reduce economic and social losses -- Annex H: facilities planning task force to coordinate the Rapid Damage Assessment Teams -- Annex I: specifies patient care continuums for both high-tempo operations (e.g., active shooter) and major complex emergencies (e.g., earthquake); UBC Hospital is assumed to have a role in both continuums but it is unclear if this role has been confirmed with the hospital	-- UBC has a draft Emergency Management Plan (EMP) that addresses mass care and specifies medical task forces and leadership structure. It has never been validated. -- UBC's response to a campus shooter is probably the most developed part of the plan, though the responsibility for responding to an incident is largely with the police, with UBC largely stepping aside. -- Campus has only light urban search and rescue capabilities. -- Staff go through EOC training annually: exercise scenarios may include events such as forest fire or active shooters, Focused on large scale events.	4	-- Have robust emergency management plan (EMP) with functional annexes (e.g., public affairs, medical, building operations, etc.) and accident specific annexes (e.g., earthquake, active shooter, etc.) -- Have light urban search and rescue capabilities -- Annex H establishes rapid damage assessment teams to inspect earthquake damage	-- Emergency response training exercises are not conducted regularly -- EMP and annexes do not establish full leadership structure -- EMP has not been validated -- Annexes are of varying levels of completeness
		10.4	Hazard and Risk Mapping	To what extent does the University understand the hazards that threaten it?	Knowing the potential scenarios that could affect the campus allows employees and staff to plan for the earthquake, flood or fire that is most likely to affect their job and responsibilities.	Multi-hazard threat assessments have been performed for all areas of campus	Some threat assessments have been performed but these may be for only some hazards or only for some areas.	There has been no threat assessment performed		-- Hazard Assessment has largely been for forest fires that could impact power supply through surrounding parks and for chemical and biological contamination events from labs	3	-- Have risk register that includes earthquakes -- Have general awareness of hazards and risks and have conducted previous assessments of earthquake risk (Glotman Simpson and Delcan)	-- Previous assessments were qualitative in nature
11	Community	11.1	Support Networks	Is the local community connected to the Campus through events, organizations and people?	Each tie a student has to the area/university increases the probability that a student would stay enrolled after a shock that may otherwise see them choose to move on. These can be churches, sports teams, clubs.	Local communities such as churches, sports teams and action groups are connected to University affairs and offer support.	Some community support is available but students may not be largely engaged	There is no connection to local community	-- EMP: mentions establishing a Volunteer Coordination Centre and a Donations Coordination Point		NR	-- UBC has wide range of student clubs and societies, and also a student council	-- Unclear how active each student club is
		11.2	Engagement	To what extent are all parts of the campus population engaged with, and participating in, matters affecting the University?	The extent that others are connected to the leader and to the campus will increase the ability to successfully navigate the chaos around an event.	Staff, leadership and students have systems in place to make decisions together	There are some systems in place to coordinate between leadership and staff but this is not always executed.	Staff and leadership have no interaction	-- EMP: "The Plan, either in its entirety or through the use of specific operational, planning or logistics aspects will be exercised, at a minimum, annually"	-- UBC has held some training exercises in the past (including evacuation of buildings) but nothing regular. -- Most recently they ran a campus shooter scenario (within the past 4 months). -- They have also conducted ShakeOut scenarios and bomb scenarios in the past but they were not very successful/effective.	2	-- Have held training exercises in the past, including building evacuations, active shooter scenario, bomb threats, and ShakeOut exercises	-- Training exercises not held regularly -- Previous exercises were not always successful or effective
		11.3	Stakeholders	Are local community leaders engaged in Campus plans and strategies?	External backing is important to the success of any system. Having a local mayor or business that is very invested in the campus will provide more advocates in times of need (for things such as funding or volunteer work)	City and Regional leaders are engaged in university wellbeing through advocacy	There is some connection with community leaders but they are not heavily involved in the campus.	Local stakeholders are not involved with the campus	-- EMP: identifies an "External Liaison" component of the EOC responsible for "representing UBC in the development or implementation of emergency response or contingency plans at Metro Vancouver or other assigned locations."		2	-- EMP identifies external liaison for coordinating with other agencies in an emergency	-- Unclear whether other agencies are aware of UBC's external liaison -- Unclear how involved UBC is in the surrounding community, especially in a non-emergency capacity
		11.4	External Ties	To what extent has the University fostered connections with external university networks?	Connection to other campuses allows the university to be supported by a greater network of funding and potential sharing of resources.	Operational connection to a greater university system for leadership redundancies.	Some connection to alternate campuses for support	University is isolated from external networks	-- EMP: discussions with Metro Vancouver's Emergency Management have indicated that UBC needs to be "self-reliant in the preparation for or in the response to emergencies of all types" -- EMP: recognizes the need for "collaborative, multi-jurisdictional planning with engagement from the entire UBCV community at large" -- EMP: notes different jurisdictional boundaries but also recognizes the interconnectedness of UEL, UNA, and Pacific Spirit Park	-- UBC has an MOU with St. Johns Ambulance to get mobile unit on campus permanently. -- UBC is currently working with the Architectural Institute of BC on an MOU for having volunteers conduct rapid damage assessments. -- UBC recognized the need for MOUs with debris management companies.	3	-- EMP recognizes the need for UBC to be self reliant -- EMP also recognizes the importance of collaborative, multi-jurisdictional planning -- Have MOUs with some organizations	-- Given financial and geographic constraints, UBC unlikely to ever be truly "self reliant"; therefore need strong external ties -- Need MOUs with debris management companies (among others)

12	Leadership	12.1	Communication Plan	To what extent is important campus information available to students and staff before and after an event?	The existence of information for students and staff to inform students and staff is critical as people will not know what to do after a shock.	Essential data is easily accessible by staff and students prior to and during an event.	Access to important data is not well advertised.	Access to important data is not available.	-- EMP: identifies "information/communications technology" as an Emergency Support Function and establishes a task force with responsibility for coordinating and executing actions -- EMP: identifies the Klinck building as the task force HQ -- EMP: identifies a "Public Affairs" component of the EOC responsible for "developing and disseminating all internal and external messaging on behalf of UBC" -- EMP: identifies an "Emergency Call Centre" component of the EOC responsible for "serving as a point of contact for public inquiries regarding the status of the University and its populace during emergencies" -- Annex D: presents an Emergency Communications Plan that "outlines guidelines for quickly communicating with UBC's campus community, community partners, and external stakeholders during an emergency." -- Annex D: establishes "the UBC emergency website as the source of accurate information" -- Annex D: identifies important audiences but gives priority "to those considered at greatest life safety risk." -- Annex D: specifies the University will "conduct annual drill of emergency management exercises, which will include a test of the Emergency Communications Plan" -- Annex D: specifies checklists of immediate and secondary response communications but does not assign responsibilities to personnel	-- UBC has a mass communication tool (Regroup) but they are having trouble deploying it on existing IT infrastructure. For example, it can take up to 7 hours to send a text message because there are only two cell phone towers on campus. Similarly, sending out a mass email would crash their servers. -- The tool also controls signboards on campus. -- UBC is currently engaging IT to consolidate its myriad communication systems; when public affairs crafts a message they have to reach out to 7 different people to get it on all platforms -- There are also amateur radio operators that could be used for communication, but there currently is no protocol	3	-- Have mass communication tool -- Have emergency call centre for handling public inquiries -- Annex D presents an emergency communications plan that outlines guidelines for quickly communicating with UBC's population	-- Mass communication tool is unreliable -- Communication channels need streamlining; currently seven different people needed to get message out on all channels -- Communication protocol for some systems (e.g., radio) is lacking -- Unclear whether regular exercises are conducted -- Emergency Communications Plan is short on detail, especially assigning roles and responsibilities
		12.2	Management Team	To what extent is there effective leadership?	Strong leadership is essential in stressful situations and will help lead others through with minimal impact.	There is a strong Leader and Decision Making team in place.	The leadership is strong but lacks a support team.	Disconnected leadership team	-- EMP: identifies two individuals with responsibility for activating the Policy Group -- EMP: specifies an EOC line of command that is six people deep (Chief Risk Officer, Director of Occupational Research, Health and Safety, etc.)	-- UBC's current approach is ad hoc and highly dependent on good leaders stepping up. -- Organizational structure in an emergency is unclear. -- TFBO is the designated leader after an emergency event	2	-- EMP specifies line of command for EOC	-- Overall implementation of response and recovery plans is ad hoc and highly dependent on good leaders stepping up -- Outside of EOC, organization structure in an emergency is unclear
		12.3	Commitments to Resilience	To what extent has the University participated in resilience activities?	People who are aware and have thought about what leads to greater resiliency are more likely to participate in resilient actions.	Campus has Signed Climate, Carbon and Resiliency Commitments. Has formed a resilience team or task force.	Campus has begun talks to be part of improved resilience initiative	Campus has not signed Climate, Carbon or Resiliency Commitments		-- Working with Rockefeller Foundation to develop Resilience program on campus.	2	-- Select staff on campus recognize the importance of resilience -- Currently funding a resilience study of campus infrastructure and processes	-- No resilience plan -- No chief resilience officer
		12.4	Staffing Plan	To what extent have staff who support critical services been identified and arrangements made for their availability in an emergency?	It is important that the staff who are required to get essential services running after an event are aware of their responsibilities and have alternates in the case that they are not available.	Essential staff are always available to maintain critical services.	A portion of staff are on call and a available during emergency events.	Staff live far from campus and or work part time		-- If the incident takes place during the silent hours, TFBO workforce is expected to be reduced during the initial 48-72 hours of an emergency due to inability of TFBO personal to reach campus	2	-- Business continuity plans identify the minimum number of staff required to perform critical functions	-- Unclear if roles and responsibilities in EMP and annexes have been communicated clearly to staff