ESTIMATION OF POST-EARTHQUAKE RECOVERY ON A UNIVERSITY CAMPUS USING REDi METHODOLOGY

N. Paul¹, I. Almufti², M. Mieler³, and J. Lee⁴

ABSTRACT

In the aftermath of previous moderate to large earthquakes (e.g. Loma Prieta 1989, Northridge 1994, and Christchurch 2011), nearby university campuses (e.g. Stanford, California State University, and University of Canterbury) have experienced widespread building damage, disruption of lecture and research, and reduction of undergraduate and graduate attendance. Other potential consequences of an earthquake could include life-safety issues and a loss of university reputation. While the value of ensuring campus-wide resilience in the face of earthquakes is apparent, the strategy to achieve measurable improved performance can be difficult to develop and quantify. This paper presents a methodology for estimating disruption and recovery of space on a university campus based on the REDi downtime assessment methodology (founded upon FEMA P-58). This is used to predict downtime for individual buildings due to building repairs and delays to the initiation of repairs (i.e. impeding factors). Hundreds of earthquake scenarios were considered to impact an example campus, and the related results are presented. Particular attention is paid to metrics of primary interest to university campuses, including restoration of different occupancy space over time and displacement of student populations.

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In the aftermath of previous moderate to large earthquakes (e.g. Loma Prieta 1989, Northridge 1994, and Christchurch 2011), nearby university campuses (e.g. Stanford, California State University, and University of Canterbury) have experienced widespread building damage, disruption of lecture and research, and reduction of undergraduate and graduate attendance. Other potential consequences of an earthquake could include life-safety issues and a loss of university reputation. While the value of ensuring campus-wide resilience in the face of earthquakes is apparent, the strategy to achieve measurable improved performance can be difficult to develop and quantify. This paper presents a methodology for estimating disruption and recovery of space on a university campus based on the REDi downtime assessment methodology (founded upon FEMA P-58). This is used to predict downtime for individual buildings due to building repairs and delays to the initiation of repairs (i.e. impeding factors). Hundreds of earthquake scenarios were considered to impact an example campus, and the related results are presented. Particular attention is paid to metrics of primary interest to university campuses, including restoration of different occupancy space over time and displacement of student populations.

Introduction

University campuses often anchor a city or town, populated by thousands of employees, students, researchers, and visitors within hundreds of buildings that are frequently clustered together. These buildings encompass a variety of occupancy types, from hospitals to residences and laboratories to assembly areas. An earthquake could significantly impact the safety of these people and the functions of the university – buildings could collapse or be rendered unoccupiable, lecture and research could be significantly disrupted, and students may become displaced. If the resulting disruption is significant, the university could suffer a loss of reputation and fail to retain students or attract new applicants, ultimately hindering the ability of the university to continue its mission of education and intellectual advancement.

This paper describes a methodology for estimating disruption and recovery of space on a university campus based on the REDi downtime assessment methodology (founded upon FEMA P-58). It discusses past performance of universities following earthquakes and more deeply investigates a case study of the predicted performance of a large university campus in Vancouver. Key findings, lessons learned, and areas of further research following this case study are presented. An effort has been made to present these findings using metrics of interest to a university, including

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the restoration of campus space over time and resulting student displacement or outmigration. These values are not intended to be appropriated for campuses generally, as they are dependent on the intensity of ground shaking, building stock, and infrastructure redundancies or interdependencies that are specific to the campus considered.

**Universities in Previous Earthquakes**

Over the past 30 years, several large universities have been impacted by earthquakes. This includes Stanford University in the 1989 Loma Prieta earthquake, CSU Northridge in the 1994 Northridge earthquake, and the University of Canterbury in the 2011-2012 Canterbury earthquakes. Although there were no fatalities on these campuses and minimal building collapses (only an unoccupied parking structure in Northridge), there was significant damage to campus infrastructure, displacement of students, and disruption to classes and research despite actions by each university to mitigate these consequences.

The M6.9 Loma Prieta earthquake rupture was approximately 48 kilometers from Stanford University, corresponding to a recorded PGA of 0.26g on campus. This event damaged many of the 400 buildings on campus, with most evacuated until post-earthquake inspection was conducted by engineers. Within two days, 22 teams of inspectors surveyed all buildings and reported minor damage to 242 buildings that could be easily repaired by maintenance staff and identified 25 buildings that had significant enough damage to be closed. Some of these buildings took up to 8 years to restore as Stanford waited for federal funding [1]. Several residential buildings were closed, displacing more than 1,000 students the night of the earthquake, most of whom stayed with friends or inside the lounge of other dormitory buildings [2]. Some students chose to sleep outdoors in tents, afraid to re-enter buildings. Most students were allowed back into their dorms within a week, except for between 150 to 200 students that were provided long-term accommodation on campus by the university. All repairs to damaged residential buildings were completed prior to the start of the next academic year, roughly 11 months later [1]. All classes were canceled the day after the quake, but most had resumed within 2 to 3 days within buildings deemed safe. The university lost 21 classrooms (14% of its academic space), half of which were replaced by modular units [3]. The next academic year, the number of applications dropped to a 10-year low, though it had declined in each of the three previous years.

The M6.7 Northridge earthquake struck 3 kilometers from California State University, Northridge (CSUN), corresponding to a recorded PGA of 1.0g on campus. All 107 buildings on campus were damaged, with 60 major buildings suffering structural damage. Power, water, and communication infrastructure on campus was also damaged [4]. Ultimately, at least a half dozen buildings were demolished and reconstruction took nearly 8 years [5]. Since most students lived off campus and commuted to class, it is unclear if there was significant displacement of students. The earthquake struck during winter break and the upcoming semester was postponed by only 2 weeks using 300 rented modular trailers and 25 off-campus classroom spaces [5]. The following academic year, enrollment dropped by 10%, although it had also declined by 7% the year before. University officials also blamed the recession and rising tuitions for this drop [6].

The M7.1 Canterbury earthquake struck roughly 32 kilometers from the University of Canterbury (UC) during a two-week teaching break. The university closed for an additional two
weeks to allow for inspections and cleanup. The M6.3 Christchurch earthquake struck several months later, roughly 12 kilometers from the campus on the second day of the academic year during the afternoon. This earthquake caused widespread damage to campus infrastructure, resulting in the demolition of several buildings on campus [7]. Campus administrators decided to reopen the university just three weeks following the earthquake, with over a dozen large tents in parking lots and increased usage of online courses [8, 9]. Since campus housing was only guaranteed for international students (14% of the total student population), most students lived off-campus in residences that suffered little or no damage (84%), likely the most important factor in the retention of students. Most students (96%) also reported satisfaction with the university’s post-earthquake response and communication efforts. Nearly half of the students reported that they left Christchurch following the earthquake, but only 6% indicated that they left permanently [10]. Despite this, enrollment dropped significantly after the earthquake, from 18,700 students in 2010 to 14,700 in 2014 [11]. This, in conjunction with insurance disputes, caused financial stress at the university and a reduction of 12% of its academic staff [12]. Student enrollment has begun to increase recently, but is still below pre-earthquake levels [13].

**Methodology for Downtime Prediction**

Research in earthquake engineering over the past decade has resulted in established frameworks, methods, and tools for predicting individual building losses following an earthquake. The Federal Emergency Management Agency developed a seismic performance assessment methodology for buildings (i.e. FEMA P-58) that combined seismic hazard assessment, structural response, damage estimation, and cost estimation to aggregate anticipated economic loss, repair time, and casualty rate of individual buildings [14]. Upon this framework, the REDi downtime assessment methodology was developed by Arup to convert repair times from a FEMA P-58 assessment into building downtime through consideration of realistic labor allocation, delays to the initiation of repairs (i.e. impeding factors), and milestones along the path to full recovery of a building (i.e., re-occupancy and functional recovery) [15].

This study of campus recovery uses the FEMA P-58 and REDi frameworks for individual buildings to aggregate campus-wide results. At each earthquake return period of interest, 1,000 risk simulations were performed per building. For a given realization, one of 40 ground motions was randomly selected based on the contribution of each earthquake source to the given hazard level. These 40 ground motions were developed through a probabilistic seismic hazard assessment conducted for Vancouver by seismic researchers at the university [16]. Simplified nonlinear analysis stick models were used to get the best estimate of structural response for each building in each of the ground motion time histories. Using that, a FEMA P-58 loss assessment was conducted to get building repair cost, repair time, and casualty rate. The repair times were then aggregated and put through the REDi downtime assessment framework to get overall building downtimes to re-occupancy and functional recovery [15, 17]. Flow charts describing the methodology for both the FEMA P-58 loss assessment and the REDi downtime assessment are shown in Figure 1.
Additional assumptions were necessary to reflect that the study was for a portfolio of buildings, as opposed to assessment of an individual structure. Each realization assumed the same ground motion affected all buildings on the campus simultaneously – there was no distribution of ground motion shaking to reflect varying soil conditions or distance from the earthquake source. In addition, the structural response was estimated based on limited data for each building and, therefore, was unable to reflect localized structural deficiencies, unique geometry, or all potential failure modes of a unique structure. In addition to the building risk assessment, utility disruption was estimated using fault tree analysis. Individual components (e.g., water pumps, electrical transformers) were modeled using fragility curves, from which redundancy and interdependencies were modeled to get system-level results of functionality [18].

**Case Study: University of British Columbia, Vancouver**

The University of British Columbia contracted Arup to conduct a seismic risk assessment of their 328 existing buildings on the Point Grey campus at four earthquake return periods: 45, 200, 475, and 2475 year. This paper focuses on the 200 and 475 year return periods, but the full report has been published online by the university and includes results at the other return periods [19]. At higher return periods (e.g. 2475 year), life-safety and collapse-prevention are paramount. However, more frequent return periods can also result in significant economic loss and disruption.
Description of building stock

The buildings on campus are predominantly low-rise light wood frame buildings and low to mid-rise concrete wall buildings. Two-thirds of the building stock were constructed prior to the establishment of modern seismic building codes. Therefore, more recent advances in earthquake science and lessons learned from previous events has not been captured in the design of many of the buildings on campus. Figure 2 and Figure 3 show the building typologies included in this study.

Figure 2. Inventory count of the 328 existing buildings considered in the study, showing construction age, number of stories, and structure type.

Figure 3. Inventory count of the 328 existing buildings considered in the study, showing marginal distribution of construction age, number of stories, and structure type.
Predicted recovery of campus buildings

An estimate of the downtime to functional recovery of campus space can be informative for planning purposes – it can give an idea of the duration of student displacement due to damage to dormitories or an approximate percentage of academic space that may need to be found elsewhere (e.g. temporary trailers or alternate buildings). For particularly damaging earthquakes that could shut down a university, restoration estimates can help the administration inform students of an anticipated re-open date, allowing students to decide if they will transfer universities or return.

Due to the probabilistic nature of this study, an entire distribution of downtime is determined for each building. These are aggregated across the campus and divided into the various occupancy categories, with median values as shown in Figure 4. As shown in the restoration curves, as little as 40% and 10% of the total floor area could be functional immediately following the 200 and 475 year earthquake events, respectively. For the remainder of space, functional recovery could take between 6 and 18 months. Functionality concerns were largely due to damage to exterior enclosure (e.g. glazing, cladding) and MEP distribution. On top of the functionality concerns for building, life-safety damage (that would also preclude functional recovery of a building) from exterior enclosure or stairways was common.

Figure 4. Median restoration curves by primary occupancy type of buildings on campus for the 200 year earthquake event (left) and the 475 year earthquake event (right).

However, a median restoration curve may not be desirable for planning purposes as it is by definition exceeded 50% of the time. In addition, different earthquake scenarios could result in systematically different results. For example, a large magnitude Cascadia Subduction Zone earthquake could disproportionately affect the tall concrete residential towers on campus due to the long duration of shaking, whereas a shallow-crustal fault source may disproportionately affect low-rises on campus. The full range of campus restoration to functional recovery is shown in Figure 5, with the median values in solid black and the 10 and 90%ile in dashed black. These curves highlight the significant range of uncertainty in these predictions, partially due to inherent variability of random phenomena and partially due to the epistemic uncertainty in the appropriateness of our models.
Figure 5. All 1000 simulations of restoration of buildings on campus for the 200 year earthquake event (left) and the 475 year earthquake event (right).

**Predicted restoration of campus utilities**

Even if buildings are relatively undamaged following an earthquake, functionality may not be resumed until utilities such as power and water are restored. Utility disruption and restoration can be challenging to estimate due to interdependencies and redundancies within the network. Anticipated disruption times for various utilities following an earthquake are presented in Table 1, as estimated for the Point Grey campus.

<table>
<thead>
<tr>
<th>Return period</th>
<th>Electric power</th>
<th>Water</th>
<th>Natural gas</th>
<th>Thermal energy</th>
<th>Sanitary sewer*</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 year</td>
<td>1 day</td>
<td>61-65 days</td>
<td>2-6 days</td>
<td>0 days</td>
<td>4 days</td>
</tr>
<tr>
<td>475 year</td>
<td>2-3 days</td>
<td>65-70 days</td>
<td>7-13 days</td>
<td>0 days</td>
<td>6 days</td>
</tr>
</tbody>
</table>

*Indicates the time to repair sewer pipe breaks. The sanitary system will be unusable as long as water is disrupted, which almost always governs.

In general, electric power, thermal energy, and sanitary sewer were not anticipated to have significant damage and disruption (i.e. beyond a week). However, water was found to be especially vulnerable, largely due to the location of the water pump station within a collapse-prone building and a lack of redundancy. Disruption of water may be particularly concerning for the campus as it could render firefighting infrastructure nonfunctional and necessitate significant reserves of potable water to be made available for students. Natural gas was also anticipated to have significant disruption, largely due to tripping of automatic gas shut off valves throughout campus that require roughly 2 to 3 hours for staff to reset per building. When aggregated across the campus, this can result in a lengthy disruption of service.
Student population vulnerability assessment

Students are essential to the vitality of a university. If many students were to outmigrate (i.e., permanently leave) following an earthquake, it could significantly alter the social fabric of the university, damage its reputation, and impact its financial health for years due to lost tuition revenue and research grants. Students may decide to outmigrate for a variety of reasons, but most notably due to: lengthy displacement from their residences, limited capacity to adapt (e.g. international students or non-local first-year undergraduates that may not have a local support network), and significant disruption to teaching.

The Point Grey campus supports over 54,000 students, 25% of which are international. At the time of this study, the university has the capacity to house nearly 12,000 students across 100 buildings on campus. Following an earthquake event, it is estimated that most students will be displaced for at least a few days due to post-earthquake inspections. However, some students could be displacement much longer due to significant damage of residential buildings and a lengthy downtime to restore those buildings. An estimate of the number of students (living on campus) displaced following various return period earthquakes is shown in Figure 6.

![Number of students (on campus) displaced over time](image)

**Figure 6.** Number of students (living on campus) displaced after an earthquake as a function of time at the probable (200 year) and rare (475 year) return periods.

Students with local support networks would likely be able to temporarily seek refuge with family or friends. However, international or non-local students are likely to return home and potentially switch universities if there will be weeks to months of displacement. Additional study is necessary to obtain more robust predictions of anticipated student outmigration percentages.

Operational measures and contingency plans

This paper has largely focused on infrastructure, but operational preparedness measures are a key component of the overall resilience of a campus. University campuses commonly create emergency response plans or conduct disaster scenario workshops to prepare for a potential earthquakes or other hazards. These can be especially helpful in avoiding cascading hazards, or
additional hazards that may occur directly or indirectly due to an initial one. However, it is less common for a university or organization to prepare for the recovery phase. Appointment of a ‘Chief Resilience Officer’ or other point-person to develop and implement risk mitigation strategies and lead further resilience initiatives, which in turn could reduce confusion and coordination delay following an earthquake or other disaster. In addition, plans to fast-track the permitting process or mobilize laborers for nonstructural repairs could significantly reduce building downtimes.

**Future Areas of Study**

This study applied state-of-the-art loss and downtime assessment methodologies to an example university campus in Vancouver. However, there were several key assumptions that limited the study. This notably includes simplified structural analysis and limited data on human behavior or factors following a large natural disaster (e.g. labor availability, contractor mobilization delays, and building inspector judgment). In addition, the study focused largely on campus infrastructure (i.e. buildings and utilities), although organizational measures are key to the recovery of any institution or community. Some related hazards were neglected in this study, including aftershocks, quantitative consideration of fire following earthquake, or release of hazardous or toxic materials that exist on campus.

Future research would be necessary to improve the reliability of quantitative assessment of key metrics of interest, including building downtime to functionality and outmigration of students. Additional data regarding labor scarcity following disasters, post-earthquake inspection statistics on placarding of structures, and mapping of component-level damage to building-level functionality by occupancy type would greatly benefit downtime estimates. Data regarding student outmigration based on duration of displacement or disrupted teaching and research would greatly benefit quantitative assessment of student population vulnerability. Reliable estimation of these metrics is at the crux of campus resiliency and could better inform universities worldwide.

**Conclusions**

Key findings of university campus post-earthquake recovery have been discussed, using both case studies of past campus performance and a research case study that aims to predict campus risk. Metrics of primary interest to university resilience, such as restoration of campus space over time and outmigration of students are highlighted. Of particular interest for recovery was moderate to rare earthquake events (e.g. 200-year and 475-year return period), where life-safety is anticipated to be reasonably achieved. At these hazard levels, a significant proportion of campus space was anticipated to be disrupted for months. During this time, some students may be displaced from campus housing, classes may be halted, and utilities may be disrupted. While these results can be indicative of the future performance of universities in earthquakes, there are some limitations to the scope of the study based on limited reliable data. However, these initial findings could also begin a larger conversation around community or city resilience. Similar to cities, universities have their own emergency response facilities, businesses, residences, and other occupancies that make up a community. Although the scale may be smaller, a similar methodology could be applied to study city resilience.
References


