Prioritization of seismic retrofit using scoring system

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ABSTRACT

As the research and engineering communities advance in their understanding of earthquakes and the associated effects, it becomes apparent that retrofit of old structures is necessary in order to protect the lives and assets of the public. Consequently, owners or stakeholders with a large inventory of buildings often ask the question: which building should be retrofitted first? A practical methodology to provide guidance on prioritization of seismic mitigation projects is proposed via a Retrofit Priority Score (RPS) that is quantitatively determined from several high-level indices. Criticality index accounts for the importance of a structure and the people affected by its loss of use. The former is measured by acceptable downtime based on business continuity and community inter-dependency, while the latter is calculated based on building area, occupant density, and occupied hours per week. Risk index reflects the deficiency of a structure relative to current seismic code requirements. Cost index addresses the economic incentive for retrofit versus replacement. All of these indices have values between zero and one, with a higher number indicating higher priority to retrofit. RPS also incorporates the seismic importance factor typically found in building codes to distinguish among normal, high-importance, and post-disaster structures. RPS does not require rigorous analysis and can be practically implemented. An example application of the proposed RPS is provided in the paper to demonstrate how it can assist in the policy, funding, and prioritization of a seismic mitigation program for a mixed-use building inventory.

1 INTRODUCTION

Earthquake engineering is a relatively emerging field. After each major seismic event, it is typical for researchers and professionals to gain further insight into the behaviour of structures and structural systems under strong ground shaking. Furthermore, seismic design provisions become increasingly more stringent with each design code iteration to address the structural deficiencies observed during these events. To address issues of public safety and property protection, the need to seismically retrofit structures becomes inevitable, even for some that were designed and constructed in recent years. For an owner or stakeholder with a large inventory of seismically deficient structures and limited funding, a key question is: which building to retrofit first? Like any investment to maximize its benefits, the answer is not readily apparent as many factors should be considered.

To facilitate the decision on which structure to retrofit first, some owners or stakeholders utilize existing rating systems developed by various organizations. The U.S. Resiliency Council (USRC) (2017) rates expected building performance when subjected to natural disasters with a current focus on earthquake hazard. Rather than being an evaluation methodology itself, USRC consists of a set of definitions and procedures by which the results of evaluations performed in accordance with ASCE/SEI 41-17 (2017) or FEMA P-58 (2019) may be translated into consistent terms or ratings. USRC assigns one to five stars to three performance measures: safety, damage, and recovery. Safety describes the potential of unharmed exit, damage is expressed as estimated repair cost, and recovery is evaluated in terms of time to regain basic functionality. Safety serves as the basic measurement from which damage and recovery are subsequently determined. USRC considers the architectural, structural, as well as mechanical, electrical, and plumbing systems of a building. When star ratings conflict with one another amongst the different systems, the minimum rating governs. The Resilience-based Earthquake Design Initiative (REDi™) is an earthquake resilience rating framework developed by Almufti and Willford (2013). To achieve a rating from REDi™, mandatory criteria must be followed in each of the three aspects of resilience: organizational, building, and ambient. The organizational resilience focuses on pre-earthquake contingency planning. It ensures that there are suitable plans in place for items such as backup utility lines and gas shutoffs, as well as food and water for occupants. The building resilience focuses on structural performance. Based on structural analysis results, mandatory criteria are to be followed. For example, to qualify for a platinum rating, structural and non-structural components have to remain essentially elastic. The ambient resilience focuses on site performance and the surrounding region. It considers hazards such liquefaction, tsunamis, as well as possible interaction with neighbouring buildings. In addition, a loss assessment is conducted to determine the downtime and financial loss of a damaged building. Each rating category has associated downtime and loss limits. The downtime methodology is based on FEMA P-58 (2019) with some alterations. Specifically, the downtime calculation estimates the delays to begin repairs in a post-earthquake situation, sequential repairs, as well as utility disruption for water, electricity, and gas based on data from previous earthquakes.

These existing rating systems have been developed mainly for evaluating different new construction options with a focus on resilience. For existing structures constructed prior to the introduction of modern building codes, they would all be rated poorly. Therefore, it is difficult for an owner or stakeholder to apply these existing rating systems and decide which structure to retrofit first. Also, these rating systems determine expected downtime and repair cost as a function of the structural response. On the other hand, for seismic retrofit decisions, it is important to determine the performance objective that an owner or stakeholder wish to achieve. The desired objective should be actively considered instead of passively determined. The proposed methodology using a Retrofit Priority Score (RPS) not only allows an unbiased evaluation of human factors, but also includes the explicit consideration of community inter-dependency. It is simple to implement without rigorous structural analysis. Each input parameter is independently calculated and weighted in a RPS evaluation. This provides a common basis of comparison when evaluating a large inventory of buildings with varying structural systems and occupancy types. It can assist in the drafting of policy and in allocating the often limited funding available for implementation of retrofits. The following section explains RPS in more detail.

2 RETROFIT PRIORITY SCORE

The objective of the proposed RPS methodology is to provide guidance on prioritization of seismic retrofit projects. RPS is useful to allocate limited resources and mitigate seismic risks. RPS is calculated by three indices as shown in Equation 1: criticality index (CRI), risk index (RSI), and cost index (COI). A seismic importance factor (IMF) similar to that used in modern building codes is utilized to reflect normal (1.0), high-importance (1.3), and post-disaster (1.5) structures.

$$RPS = (CRI + RSI) \times IMF + COI \tag{1}$$

In the evaluation of a seismic mitigation program, the RPS can be determined for each structure based on a selected earthquake shaking intensity without rigorous structural analysis. RPSs range between 0.0 to 4.0, where structures with higher values should be given the priority to retrofit. When RPSs are identical, COI can independently give a second measure to distinguish between the economic value of two candidate retrofit projects.

2.1 Criticality index

CRI is the most challenging index to quantify, and yet the most important factor to consider when deciding which structure to retrofit. The uniqueness of a CRI is that it gives an owner or stakeholder the power to choose what the acceptable downtime is for the facility in question in the context of the larger building portfolio. For example, decision makers should review the everyday utility of a structure, but also its inter-dependency with the surrounding structures to ensure business continuity as a whole, the importance the facility remains functional during post-earthquake recovery, and the significance of the facility to the wider community. Thus, multiple consistent measures can be used to arrive at the acceptable downtime. In addition, the CRI considers the number of people affected by the facility if it becomes out-of-commission due to an earthquake. This is expressed in terms of person-hours per week, and is determined based on the building area, occupancy type and corresponding occupant density, and the average hours occupied per week. Where detailed data is unavailable for these parameters, reasonable estimates of the number of people affected can be determined using typical data by occupancy type, or a rational sampling program during a visual survey. Overall, the approach has similarities to the procedures outlined in Commentary L of National Building Code of Canada (NBCC 2015) or the U.S. Green Building Council's LEED® green building program. With both the acceptable downtime and the number of people affected, the CRI is determined from the proposed matrix classification shown in Table 1. When the acceptable downtime and people affected are in between the suggested values, the CRI can be linearly interpolated. CRI ranges between 0.0 and 1.0 where a higher CRI increases the RPS.

Table 1: Matrix classification of criticality.

Number of People Affected (Person-Hours Per Week)	Acceptable Downtime: 0hr	6hr	24hr	72hr	1wk	2wk	6wk	6mth	1yr	3yr	∞
≥ 50000	1.00	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50
15000	0.95	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45
10000	0.90	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40
5000	0.85	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35
2500	0.80	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30
1000	0.75	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25
500	0.70	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20
250	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20	0.15
100	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20	0.15	0.10
50	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20	0.15	0.10	0.05
0	0.50	0.45	0.40	0.35	0.30	0.25	0.20	0.15	0.10	0.05	0.00

2.2 Risk index

RSI as given by Equation 2 is an index to indicate the structural deficiency relative to the building code or design guideline used in the assessment. Any structural analysis technique ranging from linear static to nonlinear dynamic can be utilized. The key is to conduct the same type of analysis for all the structures within an inventory in order to make a fair comparison and ranking for the retrofit prioritization through the proposed RPS. The use of the RSI has been a common practice by engineering consultants to provide an owner or stakeholder a sense of necessity or urgency to retrofit a structure. Public policies or codes, such as Vancouver Building By-law (VBBL 2019), also use a form of RSI to implement threshold values to be achieved during mandatory or voluntary seismic retrofits. As proposed in this paper, RSI alone is inadequate to provide sufficient data to make an informed decision on retrofit priority. For example, a structure with a low RSI (i.e. having a moderate structural deficiency) might have significant impact on people or property relative to a structure that has a high RSI (i.e. having a severe structural deficiency) but affects only a few occupants. The former structure should have the priority to be retrofitted when the other factors discussed in this paper are considered. RSI ranges between 0.0 and 1.0 where a higher RSI increases the RPS.

$$RSI = 1 - \frac{\mathit{Structural\ Capacity}}{\mathit{Code\ Requirement}} \quad (2)$$

2.3 Cost index

COI is an index indicating whether or not a retrofit makes economic sense. As given by Equation 3, COI is a measure of the retrofit cost against the protection of assets, both building and contents, that a retrofit could provide. Retrofit costs can be calculated using preliminary or indicative retrofit schemes, where applicable. Otherwise, unit rates based on construction type can be utilized. Replacement costs of the building components can also be calculated using typical unit rates based on construction type and occupancy type. For estimates of the building contents protected, itemized asset data as well as estimates of insurable contents or unit rates based on occupancy type could all be utilized. In this context, a building with expensive contents such as a medical laboratory will have a higher COI than an identical building with simpler contents such as administrative offices. When the estimated retrofit cost is higher than replacement cost, the COI is set to zero indicating that the retrofit does not make economic sense. Such buildings can typically be removed from the RPS rankings with seismic mitigation considered through building replacement funding mechanisms rather than through building renovation and renewal mechanisms. COI ranges between 0.0 and 1.0 where a higher COI increases the RPS.

$$COI = 1 - \frac{Retrofit\ Cost}{Replacement\ Cost} \geq 0 \tag{3}$$

3 IMPLEMENTATION OF RPS

Many facility owners or stakeholders have portfolios of buildings with a diversity of construction types, usage, construction era, and history of prior seismic upgrading. For example, municipal governments, school districts, or university campuses might contain buildings that are utilized by employees or the broader community. Some of these structures might have undergone periodic renovation, renewal or seismic upgrading while others may be in their original configuration. The effective implementation of the RPS methodology for these inventories is well suited as an intermediate phase within a broader seismic mitigation strategy.

As an initial step, the portfolio of buildings can be evaluated using a high-level seismic screening methodology such as Rapid Visual Screening (RVS) based on the FEMA P-154 (2015) guidelines. RVS is a "sidewalk" survey approach to data collection, supplemented by qualitative drawing review conducted by an experienced engineer. The RVS scoring system classifies potential seismic risk based on historical experience of the performance of a large population of structures having certain combinations of construction type, visibly identifiable irregularities, site conditions, etc. The resulting score can aid an owner or stakeholder in identifying buildings that have the greatest potential structural deficiency and warrant more detailed review. Figure 1 provides an illustrative example of the geographic layout of the obtained RVS scores for a fictitious university campus. Different hatches have been used to visually distinguish amongst the buildings likely to have Low, Medium and High seismic risk based on the RVS scores. This visual representation can eliminate buildings from further review or help to prioritize the process of completing more time-consuming and costly analytical reviews when funding is limited. As noted earlier, the detailed analytical review to establish the structural deficiencies should be completed using a standardized approach such as linear static or nonlinear dynamic analysis. The results of this analysis, expressed in terms of code strength deficiency, can then be used to adjust the seismic risk classification.

It should be recognized that both the RVS and detailed analytical studies only focus on the expected performance of the structural components and structural systems. They do not directly consider other factors for an effective seismic mitigation strategy including the downtime, people affected, value of assets to be protected, and the inter-dependency among structures. Therefore, the RVS or analytical studies alone will not be sufficient to allow an owner or stakeholder to prioritize seismic retrofit projects.

As one example of inter-dependency, consider the case of Building D in Figure 1. While the RVS and subsequent detailed analysis might indicate a Medium seismic risk, the geographic representation highlights an important consideration that essential services and utilities pass through Building D to supply Building F, the campus' Fire Hall. The Fire Hall will be critical to post-earthquake rescue and recovery operations on the campus. Significant damage or collapse of Building D may compromise the functionality of the Fire Hall. The proposed RPS methodology can consider this business continuity requirement by establishing an appropriate limit for acceptable downtime of Building D, likely identical to that of the Fire Hall.

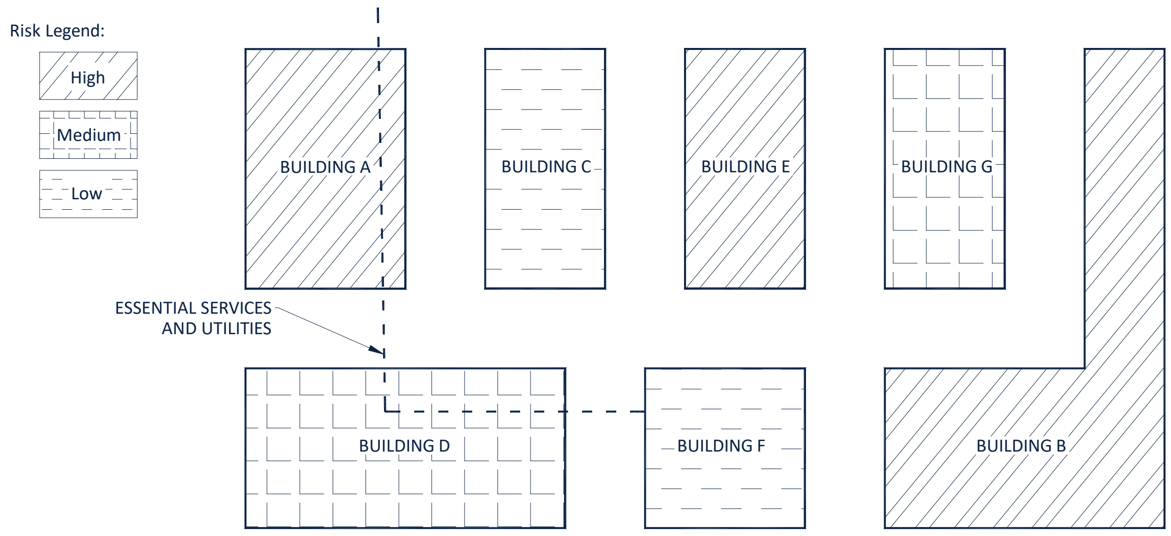

Figure 1: RVS results for a university campus.

Determination of the RPS for selected buildings on the campus is provided in Table 2. To illustrate some of the features of the methodology, each building is assumed to be multi-use. The Data & Telecommunications Centre will be classified under NBCC (2015) as a post-disaster facility. Therefore, the entire building will have this classification. Limited downtime is also required as it contains key infrastructure for business continuity and post-disaster recovery. Loss of use of the Faculty Offices and Lecture Spaces would be disruptive, but since classes would likely cease during a recovery period and relocation of the offices to temporary off-campus locations is possible, a much longer recovery time is tolerable. The Administrative Offices are assigned a high-importance classification based on their role in post-earthquake recovery, but are assigned a moderate length for acceptable downtime since many of the administrators could tend to immediate post-disaster needs from alternate sites. After 2 weeks, it is desired to have all administrative staff centrally located to gain efficiency in the coordination of the post-disaster recovery efforts. The data used to calculate the RSI is obtained from the linear response spectrum analysis of each building. Preliminary retrofit schemes are produced as part of the assessment work and used to inform the estimated retrofit costs. Replacement costs within the COI calculation can be taken from current benchmark construction costs in the region and estimates of contents from the university's insurance records.

In Equation 1, the IMF purposefully scales up the CRI and RSI based on functionality and role in recovery. The intent is to address special structures with low population density such as those housing first responders, mission-critical utilities, shelter spaces, or hazardous materials. This is separate from the increase in the RPS that occurs due to a short acceptable downtime for certain functions.

For the values described in Table 2, Building A has the highest RPS and, under this methodology, should be given the top priority for retrofit. Despite it having the highest retrofit cost per square foot this represents the best overall outcome in terms of the people and assets protected as well as acknowledging its role in the business continuity plans.

Table 2: Sample calculations of RPS for selected buildings at university campus in Figure 1.

	Building A: Offices/Data & Telecommunications Centre	**Building B: Faculty Offices/Lecture Spaces**	**Building C: Administration Offices**
IMF	Based on data centre usage for on- & off-campus activities. IMF = 1.5	IMF = 1.0	Based on post-earthquake role in campus recovery. IMF = 1.3
CRI	Acceptable downtime of 24 hours based on data centre Average occupancy: Office 20 ppl x 8 hrs x 5 days Data & Telecom Centre 4 ppl x 24 hrs x 7 days Total occupancy is 1,472 person-hours per week. CRI = 0.68	Acceptable downtime of 3 years based on suspension of classes, and design, permitting and construction of a replacement building Average occupancy: Faculty Office 50 ppl x 6 hrs x 5 days Lecture Space 500 ppl x 4 hrs x 4 days Total occupancy is 9,500 person-hours per week. CRI = 0.45	Acceptable downtime of 2 weeks based on temporary accommodation until campus operations restarted Average occupancy: Office 250 ppl x 8 hrs x 5 days Total occupancy is 10,000 person-hours per week. CRI = 0.65
RSI	Assessed capacity at 30% of modern building code RSI = 1-0.30 = 0.70	Assessed capacity at 40% of modern building code RSI = 1-0.40 = 0.60	Assessed capacity at 60% of modern building code RSI = 1-0.60 = 0.40
COI	Retrofit cost assumed as $300/sq. ft. Asset value assumed as $600/sq. ft. for building and $1000/sq. ft. for content COI = 1-300/1600 = 0.81	Retrofit cost assumed as $250/sq. ft. Asset value assumed as $600/sq. ft. for building and $100/sq. ft. for content COI = 1-250/700 = 0.64	Retrofit cost assumed as $150/sq. ft. Asset value assumed as $600/sq. ft. for building and $150/sq. ft. for content COI = 1-150/750 = 0.80
RPS	(0.68 + 0.70)*1.5 + 0.81 = 2.88	(0.45 + 0.60)*1.0 + 0.64 = 1.69	(0.65 + 0.40)*1.3 + 0.80 = 2.17

4 FURTHER DISCUSSION

It is important to recognize that the proposed RPS methodology represents a point in time snapshot of the recommended priority for seismic upgrades. As the input parameters change or the deficiency of buildings is reduced through renovations, the scores can be updated and a new ranking developed. Local contractors and insurance company representatives can be engaged to advise on updated replacement values on a periodic basis. Occupancy numbers should be updated as staffing, hours of operation, or other factors change.

High RPS indicates the priority to retrofit. It should be noted, however, that some structures with a low RPS should be preferentially considered earlier than suggested by the score in cases where future construction access will be constrained, or where planned renovation or building renewal will occur. Structures with high retrofit costs relative to asset values should be considered for possible replacement.

5 CONCLUSION

Owners or stakeholders are typically faced with limited resources for implementing a seismic mitigation program. A simple methodology using a Retrofit Priority Score (RPS) is proposed in this paper to assist on the decision: which structure to retrofit first in order to effectively mitigate seismic risk? The RPS is calculated by three indices: Criticality Index (CRI) based on acceptable downtime and people affected, Risk Index (RSI) based on the level of structural deficiency, and Cost Index (COI) based on the estimated seismic retrofit cost relative to the value of assets protected. In comparison to commonly used approaches that only consider the degree of structural deficiency as obtained through rapid visual screening or code-based structural analysis, the RPS methodology provides a more comprehensive consideration of a building and its relationship to the community. The simplicity but effectiveness of the proposed RPS methodology is demonstrated via results for selected buildings on a fictitious university campus, each having mixed-use occupancies and different importance to post-earthquake business continuity requirements. For owners and stakeholders with large portfolios of buildings, a ranked listing of the RPSs for the portfolio can be used as an effective tool to quantitatively establish the priority order of projects within a larger seismic mitigation program.

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