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RISK-BASED SEISMIC RETROFIT PRIORITIZATION OF REINFORCED CONCRETE CIVIC INFRASTRUCTURE: CASE STUDY FOR STATE OF OREGON SCHOOLS AND EMERGENCY FACILITIES

S. Tesfamariam[1], Y.M. Wang[2] and M. Saatcioglu[3]

ABSTRACT

Oregon is located in a high seismic hazard that raises serious concerns for potential damage and collapse of older concrete schools buildings and emergency facilities. In order to allocate retrofit prioritization budget, a risk-based evaluation proposed by Tesfamariam and Saatcioglu (2008) is applied over 600 Oregon's civic reinforced concrete buildings. This risk-based seismic retrofit prioritization can potentially be used by the state of Oregon to highlight those needing mitigation to minimize casualties and increase community preparedness. The risk-based prioritization can also be applied to civic structures in other high seismic regions.

Introduction

Reported damage of schools from recent earthquakes, 1999 Düzce and 2003 Bingöl earthquakes in Turkey (Gur et al. 2009), 2005 Kashmir earthquake in Pakistan (EERI 2006), and 2008 China earthquake, for example, highlight vulnerability of existing schools and importance of seismic retrofit implementation. The building vulnerability is due to older building design codes, poor design practices and poor code enforcement. Most of these schools are currently operational and are required to be evaluated and retrofitted to minimize seismic damage and improve life safety. Different school retrofit prioritization (Pina et al. 2008, Grant et al. 2007, Taylor et al. 2006) and retrofit techniques (López et al. 2007, Tena-Colunga 1996) have been reported. For a decision maker, comprehensive evaluations of all buildings are not economically feasible, and it is desirable to screen out deficient buildings and there is a need for reliable and rapid prioritization technique.

The first Oregon's statewide building code was not adopted until 1974, and it was not until 1994 that seismic considerations were added to the building code, many schools and emergency facilities are in desperate need of seismic strengthening and basic upgrades. Improving the physical deficiencies of aging schools and emergency facilities is a sound, long-term investment of fundamental importance to communities-- the fabric of our society. Oregon's

[1] Assistant professor, School of Engineering, The University of British Columbia | Okanagan, 3333 University way, Kelowna, BC, Canada, V1V 1V7, E-mail: Solomon.Tesfamariam@ubc.ca, corresponding author
[2] Geohazards section leader, Oregon Dept of Geology and Mineral Industries, 800 NE Oregon St, #28, Portland, OR 97232, E-mail: Yumei.Wang@dogami.state.or.us
[3] Professor and University Research Chair, University of Ottawa, Ottawa, Ontario Canada, E-mail: murat@uottawa.ca

recent study (discussed below), also, indicates the median age of Oregon school buildings is 46 years with almost 1,200 high occupancy school buildings over 50 years old. It was not until 1994 that seismic considerations were added to the state's building code. A high percentage of Oregon school buildings were built prior to 1994, making many of these buildings vulnerable to severe seismic damage during a major earthquake, including from a Cascadia subduction zone earthquake. Furthermore, certain types of older structures that have not been mitigated are expected to perform poorly, especially if they are founded on poor soils.

In 2001, new seismic safety laws were established for high occupancy public school buildings and emergency facilities (Wang and Burns 2006). Several thousand buildings must comply with the Oregon seismic laws to meet a minimum level of public safety. The state of Oregon recently established a seismic rehabilitation grant program to fund seismic upgrades of highly vulnerable schools and emergency facilities to improve life safety, and reduce damages, losses and impacts in future earthquakes. Starting in 2010, the grant program will distribute state bond funds using a risk-based approach in order to best control state expenditures. As part of the eligibility criteria to receive grant funds, an enhanced rapid visual screening method developed for the Oregon University System is integrated into the required benefit cost analyses (Wang and Goettel 2007). In a 2007 report released by the Oregon Department of Geology and Mineral Industries (DOGAMI), 3,352 civic infrastructure buildings were assessed for potential seismic hazards (Lewis 2007). The score and ranking used are linguistically described as – Very High, High, Moderate, and Low – that were related to the likelihood or probability of a building sustaining major life threatening damage, given the occurrence of an earthquake. The assessment was conducted using FEMA 154 rapid visual screening (RVS) (ATC 2002). The RVS results observed are approximations based on limited observed and analytical data. Each facility with high scores requires further investigated by a qualified and experienced engineer. However, this task will be expensive, therefore, unlikely to be conducted for many years.

The work described in this paper, which is an intermediate step, is an evaluation of the reinforced concrete (RC) buildings summarized in the 2007 DOGAMI database. This paper is aimed at implementing a risk-based retrofit prioritization reported by Tesfamariam and Saatcioglu (2008) for Oregon's school and emergency service buildings. This effort aims to distinguish dangerous, collapse-prone buildings from those buildings that will likely incur limited damage. The purpose is to make higher quality data available for prioritization of seismic retrofits.

Hierarchical Risk Assessment Technique for Reinforced Concrete Buildings

The complex problem of risk-based inspection can be handled through a simple and manageable hierarchical structure. The hierarchical structure follows a logical order where the causal relationship for each supporting argument is further subdivided into specific contributors. Miyasato et al. (1986) proposed a hierarchical structure for seismic vulnerability assessment of buildings, which has been adopted in this paper after some modifications (Figure 1).

Figure 1 shows a six-level hierarchical structure. Level 1 of the hierarchy is the overall goal of the analysis, i.e., seismic risk. The seismic risk is computed by integrating the parameters at level 2 that reflects building damageability and building importance/exposure. At level 3, the building importance/exposure parameter is computed by integrating building use, building occupancy and economic importance. The building damageability in turn is computed by integrating the parameters at level 3, site seismic hazard and building vulnerability. The site seismic hazard is computed by integrating site seismicity, soil type and number of stories, details of which is outlined Tesfamariam and Saatcioglu (2008).

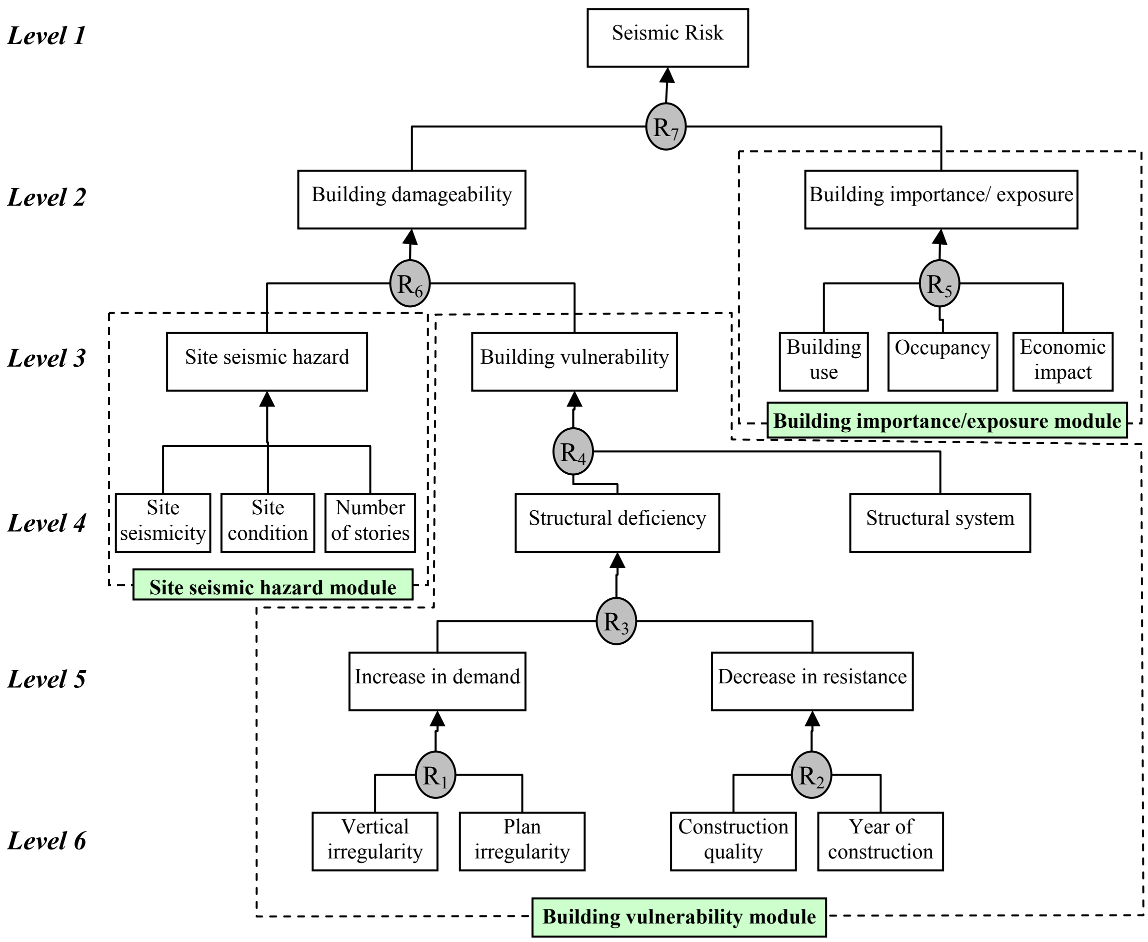

Figure 1. Hierarchical earthquake risk assessment of Reinforced Concrete Buildings (after Tesfamariam and Saatcioglu 2008).

Building vulnerability to ground shaking and associated damage can be grouped into two categories (Saatcioglu et al. 2001); factors contributing to an increase in seismic demand (e.g., soft story frame, weak column-strong beam, vertical irregularities); and factors contributing to reduction in ductility and energy absorption capacity (e.g., construction quality, year of construction, structural degradation). Obtaining and incorporating exhaustive detail of those factors is not feasible in a preliminary risk assessment of RC buildings. In this paper, the basic risk parameters considered in FEMA 154 for building vulnerability assessment have been adopted, i) building type, ii) vertical irregularity (VI), iii) plan irregularity (PI), iv) year of construction (YC) and v) construction quality (CQ). Thus, given these five parameters, the building vulnerability can be computed by integrating inherent system deficiency, structural system (SS), e.g., shear wall or moment resisting frame buildings, and structural deficiency, e.g., vertical irregularity. The structural deficiency is subdivided into input parameters that contribute to an increase in demand and decrease in resistance. Parameters that contribute to an increase in demand are vertical irregularity and plan irregularity. On the other hand, parameters that contribute towards the decrease in resistance are construction quality and year of construction.

Site Seismic Hazard

World experts on the Pacific Northwest's Cascadia subduction zone met in 2000 and issued a consensus statement on the earthquake risks. The consensus statements include: "the Cascadia subduction zone produces great earthquakes, the most recent of which occurred in 1700 and was magnitude 9," and "strong ground shaking from a M9 plate-boundary quake will last 3 minutes or more and will be dominated by long-period ground motions. Damaging ground shaking will probably occur as far inland as Vancouver, Portland and Seattle." The consensus statements from the Geological Society of America (GSA) Penrose Conference reflect the high seismic hazard that Western Oregon faces and is agreement with the USGS probabilistic ground motion levels (Clague et al., 2000). Figures 2a and 2b show the 2008 U.S. Geological Survey earthquake ground motion maps for 2% probability of exceedance in 50 years for 0.2 s and 1.0 second periods, respectively.

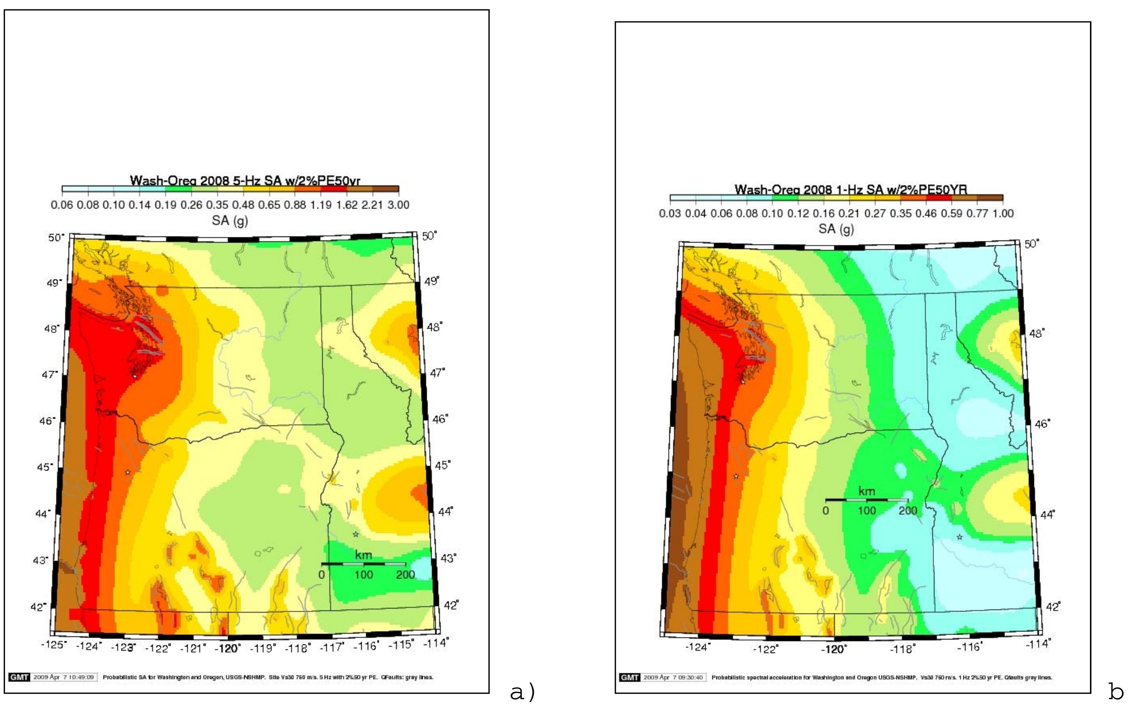

Figure 2. 2008 U.S. Geological Survey earthquake ground motion maps for 2% probability of exceedance in 50 years for period of a) 0.2 second and b) 1.0 second (Source: http://earthquake.usgs.gov/research/hazmaps/products_data/2008/maps/).

The Cascadia Subduction Zone (CSZ) stretches from Northern California to British Columbia and is the dominant seismic hazard source for Oregon. Recent studies suggest that the last great earthquake on January 26, 1700 with a moment magnitude 9 earthquake (Atwater et al.

2005). Numerous detailed studies of coastal subsidence, tsunamis, and turbidities yield a wide range of recurrence intervals, but the most complete records indicate average intervals for a full length rupture of 350 to 600 years. Recent scientific research on the CSZ indicates average recurrence intervals as short as 240 yrs on the southern CSZ from the past 2800-yr geologic record (Goldfinger et al., 2008). With over 300 years since the most recent CSZ earthquake, which was on January 26, 1700, the next CSZ earthquake could occur anytime.

The site seismic hazard is quantified through fundamental period (T_1) of the structure and response spectra. To evaluate the site specific seismic hazard for this study, we used modified site specific response spectra in accordance to the 2007 Oregon Structural Specialty Code (OSSC). The OSSC is based on the International Building Code, which includes probabilistic ground motion maps with a 2% probability of exceedance in 50 years. We modified the response spectra using NEHRP site specific soil types in the DOGAMI database and the U.S. Geological Survey web tools for 610 sites (http://earthquake.usgs.gov/research/hazmaps/design/). Finally, using the T_1 and corresponding response spectra, spectral acceleration $S_a(T_1)$ is obtained. The $S_a(T_1)$ is used in the fuzzification of site seismic hazard as will be discussed in the next section.

Fuzzy Based Modeling

Fuzzy logic provides a language with semantics to translate qualitative knowledge into numerical reasoning, which enables in modeling complex systems like buildings. The strength of fuzzy logic is that it can integrate descriptive (linguistic) knowledge and numerical data into a fuzzy model and use approximate reasoning algorithms to propagate the uncertainties throughout the decision process. The fuzzy inference system (FIS) contains three basic features (Zadeh 1973):

- linguistic variables instead of, or in addition to, numerical variables;
- relationships between the variables in terms of IF-THEN rules (rule-base); and
- an inference mechanism that uses approximate reasoning algorithms to formulate relationships.

The basic theory of fuzzy sets was first introduced by Zadeh (1965). It can deal with the nature of uncertainty in system and human error. A fuzzy set describes the relationship between an uncertain quantity *x* and a membership function μ_x, which ranges between 0 and 1. A fuzzy set is an extension of the traditional set theory (in which *x* is either a member of set A or not) in that an *x* can be a member of set *A* with a certain degree of membership μ_x. In this paper, a triangular fuzzy number is used for its simplicity.

For linguistic consequent parameters, Mamdani type inferencing can be used (Mamdani, 1977). Mamdani's inference mechanism consists of three connectives: the aggregation of antecedents in each rule (AND connectives), implication (i.e., IF-THEN connectives), and aggregation of the rules (ALSO connectives). The IF-THEN rules can be established as:

$$R_i : \text{IF } x_1 \text{ is } A_{i1} \text{ AND } x_2 \text{ is } A_{i2} \text{ THEN } y \text{ is } B_i \;, \quad i = 1, \ldots, n \tag{1}$$

The final step entails the defuzzification process using a simple weighted average method. Details of the fuzzification and aggregation process are provided in Tesfamariam and Saatcioglu (2008).

Risk Index

In the proposed hierarchical structure, the risk index I^R is quantified by aggregating the building damageability index I^{BD} and importance and exposure index I^{IE}. Indeed, similar to the quantification of I^{BD}, it can be argued that the quantification of risk is intricately associated with potential for building damage, and if there is any damage, with the consequence of failure. The final risk index I^R value is in a unit interval $I^R \in [0, 1]$. For decision making purpose, however, the risk index I^R value can be converted into a linguistic constant. In this paper, four linguistic constants are considered for final decision making purpose: Negligible, Marginal, Critical and Catastrophic, respectively, with corresponding I^R "cut off" values of [0, 0.2), [0.2, 0.4), [0.4, 0.6) and [0.6, 1.0]. It should be noted that specification of the threshold values are subject to the decision maker's risk tolerance, and need to be calibrated and a general consensus established.

Case Study of Oregon's Concrete Schools and Emergency Facilities

DOGAMI Database and Input Data

Since 2001, high risk public school buildings, with greater than 250 students, have been required by law to be mitigated to ensure a safer, more secure educational environment. In 2007, the State of Oregon evaluated 1,101 schools in 170 districts representing 97% of the total enrollment for the 2005-06 academic year. DOGAMI developed a comprehensive school building database with these five key parameters that determine the relative seismic risk of each school building: 1) zone seismicity (how hard the ground is expected to shake), 2) building structural type, 3) building irregularities, 4) original construction date, and 5) soil type (softer soils amplify the severity of ground motion). The reinforced concrete building types considered in this research are C1 (Concrete Moment Frame), C2 (Concrete Shear Wall Buildings) and C3 (Concrete Frames with Infill Masonry Shear Walls). Figure 3 shows location of each building considered. Figure 4 provides summary of the building categories, the building modifiers and spectral acceleration.

Purpose of Case Study

Schools and emergency facilities are civic infrastructure, which are important to communities. Oregon schools and emergency facilities need to mitigate the seismic deficiencies as well as address non-life safety issues, including environment-related abatement (asbestos, mold, PCBs, lead) and American Disabilities Act. Furthermore, energy efficiency needs, inadequate classroom space, modernization, or educational materials are important. Earthquake risk posed by older concrete buildings in Oregon's schools and emergency facilities need to be better identified to reduce future casualties. We conducted seismic risk evaluation of over 600 concrete civic infrastructure buildings in Oregon.

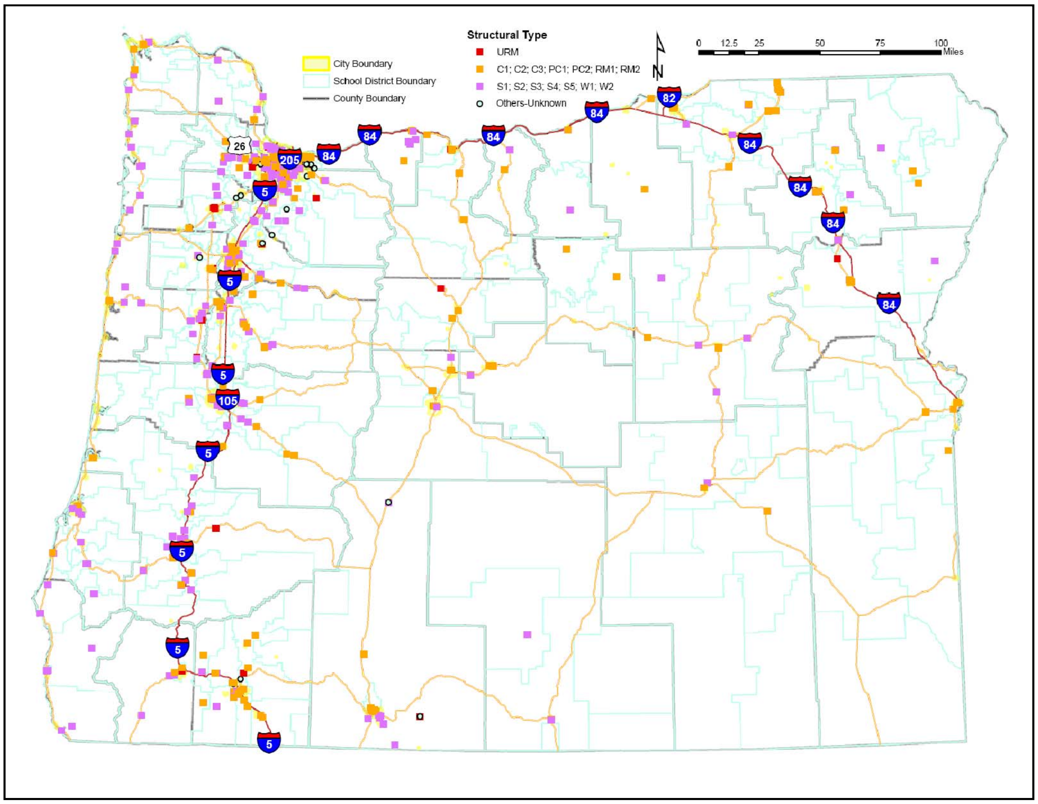

Figure 3. Location and RVS structural types of schools that are over 50 years old in Oregon.

Application and Results

The risk-based evaluation is applied for the 610 school and emergency service buildings and the results are summarized as a probability of risk exceedence in Figure 5. Results show that the probability of having risk index of Negligible, Marginal, Critical and Catastrophic are 0.37, 0.14, 0.21 and 0.28, respectively. Furthermore, the risk based prioritization for the 610 buildings are indicates that the number of buildings in Negligible, Marginal, Critical and Catastrophic risk index, are 75, 156, 98 and 281, respectively. From a decision maker's perspective, the 281 buildings should get more attention for detailed evaluation and retrofit prioritization.

Oregon's Seismic Rehabilitation Grant Program

In late 2009, Oregon launched the nation's first state-funded seismic rehabilitation grant program. The Oregon seismic rehabilitation grant program was created to eliminate collapse-prone, high-occupancy school buildings to avoid mass casualties in future major earthquakes, as well as to promote community preparedness by strengthening emergency facilities. Seismic vulnerability scores for school and emergency service buildings across the state are publicly available on www.oregongeology.org/sub/projects/rvs/default.htm and www.ode.state.or.us/go/quakesafeschools. Under the leadership of Senate President Peter Courtney, the 75th Oregon Legislature (2009-2011) authorized the first state bond sales of $15 million bond funds for seismic mitigation of public schools and $15 million bond funds for emergency facilities. Over $1 billion dollars may be distributed over the next two decades. The grant program is administered by the Oregon Emergency Management (www.oregon.gov/OMD/OEM/) (Wang, 2010).

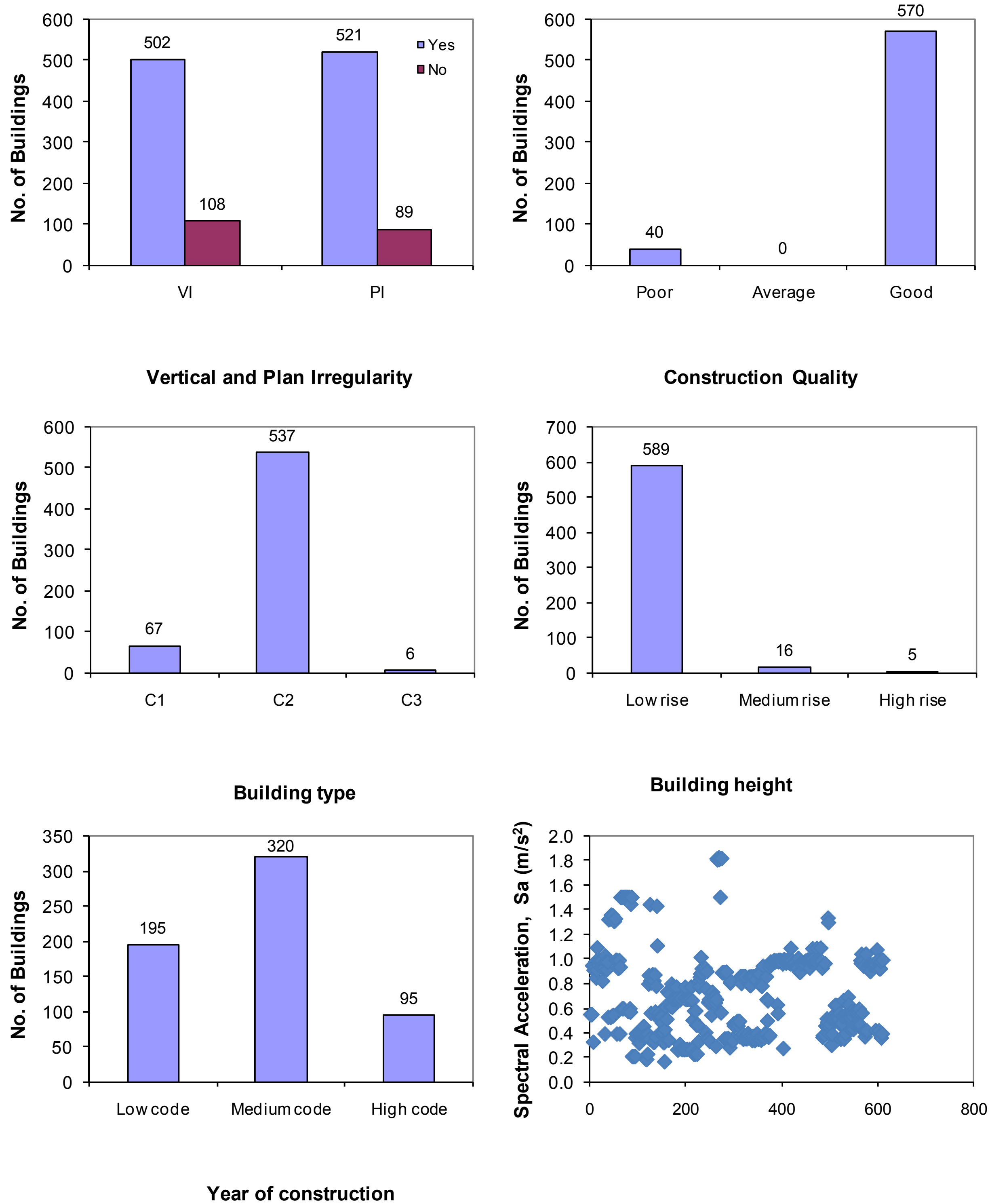

Figure 4. Performance modifiers for the building vulnerability and spectral acceleration.

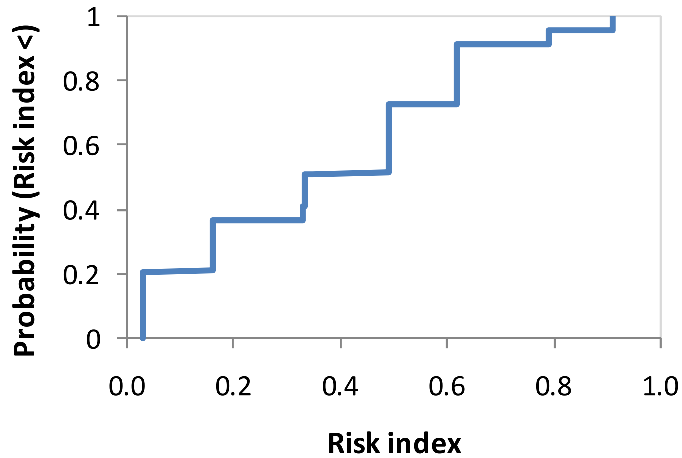

Figure 5. Risk index values of reinforced concrete buildings for case study.

Conclusions

Reported earthquake induced damage of schools highlighted vulnerability of existing schools and importance of seismic retrofit implementation. The state of Oregon is situated along the Cascadia fault line and as a result, the schools are vulnerable to seismically induced damages. The Oregon Department of Geology and Mineral Industries completed a study using the FEMA 154 rapid visual screening method for 3,352 civic infrastructure buildings. Decision makers are often faced with challenging resource allocation decisions for retrofit implementation. On this regard, this paper implemented a risk-based seismic retrofit prioritization proposed by Tesfamariam and Saatcioglu (2008) for over 600 school and emergency service buildings. The risk-based prioritization for the 610 buildings indicates that the number of buildings in Negligible, Marginal, Critical and Catastrophic risk index states, are 75, 156, 98 and 281, respectively. This risk index values can be used by the state of Oregon decision makers to fund detailed evaluation and rehabilitation of buildings in a Critical and Catastrophic risk states. This risk-based prioritization approach can be extended to other civic infrastructure in Oregon and in other seismic regions.

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