Benefit-cost analysis of the seismic risk mitigation for a region with moderate seismicity: The case of Tiberias, Israel

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Abstract

While high seismic-active regions have been widely investigated, areas with low seismic hazard has not been adequately addressed as being exposed to high risk of significant losses due to their vulnerable built environment and high exposure of population. A risk-based methodology for determining a cost-efficient risk mitigation plan, along with comprehensively seismic risk assessment, is needed for seismic-quiescent areas in facilitating cost efficient seismic mitigation plans. This article presents a methodology for investigating the economic feasibility of the building retrofit by means of benefit-cost analysis. The objectives of this study are (1) to assess the seismic risks with building and demography parameters which can fully represent the characteristic of local built environment, (2) to conduct benefit-cost analysis of the seismic mitigation activities, and (3) to verify the applicability of the present methodology by a case study. This study intends to provide public decision makers a standardized methodology for justifying the economic feasibility of seismic risk mitigation alternatives so that a cost-efficient public earthquake mitigation strategy can be achieved.

Keywords: benefit-cost analysis; casualty rate, earthquake hazard; earthquake loss assessment; HAZUS.

1. Introduction

While high seismic-active regions have been widely investigated and understood, areas with low seismic hazard has not been fully recognized as being exposed to high risk of significant losses due to their vulnerable built environment and high exposure of population. As a result, comparing with those high seismic-active regions with corresponding well-prepared seismic risk management plans, a moderate earthquake could cause more significant consequences to those low-probability/high vulnerable regions due to their lack of awareness and preparation for seismic hazards. Several studies indicate that public policies for earthquake risk mitigation commonly fail in those areas as a result of the lack of thoroughly seismic risk estimation, awareness in the general public and unclear economic drivers for seismic mitigation plans (Prater and Lindell, 2000), (Smyth et al., 2004), (Bostrom et al., 2008).

A substantial amount of researches have focused on loss assessment for high seismic regions. For instance, (Kircher et al., 2006) estimates building damage and human loss due to a repeat of the 1906 San Francisco earthquake using HAZUS software package. Also by operating HAZUS, (Schmidtlein et al., 2011) examines the spatial correlation between social vulnerability and potential earthquake losses under differing earthquake scenarios in South Carolina. These studies address on the seismic loss assessment for those areas which are identified as highly seismic-active, or have historical occurrences of major earthquakes. On the other hand, although loss assessment in the areas with infrequent damaging earthquakes starts to grab attention, there are comparatively few studies addressing this significant issue. (Tantala et al., 2008) investigates the potential high seismic risk of New York City due to its tremendous assets and vulnerability of its structures, which were not seismically designed as strong as most in the West Coast. (Remo & Pinter, 2012) compares the result of loss estimation from HAZUS to the damage surveys for the 2008 Mt. Carmel, Illinois earthquake and finds that the HAZUS overestimated the losses from the surveys. (Rein & Corotis, 2013) assesses potential consequences of major earthquakes for the Denver Region in the U.S., which is presented as a case of the seismic vulnerability of an area that is not generally considered seismically active and finds out that potential losses due to earthquakes would be amplified as a result of the low preparation of public and perception of people for earthquake risk. In sum, aforementioned researches all show the potential high risk in a low seismicity region due to its vulnerability on built environment and social-economic.
This article presents a methodology for investigating the economic feasibility of the building retrofit to the portfolios of buildings by means of benefit-cost analysis of the structural intervention. The particular objectives of this study are (1) to assess the seismic risks with building and demography parameters and casualty rates which can fully represent the characteristic of local built environment, (2) to calculate the benefit-cost ratio of the seismic mitigation activities, and (3) to verify the applicability of the present methodology by a case study. This study intends to provide public decision makers a standardized methodology for justifying the economic feasibility of seismic risk mitigation alternatives so that a cost-efficient public earthquake mitigation strategy can be achieved.

2. Background

Applying the framework of the catastrophe risk model, a basic seismic risk assessment model can be comprised by four modules: (1) hazard module, characterizing hazards in a system at risk to be investigated. In this study, a ground motion hazard is defined by its location, magnitude and frequency of occurrence; (2) inventory module, collecting data of geological characteristics such as site effects and soil attenuation for calculating local seismic intensity, and data of built environment such as occupancy types and building structural types; (3) vulnerability module, calculating social and physical vulnerability of built environment exposed to hazard. The social vulnerability generally includes social-economic information like income, ethnicity, age or ownership of property. The information of social vulnerability is the main factor in estimating the number of displaced household and temporary shelters after earthquakes. Physical vulnerability is usually defined by the fragility curve of a structure, which determines the expected building damage in a particular level of seismic intensity; and (4) loss module, evaluating the loss to the inventory by interpreting its corresponding vulnerability to the hazard. Losses, characterized as direct or indirect, can then be assessed in terms of social, economic and environmental losses.

Several risk assessment methodologies have been developed based on the typical seismic risk assessment model. (Korkmaz, 2009) provided losses assessment models for long-term disaster management considering probabilistic seismic hazards. Also, different methodologies and frameworks for seismic loss estimation have been developed and used to conduct a benefit-cost analysis for different seismic retrofit alternatives. (Smyth et al., 2004) (Boylu, 2005) (Kappos & Dimitrakopoulos, 2008). In addition, various seismic loss assessment models have been widely adopted in estimating the probable maximum loss by exceedance probability curves for assisting insurers or reinsurers in pricing the insurance policies. Examples of such studies include (Hsu et al., 2006) (Hsu et al., 2013). However, the complicated mathematical formulas and large number of variables make these loss assessment models difficult to be understood and operated by a wide range of stakeholders. Moreover, the nature of their non-standardized and proprietary code source prevents other users from modifying the models accordingly for their specific needs.

Correspondingly, a number of standardized software packages have been developed with friendly user-interface and open-source database. Most of them also utilize Geographic Information System in presenting the geographic distribution of losses for analyzing particular issues like emergency facilities layout. Examples include: Taiwan Earthquake Loss Estimation System developed by (Yeh et al., 2006) is designed to estimate the losses under different earthquake scenarios; moreover, the module of Early Seismic Loss Estimation of this program can obtain real-time estimates of seismic hazards and losses soon after the occurrence of earthquakes. KOERILoss, a Turkish-based seismic loss assessment program developed by Department of Earthquake Engineering of Bogazici University, can also estimate the losses by earthquake hazards (Erdik et al., 2003). Earthquake Loss Estimation Routine is a European-based software package for rapid estimation of earthquake shaking and losses throughout the Euro-Mediterranean region, developed under the Joint Research Project entitled Network of Research Infrastructures for European Seismology. (Hancilar et al., 2010). Although having the merit of being standardized and straightforward, these regional-based software packages have not been widely validated for their applicability to international setting and thus the international adaption of these local-based tools is still under a question mark.

3. Methodology

3.1. Benefit-Cost Analysis

Ideally, in order to protect properties and lives, all those buildings which are considered to be vulnerable to seismic hazard should be structurally strengthened to prevent them from severe damage in earthquakes. However, it may not be such a simple decision because for the purpose of the most effective means of limit resources, building retrofit is not always economically justified in some cases. For this reason, Benefit-Cost
Analysis (BCA) can serve as a straightforward and systematic tool for public and private sectors to perform a long term economic analysis in evaluating the tradeoff between safety and investment in risk mitigation alternatives. (Smyth et al., 2004) provided a detailed description to the procedures of BCA for seismic mitigation activities, including five steps: (1) specify the nature of problem, including the stakeholders, alternative options and the status quo, which can serve as a reference point for evaluating the performance of structural interventions, (2) determine the direct and indirect cost of the mitigation alternatives, (3) determine the benefits of mitigation alternatives, including the direct benefit such as the reduction of physical damage and the indirect ones such as the save in the cost for displaced households, (4) calculate the attractiveness of the mitigation alternatives, using appropriate discount rate to compare cost of mitigation alternatives to reduction in loss over a structure’s lifetime though Benefit-Cost Ratio (BCR), and (5) choose the best alternative in terms of the highest BCR. To efficiently achieve a cost-efficient earthquake mitigation strategy for public decision makers, a straightforward risk-based methodology for evaluating the economic feasibility of structural retrofit is important. For this reason, BCA have been widely adopted for the evaluation of the economic feasibility of public investment in seismic mitigation measures of: (1) upgrade of seismic design code (Peterson & Small, 2012), (2) retrofit of bridges (Nuti & Vanzi, 2003), and (3) retrofit of old concrete frame buildings in California U.S. (Liel & Deierlein, 2013), existing vulnerable buildings in Turkey (Smyth et al., 2004), in Greece (Kappos & Dimitrakopoulos, 2008), in China (Zhang et al., 2011) and in a broad scale of fourteen Latin American countries (Valcárcel et al., 2013).

Following the aforementioned procedure, in the case of seismic mitigation analysis for a public sector, the costs include the expenditure for retrofit or replacement of buildings and the benefits come from the reduction on the risks of casualties and damage of those buildings which are structurally improved by retrofit or reconstruction. Considering that the benefits of mitigation actions would be realized at some points in the future with an average annual probabilities of occurrence (FEMA, 1992), the expected annual benefits are constant in each year over the lifetime of buildings. In this regard, the future benefits are discounted to present values for comparison with the up-front costs of mitigation alternatives. The expected annual benefits of a mitigation action $EAB_t$, using Eq. (1), are the summation of the expected annual benefits due to the reduction on direct economic loss $EAB_L$ and the benefits due to reduced fatalities $EAB_F$. The benefits in behalf of reduced direct economic loss $EAB_L$ are calculated using Eq. (2) from the difference in expected annual economic losses for mitigated buildings $EALE_m$ and the original buildings $EALE_o$. Similarly, the benefits associated with reduced fatality loss $EAB_F$ are calculated using Eq. (3) from the difference in expected annual fatality losses for mitigated buildings $EALF_m$ and the original buildings $EALF_o$.

\[
EAB_t = EAB_L + EAB_F \\
EAB_L = EALE_m - EALE_o \\
EAB_F = EALF_m - EALF_o
\]

The benefits in present monetary value $E[B_t]$ over a time horizon $T$ are calculated using Eq. (4) with discount rate $r$. The benefit-cost ratios $BCR$ are obtained using Eq. (5) by dividing the expected benefits $E[B_t]$ by the reduced cost of mitigation, which is the up-front cost of mitigation $C_o$ minus present salvaged value of the retrofitted or rebuilt buildings $V_s$, which considers the increase in the value of the retrofitted or rebuilt buildings. When the $BCR$ is greater than one, it is economically justified of the investment in the designed pre-earthquake structural intervention to a building stock.

\[
E[B_t] = \sum_{t=0}^{T} \frac{EAB_t}{(1+r)^t} \\
BCR = \frac{E[B_t]}{C_o - V_s}
\]
4. Results

4.1 Building damage and economic losses

Five categories are defined in HAZUS for building damage: no damage, slight, moderate, extensive and complete. The number of damaged buildings is converted from the probability of damage to the buildings for each building type. Analyzing the number of damaged buildings of unreinforced masonry for scenarios Jordan 6.0 Mw and Jordan 7.0 Mw, as depicted in Fig. 2, 79% and 95% of URM buildings are damaged, respectively, as expected that URM is recognized as one of building types which is most seismically vulnerable (Spence et al., 2011). For concrete frame, as depicted in Fig. 3, 55% and 77% are damaged under scenarios of 6.0 Mw and 7.0 Mw, respectively. Here we investigate the vulnerability of a building type with its built year by measuring the percentage of damaged buildings with associated built year to the total number of buildings for each building type. As depicted in Fig. 3, the buildings built before 1980 account for most damaged buildings for both concrete frame and URM. 44% and 64% of URM built before 1980 are estimated to be collapse under scenarios of 6.0 Mw and 7.0 Mw, respectively. For concrete frame, 55% and 77% are damaged under scenarios of 6.0 Mw and 7.0 Mw, respectively. It can be observed that the vulnerability of a building type is increased along with the ages of the building. In this study, the economic loss considers both the loss due to direct physical damage of structural components represented by repair cost, and the loss comes from damaged contents. The economic losses under scenarios of Mw 6.0 and Mw 7.0 are $29,413,892 and $76,476,119, respectively.

4.2 Benefit-Cost analysis of building retrofit

We examine the benefit-cost ratio of retrofitting all concrete frame (CF) and unreinforced masonry wall (URM) buildings which were built before 1990 to the level of seismic performance of modern buildings designed based on the Israel Standard 413. Table 1 summarizes the result of benefit-cost analysis under the Jordan 6.0 scenario. As shown in Table 1, casualty losses are reduced by structural retrofit. Since the buildings built before 1980 are most venerable to earthquake, the casualty losses of these buildings are significant reduced by upgrading seismic performance. The benefit-cost ratios for both CF and URM built before 1980 are 1.1 and 1.3, respectively; in other words, retrofit mitigation strategies are economically feasible. On the other hand, the benefit-cost ratios of CF and URM built between 1971 and 1990 are 0.9 and 0.8, respectively. The reason for the relatively smaller BCR is that the benefits of human live avoided are not significant since these buildings are
considered partially resistant to the earthquakes. It is therefore conclude that the investment in retrofitting the buildings built between 1981 and 1990 is not economically justified.

Table 1. Benefit- Cost analysis in Jordan 6.0 scenario

| Building type (built year) | Benefit from economic losses avoided ($, million) | Live saved | Total benefit ($, million) | Cost of retrofit ($, million) | BCR  |
|---------------------------|--------------------------------------------------|------------|---------------------------|------------------------------|------|
| CF (< 1980)               | $2.1                                             | 59         | $3.6                      | $3.3                         | 1.1  |
| CF (1981-1990)            | $1.8                                             | 14         | $2.7                      | $3.0                         | 0.9  |
| URM (< 1980)              | $0.4                                             | 35         | $0.8                      | $0.6                         | 1.3  |
| URM (1981-1990)           | $0.2                                             | 12         | $0.5                      | $0.6                         | 0.8  |

5. Conclusion

This study first investigates the attributes of local built environment for seismic risk assessment, including building stock, demographic data and casualty rates of concrete frame and unreinforced masonry wall buildings. Adopting HAZUS software, we examines the economic feasibility of seismic retrofitting for both buildings built before 1980, and between 1981 and 1990, which do not comply with modern Israel seismic design code launched in 1991. The benefits of retrofitting those seismic-valuable buildings are measured in terms of reductions in economic and casualty losses in future earthquakes. The result shows that retrofitting the buildings built before 1980 is economically justified as a result of significant number of saved human live. On the other hand, since the buildings built between 1981 and 1990 hold stringer seismic-resistance and thus account for fewer casualty loss, structural mitigation activities are not economically feasible for these buildings. This study provides public decision makers a standardized methodology for justifying the economic feasibility of seismic risk mitigation alternatives so that a cost-efficient public earthquake mitigation strategy can be achieved.

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