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PUBLIC-PRIVATE PARTNERSHIP FOR EARTHQUAKE MITIGATION INVOLVING RETROFIT AND INSURANCE

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Abstract. Public-Private Partnerships involving governments and insurers have been used worldwide for mitigation of natural-hazards. However, the implementation of such systems in developing countries presents problems for their key stakeholders. On the one hand, property owners are hesitant to purchase insurance or invest in retrofit projects due to cost considerations. On the other hand, insurers are reluctant to cover potential seismic losses, because of uncertainties about the risk. This study introduces an innovative Public-Private Partnership framework for property owners, insurers and governments to facilitate decisions related to hazard insurance and structural retrofit of vulnerable buildings. This framework can also help insurance firms reduce the level of corporate financial assets available for payment of compensation to their clients, as required by regulations aimed at reducing the risk of insurer insolvencies. Property owners are motivated to participate in the framework by extra mitigation subsidies from the government. While the government will be reimbursed for part of the cost of these retrofit projects by insurance firms, whose own savings will be achieved through reductions to legally mandated corporate capital. A case study is presented to demonstrate the feasibility of this approach for mitigating seismic risk to residential buildings in a rural area.

Keywords: insurance, retrofit, public-private partnership, natural hazard.

JEL Classification: G22.

Introduction

Destruction of the built environment resulting from natural disasters has recently increased due to the repercussions of climate change and rapid urbanization in hazard-prone areas; as a result, worldwide catastrophe insurance payouts have increased more than tenfold in the last 50 years (Grossi *et al.* 2005) and often place great financial burdens on the insurance industry. Taking the 1994 Northridge earthquake in the United States as an example, the insurance industry financed more than 60% of the reimbursed loss, or approximately 30%

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of the total losses (Linnerooth-Bayer, Mechler 2007). Nevertheless, the level of penetration of catastrophe insurance in many hazard-prone regions is still very low: in low- or middle-income countries, an average of only 1% of losses are covered by insurance (Linnerooth-Bayer *et al.* 2011), and even in developed countries such as the United States, around 50% of the single-family homes in flood-prone areas are not covered by flood-insurance policies (Landry, Jahan 2011). One of the main reasons for these low penetration rates is that the high premiums charged for catastrophe insurance tend to deter property owners from purchasing it, an effect that is magnified in low-income communities (Linnerooth-Bayer *et al.* 2011). These high premiums mainly result from the abnormality of the events covered. In contrast to the high-frequency, low-consequence risks that the insurance industry typically deals with, such as petty theft, car accidents and so forth, the nature of natural disasters – i.e., low-frequency and high-consequence – requires insurers to maintain very large capital sums as a strategy for forestalling insolvency in the face of significant potential payouts (Nguyen 2013).

Although several financial mechanisms have been identified as solutions to this insolvency issue, most of them have been found to be too expensive for practical implementation. Reinsurance or catastrophe bonds, for instance, were investigated for their applicability to spreading the insolvency risk associated with earthquakes in Mexico (Cardenas *et al.* 2007); the results indicated that, although these mechanisms could successfully help the government to withstand an earthquake with a return period of 100 years without any financing gap, the expense of the scheme could also be substantial. Moreover, studies have indicated that moral hazard and adverse selection operate in catastrophe-insurance markets, making private insurers reluctant to offer catastrophe insurance to property owners (Miranda, Glauber 1997). Other efforts have also been conducted in developing more affordable catastrophe insurance; for example, Kunreuther and Michel-Kerjan (2015) suggested a remarkable advantage of multi-year insurance over short-period insurance policies after investigating several factors of property owners' purchasing intention of catastrophe insurance.

Whereas the main purpose of insurance is to transfer losses to other parties, the objective of seismic retrofit is chiefly to reduce the losses per se, especially from casualties. A number of researchers have investigated the seismic retrofitting of old buildings to enhance their structural performance, and in particular the social and economic benefits that can be ascribed to retrofit, in terms of reductions to both expected fatalities and recovery costs (Smyth *et al.* 2004; Kappos, Dimitrakopoulos 2008; Valcárcel *et al.* 2013). While in many cases, retrofit actions have been justified as economically feasible during buildings' service lives, several factors still prevent this seismic-mitigation option from being widely adopted in real-world settings. The high upfront cost has been identified as the main reason that property owners are unwilling to take the action, even in situations where this initial investment could be compensated by the long-term benefits (Nuti, Vanzi 2003). Consequently, several studies have utilized PPPs as a means of motivating property owners to undertake retrofit actions, specifically, by arranging that retrofit costs be reimbursed by the private sector. For instance, the Israeli government developed a national policy to encourage real-estate developers to retrofit old buildings in exchange for granting them the right to add additional dwelling units to the retrofitted structures. Understandably, however, this policy has only been found to be successful in areas with high housing prices (Nahum-Halevy 2013) – despite the fact that areas with low house values tend to be more vulnerable to, and therefore more in need of protection from, seismic hazards (Schmidtlein *et al.* 2011).

Several studies have examined the effect of seismic retrofit on the behavior of insurers. Kleindorfer and Kunreuther (1999) investigated the role of retrofit in improvements to insurers' solvency by examining the expected economic impacts of earthquakes that were attributable to retrofit action. Their results show that smaller insurance premiums and lower deductibles can both be achieved through the implementation of building retrofits. Grossi *et al.* (2005) found that, as the percentage of property owners adopting retrofitting increases, so does the percentage of homes for which insurers are willing to provide coverage. On the other hand, some studies indicate that property owners' motivation to undertake retrofit actions diminishes when they already have insurance coverage: a dynamic that would tend to increase the difficulty of combining these two supposedly complementary risk-mitigation strategies (Kleindorfer, Kunreuther 1999; Kelly, Kleffner 2003). However, a more recent study concludes that a combination of mandatory insurance and subsidized retrofitting could provide incentives to all parties involved in risk management plans (i.e., insurers, government and property owners), due to the positive effect retrofitting has on reducing insurers' risk of insolvency (Peng *et al.* 2014). Since this positive effect of insurance coupled with building retrofit was first identified, a number of researchers have begun to focus on how to enhance this joint mitigation strategy through the implementation of PPPs.

The low-frequency and high-consequence nature of natural disasters results in difficulties in implementation of risk mitigation strategies to all participating parties. Kunreuther discussed potential PPP approaches to encourage property owners, insurers and government agencies to mitigate risk through risk-based insurance premiums, mitigation loans and other alternatives (Kunreuther 2015). In fact, many governments have utilized PPP approaches in cooperation with insurance companies to provide affordable natural-hazard cover to property owners. The Japanese government, for example, has partnered with insurance companies to provide discounts on premiums of up to 30%, depending on the levels of seismic retrofit that are implemented (Tsubokawa 2004). Nevertheless, the involvement of insurance companies remains very low, with insurers only responsible for around 10% of the total liability associated with seismic insurance, as against the government's 87% (Tsubokawa 2004). A national obligatory insurance program to mitigate earthquake impacts in Turkey, known as the Turkish Catastrophe Insurance Pool (TCIP), was established in 2001 as a partnership between the Turkish government and local insurance companies. The objectives of the TCIP include providing earthquake-insurance coverage to property owners at affordable yet actuarially sound rates; limiting the government's financial exposure to natural disasters; and encouraging risk-transferring and risk-mitigation practices in residential construction (Gurenko 2006). With the help of its mandatory nature, as well as the reasonable premium levels that have resulted from state-of-the-art earthquake risk assessment, TCIP reached a 20% penetration rate within six years of its establishment (Cummins, Mahul 2009).

Meanwhile, several PPP projects involving natural-hazard insurance have also been implemented in low-income regions. Micro-insurance, for instance, has become an increasingly popular hazard-insurance mechanism in the poorest parts of India. Micro-insurance aims to provide low-income people with protection against specific hazards, such as earthquakes or drought, in exchange for a premium payment that is acceptable to the policy holders, i.e., is low enough that the schemes must rely on the support of government or NGOs. For this reason, micro-insurance has reached more than 10% penetration in low-income parts of India, as compared to the average of just 1 percent for low-income regions worldwide (Clarke, Grenham 2013).

On the whole, despite the affordable insurance premiums that have resulted from most PPP frameworks developed in the past, low penetration rates due to the reluctance of property owners to purchase insurance still place a great financial burden on governments, while at the same time presenting a serious threat to insurers in the form of greater risk if only financial methods are used and no retrofits are implemented. Therefore, with the intention of addressing such gaps and utilizing the positive effect of retrofit in reducing insurers' insolvency risk, the present study proposes an innovative PPP framework involving government, insurers and property owners, aiming to lessen the financial support for retrofitting required from government; to reduce the insolvency risk of insurers; and to motivate property owners to undertake these two risk-mitigation actions. It is hoped that the present research will serve as a basis for further studies of earthquake mitigation through PPP approaches that combine retrofit and insurance.

1. Methodology

1.1. Earthquake risk

Earthquakes in this study are considered as events with certain probabilities of occurrence. For an earthquake at level k, the probability of occurrence is p_k within a return period, which is taken to be one year for purposes of this paper. The damage to a building inventory in an earthquake k is calculated using HAZUS software, a standardized GIS-based risk assessment software developed by the U.S. Federal Emergency Management Agency (FEMA 2013), but which is customizable based on local conditions. Damage to buildings is then classified into five groups as defined by the HAZUS software, i.e., no damage, slight damage, moderate damage, extensive damage and complete damage. According to the loss estimation from HAZUS simulation for each damage state, the total direct loss from an earthquake event i is calculated as L_i. Historical data on earthquake losses and occurrence probabilities in the study region is used to calculate the annual average loss (*AAL*) for that region, according to the equation presented below (Grossi *et al.* 2005).

The exceedance probability (*EP*) curve for earthquake risk in the study region is calculated from the *AAL*, with p_e as the dependent variable and L_e as the independent variable. Based on the relationship between the magnitude and the return period of earthquakes, the *EP* curve will contain a low-end, a mid-range, and a right-hand tail, representing a relatively high probability of low-level losses and a low probability of extremely high losses. Seismic retrofit can help to reduce the potential consequences of various earthquake scenarios. Depending on the different levels of seismic retrofit that are applied to the building inventory, the cost of retrofit and the retrofitted buildings' expected seismic performance can vary sharply. Nevertheless, by reducing potential levels of damage in earthquakes of different magnitudes, seismic retrofit methods help to reduce both the worst-case loss and the *AAL* from earthquakes (Grossi *et al.* 2005).

1.2. Insurance-firm insolvency

Each insurance company seeks to maintain a certain capital value so that its annual probability of insolvency will not exceed a certain level, and the amount of capital value maintained to keep solvency is defined in this paper as Required Holding Capital (*RHC*). To simplify this calculation for purposes of this paper, financial methods of transferring insurers' risks – such as reinsurance – are not considered, since risk-transferring ultimately costs as much as maintaining capital holdings. The amount of capital holding, then, is directly related to the potential losses to the insured property in major earthquakes, defined as worst-case loss (*WCL*) (Grossi *et al.* 2005). For insurance policies that include no deductible or a fixed deductible, the *RHC* for an insurer is considered equal to *WCL*, since *WCL* can be significantly larger than the aggregate amount of the relevant deductibles. Taking deductibles as a certain proportion ξ of the total loss associated with a group of policies, the relationship between *RHC* and *WCL* can be presented as:

$$RHC = \left(1 - \xi\right) \cdot WCL, \tag{1}$$

where: *RHC* – Required Holding Capital; *WCL* – Worst Case Loss; ξ – Deductible Proportion.

For a given building with insurance coverage, the *WCL* is calculated from the building's *EP* curve as the level of loss at an annual *EP* of δ, which may change based on regulations imposed by government, and/or solvency considerations on the part of the insurer. The *WCL* at an exceedance probability of δ can be deduced from the *EP* curve mentioned above. The shape of the *EP* curve for insurers is affected by various issues: the left-hand tail can be influenced by elements including premiums and deductibles; while the shape of the right-hand tail, which is related to the *RHC*, can only be improved by risk-transfer methods such as reinsurance or CAT bonds at a substantial cost, or else improving the seismic-resistance level of the building itself.

An effective earthquake-mitigation project can change a building's *EP* curve significantly. In general, because earthquake mitigation improves the resistance level of the building to earthquakes of different magnitudes, the *EP* curve of the mitigated building would be located below its original *EP* curve, indicating that the *EP* of a particular amount of loss drops. For different parts of the curve, however, the *EP* may drop to different values below the original value, reflecting the varying performance of the mitigated building at different magnitudes of earthquake. As previously mentioned, the influence that earthquake mitigation has on the reduction of *RHC* is expressed by the potential loss at an *EP* of δ. The reduction of potential loss at an *EP* of δ varies with the effectiveness of the earthquake-mitigation work. The benefit, i.e. reduction of this potential loss, should be weighed against the cost of earthquake mitigation to determine whether mitigation alternative is desirable.

1.3. Proposed PPP framework

Reduced insurance premiums have been widely used to incentivize property owners to undertake seismic-retrofit projects, with the premium reductions achieved through reduction of expected *AAL*. The proposed framework provides dual motivation for property owners – to undertake seismic retrofit and to purchase earthquake insurance – funded by applying part of insurers' benefit in terms of reduced *RHC* to seismic-retrofit reimbursement. The reduction in *RHC* caused by earthquake mitigation is comparable, in certain cases, to the cost of the mitigation itself; and the opportunity for insurance companies to use such *RHC* reductions for further investment is of great value, which may be able to compensate for the cost of mitigation.

As shown in Figure 1, our PPP model includes three parties: a relevant government agency, the insurer, and the property owner. For the property owner, an immediate seismic retrofit is encouraged by the offer of "free mitigation with the purchase of earthquake insurance", provided on the condition that they agree to sign a contract to purchase earthquake insurance for multiple years, defined as the duration of insurance *i*. The government provides full seismic-retrofit subsidies to the property owners who take up such insurance contracts, and is reimbursed for a large proportion of the subsidy money by the insurance company over the following years. The insurance company contracted with the property owners is asked to reimburse certain proportion of the retrofit cost to the government in the contracted year *j*. This reimbursement will come from the insurer's *RHC* savings achieved by insuring a retrofitted rather than a non-retrofitted house. Thus, in regions where this framework can be applied, the partnership provides a beneficial alternative for all three parties.

As shown in Table 1, the benefits of this PPP to the government include improved seismic-hazard resistance, increased insurance penetration, major reductions in the expected human and economic losses on its territory, and large reductions in the aggregate amount of government compensation payable to earthquake victims. The property owners receive both earthquake mitigation and insurance at the price of earthquake insurance alone – or possibly a lower price than their insurance would have cost if mitigation work had not occurred. Finally, insurers are able to secure multi-year contracts on relatively low-risk buildings, allowing their expected profits to increase, even after payments to the government are factored in.

Fig. 1. PPP framework for seismic mitigation

Table 1. Cost-benefit comparison for participating parties

	Baseline Situation	Situation under PPP’
Government	Low mitigation & insurance coverage High potential loss & fiscal deposit	Providing the mitigation mortgage and subsidy Higher mitigation & insurance coverage
Insurer	High premium resulting in low policy quantity High potential risk to each policy	Reimbursing part of retrofit cost Guaranteed multi-year policies with lower potential risk
Homeowner	High cost for both mitigation and insurance High seismic risk and casualty rate	Purchasing multi-year insurance policy Free mitigation with discounted insurance coverage

1.4. Feasibility measurement criteria

The proposed framework is economically feasible only if there is enough benefit to insurance companies that they are able to pay the cost of mitigation. The mitigation cost for a region k is denoted as C_k^M, and results in a reduced *RHC* denoted as RHC_k'. As stated previously, the *EP* of *WCL* is p_k^{RHC}, while the *RHC* needed before mitigation is defined as RHC_k. The reduction in *RHC* for building *k*, $\Delta RHC_k = RHC_k - RHC_k'$. The benefit received by the insurer (Π_k) from mitigation is the opportunity cost for the reduction of *RHC* , which in this case can be calculated as:

$$\Pi_k = \Delta RHC_k \cdot \left(1 + \frac{rf}{\gamma}\right)^t - \Delta RHC_k, \tag{2}$$

where: rf – Risk-free Rate of Interest; γ – Standardization Factor; t – Duration of Contract; ΔRHC_k – reduction in *RHC* for building *k*.

Let us imagine a partnership in which the insurance company would like to use a certain proportion, defined as returning proportion (η), of its annual benefit from the reduction in *RHC* to fund reimbursement of the government’s building-retrofit outlays. This reimbursement takes the form of one payment annually during each of the contracted years. For purposes of comparison with the retrofit cost, the total of annual reimbursements in future years is translated into current values. Then, for the duration of the contract j_k (taking one year as the unit), the proportion of reimbursed retrofit cost ζ can be calculated as:

$$\zeta = \frac{\Pi_k \cdot \eta \cdot \dfrac{(1+r)^{j_k} - 1}{r(1+r)^{j_k}}}{C_k^M}, \tag{3}$$

where: r – Annual Interest Rate; Π_k – Total Benefit Received from this Framework; η – Proportion of Benefit Used for Retrofit Reimbursement; C_k^M – Cost of Retrofit; ζ – proportion of reimbursed retrofit cost; j_k – contract year.

To guarantee the insurer a stable benefit income with which to pay the mitigation reimbursement, the duration of insurance (i_k) should be no less than the reimbursement time, as:

$$i_k \geq j_k, \tag{4}$$

where: i_k – duration of insurance; j_k – contract year.

While implementation of this framework will always be profitable for the insurance company as long as $\Delta RHC_k \geq 0$, the most appropriate decision-making criterion for its feasibility should be the reimbursement ratio ζ. The larger the value of ζ, the greater the economic viability of the partnership.

1.5. Measuring benefit

While the reimbursement ratio ζ reveals the economic feasibility of introducing our PPP framework in different regions, the total benefit produced by this framework also needs to be calculated and compared against other traditional methodologies. The total annual benefit to all parties in region k under this framework is Π_k (Eq. 2). Accordingly, to compare the benefit of this new framework with the typical benefit from seismic retrofit, we define the reduction of *AAL* – the *Framework Benefit Factor* (λ) – as the ratio between the total benefit from this framework (Π_k) and the reduction of *AAL* achieved by the same level of retrofit (ΔAAL_k):

$$\lambda = \frac{\Pi_k}{\Delta AAL_k}, \tag{5}$$

where: λ – *Framework Benefit Factor*; Π_k – Total Benefit Received from this Framework; ΔAAL_k – reduction of *AAL*.

A higher value of λ indicates a greater benefit generated from our framework, while a λ value greater than 1 may suggest a more efficient way of utilizing seismic retrofit than traditional risk-mitigation instruments, such as a discounted insurance premium.

2. Case study

The expected economic losses that would be suffered by old reinforced-concrete (RC) buildings in all 12 neighborhoods of the city of Tiberias, Israel, under seismic scenarios were estimated. Two sets of assessments covered the as-built and retrofitted building inventories over their service lives (which were estimated for purposes of this research as 30 years). The proposed methodology was then verified in each neighborhood, based on the expected losses to both types of inventories.

2.1. Earthquake loss estimation

Economic losses from earthquakes, in the form of repair costs for a portfolio of 3,220 old residential RC buildings in Tiberias, were evaluated using HAZUS. The old RC building stock was found to be the riskiest in terms of predicted seismic casualties: representing 40% of the total buildings in the city, but 48% of total annualized human losses from earthquakes (Wei *et al.* 2015a). Three sub-cases – the as-built building inventory, and inventories retrofitted via two different design methods proposed by Shohet *et al.* (2014) – were investigated for their seismic performance. The two retrofit approaches, RC_{rm} and RC_{rh}, were designed to satisfy different levels of seismic performance: RC_{rh} to achieve HAZUS high-code performance at a high-level retrofit cost, and RC_{rm} to achieve HAZUS moderate-code performance at a mid-level retrofit cost. The seismic events we used were the 12 synthetic earthquake scenarios along four active and suspiciously active faults that were recently modeled by the Geological Survey of Israel, based on local maps of the seismogenic zones (Shohet *et al.* 2014). Each event was named for its associated fault followed by its magnitude: Jordan 7.0, for instance, indicates a hypothetical 7.0 MW earthquake caused by the Jordan Fault. Finally, the expected number of buildings that would be placed in each of the four building-damage states defined in the HAZUS technical manual (FEMA 2013) was obtained using HAZUS (Table 2).

Table 2. Number of buildings damaged in historical earthquakes

Earthquake Scenario	Return Period (years)	Damage State			
		Slight	Moderate	Extensive	Complete
Jordan 7.5	1500	92	340	513	1024
Poria 6.5	1200	182	496	626	597
Almagor 6.5	900	273	575	600	346
Jordan 7.0	850	288	578	581	326
Jordan 6.5	800	418	568	402	95
Almagor 6.0	650	436	559	368	64
HaOn 6.5	600	438	542	349	64
Jordan 6.0	500	454	469	250	29
HaOn 6.0	250	430	344	139	8
Bet HaKerem 6.0	200	430	327	121	5
Almagor 5.0	150	248	110	23	0
Poria 6.0	100	2	4	3	1

Based on data generated by prior research on the same region (Wei *et al.* 2015a), we created *EP* curves for the as-built inventory and retrofit designs RC_{rm} and RC_{rh}; these three curves are depicted in Figure 2. From the right tails of the *EP* curves, we can see that the reductions in economic losses associated with retrofitted buildings become more significant as the seismic magnitudes become more severe (lower *EP*).

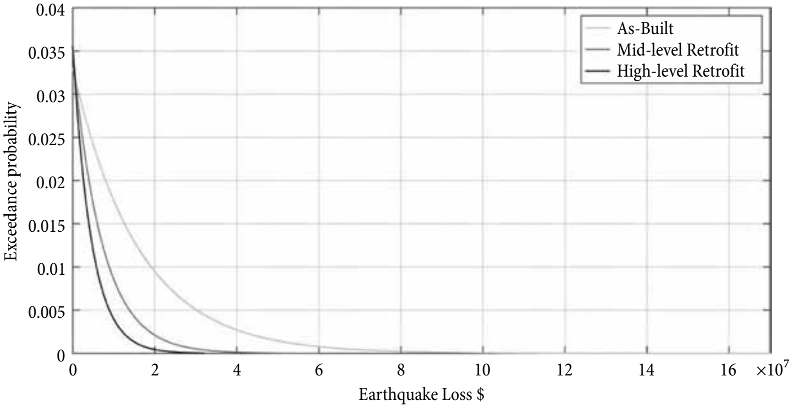

Fig. 2. *EP* curves for different retrofit levels

2.2. Retrofitting reimbursement calculation

With regard to the *EP* curve for seismic building loss in the study region and each of its 12 sub-regions, the expected reimbursement in a period j_k can be calculated using Eq. 3 and 4. The contract term is assumed to be 10 years, and the London Interbank Offered Rate (LIBOR) is used just as the offering rate *rf* in this case. For annual benefit, *rf* in this case can be defined as an interbank offered rate for three months and $\gamma = 3$, in a financial standard, while $t = 12$ indicates that the benefit is counted once every 12 months (Brealey *et al.* 2008). In consideration of the highly fluctuating nature of *rf* and the relatively long-term contract investigated in this paper, the value of *rf* is used as an average of U.S. dollar LIBOR from the last 10 years, provided by the Federal Reserve Bank of St. Louis (IBA 2014). The insurer's acceptance level of annual insolvency probability (δ_k) is assumed to be 1%, based on the annual average insolvency rate of insurance companies (Zanjani 2002). The annual interest rate is assumed to be 7% (Grossi *et al.* 2005). We also assume that the benefit from reduction in *RHC* is evenly shared by the government and the insurer, which means η = 50% in this case. For insurance policies with no deductibles ($\xi = 0$), the estimated largest possible payback ratio, by region ID, is shown in Figure 3. To better understand how the benefit generated by this framework may differ from the pure benefit of seismic retrofit, the Framework Benefit Factor λ has been calculated for each of the study's 12 sub-regions, as shown in Figure 4.

2.3. Sensitivity analysis

Sensitivity analyses are conducted using two criteria: the reimbursement ratio ζ representing the feasibility of the framework, and the framework benefit factor λ representing its benefit level. Because of the highly changeable nature of financial parameter utilized in this framework, we investigate the sensitivity of this framework via several parameters involving the value of *rf*, contracted year *i*, and the annual interest rate *r*. The other parameters

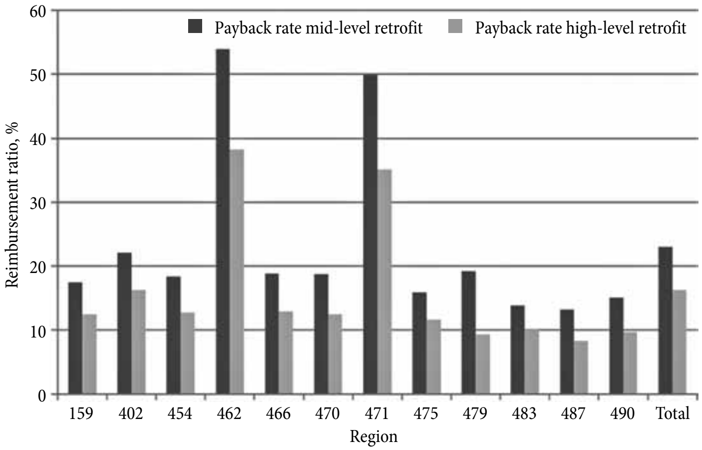

Fig. 3. Estimation of reimbursement ratio (η = 50%, i = 10)

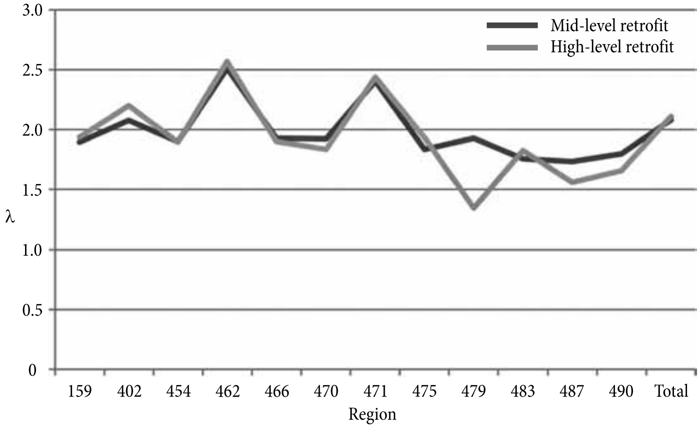

Fig. 4. Estimation of framework benefit factor ($\eta = 50\%$, $i = 10$)

will remain the same as in Retrofitting Reimbursement Calculation Section, and the mid-level retrofit and its consequences vis-à-vis the whole study region are considered in this analysis. The data for reduction in AAL (ΔAAL) was analyzed and presented in a previous study (Wei *et al.* 2015b).

The LIBOR for the U.S. dollar, here used to calculate rf, has been a highly fluctuating variable in recent years, with a range from about 0.5% to 12%. Figure 5 shows the feasibility and relative benefit of our framework under rf values from 0.5% to 11%.

It is worth noting that the reimbursement ratio ζ and framework benefit factor λ both have near-linear relationships with the risk-free rate of interest rf, and that the feasibility of the framework is highly influenced by rf. For the lowest point, i.e. where rf is 0.5%, the 10-year reimbursement ratio is only 5.65% and its positive effect on retrofit is likely to be minor; whereas when rf reaches 8%, a full reimbursement can be achieved within 10 years. Considering a highly fluctuating rf and a relatively long period of framework implementation, the use of average reimbursement ratio presented in Retrofitting Reimbursement

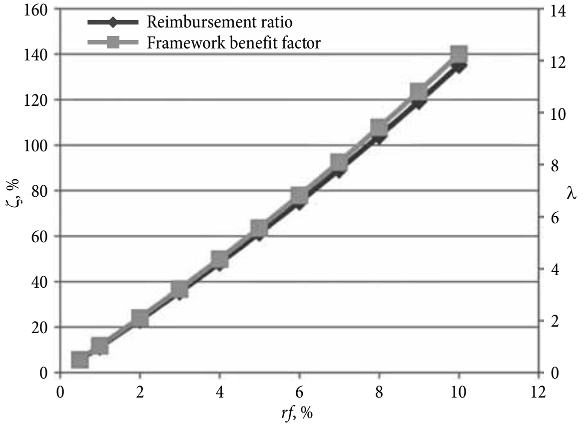

Fig. 5. Sensitivity analysis based on varying rf

Calculation Section can be a more accurate estimation. Figure 6 sets forth the reimbursement ratios for possible contract lengths ranging from one year up to the expected building service life of 30 years. Since λ is an annual measuring factor and therefore unaffected by variance in the contract term, it is not included here. Due to the loss for future incomes as current value, the relationship between contract year and reimbursement ratio is not linear, and yearly benefit from the framework diminishes. Over a building's service life, the framework is expected to provide 40% reimbursement of the retrofit cost.

The effect of the annual interest rate (r) in this framework ranges from 3% to 7.5%. Again, as in the case of contract length and for the same reasons, only the reimbursement ratio is investigated. As shown in Figure 7, the reimbursement ratio exhibits a minor decrease as the annual interest rate increases, since the standard (r) of calculating equivalence current value from future incomes changes. The effect of the annual interest rate (r) in this framework ranges from 3% to 7.5%. Again, as in the case of contract length and for the same reasons, only the reimbursement ratio is investigated. It is also shown in Figure 7 that the reimbursement ratio exhibits a minor decrease as the annual interest rate increases, since the standard (r) of calculating equivalence current value from future incomes changes.

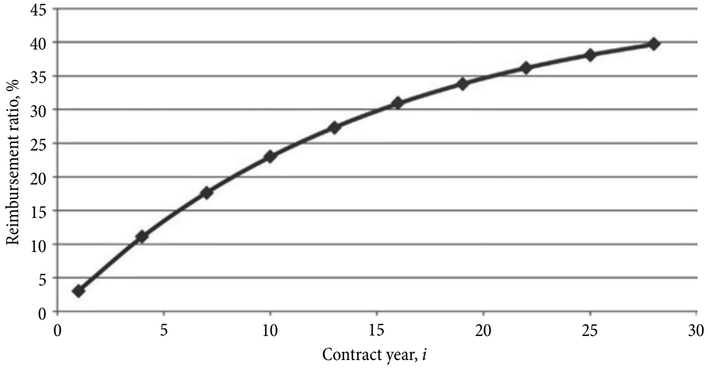

Fig. 6. Sensitivity analysis based on varying contract term

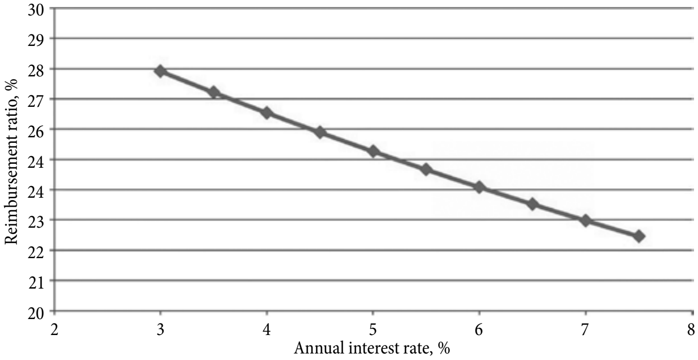

Fig. 7. Sensitivity analysis based on varying annual interest rate

3. Discussion

From the results presented in Retrofitting Reimbursement Calculation Section, it can be seen that the benefit from retrofit-derived reductions in *RHC* can, in some cases, offset the entire retrofit cost within 10 years. However, the ratio of the benefit to the original retrofit cost varies immensely, between less than 20% and more than 100%, depending on regional characteristics and the available retrofit alternatives. In the particular case discussed in this paper, a mid-level retrofit would always be more cost-effective than a high-level one. As regards differences between sub-regions, we can assess the mid-level retrofit's effectiveness level in different neighborhoods by considering the reduction of completely damaged buildings as a proportion of the total building inventory in the region, following major earthquakes (i.e. with return periods of 1,500, 1,200 and 900 years). The results of such an assessment are shown in Figure 8.

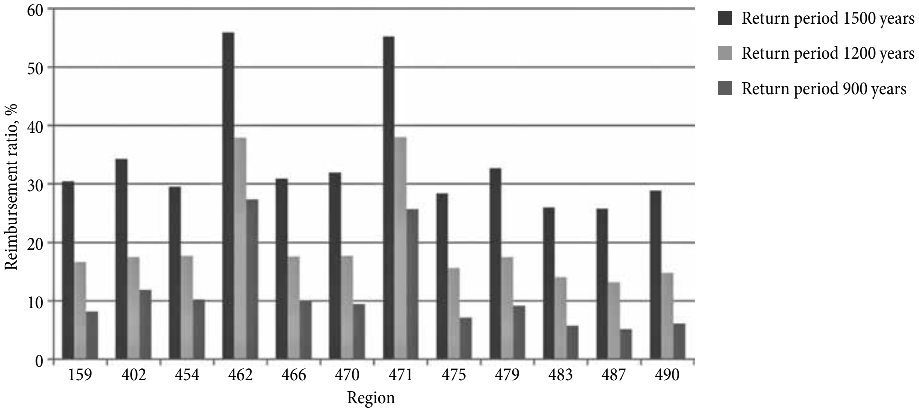

Fig. 8. Proportion of buildings in a state of complete damage

It can be seen that the values in Figure 3 and Figure 8 are highly correlated, meaning that the framework is more cost-effective in areas with higher vulnerability to earthquakes. This feature may be key to generating market-driving earthquake-mitigation partnerships. The framework may not be deemed worthwhile in highly earthquake-resistant regions, in light of seismic retrofit reimbursement of perhaps less than 20% and a payback time as long as 10 years; however, in highly vulnerable regions, this partnership between government and insurer alone can provide enough benefit to cover the whole retrofit cost, and this should make it attractive to all parties. Figure 4 has also shown that the total benefit from this PPP is up to double the amount of benefit utilized from the reduction of *AAL* each year, which can provide a much higher motivation to undertake seismic retrofit in highly vulnerable regions. It is also worth noting that the use of this framework is not necessarily limited to earthquake-mitigation purposes, but could have a wide range of applications in areas confronting other natural hazards and requiring similar patterns of building retrofit and catastrophe insurance. The reimbursement ratio and framework benefit factor calculated below are based on hurricane damage data for residential structures in Miami/Dade

County, Florida, as provided by Grossi *et al.* (2005), with all assumptions and parameters remaining the same as in Retrofitting Reimbursement Calculation Section, above. As indicated in Table 3, our framework is highly suited to adaptation for hurricane-affected areas, and the reimbursement ratio may in fact be further improved if partial mitigation is implemented.

Table 3. Case study result for Miami/Dade

Miami/Dade	Reimbursement ratio ζ	Framework benefit factor λ
Full Mitigation	31.17%	1.76

Our sensitivity analysis has shown that the proposed framework is highly affected by the risk-free rate of interest, which is inherently highly fluctuating. Yet, if a mitigation project is maintained as a long-term partnership, the influence of rf can be minor. The research suggests that longer contract periods can result in a slightly lower marginal benefit, and so a partnership length at which the reimbursement ratio is satisfactory to the government is likely to be the optimum choice. A lower interest rate, meanwhile, can result in a slightly higher reimbursement ratio, yet such changes can be minor and may not affect the overall feasibility of the framework.

Conclusions

The two main methods of seismic risk mitigation – seismic retrofit and insurance – have been used around the world, yet not always successfully, due to their high cost and low incentives both to governments and property owners. This paper has presented a novel PPP framework, between the government and insurance companies, that can fully utilize the projected future benefit from retrofitting to reimburse the cost of the retrofit projects themselves for the government. Meanwhile, the partnership also provides benefits for the insurer in the form of earthquake insurance and partial government subsidies for building-retrofit projects. As a result, the proposed framework can motivate property owners to purchase insurance as well as undertake retrofit – which have been mentioned as a cost-effective approach for seismic risk mitigation, but never thoroughly investigated in previous relevant studies (Kunreuther, Michel-Kerjan 2009; Michel-Kerjan 2010), in which although implementation of long-term insurance and mitigation loans was found to help reduce associated potential losses of property owners, it has very little incentive for owners to undertake action since the amount of reduction on potential losses is less than the cost of the long-term loans.

A case study of earthquake mitigation carried out in a highly vulnerable city in Israel demonstrates the general feasibility of this framework. The result also confirms the market-driving nature of this framework, which has the potential to generate momentum for mitigation action in most vulnerable regions through market behavior. The framework benefit factor, proposed and calculated in this research to compare the effectiveness and benefit of various schemes involving retrofit and insurance, shows the much larger overall positive influence of our framework. Despite these advantages, the proposed framework is subject to some limitations. First, the study evaluated feasibility and effectiveness of the framework mainly from the perspective of governments; however, the potential additional benefits and costs of implementation of the framework to insurers and property owners also require further investigations and evaluations. Also, the case study of this study takes consideration into only earthquake risk mitigation, feasibility studies to other natural hazards, such as flooding, hurricane, or even multi-hazard events should also be performed in further research to examine the effectiveness of this framework in a wider field of use.

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