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Simplified Seismic Risk Quantification Methodology for Emerging Markets

M. MASUDA[1], F.AHMAD[2] and M. RAHNAMA[3]

[1] *Lead Catastrophe Risk Modeler, Model Development, Risk Management Solutions, Inc., Newark, CA. USA*
[2] *Senior Catastrophe Risk Modeler, Model Development, Risk Management Solutions, Inc., Newark, CA. USA*
[3] *Vice President, Model Development, Risk Management Solutions, Inc., Newark, CA. USA*
Email: mmasuda@rms.com

ABSTRACT :

Probabilistic seismic risk models have been widely accepted and used by the insurance and re-insurance industry over the past decade as risk quantification tools. However, because developing a detailed probabilistic risk model requires a significant amount of time, special expertise, and high expenses, seismic risk modeling tools generally have not been available in emerging markets.

This paper introduces a simplified seismic risk modeling methodology based on experiences acquired in detailed probabilistic risk model development for countries with both high and low seismic risk. This methodology requires only key attributes such as the 500 year return period PGA, soil classification, approximate exposure, and design base shear or a design spectrum, in order to produce benchmark losses, including average annual losses, loss costs, and exceedance probability losses for key return periods. Simplification for PGA-based vulnerability development with performance design objectives and a hazard curve classification/mapping scheme are discussed in detail. Simplification of each risk component (hazard and vulnerability) is verified and calibrated using interim loss results from the separately-developed detailed probabilistic risk model. This case study uses a Chinese risk model as an example and demonstrates the impact of typical risk mitigation measures.

Although estimated losses from this methodology involve many assumptions, they can be used as benchmark losses or one of the decision-making elements within preliminary risk assessments in emerging markets. This methodology is particularly applicable in areas of high earthquake potential and high building vulnerability due to the lack of building code enforcement.

KEYWORDS: Risk Quantification; Approximate Loss Estimation; Developing Countries; China Earthquake.

1. INTRODUCTION

According to GeoHazards International, “Urban earthquake risk is most rapidly growing in developing countries. In 1950, slightly more than half the urban population at risk from earthquakes lived in developing countries; in the year 2000, that number increased to more than 85%” as shown in Figures 1 and 2. [14]

Little has been done to reduce seismic risk in developing countries because of low awareness and limited access to state-of-the-art knowledge in earth sciences and earthquake engineering. Commonly, neither risk management experts nor commercial risk assessment tools are available in those countries for risk quantification—which in fact are the very first and most important steps of all risk mitigation measures. Furthermore, insurance companies are reluctant to take risks in countries where no risk assessment tool is available because of the great uncertainty that exists. This paper introduces a simplified seismic risk modeling methodology, including pre-compiled losses, that would allow it possible for local policymakers and insurance agents to quickly assess seismic risk without performing detailed computer simulations. Although users need to be aware of uncertainties, the results obtained using this methodology would provide a useful first step in evaluating seismic risk.

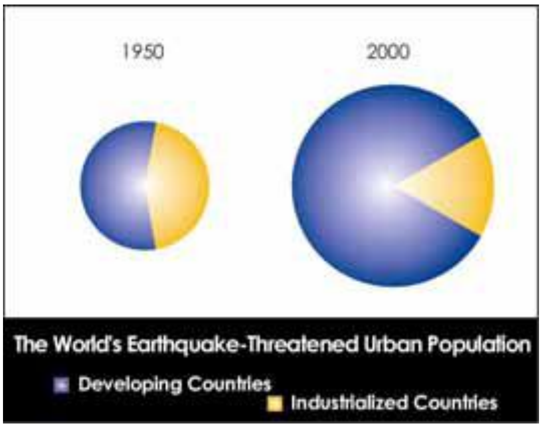


Figure 1 World Urban Population [14]

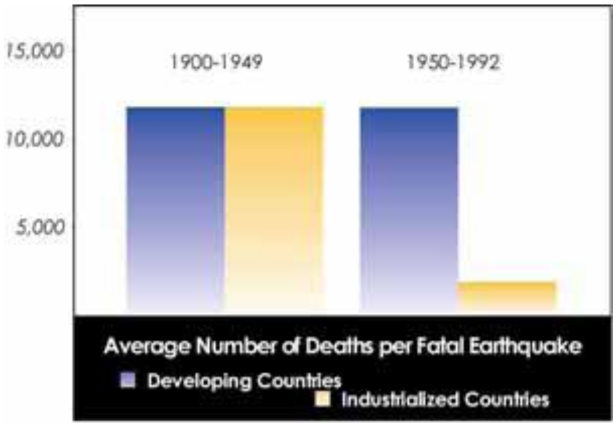


Figure 2 Increased Risk in Developing Countries [14]

2. FRAMEWORK FOR THE SIMPLIFIED LOSS ASSESSMENT

The goal of this paper is to describe a tool/methodology that produces approximate losses by using only publicly available information. In order to achieve this goal, all seismic risk modeling modules, such as hazard, vulnerability and exposure, are significantly simplified. First, peak ground accelerations (PGA) on rock at key return periods are estimated by scaling a given 500 year return period PGA. Second, hypothetical events are created from exceedance probability PGA curves that are estimated by discretizing the total rate. Third, vulnerability functions are developed based on historical observed losses and are used to compute loss costs and exceedance probability (EP) losses. In this step, only vulnerability-related uncertainty (around mean damage) is considered; hazard-related uncertainty is taken into account when the EP PGA curve is derived. Finally, monetary losses are obtained by separately multiplying the estimated exposure based on population in the region and the countrywide GDP per capita. Each simplification will be discussed in the following sections in detail.

Only the following seven attributes listed below are required to run this simplified model:

Required Input Data

1. 500 year return period PGA on rock or firm ground
   GSHAP [12] provides global grid data in digital format. More detailed information is often available in regional seismic hazard studies.
2. Design Base PGA
   Most building codes provide a Design Base PGA. Otherwise, an elastic design spectrum for a short period (before applying ductility factor) / 2.5 can be used to estimate Design Base PGA.
3. Soil Type
4. Engineered Building Ratio
   This ratio reflects building inventory in terms of seismic code enforcement and construction practice. The ratio ranges from zero (Unreinforced Masonry or Adobe) to 1.0 (Reinforced Concrete compliant with the latest building code).

Optional Input Data

1. Population
2. GDP (purchasing power parity) per capita
3. Urban/Rural/Unknown
   Urban/Rural classifications are available in Global Rural-Urban Mapping Project (GRUMP) [13] whose definitions are mostly consistent of those of the United Nations.

3. EXCEEDANCE PROBALILITY PGA ESTIMATE

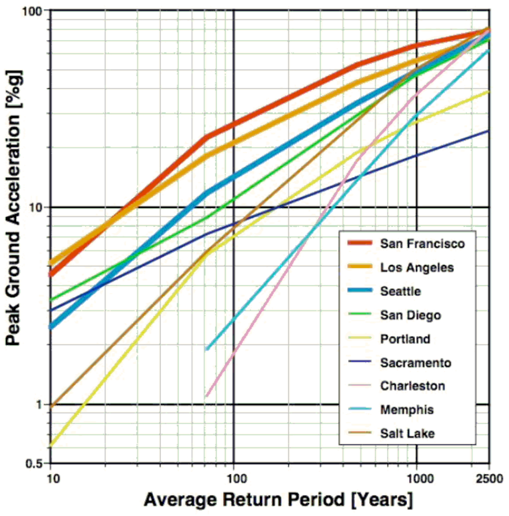


Figure 3 Ground Shaking Hazard Recurrence USGS Frankel 2002

The hazard module is a key component for any probabilistic risk model. However, developing this component is a very time-consuming process, which requires thorough understanding of the characteristics of seismicity and geology in the region. Generally, this process includes comprehensive analyses of multiple catalogs, seismic sources, and recorded ground motions with associated local site conditions. The methodology presented in this paper bypasses these steps to estimate PGA exceedance probability curves by scaling PGAs at a 500 year return period based on the observed trend between overall seismicity in the region and relativity among PGAs at different return periods. Figure 3 shows PGA exceedance curves in major seismic prone cities across the United States. The Western United States is a high seismic activity region while the Central and Eastern United States have moderate and low seismicity, respectively. The variability between exceedance curves at difference cities is considered to account for the variation in the seismicity across those regions. There are many exceptions by region, but it would be fair to indicate that lower seismic regions have higher ratios of PGA at long return periods compared to PGA at short return periods.

In order to capture this trend, Japan, China and Australia, which represent high, medium and low hazard regions, were selected and reviewed using detailed risk models developed by Risk Management Solutions, Inc.. Japan is a country with high seismic risk and many large subduction events, while China and Australia have moderate to low hazard with mostly crustal events. Uniform exposures, approximately 2,000 locations per country covering the entire areas, were created and PGA probability exceedance curves at each site were computed. Figure 4 plots 5,000 and 1,000 year return period PGAs normalized by 500 year PGAs at each location. Average normalized PGAs at key return periods (10, 25, 50, 100, 200, 250, 500, 1000, 5000 and 10000) are summarized in Table 1, which can be used as scaling factors for exceedance probability PGA estimation. Binning of the 500 year return period PGAs is introduced here to account for regional seismicity. Again, as shown in Table 1, there is a clear trend that is consistent with the observation from Figure 3.

Usually 500 year return period PGAs are available in publications based on regional seismology. Otherwise, they can be found in the GSHAP report [12], which includes the hazard map of 500 year return period for the whole world.

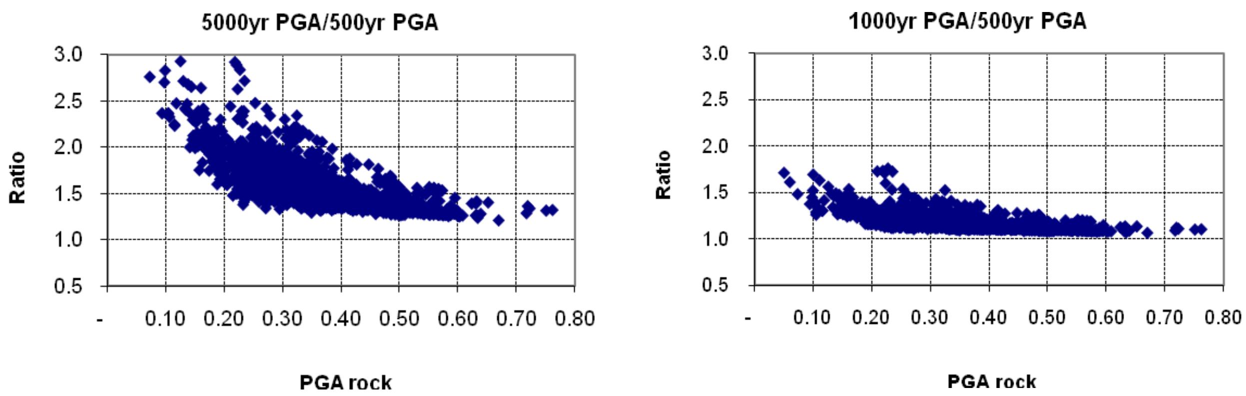
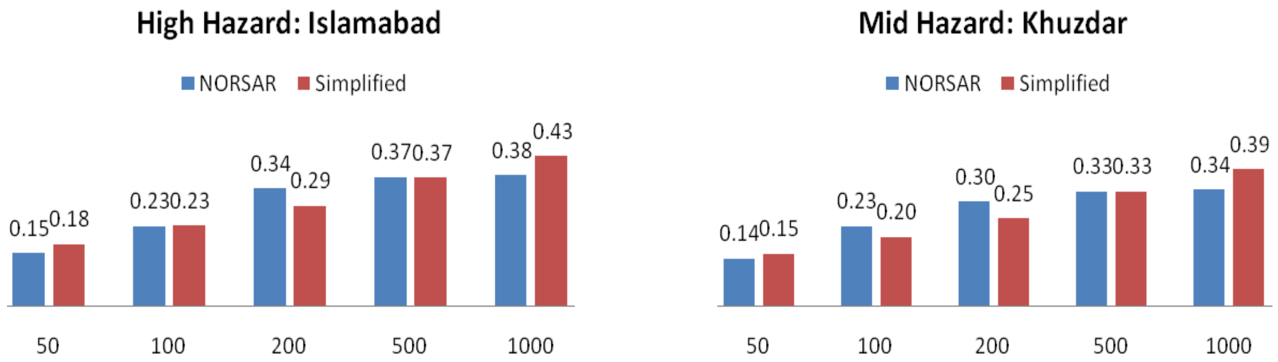


Figure 4 Exceedance probability PGAs at key return periods normalized by 500yr

Table 1 Average PGAs at key return periods normalized by 500 year PGAs

500yr PGA (in g)		Return Periods										
From	To	10000	5000	2500	1000	500	250	200	100	50	25	10
0	0.025	6.99	5.30	3.85	2.19	1.00	-	-	-	-	-	-
0.025	0.05	4.59	3.58	2.69	1.66	1.00	0.19	0.10	0.00	-	-	-
0.05	0.1	3.30	2.65	2.07	1.43	1.00	0.59	0.46	0.12	0.01	-	-
0.1	0.2	2.74	2.26	1.83	1.33	1.00	0.70	0.60	0.30	0.08	0.01	0.00
0.2	0.3	2.10	1.85	1.60	1.25	1.00	0.77	0.71	0.52	0.36	0.21	0.07
0.3	0.4	1.76	1.59	1.42	1.18	1.00	0.83	0.78	0.62	0.48	0.34	0.14
0.4	0.5	1.56	1.44	1.31	1.14	1.00	0.85	0.81	0.66	0.52	0.38	0.21
0.5	0.6	1.50	1.39	1.28	1.13	1.00	0.86	0.82	0.67	0.52	0.36	0.19
0.6	0.7	1.50	1.39	1.28	1.12	1.00	0.86	0.81	0.66	0.53	0.43	0.28
0.7	2.0	1.41	1.32	1.23	1.10	1.00	0.89	0.85	0.71	0.55	0.40	0.27

The scaling factors introduced in Table 1 are verified with Seismic Hazard Analysis and Zonation for Pakistan, NORSAR (2007) [11]. The report includes hazard curves in several key cities in Pakistan such as Islamabad, Khuzdar, Peshawar, Quetta, Karachi and Gwadar ranging from high to low seismic regions. Figure 5 shows the comparison of estimated ground motions at different return periods from the simplified model and the detailed model developed by NORSAR. The consistent trend for relativity among PGAs is seen in mid and high seismic regions, although low hazard areas at short return periods show slight differences. However, these issues are not problematic for risk modeling, as contribution to the overall risk in the region from losses at those return periods is generally very small.



Figures 5 Estimated PGAs at key return periods - Simplified model vs NORSAR studies

Table 2 Accuracy of the estimated PGAs as a function of the PGA on rock

500yr PGA_rock bins		Estimated PGA rock with one and two stds					
		10,000yr		2,500yr		1,000yr	
From	To	1 std	2std	1 std	2std	1 std	2std
0	0.025	±35.9%	±71.7%	±26.9%	±53.7%	±18.7%	±37.4%
0.025	0.05	±48.4%	±96.9%	±32.1%	±64.2%	±18.3%	±36.6%
0.05	0.1	±32.3%	±64.6%	±19.6%	±39.1%	±11.1%	±22.2%
0.1	0.2	±22.2%	±44.3%	±12.6%	±25.2%	±6.4%	±12.9%
0.2	0.3	±15.8%	±31.7%	±12.3%	±24.6%	±7.1%	±14.2%
0.3	0.4	±11.6%	±23.2%	±8.8%	±17.6%	±4.9%	±9.9%
0.4	0.5	±9.3%	±18.7%	±7.0%	±14.1%	±4.1%	±8.2%
0.5	0.6	±10.5%	±21.0%	±7.8%	±15.6%	±4.5%	±9.0%
0.6	0.7	±14.8%	±29.5%	±10.5%	±21.1%	±5.9%	±11.8%
0.7	2	±2.6%	±5.2%	±1.8%	±3.6%	±1.0%	±1.9%

In addition, estimated PGAs are compared to those from the detailed model using uniform exposure in Japan, China, and Australia, with the results summarized in Table 2. Estimated PGAs were observed to be scattered in relatively narrow ranges considering given a level of uncertainty. For example, PGAs at a 2,500 year return period corresponding to a 500 year PGA on rock between 0.3g and 0.4g are within ±18% using two standard deviations of the PGAs computed using the detailed model.

4. VULNERABILITY ASSUMPTIONS

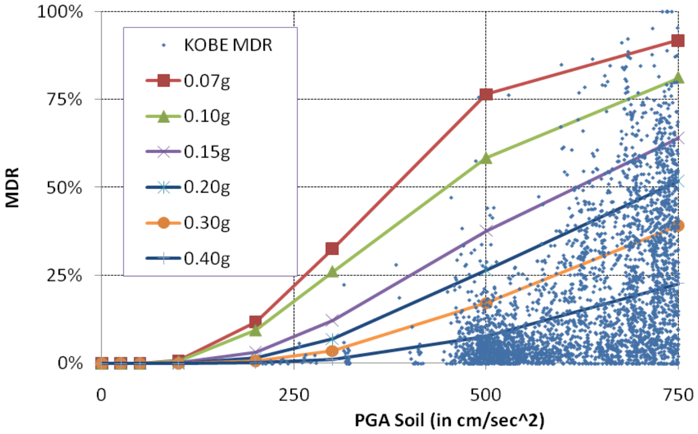


Figure 6 Damage functions per Design Base PGAs

The damage functions used in the model are primarily based on the seismic evaluation concept with IS (Structural Seismic Index) that has been widely used in Japan for years. The IS index is defined in the Japanese seismic evaluation guideline to represent structural performance as a product of building strength and ductility index, where IS=0.6 meets the "Life Safety Performance Design Objective" for major events such as the 1923 Great Kanto Earthquake, whose observed surface PGAs range from around 0.3g to 0.4g. It has been validated with several major earthquakes in which IS indexes are closely tied to observed damages. Hayashi *et al.* (2000) [5] and Okada *et al.* (1988) [6] derived fragility and damage functions in the PGV domain for given IS indexes by regression analyses using damage statistics from the Hyogoken Nanbu [9], Tokachi-oki, and Miyagiken-oki earthquakes. In this study, the concept is extrapolated to the PGA domain with additional adjustments for MDRs at lower intensities. The detailed development procedure is discussed in Beck J. *et al.* (2002) [10].

In summary, assuming an IS index = 0.6 is equivalent to using a design base PGA of about 0.3g to 0.4g. By definition, damage functions developed using IS indexes are reasonably mapped to those using design base PGAs.

Losses are computed for discretized events from PGA probability exceedance curves that include vulnerability-related uncertainty. In Figure 7, loss costs estimated by the simplified model are compared with those from the detailed model using uniform exposure for approximately 2,500 locations in China. Differences are not small but it appears that estimated loss costs are scattered within acceptable ranges (±50%) for preliminary studies, especially at locations with relatively large loss costs.

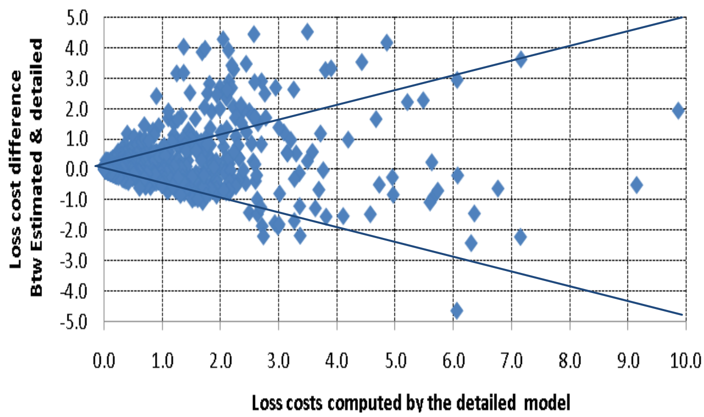


Figure 7 Loss cost differences between simplified vs detailed models in China

5. EXPOSURE ESTIMATE

Figure 8 shows the relationship between GDP per capita and the average dwelling cost per person for several European countries as well as a few Asian and Latin American countries, based on findings from a housing survey conducted by the United Nations [7]. Although it is observed that exposure is highly dependent on regional economic conditions and construction practices, there is some correlation between the two parameters, especially in countries with low GDPs. Alternately, a housing affordability ratio (average median home price / average household income) with the number of dwellings, is a relatively reliable way to estimate residential exposure. According to a World Bank report, modest housing unit costs approximately 2 to 4 times the median household income in urban areas in developing countries [3]. The urban/rural option in the model takes into account the relative construction cost between urban and rural regions by scaling nationwide average values per dwelling per person. Scaling factors are assumed to be 1.25 and 0.62 for urban and rural, respectively, based on worldwide population splits and relative urban/rural housing costs.

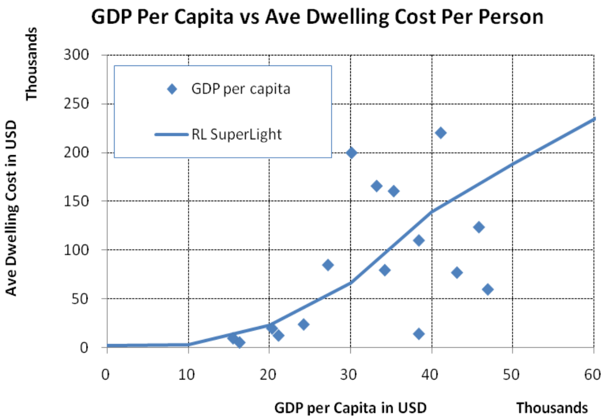


Figure 8 GDP per capita vs. ave dwelling cost per person

Average dwelling cost per person (a fitted curve in Figure 8):

Where,	GDP per Capita < USD 60,000	2.0×10^{-7} x GDP per Capita $^{2.57}$	(1)
	GDP per Capita>= USD 60,000	4.62 x GDP per Capita – 42,800	

It should be noted that the formula above was introduced only for completeness of the overall simplified methodology; in general,, more accurate exposure can be found in local government statistics or construction and real estate journals.

6. BENCHMARK LOSSES AND AN EXAMPLE OF APPLICATION

Because the simplified methodology introduced in this paper is independent of regional seismicity, benchmark losses with various permutations of key parameters can be tabulated; these are applicable to the entire world for general use. Table 3 shows a sample of estimated losses for selected combinations. By reviewing the loss costs and loss ratios from the pre-compiled table for given conditions and parameters, it is fairly easy to capture a profile of seismic risk for various levels of exposure, including a region, group of buildings, and even a single building.

Scenario:

A regional emergency response official in the local goverment is interested in the potential impact of seismic code enforcement in a city with a population of 100,000. The current code enforcement is assumed to be almost nonexistent. The building official would like to review three scenarios: 50% enforcement, 100% enforcement, and 100% enforcement with a higher code requirement. Among seven input parameters, only "Design Base PGA" and "Engineered Ratio" are varied and other parameters such as 500 year return period PGA, soil condition, population, GDP per capita and the Urban/Rural option are kept constant.

For these parameters, the official is able to find loss costs and exceedance probability loss ratios at key return periods, which are highlighted in yellow in Table 3. The loss costs for the worst and best senarios are 11.6 and 0.49, respectively. Multiplying these loss costs by the total residential exposure of USD 2.9 trillion, which is separately estimated with Eqn. (1), yields average annual losses and expected losses at key return periods, as summarized in Figures 9 and 10. For this specific exposure located in a relatively high seismic region, a reduction of roughly 80% is expected both in AALs and EP losses due to increased code enforcement with an even greater impact observed at shorter return period losses. The introduction of new design requirements close to the 500 year PGA shows further reductions in expected losses.

Table 3 Selected bench mark losses

Design PGA	500yr PGA	Soil	Eng. Ratio	Loss Cost	Key RP Loss Ratios				
					0.0004	0.0010	0.0020	0.0100	0.0050
					2,500	1,000	500	100	50
0.45	0.60	Soft	1.0	1.22	27.8%	19.5%	13.3%	2.8%	0.9%
0.45	0.45	Soft	1.0	0.49	14.5%	8.8%	5.5%	1.1%	0.3%
0.45	0.30	Soft	1.0	0.13	5.2%	2.5%	1.4%	0.2%	0.0%
0.45	0.60	Hard	1.0	1.04	25.6%	17.5%	11.4%	2.2%	0.7%
0.45	0.45	Hard	1.0	0.39	12.4%	7.2%	4.2%	0.7%	0.2%
0.45	0.30	Hard	1.0	0.08	4.0%	1.8%	0.8%	0.1%	0.0%
0.30	0.45	Soft	1.0	2.10	36.7%	27.6%	20.5%	6.1%	2.0%
0.30	0.30	Soft	1.0	0.66	19.9%	12.4%	7.8%	1.4%	0.3%
0.30	0.15	Soft	1.0	0.09	5.4%	2.2%	0.8%	0.0%	0.0%
0.30	0.45	Hard	1.0	1.72	33.5%	24.5%	17.5%	4.6%	1.5%
0.30	0.30	Hard	1.0	0.43	16.7%	9.5%	5.3%	0.6%	0.1%
0.30	0.15	Hard	1.0	0.05	3.3%	1.0%	0.3%	0.0%	0.0%
0.30	0.45	Soft	0.0	11.66	96.3%	91.2%	83.1%	39.4%	20.0%
0.30	0.30	Soft	0.0	3.84	80.6%	59.4%	41.3%	11.6%	3.1%
0.30	0.15	Soft	0.0	0.53	31.3%	16.3%	6.9%	0.0%	0.0%
0.30	0.45	Hard	0.0	9.68	95.2%	89.1%	78.1%	31.3%	13.8%
0.30	0.30	Hard	0.0	2.48	75.0%	50.3%	32.5%	5.0%	0.9%
0.30	0.15	Hard	0.0	0.31	22.5%	8.6%	2.3%	0.0%	0.0%
0.10	0.15	Soft	1.0	0.83	36.1%	24.1%	14.1%	0.2%	0.0%
0.10	0.10	Soft	1.0	0.36	23.4%	12.2%	4.5%	0.0%	0.0%
0.10	0.05	Soft	1.0	0.10	8.1%	1.8%	0.3%	0.0%	0.0%
0.10	0.15	Hard	1.0	0.51	29.1%	16.3%	7.2%	0.0%	0.0%
0.10	0.10	Hard	1.0	0.20	15.3%	5.6%	1.4%	0.0%	0.0%
0.10	0.05	Hard	1.0	0.05	3.0%	0.4%	0.1%	0.0%	0.0%
0.10	0.15	Soft	0.0	1.31	49.4%	34.4%	22.5%	0.6%	0.0%
0.10	0.10	Soft	0.0	0.57	33.4%	19.4%	8.8%	0.0%	0.0%
0.10	0.05	Soft	0.0	0.17	14.1%	3.9%	0.5%	0.0%	0.0%
0.10	0.15	Hard	0.0	0.82	40.9%	25.0%	13.1%	0.2%	0.0%
0.10	0.10	Hard	0.0	0.34	23.8%	10.9%	3.4%	0.0%	0.0%
0.10	0.05	Hard	0.0	0.08	5.9%	1.1%	0.2%	0.0%	0.0%

Table 4 Input Data for Code Enforcement Sensitivity Study

Item	Existing Condition	50% Enforcement	100% Enforcement	100% Enforcement with higher standard
Design Base PGA	0.30	0.30	0.30	0.45
Engineered Ratio	0.0	0.5	1.0	1.0

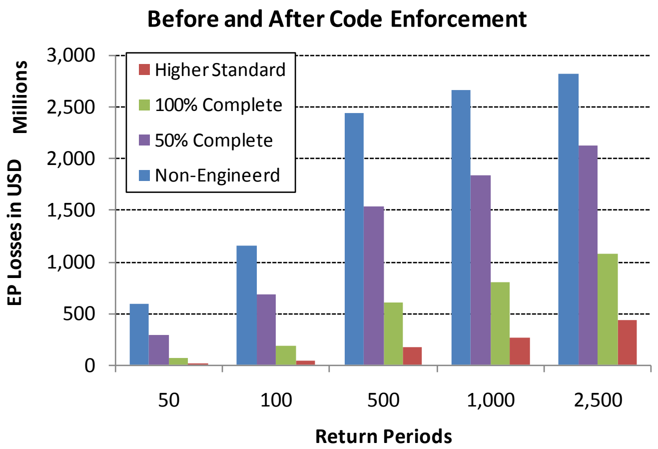


Figure 9 Impact for EP losses of the code enforcement

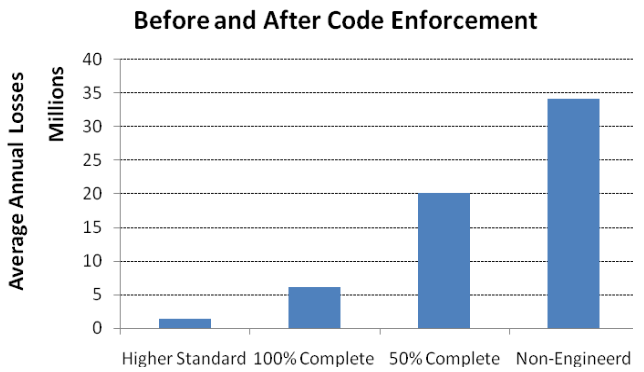


Figure 10 Impact for Loss Costs of the code enforcement

It should be noted that a risk mitigation study for a structural upgrade to a single building can be conducted using the same exercise by modifying the exposure value and defining the "Engineered Ratio" to be 1.0, representing a 100% retrofit.

7. CONCLUSIONS AND FUTURE WORK

Despite rapid growth of seismic risk in developing countries, effective risk mitigation measures have not taken place because of low public awareness and limited access to state-of-the-art technology. This paper presents a simplified probabilistic seismic risk model that offers meaningful risk profiles for various regions and exposures based on publically available information. A sample pre-compiled loss table and a case study were included to demonstrate the application of the methodology. Estimated losses were verified against results from the detailed risk model (developed in-house) and ranges of deviations were also discussed. Although the methodology involves a number of assumptions, it is fair to conclude that the tool produces useful information for preliminary risk assessments in emerging markets.

The authors are currently exploring additional parameters such as distance from major sources, building height, building type, etc., which might improve the accuracy of the estimation.

8. ACKNOWLEDGEMENTS

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