SEISMIC RISK AND COST-EFFECTIVENESS OF BASE ISOLATED BUILDINGS IN PERU

Luis A. BEDRIÑANA[*] **Supervisor: Taiki SAITO**[**]
MEE09195

ABSTRACT

The principal objective of this study is to evaluate the cost-effectiveness as well as the seismic safety of a base isolated building located in Peru. A methodology to evaluate quantitatively the seismic risk and the cost-effectiveness of a base isolated building during its lifetime is presented. The process starts with the hazard analysis and the earthquake ground motion generation in the studied area. Lima area is considered in this study. Series of artificial earthquake ground motions are generated by a stochastic method in the studied area. Then a preliminary seismic design of the target building is carried out, by using the Peruvian seismic code. To get the response distribution of the target building, several dynamic nonlinear analyses are performed by using the generated artificial motions as input waves. By assuming a structural response distribution, the seismic risk analysis is performed in terms of three structural parameters such as: interstory drift ratio (*IDR*), floor acceleration (*FA*) and the structural damage index (*DI*). The damage of the target building is evaluated by using damage index. Finally, the cost-effectiveness of using base isolation system is examined, by comparing exceendance probability of repair cost in the target building with and without base isolation during a given time period.

Keywords: Cost-Effectiveness, Seismic Risk, Base Isolation, Damage index, repair cost.

1. INTRODUCTION

Peru is an earthquake prone country, which has experienced many severe earthquakes in its history. Most of those severe earthquakes have been a big disaster, producing huge losses and fatalities. Many important lessons have been learned from theses events and the most important problems noticed in buildings are: low resistance, high level of damage, and no protection of contents. To increase resistance in buildings several improvements have been made in seismic code; however, there is no any regulation about damage limit levels in buildings in current codes. Moreover, current provisions do not provide any protection to nonstructural components, equipment and contents of buildings.

One of the best alternatives to reduce the damage and to provide protection of contents in buildings is the use of base isolation. Base isolation has proved to be a reliable technology to prevent damage in buildings and to increase its performance; however current seismic provisions do not provide information of the real safety of base isolated buildings. Furthermore, in developing countries the use of base isolation is not massive due to the high construction cost of isolation system. So, a methodology to evaluate the real seismic safety and cost-effectiveness in base isolation is needed to meet current performance requirements in buildings.

2. SEISMIC HAZARD AND GROUND MOTION MODELING

The historical data of past earthquakes (Figure 1) from the Peruvian seismic catalog (Tavera *et al*. 2007) are used to model the earthquake occurrence of magnitude (*M*) and hypocentral distance (*R*)

---

[*] Center for Earthquake Engineering Research and Disaster Mitigation (CISMID), Peru.
[**] International Institute of Seismology and Earthquake Engineering, Building Research Institute, Japan.

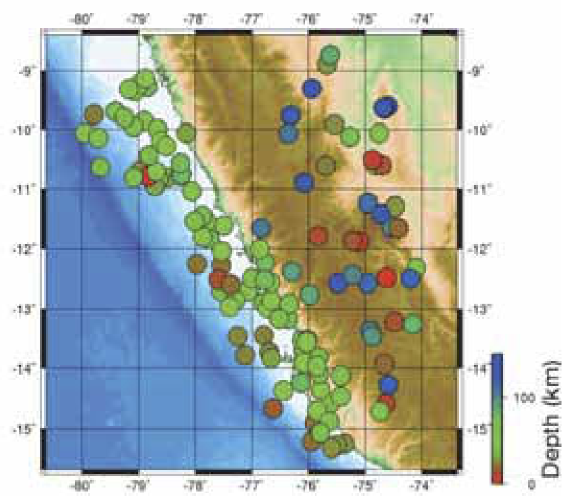

Figure 1. Distribution of earthquake epicenters around Lima from 1963 to 2005.

The earthquake occurrence of magnitude and hypocentral distance is modeled by a truncated G-R formula and the Beta probability function respectively as is shown in Figure 2. To generate the artificial ground motions, sets of *M* and *R* are randomly generated according to their probability distributions. Each set of values of *M* and *R* is related to ground motions by an attenuation formula in terms of spectral acceleration for Peru subduction earthquakes. Then, the earthquake ground motion is generated as a nonstationary stochastic process compatible with the response spectrum calculated with the attenuation formula. Using random vibration theory, a simple model of earthquake ground motion $A(t)$ is expressed as a product of a wave $x(t)$ from a stationary random process, with a power spectral density $PS(\omega)$, and an intensity envelope function $E(t)$ (Shibata 2010) as follows

$$A(t) = E(t).x(t) \tag{1}$$

In this study, the Jennings's intensity envelope function is used (Jennings et al. 1969). This function takes into account the transient effects in time of earthquake ground motions. The sample wave $x(t)$ is generated by a combination of harmonic functions, with a given power spectral density $PS(\omega)$ (Gasparini et al. 1976). This power spectral density $PS(\omega)$ represents the importance of the harmonic function, in some specified band frequencies, and it matches the target spectrum defined previously. A total number of 800 artificial earthquake ground motions are generated for the studied area.

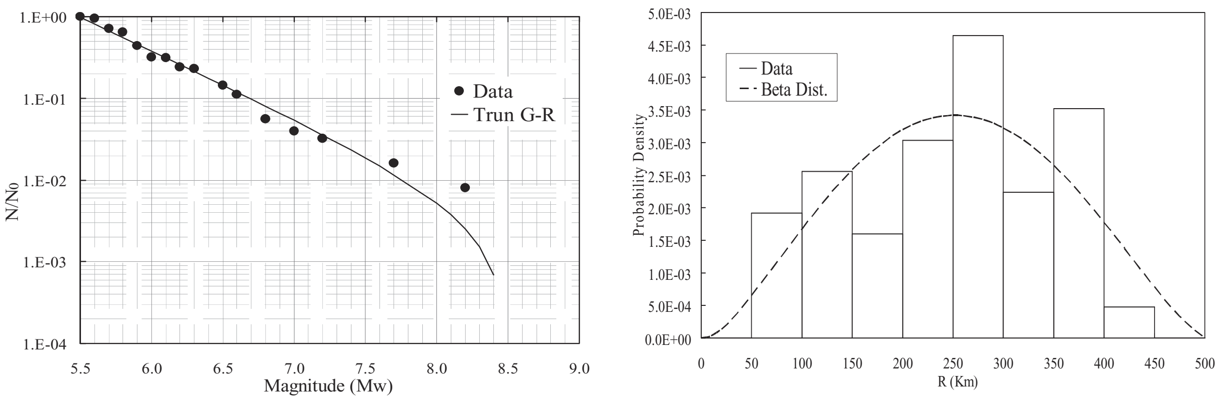

Figure 2. Earthquake occurrence of magnitude *M* and hypocentral distance *R* (1963 to 2005).

3. TARGET BUILDING AND STRUCTURAL RESPONSE

3.1. Design of the target building

The target building for this study is an RC office building with 8 stories as is shown in Figure 3. This building is assumed to be located in Lima downtown and is a representative mid-rise building. Concrete used in this building has a nominal strength of $f'c=21MPa$, and the nominal strength of steel is $fy=412MPa$. The total weight of the structure is around 46174kN, and the fundamental period is 0.65s in X direction and 0.54s in Y direction. The target building is designed according to the Peruvian seismic code. The design base shear coefficient is 0.08 in X direction and 0.09 in Y direction.

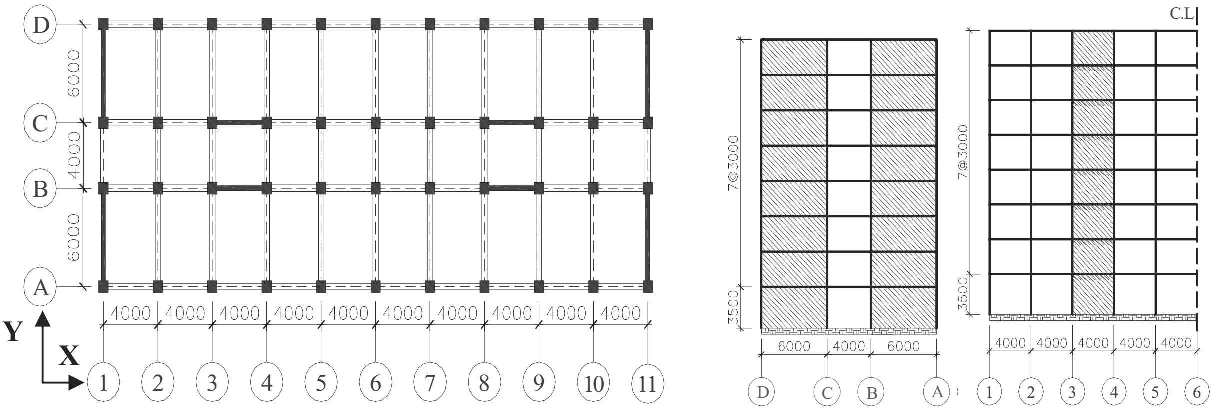

Figure 3. Plan and elevation view of target building.

3.2. Design of base isolation

Table 1. Dimensions of isolation devices.

	LRB-600	LRB-500
Shear Modulus (N/mm2)	0.39	0.39
Shear Modulus lead (N/mm2)	0.59	0.59
Exterior Diameter (mm)	600	500
Interior Diameter (mm)	100	100
Thickness of rubber layer (mm)	4	3.5
Total rubber thickness (mm)	144 4×36	123 3.5×35
Primary Shape Factor S1	37.5	35.7
Secondary Shape Factor S2	4.2	4.1
Number of Bearings	36	8

In this study, the equivalent SDOF method (Okamoto et al. 2002) is used to design the base isolation system in the target building. This method considers an isolated building as rigid body moving with hysteretic properties of isolation devices, with a bilinear model. The lead rubber bearing LRB is used as isolation devices in this study. The total design yield force of the isolation system is set to 4% of the total weight and the design limit displacement is 300mm. Moreover, the design target period of the isolation system is 2.24s. Table 1 shows the dimensions of isolation devices.

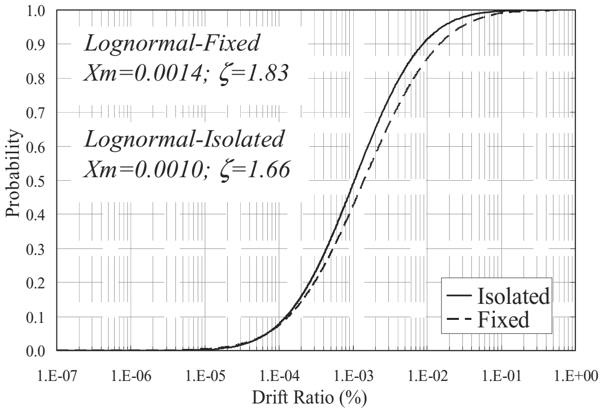

Figure 4. Lognormal distribution of *IDR* in 1st story.

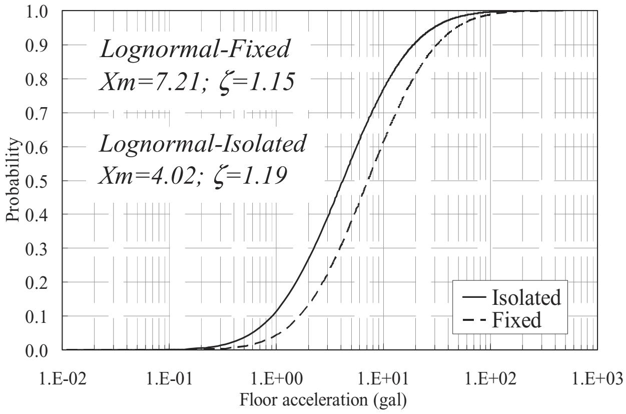

Figure 5. Lognormal distribution of *FA* in 1st story

3.3. Structural response distribution

A total of 800 nonlinear dynamic analyses are carried out in the target building, with and without base isolation, by using artificial earthquake ground motions previously generated. In this study structural uncertainty is assumed to be small compared with uncertainties of ground motions. With information of structural maximum response in each analysis, the probability distribution of the interstory drift ratio (*IDR*) and peak floor acceleration (*FA*) are obtained. The structural response is modeled by a lognormal distribution in this study. Figure 4 and Figure 5 show the distribution of *IDR* and *FA* respectively in the first story of the target building.

3.4. Structural damage distribution

Additionally to the structural response, the structural damage in the target building is evaluated. To correlate the values of *IDR* with damage, the Park-Ang's damage index (1985) is used. This damage index considers earthquake damage in RC members is composed of the damage caused by the maximum displacement and the absorbed hysteretic energy. The damage index *DI* is expressed by equation (2), where Q_y is the yield strength, *Eh* is the total hysteretic energy dissipated during earthquake, δ_m is the maximum drift during earthquake, δ_u is the ultimate drift under monotonic loads, and β_c is a constant to take into account the number of cycles (a value of 0.05 is taken in this study).

$$DI = \frac{\delta_m}{\delta_u} + \beta_c \frac{Eh}{Q_y \delta_u} \tag{2}$$

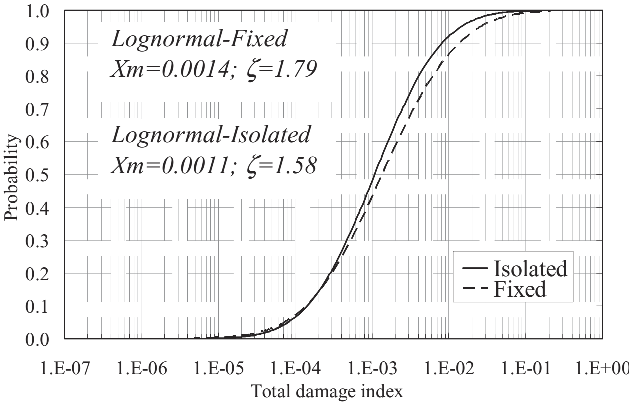

Figure 6. Lognormal distribution of DI_T.

Based on the 800 values of maximum *IDR* showed previously, the damage index is calculated for each and every case. Additionally, the total damage index in the building is calculated as an average of damage indices in each story (Park *et al.* 1985). Park and Ang (1985) determined that the damage index is reasonably lognormal distributed. Figure 6 shows the lognormal probability distribution of total damage (DI_T) in the target building. It can be seen from this plot that the median value and the standard deviation of damage distribution of isolated building are lower than fixed building.

4. SEISMIC RISK ANALYSIS

4.1. Exceedance probability of a random variable

To evaluate the exceedance probability of a random variable *X*, which represents structural response, the Poisson process model is used. If *X* is the random variable evaluated, *F(X)* is the cumulative distribution of *X*, and ν is the annual occurrence of the event; the exceedance probability that $X>X_m$ in *t* years is given as follows (Saito and Wen 1994)

$$p_f = P(X > X_m \| [0,t]) = 1 - \exp[-\nu t (1 - F(X_m)] \tag{3}$$

4.2. Seismic risk in terms of exceedance probability

The seismic risk of the building can be quantified in terms of exceedance probability of the structural response. To estimate the probability that the *IDR* will exceed some threshold value, the Poisson process model is assumed for the earthquake occurrence. The annual earthquake occurrence is $\nu=2.98$ in this study. Figure 7, shows the expected values of *IDR* with 10% of exceedance probability. The values of *IDR* for the isolated building are much lower than values for fixed building. So, it can be said that isolated building has better seismic safety than fixed building.

The seismic risk of the structure can be also quantified in terms of exceedance probability of damage index. Figure 8 shows the values of *DI* with 10% of exceedance probability. It is observed that fixed building suffers a large damage for long time periods and after 100 years there is a 10% exceedance probability to have a value of *DI* equal or more than 0.60. Damage in main structure is reduced by using the base isolation system, so the probabilities to have severe damage are significantly lower than the case of fixed building.

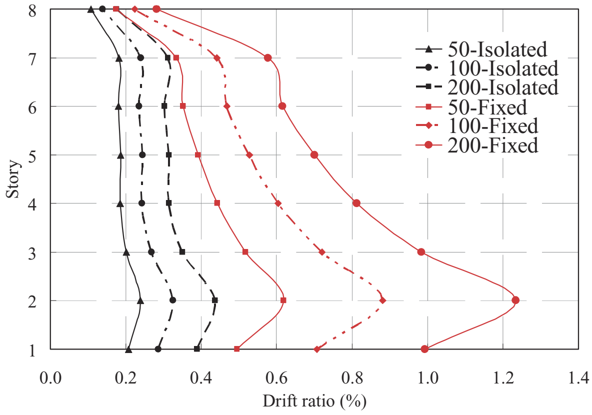

Figure 7. Values of *IDR* with 10% of exceedance probability in 50, 100 and 200 years.

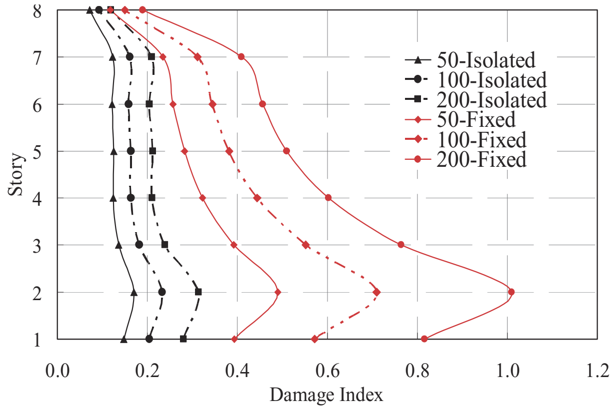

Figure 8. Values of *DI* with 10% of exceedance probability in 50, 100 and 200 years

5. COST-EFFECTIVENESS ANALYSIS

5.1. Repair cost model

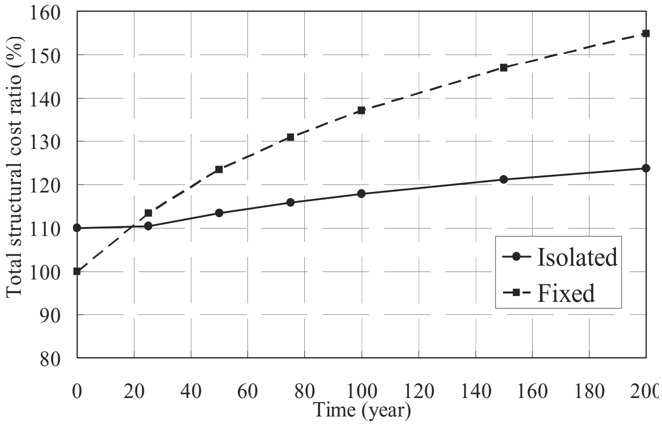

Figure 9. Expected values of total cost with 10% of exceedance probability in 50, 100 and 200 years

In addition to the seismic risk analysis, the cost-effectiveness analysis of the target building is carried out. In this study just the structural cost is taken into account. The cost-effectiveness is evaluated by a model which correlates damage index into structural repair cost of each story, so the total cost is the sum of repair cost in each story. The repair cost is defined by the structural repair cost ratio R_S (Takahashi and Shiohara 1987), which is the normalized repair cost by the cost of total replacing with new one. The repair cost ratio R_S is defined by equation (4), where *Dc* is taken as a value of 0.01.

$$R_S = \begin{cases} 0.0; & DI < Dc \\ \dfrac{DI - Dc}{1 - Dc}; & Dc \le DI < 1 \\ 1.0; & DI \ge 1 \end{cases} \tag{4}$$

5.2. Structural cost based in exceedance probability of damage index

Results obtained in damage analysis are related to repair cost by the cost ratio. Using values of damage index with 10% of exceedance probability, the structural cost repair ratio can be obtained in every case.

Figure 9 shows the expected value of total structural cost with 10% of exceedance probability. It is noticed from this figure that fixed building has large values of R_S; especially in long time period. If the life time were 100 years; it would be expected a value of 37.1% for total cost ratio in the fixed building, which is about 4.7 times larger than value of isolated building.

6. CONCLUSIONS

The methodology presented here is a useful tool to quantify the seismic risk and the cost-effectiveness of base isolated buildings. Additionally this procedure could be extended to any kind of building structure.

The total damage in conventional building is considerably larger than isolated building. The expected value of the total damage index in 50 years, with 10% of exceedance probability, for the fixed building has a value of about 2.47 times larger than isolated one.

Although the initial total structural cost in the isolated building is larger that in fixed one, the total structural cost in isolated building is much smaller for long time interval. So, base isolated building is cheaper than fixed building during the lifetime of the target building.

It can be concluded that the seismic risk is much lower in isolated building; moreover, the cost-effectiveness in isolated building is better than fixed building, during lifetime period when large damage is expected.

The use of seismic isolation should be encouraged in Peru to reduce seismic risk in buildings. Moreover; an upgrade in the Peruvian seismic code is needed in order to include probabilistic methodologies.

AKNOWLEDGEMENT

The information of the seismic catalog of Peru was provided by H. Tavera from the Geophysical Institute of Peru and the information of the attenuation equation was provided by J. Chavez; their collaboration is acknowledged. Special thanks are also given to CISMID and its director Carlos Zavala for their valuable collaboration.

REFERENCES

Gasparini D. A., Vanmarcke E. H., 1976, Simulated earthquake ground motions compatible with prescribed response spectra, Report R76-4, Dep. Civil Eng., MIT, Cambridge, Massachusetts.

Jennings P. C., Housner G. W., Tsai N. C., 1969, Simulated Earthquake Motion for Design Purpose, proc. 4th WCEE, Santiago, Vol. I A1, 145-160.

Midorikawa M., Iiba M., Koshika N., Kani N., 2006, Performance-Based Seismic Provisions for Seismically Isolated buildings in Japan, proc. 3rd ICUEE, Tokyo.

Park Y. J., Ang A. H–S, 1985, Mechanistic Seismic Damage Model for Reinforced Concrete, Jour. Struc. Eng., ASCE, Vol. 111, SE 4, 722-739.

Park Y. J., Ang A. H–S, Wen Y.K., 1985, Seismic Damage Analysis of Reinforced Concrete Buildings, Jour. Struc. Eng., ASCE, Vol. 111, SE 4, pp. 740-757.

Saito T., Wen Y. K., 1994, Seismic Risk Evaluation of R.C. Buildings in Japan, Report UILU-ENG-94-2003, Structural Research Series No 587, Univ. of Illinois, Illinois.

Shibata A., 2010, Dynamic Analysis of Earthquake Resistant Structures, Tohoku University Press, Sendai.

Takahashi N., Shiohara H., 2004, Life Cycle Economic Loss due to Seismic Damage of Nonstructural elements, proc. 13th WCEE, Vancouver, paper No. 203.

Tavera H., Agüero C., Fernandez E., Rodriguez S., 2007, Seismic Catalogo of Peru, Geophysical Institute of Peru, Lima. (In Spanish).