



TECHNICAL-ECONOMIC EVALUATION OF THE USE OF SEISMIC ISOLATION IN A PERUVIAN OFFICE BUILDING

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Abstract

The current Peruvian Seismic Code specifies that hospital buildings, located in most dangerous zones, must be projected as seismically isolated buildings. This requirement has been discussed by Peruvian engineers on whether Seismic Isolation Technology is the unique way to reduce structural and non-structural damage, and if its implementation cost can be justifiable in the building lifetime.

The objective of this paper is to evaluate if cost and implementation requirements of seismic isolation technology can be justified with the reduction of expected losses for future seismic events in building lifetime of 50-75 years.

This paper evaluates a mid-high-rise office building. This building was proposed in two types of structural system: seismically non-isolated building (RC Structural Wall System); and seismically isolated building (with lead-rubber bearing LRB isolator devices). Both structural systems were designed following Peruvian Seismic Code for seismic analysis, RC Peruvian Code for RC element and ASCE 7 for the design of isolation devices.

Nonlinear behavior of RC beam, RC column, RC shear walls and isolation devices were modeled in tridimensional model. Damage states are defined for these elements and related to fragility and consequences curves. Both systems were evaluated to 8 levels of seismic intensity and 20 seismic records for each one, following Incremental Dynamic Analysis and FEMA P-58 methodologies. Expected loss were estimated with PACT program considering all possible local and global damage.

Expected Annual Loss is calculated for Seismically isolated and non-isolated building. Then Cost-Benefit was carried comparing the Expected Losses in building lifetime with the implementation cost of this technology. It permitted to evaluate the effectiveness of the seismic isolation system in the building lifetime, considering the probability of occurrence of earthquake of different intensities.

Results indicate that implementation cost of Seismic Isolation Technology could be justifiable in the reduction of expected losses in 10 years, and total benefit in building lifetime could be 3 times the implementation cost of this technology.

Keywords: cost-benefit analysis, expected losses, seismic isolation



1. Introduction

Seismic Isolation Technology has theoretically proven to be highly effective mitigating building damage in seismic events. However, in countries like United States and New Zealand its use has been limited to important buildings such as hospitals or other essential buildings, seeking continuous functionality after a severe earthquake [1]. The main reason for its limitation is its “high” initial cost compared to a conventional building, although researches have demonstrated its benefit in seismic events [2, 3].

Theoretically, the use of Seismic Isolation Technology is justified when its post-seismic benefit in reduction of expected losses is greater than its implementation cost. The Net Present Value (NPV) of a building is defined as its initial cost decreased by its expected losses in future earthquakes. Researches [1] obtained a positive NPV for the implementation of this technology, but also concluded that analysis is highly sensitive to seismic zone, the details of structural design, the period of analysis, the return period of earthquake and the unit costs of each zone.

Several researchers [4, 5, 6, 7, 8] have analyzed the expected financial losses in conventional and isolated buildings and demonstrate that the expected benefit in the lifetime of isolated building is significantly greater than the seismic isolation implementation cost. In addition, Terzic [9] applied FEMA P-58 methodology [10] to estimate the cost and benefit in the lifetime of isolated buildings and found that the equilibrium point for the investment occurs at a ratio between 3.4% and 4.9%, depending on the ductility of the structure and the type of seismic isolation.

Currently, Seismic Isolation Technology has been commonly used in Peruvian Buildings like Hospitals, Office and Apartments; and right now, there are already 50-100 seismic isolated buildings around the country. This technology has been presented as an alternative to reduce structural and nonstructural damage. Therefore, the current Peruvian Seismic Code [11] specified that essential building in most dangerous zones must be projected with seismic isolation system. This study presents a study case of life cycle analysis in order to understand the cost and benefits of a seismic isolated building over a conventional building.

2. Conceptual framework and methodology

2.1. Methodology for cost-benefit analysis of buildings

(a) Assessment of Expected Losses in seismic events: The methodology to estimate expected losses and decision variables of the Pacific Earthquake Engineering Research (PEER) [12] is followed in this paper. It is divided in four stages:

Hazard Analysis ($d\lambda(im)$): It is represented as the annual probability of occurrence, λ , of an intensity value, im .

Structural Analysis (edp/im): Nonlinear Time History Analysis and the methodology of Incremental Dynamic Analysis IDA [13] is used to estimate the seismic response, edp , for each seismic intensity, im .

Damage Analysis (dm/edp): It represents the damage measure for structural and non-structural response, dm , according to the building seismic response, edp .

Loss analysis (dv/dm): It include repair cost, repair time or human losses. These losses are decision variables, dv , which are estimated for each damage measure.

This methodology is represented by the equation Eq.1:

$$P(DV > dv) = \int_{im} \int_{dm} \int_{edp} G(dv|dm) dG(dm|edp) dG(edp|im) |d\lambda(im)| \quad (1)$$



2.2. Time Based Assessment

Time-based assessment considers the occurrence probability of earthquakes of different intensities and their damaged caused over in building lifetime. These results are necessary to calculate the Expected Annual Loss (EAL), which can be estimated with expression presented in Eq.2 [12]:

$$EAL = \int_{IM} E [Loss|IM] |d\lambda(IM)| \tag{2}$$

where $E[Loss|im]$ correspond to the expected direct monetary loss for a given IM.

Cutfield [1] simplified expressions in Eq. 3 to estimate Expected Losses (EL) in a lifetime, L, takes into account the Expected Annual Loss (EAL) and the Discount Rate (DR).

$$EL = EAL \left(\frac{1 - e^{-DR(L)}}{DR} \right) \tag{3}$$

2.3. Cost and Benefit of Seismic Isolation Technology

Implementation Cost (C) and Benefit (B) of the technology are presented in Eq.4 and Eq.5.

$$B = EL_{snib} - EL_{sib} \tag{4}$$

$$C = C_{snib} - C_{sib} \tag{5}$$

Where EL_{snib} and EL_{sib} are the Expected Losses of seismically non-isolated and isolated building. C_{snib} and C_{sib} are their Implementation Cost. Technology's effectiveness can be evaluated comparing its Cost and its Benefit. Fig. 1 resumes the methodology followed in this paper.

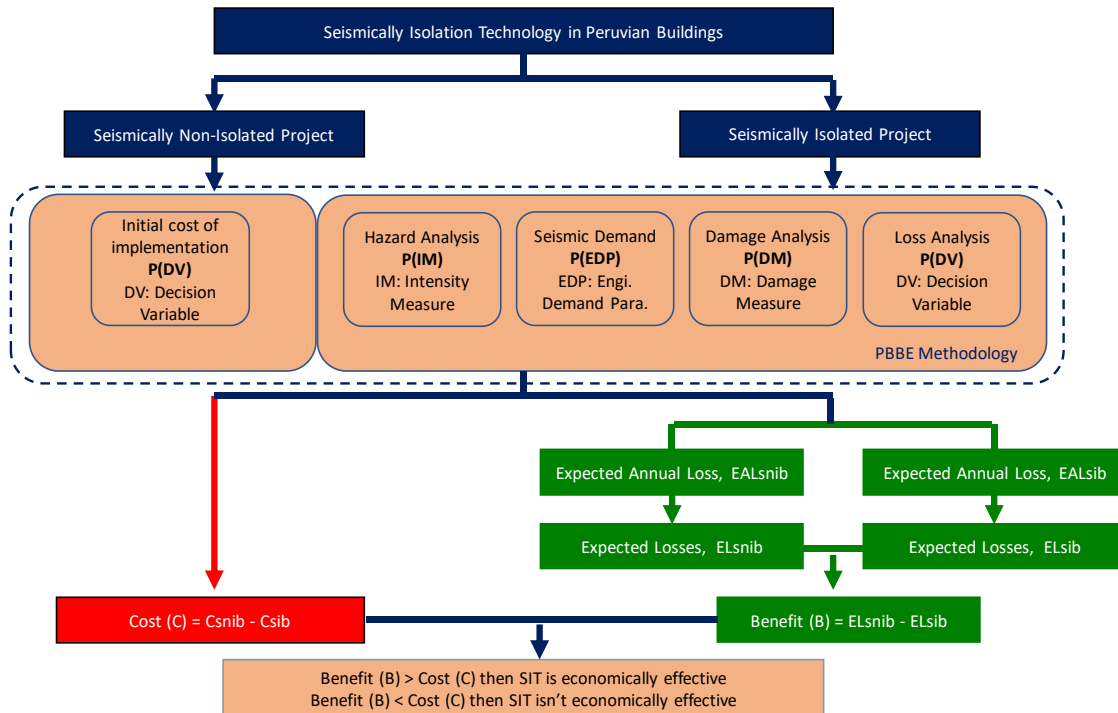


Fig. 1 - Methodology for the evaluation of technical-economically use of Seismic Isolation Technology in Peruvian Buildings



3. Application of methodology

3.1. Description of the building

Office building was proposed with two type of systems: RC Structural Wall System and Seismically Isolated System. In the first structural system, RC Walls are responsible of more than 80% of total seismic force and RC columns only resist gravity loads with very low seismic forces. In the second, the superstructure corresponds to a frame structure, with elastomeric isolator devices on the level of the first basement and sliders under the elevator box in the deepest story level. Table 1 presents characteristics of the building.

Table 1 - Building characteristics

Material	Office building
Concrete	4 basements ($f'c$ 35 MPa) 7 superior levels ($f'c$ 28 MPa) 1 roof ($f'c$ 21 MPa)
Steel rebar	Yield fluency (f_y) of 420 MPa
Structural elements dimensions	RC columns .70x.70m RC beams .80m depth RC walls of .30-.40m of thickness

Both buildings were designed according Peruvian Seismic and Reinforced concrete code [11, 14], which are based on American codes ASCE 7-10 [15] and ACI 318-99 [16]. Peruvian codes are more exigent because Shear Design Force is related to the non-effective stiffness of structural building. Fig. 2 presents three-dimensional model of structural systems in ETABS model [17].

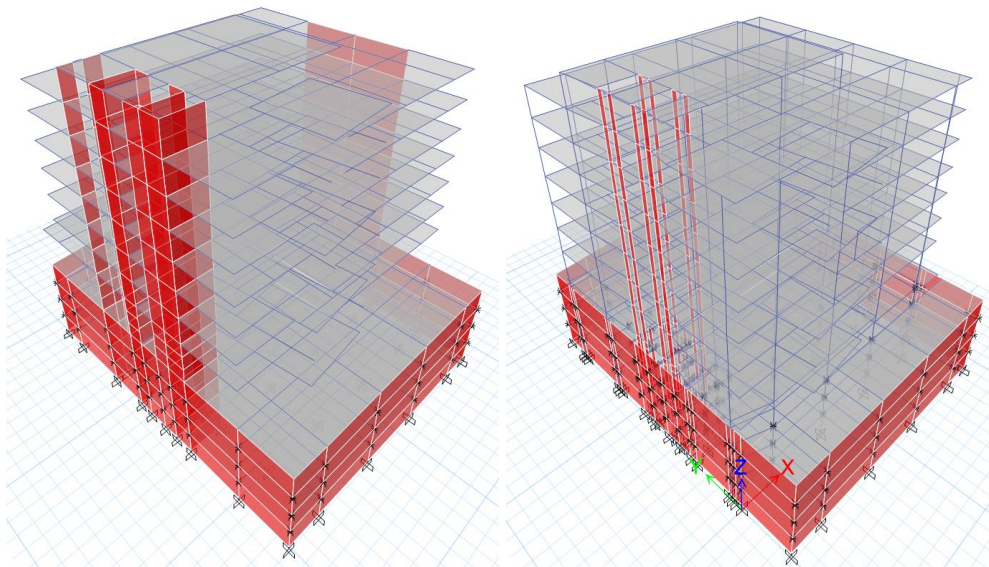


Fig. 2 - Office Building: (left) Structural Wall System; and (right) Seismically Isolated System.



3.2. Assessment of expected losses

(a) Hazard Analysis

Office building is located in Lima, one of the most dangerous seismic zones according to Peruvian Seismic Code [11]. Resume of seismic risk studies [18] is presented in Fig. 3, which indicates a Peak Ground Acceleration (PGA) of 0.48g for Lima in a rare earthquake correspond to 475-years period return.

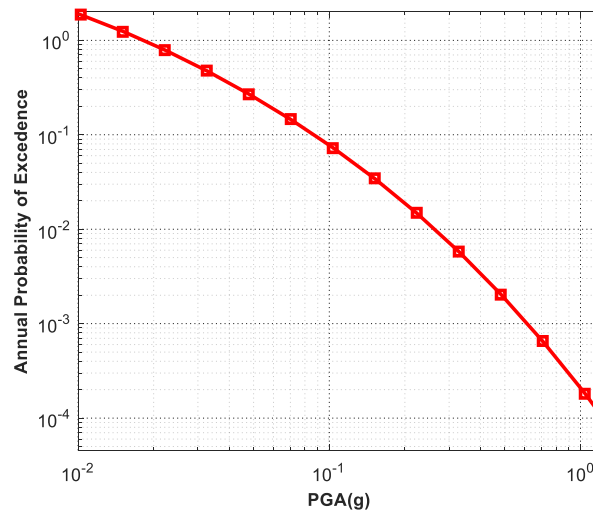


Fig. 3 - Hazard Seismic Curve of Lima city.

(b) Structural Analysis

The structure was three-dimensionally modeled considering: RC columns and beams as frame elements with inelastic behavior focused on hinges in the boundary zones; RC walls as shells with fiber elements those have nonlinear properties; and slabs as membrane elements with the only function to transmit loads. Hysteretic behavior of steel rebar and concrete was represented for Takeda model [19] and Concrete model [17]. The analysis was realized with the PERFORM program [20].

Buildings are evaluated for eight intensities, represented by twenty Peruvian and Chilean seismic records (see Table 2), those were made spectrum compatible with Peruvian Seismic Code.

Table 2 - Seismic Peruvian and Chilean records

Epicenter	Seismic Record	Date	PGA (g) NS - EW	Focal Depth (km)	Magnitude	Duration (s.)
Perú - Lima	Lima	17/10/1966	0.27 - 0.18	30	8.1 Mw	66
Perú - Ancash	Huaraz	31/05/1970	0.11 - 0.10	64	7.9 Mw	45
Perú - Lima	Lima	03/10/1974	0.20 - 0.18	13	8.1 Mw	98
Chile - Valparaíso	Llolleo	22/02/1996	0.11 - 0.16	46	5.9 Ms	31
Chile - Coquimbo	Punitaqui	15/10/1997	0.29 - 0.37	56	7.1 Mw	105
Perú - Arequipa	Arequipa	23/06/2001	0.30 - 0.22	33	8.4 Mw	199
Chile - Tarapacá	Tarapacá	13/06/2005	0.53 - 0.73	108	7.8 Mw	252
Perú - San Martín	Moyobamba	25/09/2005	0.13 - 0.10	115	7.5 Mw	27



Perú - Ica	Pisco	15/08/2007	0.28 - 0.34	40	8.0 Mw	218
Chile - Antofagasta	Tocopilla	15/11/2007	0.44 - 0.50	40	7.7 Mw	215
Chile - Antofagasta	Tocopilla	16/12/2007	0.48 - 0.40	40	7.7 Mw	215
Chile - Biobío	Concepción	27/02/2010	0.50 - 0.32	30	8.8 Mw	180
Chile - Biobío	Angol	27/02/2010	0.89 - 0.52	30	8.8 Mw	180
Perú - Pucallpa	Pucallpa	24/08/2011	0.06 - 0.05	149	7.0 Mw	135
Perú - Arequipa	Arequipa	25/09/2013	0.04 - 0.03	30	6.9 Mw	150
Perú - Ica	Ica	15/03/2014	0.03 - 0.02	25	6.2 Mw	150
Chile - Iquique	Iquique	01/04/2014	0.57 - 0.41	39	8.2 Mw	141
Chile - Iquique	Moquegua	01/04/2014	0.05 - 0.03	39	8.2 Mw	141
Chile - Coquimbo	Coquimbo	16/09/2015	0.72 - 0.83	23	8.3 Mw	150
Chile - Chiloé	Chiloé	25/12/2016	0.35 - 0.27	35	7.6 Mw	159

c) Damage Analysis

Moment - rotation hinges ($M-\theta$) were based on curvature analysis (following stress-strain relation of unconfined concrete, confined concrete and steel rebar) of the section and the supposed length of plastic hinge [21]. Mander [22] stress-strain relation for concrete was considered with a maximum strain of 0.005 and 0.02 for unconfined and confined concrete, respectively. A maximum deformation of 0.03 was considered to take account the buckling and fracture of steel rebar [23, 24]. Shear behavior of RC elements was represented using Shear–Curvature ductility model proposed by Priestley [25].

Moment curvature diagram permitted to link curvature to displacements and damage states of the concrete and steel rebar [26]. Theoretical moment capacity decreases after the buckling rebar or concrete core failure. Theoretical hinges of each element were compared with the nonlinear criteria, limits and damages states of ASCE 41-13 [27] and FEMA P58 [28, 29].

(d) Assessment of expected losses

New libraries of consequences curves in FEMA P58 were created for structural and nonstructural elements associating expected losses to typical Peruvian Times and Costs. PACT program from FEMA P58 was used to estimate repair cost of building for different intensities considering a total dispersion of 0.47 for loss analysis, based on quality construction and the type of analysis. This project has considered only expected losses in terms of repair costs of structural elements. The inclusion of non-structural elements and machines requires a more detailed analysis, and in this paper, it is only approximated with a correlation factor.

Hirakawa [30] evaluated the percentage of seismic losses for structural, non-structural components and the contents of 210 buildings those were damaged by the 1995 Hyogo-ken Nanbu earthquake. Their results indicate that structural, non-structural elements and components represent 40%, 40% and 20% of the total repair cost. In addition, Taghavi & Miranda [31] estimated that ratio for structural components in retrofitting actions is only 18% for Office Buildings. In this paper, based on these results and according to Peruvian experts, it has been considered that structural elements for Office Building only represent 25% of the total building cost.



e) Dynamic response of isolated and non-isolated building

Fig. 4 and 5 show first and second level drift for buildings analyzed in this paper. Fig. 6 presents the maximum acceleration in seismically non-isolated and isolated building

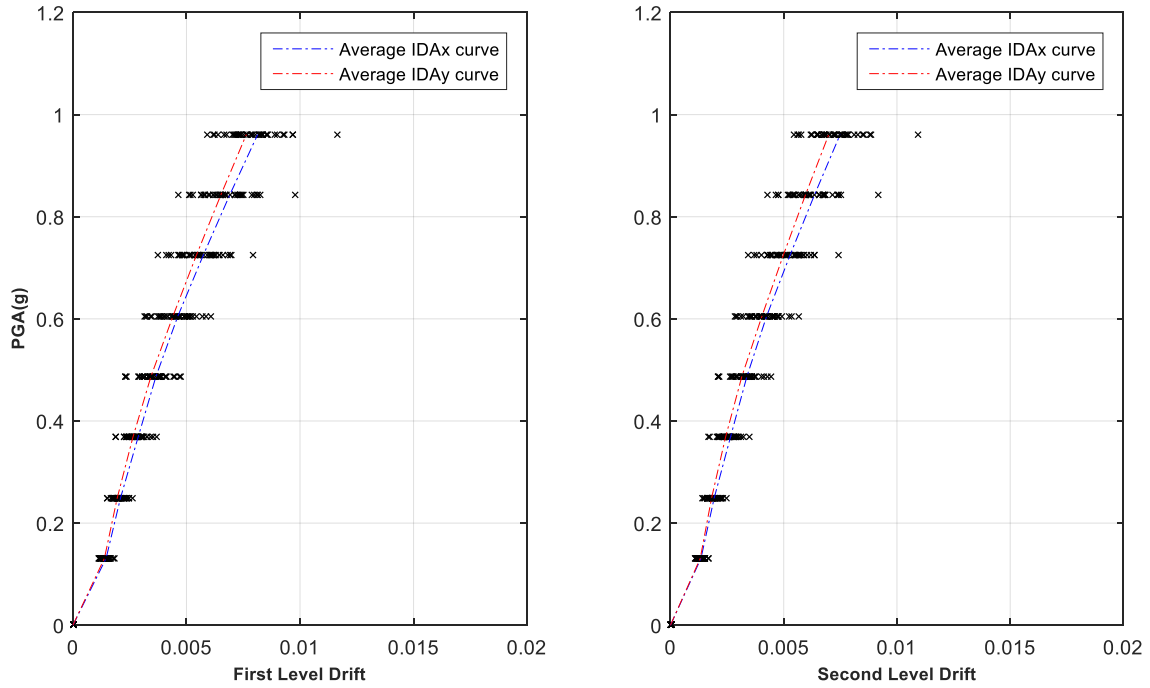


Fig. 4 - First and Second Level Drift for Non-Isolated Office.

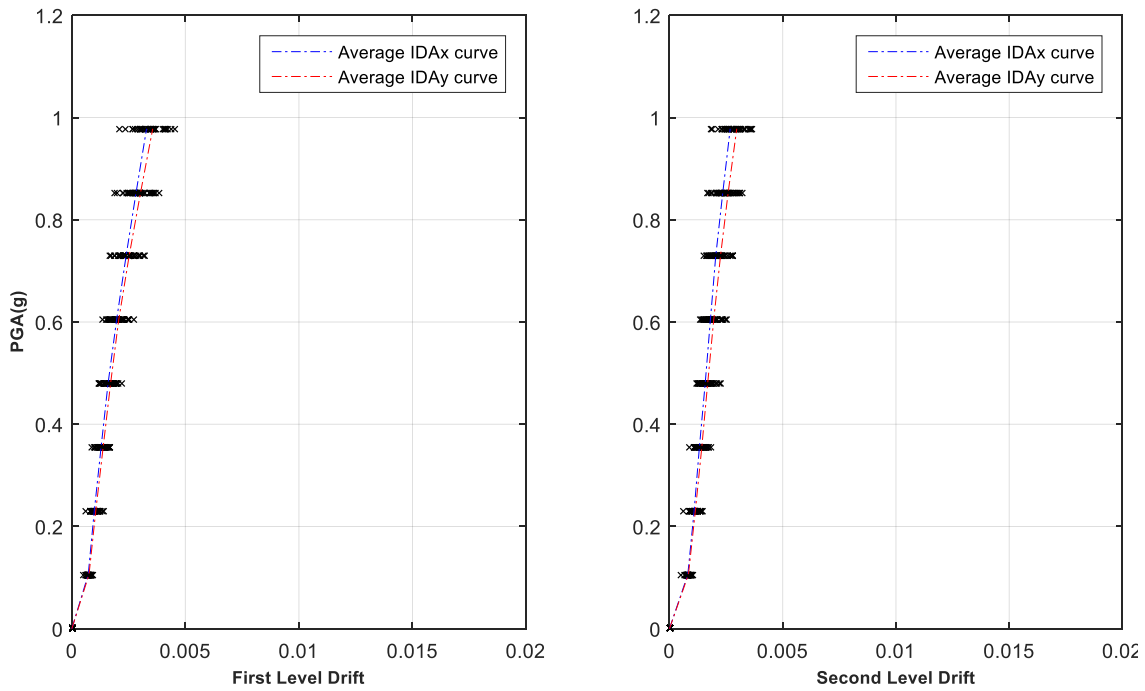


Fig. 5 - First and Second Level Drift for Isolated Office.

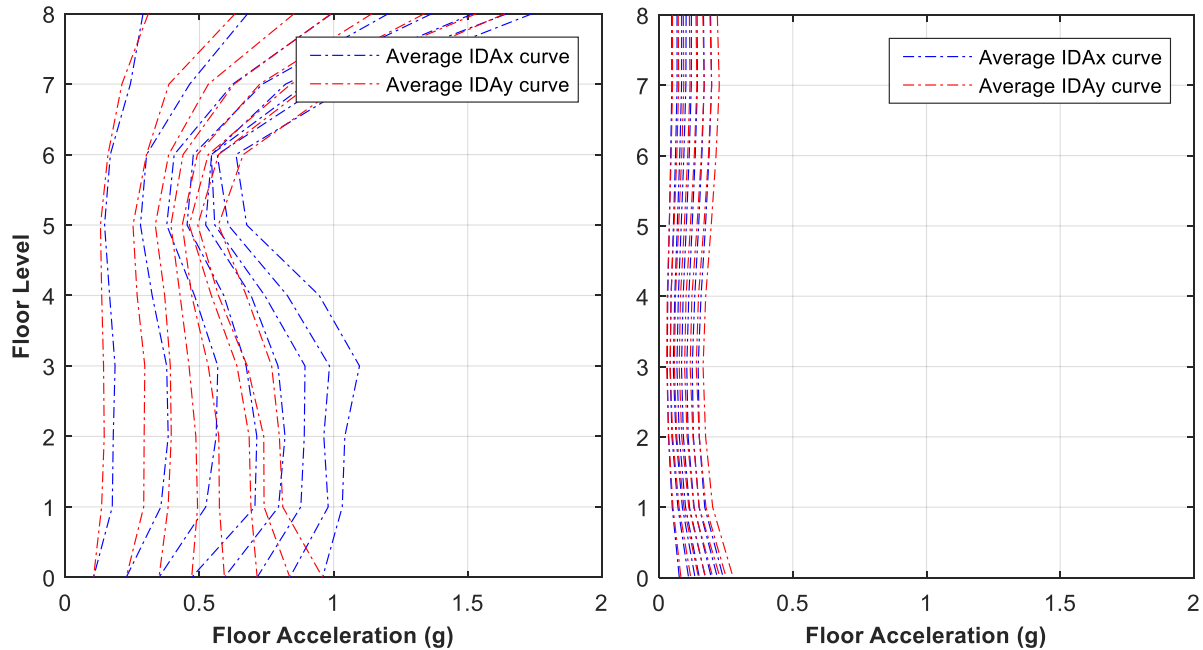


Fig. 6 - Acceleration for different intensities: (left) Non-Isolated Office building; and (right) Isolated Office building.

Results indicate the clear benefit of seismic isolation technology in the reduction of story drift and floor acceleration against all seismic intensities. For a rare earthquake, seismically non-isolated and isolated building reach a maximum drift of 8.0 % and 3.5 %, respectively. Absolute acceleration is reduced from approximately 1.5 g to 0.5g.

(f) Expected losses for seismic intensities

To estimate the expected losses in non-structural elements, it was used the same factor obtained from expected losses in structural elements. It's based on a similar reduction of displacement and absolute acceleration with the use of Seismic Isolation Technology.

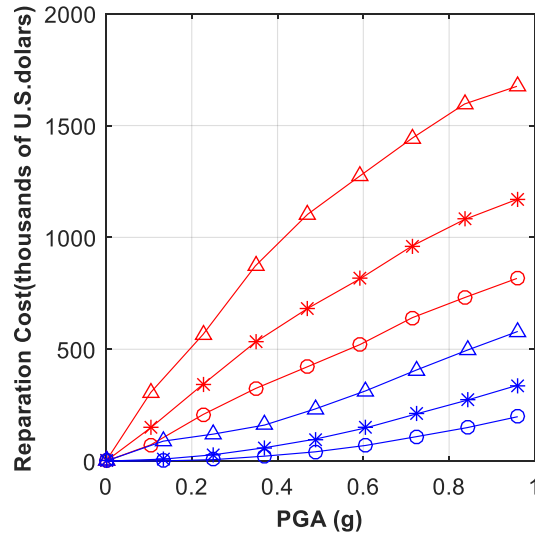
Table 3 presents buildings initial cost and their expected losses in a rare earthquake. In office building, technology implementation cost is \$168,663 (17.5% of superior levels structure and 4.4% of total building cost). According to experts, implementation cost of seismically isolation technology may be around 4-6% to be effective.

Table 3 - Building Cost and Expected Loss for Rare Earthquake

Cost (\$)	Non-isolated Office (\$)	Isolated Office (\$)
Basements structure	1,284,922	1,281,147
Superior levels Structure	961,599	895,062
Isolation Devices	-	235,200
Non-structural components	2,884,797	2,884,797
Building Cost	3,846,395	4,015,059
Expected Loss for Rare Earthquake	682,600	98,320
	18%	2%



For a rare earthquake, application of SIT in office building permitted to reduce expected losses from 18% to 2% (3.46 times the implementation cost of SIT). Fig. 7 shows the Expected Losses estimated for non-isolated and isolated buildings in different seismic intensities. Expected losses in isolated building is already 2% building cost, a value related to the concept of Continue Functionality [32].



- △— P(Repair Cost Non-Isolated Building ≤ \$C)=0.50
- P(Repair Cost Non-Isolated Building ≤ \$C)=0.05
- *— P(Repair Cost Non-Isolated Building ≤ \$C)=0.95
- △— P(Repair Cost Isolated Building ≤ \$C)=0.50
- P(Repair Cost Isolated Building ≤ \$C)=0.05
- *— P(Repair Cost Isolated Building ≤ \$C)=0.95

Fig. 7 – Expected losses of Office building.

3.3. Time Based Assessment

Fig. 8 presents the Expected Annual Loss of Office building with the two structural configurations. EAL in buildings is reduced to 11% (from \$23293 to \$2658) with the use of SIT.

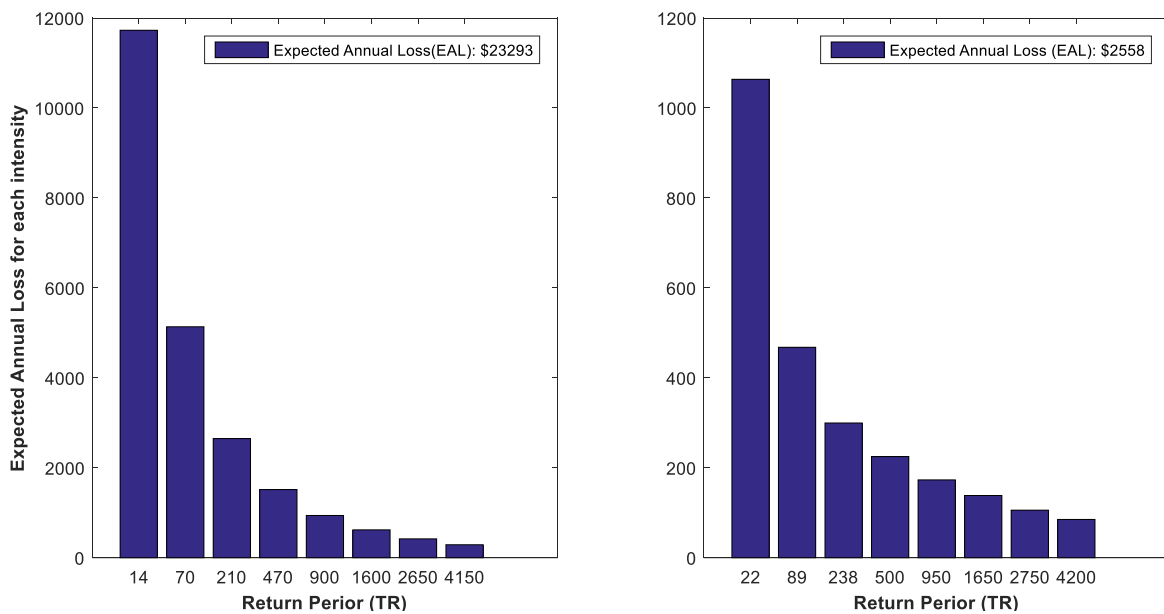


Fig. 8 - Reparation Cost for Office Building: (left) Non-isolated; and (right) Isolated.



3.4. Cost and Benefit of Seismic Isolation Technology

Some references [33, 34] indicate that Discount Rates for reparation actions ranges between 2% and 7%. Also, the current reference interest rate in Peru can be approximated to 4% [35, 36], value which is used in this paper.

For Office Building, results indicate that Benefit will reach Implementation Cost in 8.1 years; and also, in a lifetime of 50 years, Benefit will be 2.66 times its Implementation Cost. Table 4 presents Cost and Benefit of SIT in Office building.

Table 4 - Cost and Benefit of Seismic Isolation Technology in the building

Cost and Benefit	Seismically Non-isolated Office (Cnsib)	Seismically Isolated Office (Cnsib)
Implementation cost	3,846,395	4,015,059
Benefit in 25 years		327,675
Benefit in 50 years		448,221
Benefit in 100 years		508,881

4. Conclusions

Expected loses of seismically non-isolated building, in a rare earthquake, are 18% of its building initial. It indicates that Peruvian Seismic Code permits a good seismic performance according to American codes. However, the confinement of RC structural walls should be studied because is one of the most important factors to evaluate seismic damage in elements and a better detail of boundary zones could reduce expected losses. Expected losses of seismically isolated building, in a rare earthquake, are approximately 2% of its initial cost. Failure in both buildings will occur when the seismic displacement beats separation joint.

In a typical middle high office building, implementation cost of SIT could be quickly justified with its benefit in the reduction of expected losses in 10 years. In a typical lifetime of 50 years, results indicate that benefit will be much greater than its implementation cost.

This study demonstrates the high benefit of seismic isolation technology in the lifetime of common building. It is suggested that Peruvian structural designers study the proposal of seismic isolation such a common alternative in mid-rise buildings.

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