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COST-BENEFIT ANALYSIS TO ASSESS SEISMIC MITIGATION OPTIONS, CASE STUDY: PUBLIC MEXICAN SCHOOLS BUILDINGS

M. Jaimes [(1)], M. Niño [(2)]

[(1)] *Associate Researcher, Coordination of Structural Engineering, Institute of Engineering, UNAM, MJaimesT@iingen.unam.mx*
[(2)] *Associate Professor, Department of Structures, Faculty of Engineering, UNAM, MNinoL@iingen.unam.mx*

Abstract

This paper presents a methodology to perform a cost-benefit analysis to assess possible options such as retrofitting or reconstruction of structures focused on mitigation of direct physical losses due to seismic actions. The case of all public school buildings located in Mexico City is presented as an illustrative example, using as decision variable the expected annual loss (*EAL*) and probable maximum loss (*PML*). The proposed methodology is comprised of the following steps: 1) Gathering of design information of typical school buildings designed according to different past seismic codes of the region. 2) Proposal of seismic mitigation actions such as retrofitting or stiffening of the structural system in order to comply with the current Mexico City seismic design code (RCDF-2004). 3) Calculation of vulnerability functions by carrying out non-linear Incremental Dynamic Analyses (*IDA*) for the original designed structural systems and those modified according to the performed mitigation actions. 4) Probabilistic seismic risk analysis taking into account all locations of public school buildings in Mexico City. 5) Cost-benefit analysis assuming two different cases: a) retrofitting and/or stiffening the structural system and b) demolish and reconstruct a completely new school building. This analysis is carried out at two different levels: 1) definition of vulnerability functions of structures considering the two mitigation actions and comparison between them, and b) combination of the different mitigation alternatives in order to determine, the number and location of schools that required mitigation actions assuming that economical resources is limited, by means of the estimated EAL and PML.

It is shown the utility of carrying out a cost-benefit analysis by computing in a formal way the seismic risk to formulate and define mitigation strategies that allow decision-maker prioritize the use of the economic resources. The benefit of this approach is that the obtained results will be presented in a way that may be easier to communicate to decision-makers even if they are not familiar with formal risk studies.

Keywords: Cost-benefit analysis, Schools, Site effects, retrofitting, seismic risk

1. Introduction

Mexico City's building codes throughout history (e.g. RCDF-1977, RCDF-1987 RCDF-2004, among others) [1, 2, 3] have been one of the most advanced codes in the world. However, after the severe damage that occurred during the 1985 earthquake M8.1 on the Michoacan Gap of the Mexican subduction zone, the need to reduce the seismic risk of Mexico City's structures was a priority. Authorities reviewed and updated the existing building code at that time [2], resulting in new parameters of seismic coefficient, displacement limits, stability, use of structures, materials, resources among others new characteristics e.g., [4]. As Mexico City's building codes have been modified along the years, since its earliest version of 1942 to the latest one published in 2004, several structures are lagging behind in terms of seismic safety. There are buildings in Mexico City that are still under old regulations for which it is necessary to carry out a cost-benefit analysis to find a better way to orient technical and limited economic resources to fully achieve the goal of reducing seismic risk.

For such purpose, the study of seismic vulnerability to establish cost-benefit analysis is an important issue, therefore, many researchers have contributed to the development of this topic. For instance, Kappos *et al*. [5] developed a research in Greece to establish a hybrid method for calculating seismic vulnerability, which is based on analytical and empirical methods. On the seismic vulnerability based cost-benefit analysis, Kappos and Dimitrakopoulos [6] established that retrofitting structures by stiffening to mitigate the damage by seismic impacts is feasible. This research brought more interest to perform this type of studies in Mexico considering, in this case, the cost-benefit analysis in terms of seismic risk.

As it indicated by Chrysostomou *et al.* [7], given their particularly sensitive role in society, schools are given high priority when earthquake strengthening programs are discussed. Therefore, in this study a cost-benefit analysis for public schools in Mexico City was carried out to assess possible options such as retrofitting or reconstruction of structures, focused on mitigation of direct physical losses due to seismic actions.

2. Methodology

The basic framework of probabilistic risk assessment consists of the following steps:

2.1 Seismic hazard evaluation

In this study, hazard is defined as a stochastic set of events, collectively exhaustive and mutually exclusive, that describes the spatial distribution, the annual frequency, and the randomness of the hazard intensity at the site of interest. Seismic hazard intensity is quantified in terms of a relevant seismic intensity parameter related to the performance of the structures; in this investigation, the intensity measure used is the spectral pseudoacceleration of the fundamental mode of the structure. The hazard intensity of each seismic event considered is represented as a random variable by, at least, its first two probabilistic moments: (1) the expected value and (2) the variance. The uncertainties considered for the variance estimation must be those related to the input data used and the simplifications of the models. There are no formal approaches to evaluate these uncertainties; however, the analyst should make an effort to estimate and include them in the seismic risk assessment; this process is completed by reviewing historic events and previous scientific studies on the region of interest.

2.2 Defining the inventory of exposed elements

The exposed elements are mainly related to the infrastructure components, or to the exposed population that may be affected by hazard events. To characterize the inventory, it is necessary to identify the individual components, including location, physical characteristics, vulnerability, economic value and the expected human occupation during a given event. The degree of precision of the results depends on the level of resolution and detail of the exposure inventory information.

2.3 Assigning a vulnerability function to each exposed element

The vulnerability function quantifies the expected damage caused to each asset class to the intensity of a given hazard. The classification of the assets is based on a combination of construction material, construction type, building occupancy and number of stories. It is strongly recommended (or desirable) that particular vulnerability functions are available for each building typology.

2.4 Probabilistic risk assessment

The risk due to natural hazards is commonly expressed in terms of the expected annual loss, $E(loss)$, and the loss exceedance rate, $\nu(loss)$, which specifies the frequency, usually annual, of the occurrence of the losses [8, 9]. Further details are presented in Section 7.

3. Seismic hazard definition

3.1 For a single site

The seismic hazard evaluation in Mexico City is based at the reference station CU (*Ciudad Universitaria*), where strong ground motions have been recorded since 1964 for more than 40 earthquakes with magnitude larger than 6; since the early nineties this station has a broadband recorder. It is located at a hill zone site over basaltic lava flows, and it has become the reference site to study the dynamic amplification at the lakebed zone of Mexico City [10, 11, 12, 13]. The seismic hazard intensity must be quantified in terms of relevant seismic intensity related to damage. As it shall be discussed later this study uses spectral pseudoacceleration (5% damping) for certain structural period related to the studied structures. The ground motion intensity of each event is represented as a random variable by, at least, its first two probabilistic moments: the expected value and the variance. For this purpose, an **.ame* type file is created (*ame* comes from amenaza -hazard- in Spanish) which includes a description header and multiple geocoded grids representing a hazard event set for each event with its associated rate of occurrence [14]. The uncertainties considered for the variance estimation are those related to the data and the simplifications of the model. The seismic hazard evaluation for other sites in Mexico City are presented later in this paper.

3.1.1 Ground motion prediction equations

Once the seismicity has been determined for each seismic source, the effects generated by each source must be evaluated at the site of interest in terms of seismic intensity. The expressions that relates the magnitude of any event and the seismic intensity at a determined site are known as ground motion prediction equations or attenuation laws. The first step is to calculate the intensity on firm soil or rock sites, and if applicable, at the soil amplification sites. The seismic intensity employed in this study will be the spectral pseudoacceleration computed on firm soil (station CU). The intensity is assumed to be a random variable with a normal logarithmic distribution, where the mean is expressed as a function of the magnitude of the earthquake and the distance between the source and the site. The natural logarithm of the standard deviation of the intensity is also defined.

In this study, the types of earthquakes that each seismic source may generate are classified in three groups: interplate, intermediate depth and shallow crustal earthquakes. A different attenuation law is associated with each one of these types of earthquake for Mexico City:

(1) Interplate earthquakes. For the peak ground acceleration caused by earthquakes generated on the south coast of the Pacific, the attenuation law of Jaimes *et al*. [15] is used. This law was developed based on numerous records of acceleration obtained by the UNAM Accelerograph Network, which include the records of the great earthquake of 19 September 1985.

(2) Intermediate depth earthquakes. In this case, an attenuation model developed by Jaimes *et al*. [16] is employed. This model was developed based on 22 earthquakes with magnitudes between 5.2 and 7.4 and depths between 40 and 128 km.

(3) Local earthquakes. In order to model the attenuation of local earthquakes, the ground motion prediction equations developed by Jaimes *et al*. [17] using 15 local earthquakes in hill zone of Mexico City of the Mexico basin are employed.

3.2 For multiple sites

The next step involves the calculation of intensities, at other sites in Mexico City based on the seismic hazard analysis of station CU. As it was previously mentioned, it is assumed that the strong ground motion in CU is an intensity reference of the seismic input motion that excites the soft soil of Mexico City. There are different ways to characterize the response at instrumented sites located at the lakebed zone that have recorded at least one earthquake [15]. The method used in this study consists on multiplying the spectral intensities by response spectral ratios (RSR, empirical transfer functions between each instrumented site and the reference station) [18]. It will be always uncertain, however, whether this relative amplification will remain the same for all strong ground motion; but at least for Mexico City, it is well known that the clay behaves almost linearly for most of the sites, and that the observed non-linear behavior, if any, is very small [19]. These RSR have been obtained from the response spectra of accelerograms produced by several earthquakes and registered in dozens of sites in the firm ground, transition and lakebed zones [18, 20]. However, the spectral amplification is also required at non-instrumented sites. Then, a statistical scheme to restrict the spatial interpolation of transfer functions by means of the use of a Bayesian regression technique is used [21, 22]. The interpolation procedure can be summarized in the following steps: 1) each RSR is normalized with respect to its dominant period [23]; 2) the normalized RSR are used in a two-dimensional interpolation scheme to obtain the normalized RSR at an arbitrary site; and 3) this RSR is renormalized with respect to its dominant period. To reduce the computing time of the calculation, the RSR for selected sites were pre-calculated. Finally, the ground motion intensities at lakebed sites are obtained as the product of the spectral accelerations of the seismic intensity employed at CU and the RSR.

4. Definition of exposure dataset

For characterizing the inventory of schools, it is necessary to identify each asset, considering location, physical characteristics, vulnerability and economic value. We have obtained from the SEP (Ministry of Education) through IFAI (Federal Institute for Access to Public Information and Data Protection) a database of all public schools located in Mexico City [24]. With this information, we have created a database in a geographical information system (GIS) (Fig. 1) considering the number of stories, the construction year, structural system and material. The replacement value of the asset may be that given directly by the owner or that estimated from secondary sources (*e.g.* INEGI National Institute of Statistics and Geography, 2015) [25]. The precision of the results will depend on the level of resolution and detail of the available information.

5. Vulnerability due to seismic actions

Structural vulnerability means the damage or impact, i.e., monetary loss, etc., that a specific property will suffer if a hazardous event occurs. It is generally measured as an average percentage of damage or the economic value required to repair the impacted property and restore it to a state equivalent to that prior to the occurrence of the event. Vulnerability is expressed in terms of “vulnerability functions”, which express the distribution of loss probabilities as a function of the intensity produced during a specific event. Vulnerability functions for structures are expressed as curves associating mean damage ratio, also expressed as β, with a measure of event intensity. The standard deviation of the latter parameter, as well as the intensity function for the event, should also be taken into account [26].

In developing the vulnerability function, the intensity measure selected is generally the parameter that best represents the performance and, as a consequence, the damage of each specific structure. In this paper the considered parameter is the pseudoacceleration as the seismic hazard is measured in terms of spectral acceleration, *i.e.*, for different structural periods, expressed as elastic structural response for a specific damping factor, usually 5%.

Three typical reinforced concrete (RC) schools, 1-, 2- and -3 stories, were considered as cased studies; such number of stories are typical in building schools at Mexico City. In order to define realistic strength and stiffness values of the studied buildings, they were designed according to three representative building codes published in Mexico City along the years: 1977 [1, 29], 1987 [2, 30, 31] and 2004 [3, 32, 33] building codes.

To define β value and its associated standard deviation, Incremental Dynamic Analyses, IDA, [27] were carried out to compute the structural response where the interstory drift was used to define structural damage. The seismic demands used were 98 seismic accelerograms recorded at different sites of the lake bed zone of Mexico City. Such set was assembled by Ruiz-García and Miranda [28] to study strength demands of structures built in soft soils. For brevity sake, Fig. 2 shows only results in term of interstory drift *vs.* spectral acceleration for the three-story school for the three considered building codes. For one-story and two-story schools were similarly calculated, however, due to length paper restrictions, this results are not shown here.

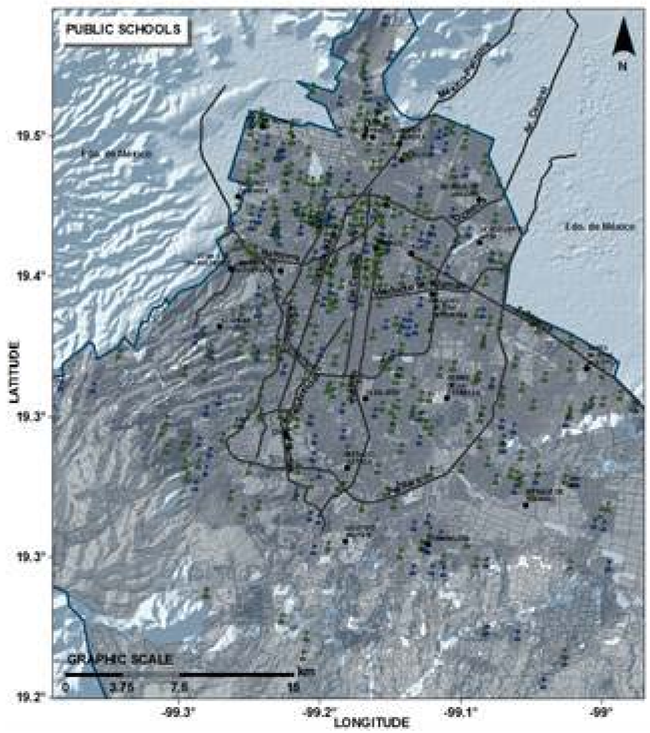
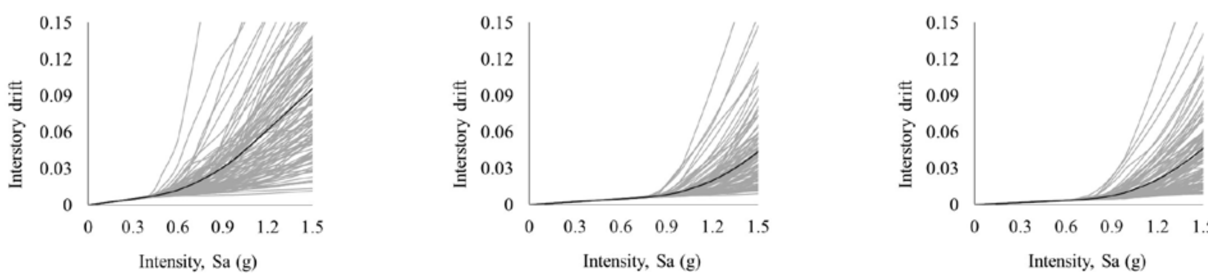


Fig. 1 – Location of public schools in Mexico City



a) b) c)

Fig. 2 – IDA curves for a three-story school according to: a) 1977, b) 1987 and c) 2004 Mexico City Building Codes

5.1 Interstory drift vs. structural damage

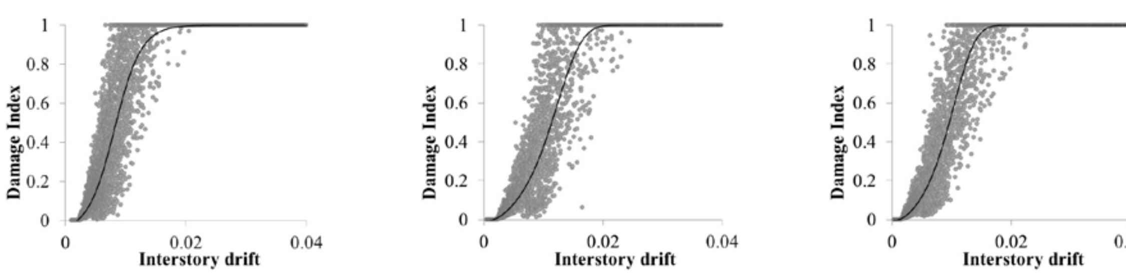
To assess structural damage generated in structures due to seismic actions, the authors employed the interstory drift associated to the damage index proposed by Teran *et al.* [34]. An index value of zero indicates the absence of damage and one denotes total damage or a complete lack of strength. The most known Damage Index is that proposed by Park and Ang [35], however, it has the inconvenience of giving values larger than zero for undamaged conditions and values larger than one for complete damage, therefore, its use was not considered in this study. As many other damage indexes, Teran damage index, ID_{TJ}, does not consider soil-structure interaction; however, it does employ hysteretic energy dissipated by a SDOF system and its associated displacement in terms of ductility (Eq. 1).

$$ID_{TJ} = \frac{NE_{H\mu}\left(2-c\right)}{r\left(2\mu_u - 1\right)} \tag{1}$$

In Eq. (1), μ_u is the capacity in terms of ductility due to monotonic loading, c and r are structural parameters that measure the structural stability of the hysteretic cycle, and $NE_{H\mu}$ is the normalized hysteretic energy demand due to a given seismic excitation, which is defined as

$$NE_{H\mu} = \frac{E_{H\mu}}{F_y \delta_y} \tag{2}$$

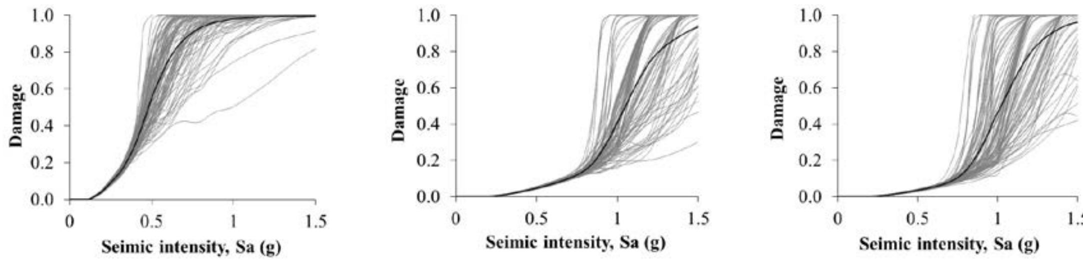
where $E_{H\mu}$ is the hysteretic energy demand during a hysteretic cycle, F_y is the yielding lateral strength and δ_y is the yielding displacement. This damage index was computed for SDOF systems of reference representing the characteristics of the fundamental mode such as vibration period, lateral strength, proportional mass for each typical structure. Since the case studies considered are RC frame structures, the modified Ibarra and Krawinkler model implemented in Opensees [36] was used to compute the non-linear response. For this purpose, eleven thousand non-linear analyses were carried out using as input ground motion synthetic records obtained by Niño *et al*. [37]. Since one of the parameters employed to define the damage index is the displacement of the SDOF system, the maximum interstory drifts may be computed straightforward using as high. Fig. 3 shows the results obtained from the analyses of the SDOF reference systems of the three-story schools designed with 1977 (Fig. 3a), 1987 (Fig. 3b) and 2004 (Fig. 3c) Mexico City building codes, along with an interstory drift *vs* damage index curve attained via non-linear regression analysis. It can be observed that, qualitatively speaking, there is not a significant difference between Fig. 3b and Fig. 3c. This is attributed mainly to two reasons: 1) that the expression to compute the modulus of elasticity of the 1987 and 2004 building codes is the same and 2) the seismic coefficient and security guidelines employed in their design are rather similar. On the other hand, the interstory drift vs damage index curve of the school designed with the 1977 building code is, as expected, quite different from the others since the seismic coefficients are not the same as those of the later versions of the code.



a) b) c)

Fig. 3 – Damage Index (Eq. 1) vs. Interstory drifts relationship of a SDOF systems representing three-story buildings according to: a) 1977, b) 1987 and c) 2004 Mexico City Building Codes

From the aforementioned results, the vulnerability curves of the structures were defined. Fig. 4 depicts the individual vulnerability curves associated to each ground motion record (grey lines) and the expected value of damage (black lines) for the three-story schools designed according to 1977 (Fig. 4a), 1987 (Fig. 4b) and 2004 (Fig. 4c) Mexico City building codes. As it was expected, the same trend noticed in Fig. 3 was observed in this plots, as the vulnerability curves for schools designed with the 1987 and 2004 building codes present similar damage level for a given seismic intensity.



a) b) c)

Fig. 4 – Expected damage for three-story structures designed according to: a) 1977, b) 1987 and c) 2004 Mexico City Building Codes

5.2 Retrofitting

After the occurrence of a hypothetical earthquake, several structures would need to be either demolished, due to the severity of the damage reached, or retrofitted to comply with the new building code standards [3, 32, 33]. Moreover, to take into account the possible modifications made to the schools, the designed typical schools in their original condition, hereafter called originals, were evaluated with 2004 Mexico City building code [3, 32, 33] and retrofitted as they needed. From this evaluation, it was observed that structures have enough strength to fulfil the requirements established by the 2004 building code; however, they do not have enough stiffness since interstory drifts were beyond the permissible limits. To comply with the current design criteria, a stiffness upgrading was proposed based on concentric braced tensors in both in-plane horizontal directions (retrofitted condition). For the retrofitted structures, IDA were performed employing the same 98 seismic records and damage indexes were re-computed for SDOF systems with the new characteristics. Fig. 5 show the vulnerability curves that define the expected damage of two reference retrofitted buildings to accomplish with 2004 building code, *i.e*. buildings designed with the 1977 and 1987 building codes.

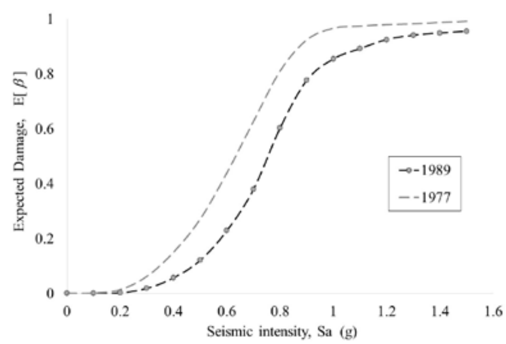


Fig. 5 – Vulnerability curves of retrofitted three-story buildings to accomplish with 2004 building code

5.3 Standard deviation of damage

To fully characterize in a probabilistic manner, the damage of the structures, the standard deviation of each vulnerability curve was computed directly for each intensity based on the dispersion given for each obtained curve as is observed in Fig. 4 (grey lines). The density of damage probabilities is considered Beta-type for each seismic considered intensity. Fig. 6 shows such vulnerability curves (continuous line) and its associated standard deviations (dashed line) for the original designed structures. Following the same procedure, Fig. 7 shows information for the retrofitted structures originally designed with 1977 and 1987 building codes for one story (1-ST), two stories (2-ST) and three stories (3-ST).

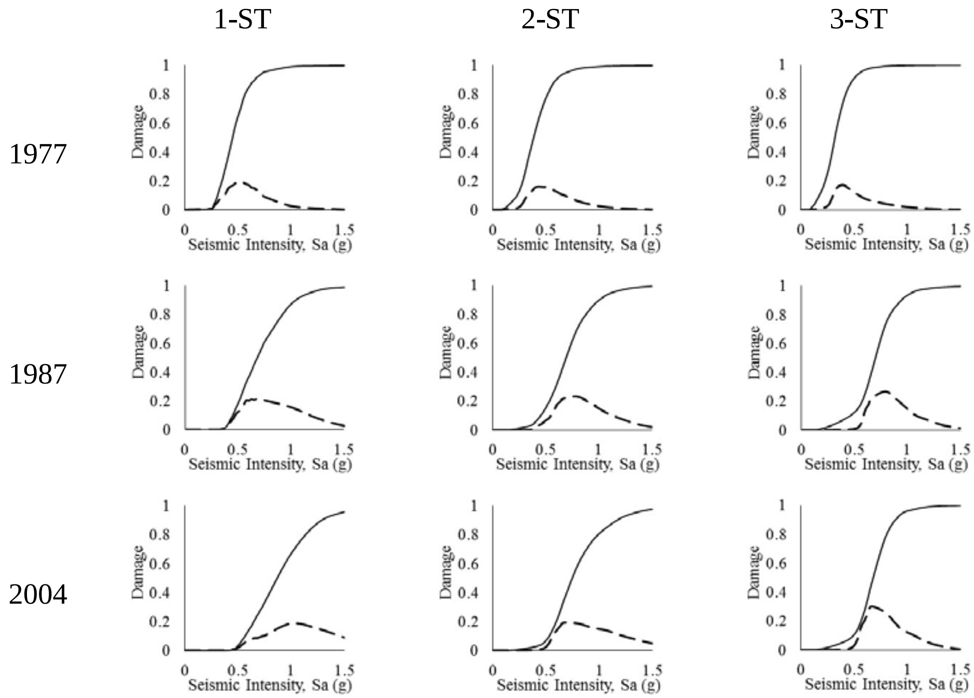


Fig. 6 – Vulnerability curves and its associated standard deviation for the different story structures and different Mexico City building codes for one story (1-ST), two stories (2-ST) and three stories (3-ST)

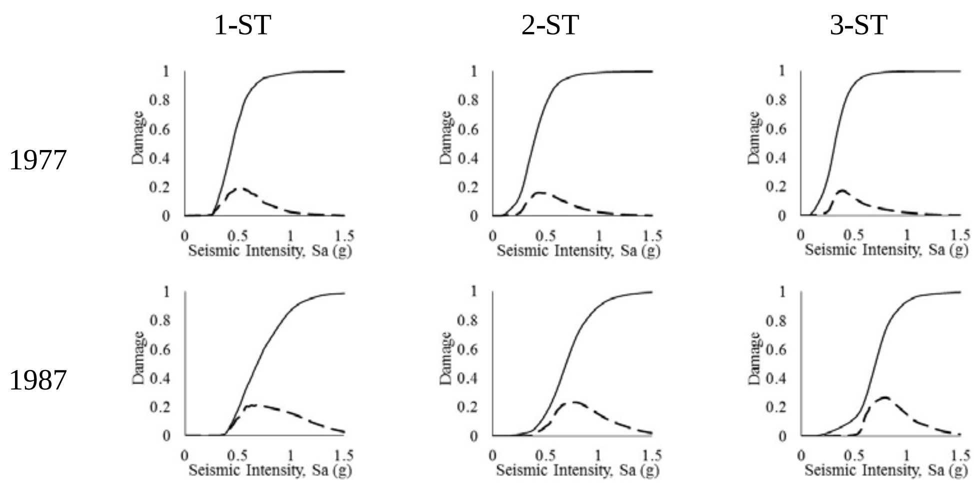


Fig. 7 – Vulnerability curves and its associated standard deviation for the different story structures designed with 1977 and 1987 building codes and retrofitted to accomplish with the 2004 Mexico City building code for one story (1-ST), two stories (2-ST) and three stories (3-ST)

6. Reconstruction cost

The costs of each structure, for both the original and retrofitted conditions, were computed through a unit price analysis. It is important to point out that only material and labour were considered in this analysis, using current prices in Mexico City. Based on these assumptions, the reconstruction costs calculated for each building are presented in Table 1. In order to consider the current reconstruction costs for the exposed assets database, declared values were updated to April 2016 by using National Index of Prices to Customers (INPC), published online by the Mexican Ministry of Finance (SHCP).

Table 1 – Reconstruction costs used [USD]

	Original condition			Retrofitted condition		Reconstruction condition
	1977	1987	2004	1977	1987	-
One-story school	83,669	86,490	87,304	84,486	87,169	87,304
Two-story school	90,393	125,350	127,203	93819	108,168	127,203
Three-story school	97,118	105,920	107,254	103,153	129,167	107,254

7. Risk assessment

Probabilistic risk analysis is a technique that allows dealing with the uncertainty of the occurrence of disasters and risk, which may be expressed in terms of known metrics such as annual expected average loss, maximum expected loss, losses for a given event, amongst others. In this paper, the cost-benefit analysis was carried out using as measure the first two parameters. The analysis was carried out considering two uncertainties 1) that one around the occurrence or non-occurrence of unknown seismic intensities (this uncertainty is included in the ground motion prediction equations used) and 2) the uncertainty of the size of losses given that specific event that has occurred. The second uncertainty, associated to the standard deviation of a vulnerability curve, is employed to take into account that identical events can cause different amount of losses, resulting in a range of possible values with different probabilities. Moreover, this uncertainty also reflects that structures with the same characteristics affected by the same event could have different loss.

7.1 Expected Annual Loss, *EAL*

Accepting that each hazard type is defined by *EN* events that are collectively exhaustive and mutually exclusive, the *EAL* for any hazard can be estimated with the following expression:

$$EAL = \sum_{i=1}^{EN} E\left(loss_i\right) P_A\left(i\right) \quad (6)$$

where $E(loss_i)$ is the expected loss that an event i causes to the exposed asset, and $P_A(i)$ is the annual occurrence probability of event i.

7.2 Probable Maximum Loss, *PML*

This indicator represents the loss that would be exceeded in a certain period, this parameter defines with precision, the total amount of expected losses and may be computed with the following expression

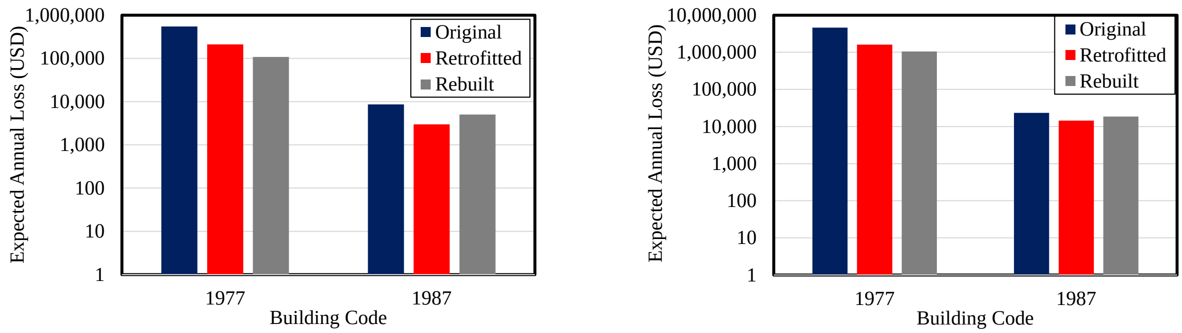
$$\nu\left(l\right) = \sum_{i=1}^{EN} \Pr\left(Loss > loss \middle| i\right) P_A\left(i\right) \quad (7)$$

where $\nu(loss)$ is the exceedance rate of an established *loss*, due the occurrence of the *i*-th event generating *Loss* weighted for the annual occurrence probability $P_A(i)$ of this event.

To compute the *EAL* required to define the proposed index, any of the many open access software tools to compute losses due to natural hazards that have been developed and distributed around the globe can be used. An example of this platforms is CAPRA [14], that computes losses based on a probabilistic approach.

8. Cost/Benefit analysis

The physical seismic risk for each structure (original and retrofitted) was evaluated via the mean of the convolution of the hazard with the vulnerability of the exposed elements. The results are the potential economic consequences expressed in terms of: (1) the *EAL* computed as the sum of the *EAL*s for all public schools in Mexico City and (2) the loss exceedance curve (LEC) which represent the annual frequency for which a loss of any specific monetary amount will be exceed. In this study, the *EAL* due to earthquake events is show in Fig. 8 for one-story (Fig. 8a) and two-story buildings (Fig. 8b). Notice that *EAL* values are of ~US$0.5 and 4.5 million dollars for one and two-story schools without retrofitting (original), respectively; *EAL* decrease to ~US$0.2 and 1.6 million for one and two-story schools with retrofitting, respectively; *EAL* decrease to US$0.1 and 1.0 million for one and two-story schools rebuilt, respectively.



a) b)

Fig. 8 – Expected annual loss obtained for schools of Mexico City of: a) one-story and b) two-story buildings

Figure 9 shows the LECs obtained for schools of Mexico City: original (black line, schools without retrofitting), retrofitted (red line, schools with a stiffness upgrading based on concentric braced tensors in both in-plane horizontal directions) and rebuilt (grey line, schools that would be demolished and rebuilt entirely). It is possible to observe that for annual frequencies larger than 0.01 the difference between schools without retrofitting (original) and schools retrofitted is significant. This implies that the best option is to retrofit schools for return periods lower than 100 years.

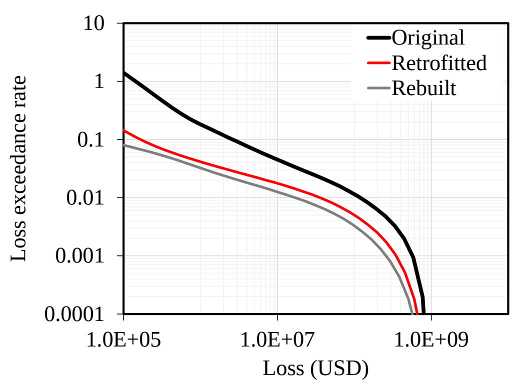


Fig. 9 – Loss exceedance rate obtained for schools of Mexico City

9. Conclusions

An approach to carry out a cost-benefit analysis to assess possible options such as retrofitting or reconstruction of structures focused on mitigation of direct physical losses due to seismic actions is presented. Given their particularly sensitive role in society, this methodology was employed to determine the best possible mitigation option for public schools located in Mexico City, using as measure parameters the expected annual loss (*EAL*) and probable maximum loss (*PML*). The typical reinforced concrete school buildings considered in this study were designed according to three versions of the Mexico City Building Code corresponding to the years 1977, 1987 and 2004. This type of analysis allows us to identify public schools at risk, assess the level of risk and optimize available resources for mitigation and emergency response. It was observed that those constructions designed according to 1977 building code should be reconstructed in order to minimize the expected losses. On the other hand, retrofitting actions are more suitable for structures designed with the 1987 building code.

10. Acknowledgements

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