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SEISMIC RISK ASSESSMENT OF PUBLIC SCHOOLS AND PRIORITIZATION STRATEGY FOR RISK MITIGATION

R. Rincón[1], L. Yamin[2], A. Becerra[3]

[1] *Research Engineer, Universidad de los Andes, Bogotá, Colombia, jr.rincon3391@uniandes.edu.co*
[2] *Associate Professor, Universidad de los Andes, Bogotá, Colombia, lyamin@uniandes.edu.co*
[3] *Research Assistant, Universidad de los Andes, Bogotá, Colombia, af.becerra617@uniandes.edu.co*

Abstract

Seismic vulnerability of schools buildings have been recognized as one critical aspect in recent earthquakes. The situation is more dramatic in developing countries in which self-construction is a common practice, low quality materials are commonly used and lack of control is very common, especially in geographically remote areas. Governments, non-governmental organizations and specialist communities are interested in improving earthquake school safety. Seismic risk mitigation programs are developed with the main objective of reducing the risk of death or injuries in the educational sector and improve the expected behavior of the infrastructure during earthquakes. Known difficulties for this purposes are the availability of information, the lack of reliable vulnerability assessment tools and the need of a relatively simple prioritization strategy once an intervention plan is defined. The poorly and unreliable information available for school buildings and the high uncertainties in the data collected aggravates the problem. The definition of a procedure to decide the optimum type of intervention according to the vulnerability assessment is also a problem for developing such programs.

This paper presents a methodological approach for the seismic risk mitigation in school infrastructure and the subsequent definition of the prioritization strategy for the implementation phase. Vulnerability assessment requires the definition and characterization of sets of buildings with similar seismic response in the entire school infrastructure portfolio. Probabilistic seismic risk assessment in terms of economic losses is used to quantify the annual expected losses for each school building and the entire portfolio. After this, the average annual loss (AAL) is defined as the main parameter for the prioritization criteria at school facility level. Total cost of intervention is calculated depending on the intervention type selected. Cumulative average annual loss curves (CAAL) are proposed for the definition of regional plans which permits the quantification of the target number of schools facilities for intervention activities depending on the availability of economic resources by regions. The definition of different implementation periods and the determination of the impact in terms of number of schools intervened, number of students benefitted and effective risk reduction at each stage of the program is possible according to this methodology. The applicability and effectiveness of the methodological proposal is validated through the case study of the school infrastructure in Lima-Peru.

Keywords: school safety, seismic risk reduction, average annual loss, intervention plan, prioritization strategy.

1. Introduction

The definition of structural school building typologies is one of the more relevant factors in order to evaluate the seismic response for improving the school earthquake safety. Different structural typologies are usually used for school buildings despite the high variability in architectural functional characteristics due to regional conditions. In developing countries, most common construction typologies are the adobe, unreinforced masonry, confined masonry and reinforced concrete frames system. For each structural type, the expected seismic performance can be defined and probabilistic losses can be estimated [1], [2], [3].

Commonly, the selection of the structural typologies for school buildings is based on the lowest construction cost possible, not recognizing the high vulnerability of the selected construction system. More complex variables are involved in the school buildings vulnerability assessment. Age of construction present the first approximation to the vulnerability as related to the seismic design code used for the design. It also permits the recognition of construction techniques and quality. Construction quality is another important variable associated with the person or company in charge of the construction. Usually, the construction of public school facilities is under the responsibility of individuals or groups which belong to government entities, non-government organizations, private enterprises, self-construction groups from the communities, and others. Depending on the builder, uncertainties should be estimated. Also geographical location imposes important uncertainties because it involves the experience acquire from past events, quality of materials and socio-economic characteristics of each particular region.

Behavior of school buildings in recent seismic events demonstrate the low seismic design level and the high vulnerability of this important structures. Recent events as the ones in Düzce (Mw7.2-1999) and Bingöl (Mw6.4-2003) earthquakes in Turkey [4], Nazca (Mw7.7-2001) earthquake in Perú [4], Molise (Mw5.9-2002) [5], Bam (Mw6.5-2003) earthquake in Iran [6], and others, demonstrate an inadequate seismic performance of public school buildings affecting the physical infrastructure and the safety of the occupants (see Fig. 1).

(a) (b)

Fig. 1 Vulnerability and deficiencies problems presented in school buildings during earthquakes: (a) Captive columns in schools in Perú (Figure 18 from reference [4]); (b) Adobe school totally collapsed in Iran (Figure 6a from reference [6]).

One common structural characteristic of school building that has been the cause of important damages is the well-known “captive columns” in reinforced concrete frames. Main reinforced concrete frames schools typologies located in seismically active countries have presented a shear failure of the columns before developing its full flexural capacity of members. Captive columns are developed by an inappropriately separation between infill walls and frame columns. Other structural typologies such as adobe or unreinforced masonry buildings have also evidenced structural capacity problems related with their deficiency to resist seismic forces, especially for out-of-plane seismic effects, generating partial or total collapse when subjected to high seismic forces.

High risk of physical damage to infrastructure and loss of lives or even personal injuries to the educative community need to be reduced. Educative infrastructure is require to remain in operational state for serving as shelter in case of earthquakes. Improving earthquake safety in public school buildings should be a principal objective in government plans. The need to develop methodologies for risk assessment and risk mitigation is a problem of public concern in order to implement this task. Determination of type of interventions and prioritization of the mitigation plans are the main difficulty during the implementation phase. This paper presents a consistent risk assessment and definition of prioritization criteria methodology towards the implementation of a risk reduction program for school facilities. A case study in which government, non-government organizations and academic researchers have been working together in order to define such risk mitigation strategy is presented for the case of Lima-Perú.

2. Risk assessment and intervention prioritization

2.1. Conceptual framework

Methodologies for proposing optimal intervention alternatives examines all relevant variables which can define the vulnerability and in this way the seismic risk of structural typologies. These will determine the actual vulnerability of each exposed asset and an optimal intervention can be proposed with the main objective of reducing the risk. Risk reduction is reached through strategic management of the financial resources available by the local, regional or national governments.

The geographical location of each building is a relevant variable. Seismic zones at country level are usually known at the present in most countries and they are related to geographical zones. Seismic code specifications are more demanding in high seismic zones generating a better expected seismic response in structural systems in those zones. This variable have to be considered of course in the vulnerability assessment process. Another important variable to consider is whether the construction is located in an urban or rural area. For example, in developing countries, rural areas are not totally under the supervision of government entities to guarantee the quality of construction. Similar structural typologies can have a significantly different behavior whether they are classified as urban or rural. An optimization plan needs to consider the vulnerability and its uncertainties depending on the geographical location.

Quality in construction is another relevant variable and usually depends on specific historical characteristics. Many factors affect the construction quality including the characteristics of the builder, the date of construction, the seismic code specifications used in the design phase and others. Better quality and good seismic performance is expected in schools built by government and private entities. The year of construction can usually be correlated to the seismic design level or seismic code specification. Older structures should be considered of course more vulnerable. Other important variables to consider in the vulnerability assessment are the number of stories, the span length, the existence of captive columns, the current building state and other. All these factors are determinant in the vulnerability characterization and therefore in the determination of the optimal type of intervention and the cost associated. In addition it has to be considered that the intervention cost depends on the intervention option selected and the geographical location of the school facility.

Countries advocating for risk mitigation plans have to organize and prioritize the intervention. Optimization of intervention plans should be prepared according to the financial resources available. Variables such as school facilities size in terms of constructed area, specific use of each building (classrooms, bathrooms, administration offices, kitchen, etc.) and human occupancy (students, teachers, staff, etc.) are recommended to determine the prioritization criteria. Regional mitigation plans are the final product of all this process. With them the government have the technical and practical information to proceed into the implementation phase of the programs. Regional mitigation plans shall include the prioritization strategy in terms of geographical location and structural typologies.

The intervention strategy depends on regional specific criteria and limitations. It is defined depending on available financial resources, time frame for the program and current government political interests. It is necessary to select the optimal intervention schemes in order to demonstrate relevant results in the short term and high impact in reducing risk.

In countries with low capacity of financial resources, the definition of specific programs with defined objectives is a requirement. Interventions such as demolition and total replacement of school facilities is usually a not benefit/cost option. Governments, specialists and academics are encouraged to investigate and incorporate innovative programs for these objectives. Disaggregation of intervention depending on the structural type, hazard zone, location, uses of the building and occupancy is one of the main contributions of the proposed methodology. In this way, school buildings characteristics are used to define the type of intervention which should consider a total replacement, integral reinforcement, incremental reinforcement, partial or total rehabilitation or maintenance intervention. School facilities characteristics are used to define the prioritization criteria considering the financial resources available.

2.2. Risk mitigation plan components

In order to estimate the regional plan for seismic risk mitigation in public schools the following components are defined:

- Assessment of financial gap: economic resources necessary for an intervention for fully compliance of the seismic code requirements. The definition of costs related to demolishing, total replacement and fully integral reinforcement are required.
- Seismic risk assessment for the entire portfolio of buildings: Average Annual Loss (AAL) is required for each building asset. AAL is the risk pure premium and represents the amount to be paid annually in order to cover future expected losses produced by the seismic hazard [1].
- Level of intervention required for optimized programs selected: in accordance with objectives of the selected plan, the costs for each type intervention shall be quantified.
- Prioritization criteria for school facilities: the prioritization criteria selected is the risk reduction by selecting the AAL for school facilities. The AAL of each school facility corresponds to the summation of AAL of all individual buildings included in each facility.
- Methodology for the implementation phase: definition of the schedule and reallocation of the amount for different implementation sub-programs.

3. Implementation of the methodology

In order to implement the above mentioned procedure to reach an intervention plan for risk mitigation, the following methodological approach is proposed.

3.1. Data Gathering

The information of school infrastructure in the region of study has to be collected for a complete characterization of the exposed assets. For this activity a group of specialist is requested to prepare a standardized form which allows the evaluation of the existing structures and the best methodology to fill the forms. Obtaining this information for a wide region requires a great effort and shall usually be accomplished by technicians and not by engineers.

The information needs to be collected for each building in order to define a structural typology and vulnerability for the risk assessment procedure. Typologies definition should consider the local knowledge in design and construction, quality of local materials, lessons learned from recent earthquakes and other characteristics; detailed assessment is not required for each building. Using the available information, the structural typology can be assigned through assignation algorithms. Many other parameters can be assigned using correlations based on statistics for school infrastructure, which take into account the economic development level of the country, the complexity of the urban or rural area, and other geographical factors already mentioned.

3.2. Evaluation of seismic vulnerability

Individual estimation of the seismic vulnerability of individual school buildings in extensive portfolios requires a great effort which is not usually compatible with the type of risk assessment that is required. Instead, approximation of the structural behavior by groups of buildings with similar structural system is recommended. Code level, number of stories, quality of construction and many singular characteristics as captive column presence or plan irregularities should be considered for the evaluation of seismic vulnerability.

Several methodologies have been proposed for conducting vulnerability assessment of buildings for different seismic intensities. Yamin et al. [2] presented an approach to estimate vulnerability functions for different building typologies based on fragility functions proposed in the Hazus project [3] or any other. Some methodologies, such as the one proposed by Yamin et al. [7] and Rosseto et al. [8] use response history analysis and/or displacement-based methods in order to obtain accurate vulnerability curves. Other methodologies presented by Yamin [9] and Hurtado [10], present the assessment of vulnerability based on the accumulation of losses for different seismic intensities. D'Ayala [11] presents the seismic vulnerability assessment of low/mid-rise buildings. Finally, Rincón [12] presented a complete methodology application of vulnerability assessment for reinforced concrete frames buildings. Any method can be conducted to obtain the vulnerability functions in the present methodology. For the case study, the Yamin et al. [2] methodology was used.

3.3. Risk assessment

The risk assessment methodology includes 3 main modules. The hazard assessment, the exposed assets identification and characterization and the vulnerability assessment for the selected typologies. Once the results of the risk assessment process are available, both the intervention options can be identified and the prioritization criteria can be defined. This information is the basis to define the implementation plan of the risk mitigation program. Fig. 2 presents a summary of the risk assessment activities in order to arrive to the objectives.

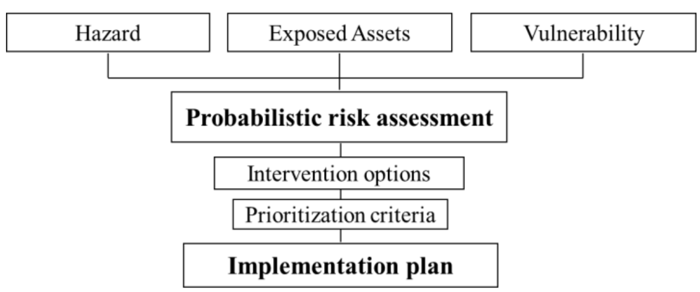


Fig. 2 Implementation of the methodology for risk mitigation programs

3.3.1. Hazard assessment

The seismic hazard is one of the most important components of risk assessment. A seismic intensity and its associated dispersion for different return periods is required. The analysis should include the important seismogenic sources into the region of study and the characterization of the magnitude recurrence of each source.

In this methodology, a probabilistic hazard assessment is developed for the zone of interest. The software CRISIS [13] is used in order to obtain the intensity parameter of interest in firm soil deposits. Spectral acceleration at the first structural vibration period (*Sa (T)*) is selected for the analysis as the main indicator of structural response. The result of this component is a Probabilistic Hazard Assessment (PHA).

3.3.2. Site effects determination

Soils softer than firm ground usually produce a significant amplification depending on the characteristics of the deposit including the depth to the basement, the geotechnical parameters (as shear velocity, *Vs*, soil density, γ, etc.) of each individual deposit and the dynamic response characteristics of the soil types. Site effects are quantified using the available information of the existing seismic microzonation studies in the region of interest.

When information of seismic microzonation does not exist, the soils of the zone of study has to be classified and the dynamic properties should be determined with simplified methodologies. Techniques to derive first-order site-condition maps directly from topographic data have been developed recently [14]. This techniques evaluate global seismic site conditions, through the average shear velocity to 30 m depth (Vs30). Determination of dynamic amplifications of soils can be obtained based on Vs30 [15].Even though several limitations should be considered when using this methodology, is acceptable to use it instead of developing risk assessment without site effects.

3.3.3. Exposed Assets Information

Schools facilities databases shall contain the main information required to define the seismic vulnerability of each asset, the total number of occupants and total replacement cost. Many parameters can be used in order to determine the structural system, the number of stories, the builder information, the age of construction, the plan area, the mean cost/replacement value of the study region, the number of students per square meter, the population of the region and others.

The seismic structural behavior of each school building should be related to a vulnerability classification. Also, the exposed value of each school building shall be evaluated to determine the cost of replacing the entire structure with a new building. This exposed value can be determined in terms of replacement cost, commercial cost, insured value, or any other costs of reference. For this methodology a unique value per square constructed meter can be assumed independently of structural type. The replacement cost can be assumed to vary as well with each particular geographic region depending on particular local conditions.

3.3.4. Vulnerability functions

Grouping structural typologies with a similar seismic response is required to evaluate the risk of portfolios conformed by a large number of exposed buildings. Selection of the vulnerability functions (from literature or evaluating the seismic performance for each typology) should be done with algorithms considering the main variables for determining the seismic structural response, quality in designs, quality in construction and proper vulnerability of the exposed building. The mentioned algorithms are generated for each project considering the data gathered.

3.3.5. Seismic Risk Assessment

Risk assessment is conducted with the main components of the building exposure database. The analysis consists in building by building probabilistic seismic risk assessment. Results are grouped by school facilities, for the entire portfolio and for geographical regions. The results of the probabilistic seismic risk assessment is given in terms of average annual loss (AAL).

3.4. Decision making for improving School Earthquake Safety

Government and private entities should decide how and when to intervene a school for seismic risk reduction. The risk assessment will provide the adequate tools for decision making processes. The risk assessment figures such as the AAL and the Probable Maximum Loss (PML) allows the categorization of risk in order to define the best option of intervention including replacement, reinforcement, retrofitting or maintenance. The type of intervention is defined considering the financial resources available and the interest of the government in risk reduction programs. Finally, the results of this methodology are the definition of the plan objectives depending on available financial resources, time frame for the program and current government political interests.

The optimal intervention is defined using benefit-cost relation for each building typology. First, different interventions options are selected. Each one of them are carefully evaluated in terms of engineering consideration in order to achieve in each case to the expected seismic behavior defined. For each option a detailed structural analysis is performed and an estimation of the cost of intervention is evaluated.

In order to establish the prioritization criteria individual school building intervention is not practical. Instead, the AAL parameter for each school facility is calculated and organized from the highest to the lowest. With this prioritization scheme the cumulative cost of intervention, number of students benefitted and the risk reduction effectiveness are determined. For a given amount of financial resources, the effectiveness of the reduction program can be defined in this way.

4. Case Study

The Research Center for Materials and Civil Works – CIMOC at Universidad de los Andes, Colombian has worked in 2014 for an advisory in Risk Assessment and Intervention Prioritization Program [16]. This initiative looks for alternatives to reduce the seismic risk in educational infrastructure in Lima, Peru.

Lima is located at the central Peru coast, which is considered a very active seismic region by its proximity to the subduction of the Nazca plate. This region has been repeatedly affected by large earthquakes beneath the South American plate. Recent studies [17] demonstrate the possibility of occurrence of megathrust earthquake, being a catastrophic scenario for schools. In this studies, simulated average pseudospectral accelerations are above 1.5g for wide areas in Lima for structural periods about 0.3 s.

The characteristic period of the majority of school buildings in Lima is about this 0.3 s. This is representative for low-mid rise buildings of reinforced concrete or masonry buildings. Lima's school buildings structural systems are typically represented by adobe, reinforced concrete frames and masonry building. Field work and local specialist knowledge [16] confirms the high vulnerability in the infrastructure.

4.1. Exposure information

The Census, CIE, was realized in 2013 by the MINEDU of Peru for the entire country. This census compiled information for the school facilities about general information, location, specifically information about structures, functional characteristics, number of students, etc. Although important information was collected, for example the structural system, the data gathering task was performed by non-engineers leading in incorrect data gathered in the structural chapter. Fig. 3 present an example of two buildings classified as "reinforced masonry" instead of "reinforced concrete frames" in the CIE structural evaluation. Other additional limitations in the CIE increase the uncertainty in the information.

Fig. 3 Example of buildings classified as "reinforced masonry" in the case study. Photos from [12].

4.2. Evaluation of seismic vulnerability

Data collected from structural response and damage presented in past earthquake events, knowledge from MINEDU's specialists, expert experience and field visits to the school facilities are the main input information for characterization of seismic vulnerability in Lima's school buildings. Self-construction is identified as one of the main problems in the evaluation of seismic vulnerability considering the high uncertainty on this practice. Lack of control and supervision in design and construction process is one of the main problems identified in this case study.

Evaluation of vulnerability, according to specialists, has been a participative activity which consider the experience in past earthquakes, revision of design codes and practices, compilation of recent field work in school facilities material characterization and interviews with local engineers who knows the main problems in the structural behavior of these structures.

4.3. Risk assessment

4.3.1. Hazard assessment

Peru is located in a very active seismic region and this is captured in high spectral accelerations obtained in the hazard assessment. Fig. 4 presents probabilistic seismic hazard maps for three return periods selected. Almost a 1 g of spectral acceleration is expected for mid-rise buildings (0.3 s period) in the city of Lima.

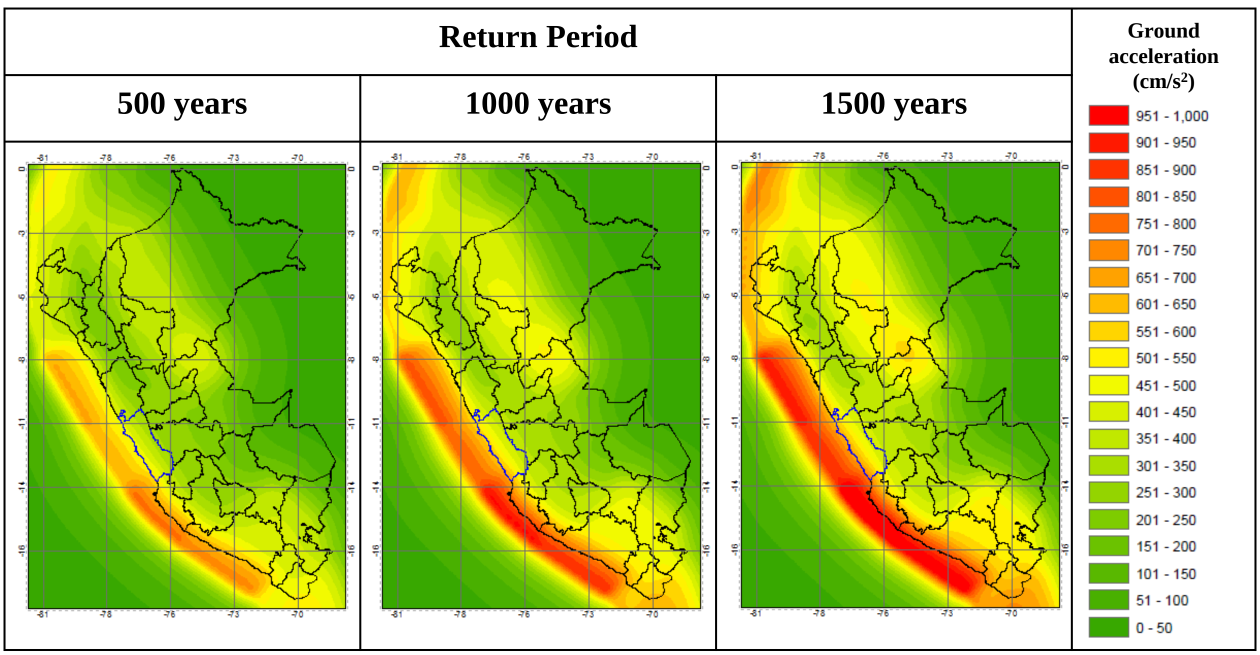


Fig. 4 Probabilistic Seismic Hazard maps obtained from the analysis for a structural period of 0.3 s.

4.3.2. Site effects

Fig. 5a presents the Vs30 map for the region of Lima. Determination of dynamic amplifications of soils are developed using 1-D propagation methodologies [18]. For this, template stratigraphic profiles are selected for the analysis. Amplification factors are obtained using representative seismic records according to the hazard assessment.

4.3.3. Exposed Assets Information

The Census, CIE, present a total of 20,445 public school buildings which conform a total of 2,910 school facilities in Lima. This buildings serve for 1.1 million of students and are represented geographically in Fig. 5b. According to CIE, the builders are conformed by national government, regional government, private entities, non-government organizations and self-construction groups. In Lima 12% of school buildings were constructed before 1977, 48% represent the buildings built during 1977 - 1998 and the remaining 40% were built after 1998. This dates represent the seismic code actualization times.

The main representative structural types defined for the exposure data are: adobe (A, 5%), unreinforced masonry (URM, 10%), precarious systems (P, 10%), temporary classrooms (TC, 3%), wood systems (W, 2%), steel structures (S, 0.5%), reinforced concrete systems design without supervision (RCF, 26%), and three categories of template reinforced concrete buildings constructed by government: before 1977 (B77, 0.5%), between 1977-1998 (PRE98, 26%) and posterior to 1998 (POST98, 17%). The seismic vulnerability curves for these typologies are shown in Fig. 6.

Replacement cost is assigned same for all the structural typologies defined. This assumption is made because this value represents the construction cost of a new seismic designed building.

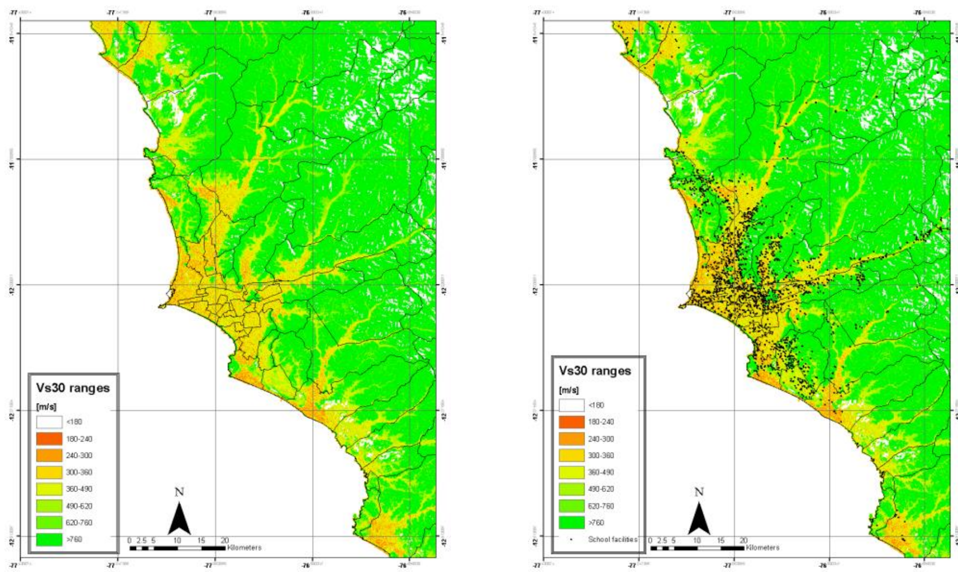


Fig. 5 a) Soil classification obtained with topographic correlations, b) School facilities located in Lima

4.3.4. Vulnerability functions selection

Fig. 6 present the vulnerability functions obtained for the seismic risk analysis. Methodology in reference [2] was used for these purpose.

4.3.5. Seismic Risk Assessment

Precarious, adobe and unreinforced systems represent the most vulnerable buildings. Nevertheless, economic losses are concentrated in the concrete reinforced systems. This means, reinforced concrete systems are moderate vulnerable system, for this case, and represent an important percentage of the portfolio. These characteristics represent an important percentage of the total physical value of the AAL. Vulnerable systems (high relative AAL, red bars) and the concentration of physical losses (high AAL, blue bars) are presented in Fig. 7.

4.4. Information required for decision making

Decision making is the final step in the methodology. Posterior to the risk assessment, types of intervention are selected according to the vulnerability and the expected losses evaluated by structural type. In this case study, demolition and construction of new buildings is recommended for most vulnerable systems (A, URM, P, W) and retrofit is recommended for moderate vulnerable systems (RCF, B77, PRE98). No intervention is the recommendation for buildings with low AAL. These types of intervention permits the optimization of the available investment amount for seismic risk reduction programs.

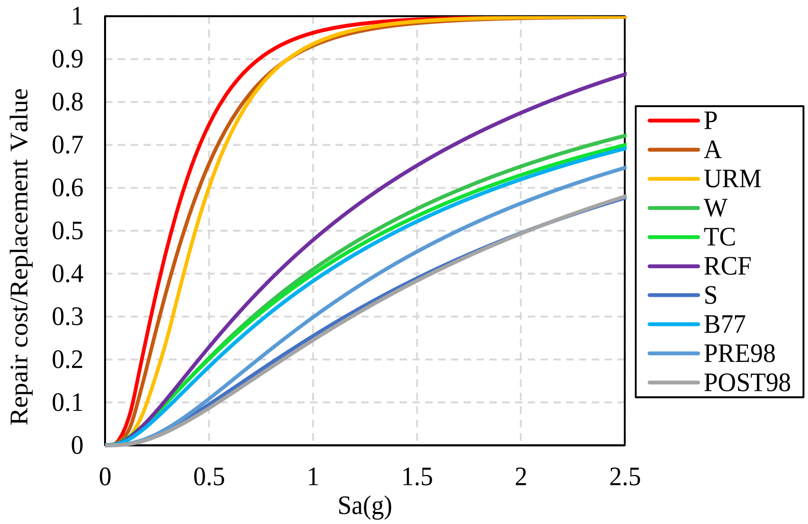


Fig. 6 Vulnerability curves for risk analysis [16]

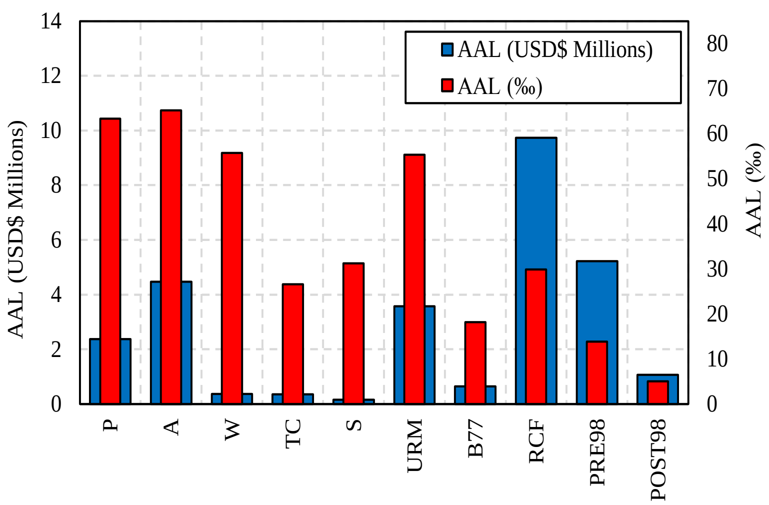
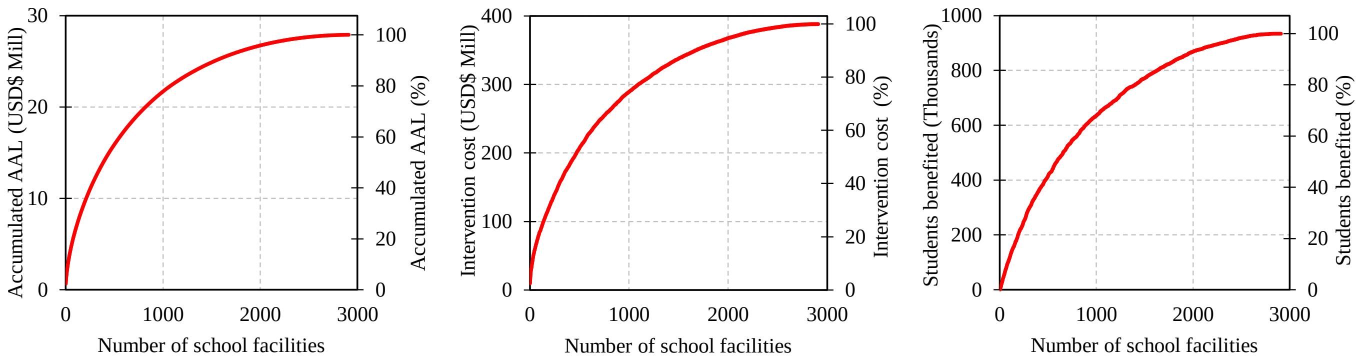


Fig. 7 Annual average loss per structural type

Fig. 8a presents the Cumulative Annual Average Loss (CAAL) curves for the study case portfolio. Fig. 8b and Fig. 8c present the intervention cost and the number of students which can be benefitted according to the financial resources. For preparation of this figures the AAL is calculated by school facility and organized from the highest to the lowest. Then, the AAL is added sequentially by each school facility. In the same order obtained, intervention cost and students in each school facility are cumulated to recognize the overall benefit in the program.

Use of this CAAL requires the definition of the investment amount for the plan. For example, assuming 300 USD$ Millions as available amount (Y-axis), Fig. 8b present a total of 1000 school facilities (X-axis) possible for intervention. This number of school facilities is used in Fig. 8a for calculating the accumulated AAL (22 USD$ Millions of expected losses) and is used in Fig. 8c for obtaining an approximately of 600,000 students benefitted.



a) b) c)

Fig. 8 – Cumulative Risk for Lima's schools facilities listed for AAL, in terms of a) Cumulative AAL, b) Cumulative cost of intervention and c) Cumulative students to be benefited

5. Discussion and conclusions

This paper presents a methodological approach for seismic risk mitigation in school infrastructure and the subsequent definition of the prioritization strategy for the implementation phase. Vulnerability assessment needs the definition and characterization of sets of buildings with similar seismic response in the entire school infrastructure portfolio. Probabilistic seismic risk assessment in terms of economic losses is used to quantify the annual expected losses for each school building, each school facility and for the complete portfolio. After this, the average annual loss (AAL) is defined as the main parameter for the prioritization criteria at school facility level. Optimization in reducing risk programs is reached by initiating the intervention in the most vulnerable school facilities (concentrated of economic losses). Programs of intervention should depend on the type of intervention selected for each structural typology.

Cumulative average annual loss curves (CAAL) are proposed for the definition of regional plans; these permit the quantification of the amount of possible number of schools facilities to be intervened according to total of available investment. Definition of different implementation stages will be possible according to this methodology. This plans derives in a total amount of reduced risk (quantifiable), a number of students, teachers and staff benefited and an optimized plan which do not have the demolition and reconstruction (most expensive decision) as the main alternative for risk reduction.

This methodology enhanced the effort of different interested groups in reducing seismic risk and school earthquake safety. Government can trace a clear route plan which allows it to fundraising for local and national plans. The applicability and effectiveness of the methodological proposal is validated through the case study of the school infrastructure in Lima-Peru.

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