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SEISMIC VULNERABILITY OF SCHOOL BUILDINGS IN LIMA, PERU

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SUMMARY

An assessment of the seismic vulnerability of all school buildings located in the districts of Chorrillos and Barranco, Lima, the capital city of Peru, was conducted using a methodology that includes a visual inspection of the structures, an estimation of their expected earthquake behavior, and school population. A total of 28 schools were evaluated in Barranco and 80 in Chorrillos, encompassing all kindergarten, primary, and secondary schools. Four degrees of seismic vulnerability are proposed as a combination of the expected earthquake behavior and school population. Even some new schools are high vulnerable.

INTRODUCTION

Lima, the capital city of Peru, is located in the Circum Pacific Rim where more than 80% of the world seismic activity occurs (Fig. 1). This activity is mainly generated by the interaction of the South American Plate and the subducting Nazca Plate. Along the Peruvian coast, earthquakes as powerful as XI on the Modified Mercalli scale have been observed in the past, Alva [1]. Past earthquakes in 1940, 1966, 1970, and 1974 have caused significant damage to Lima, particularly in localized areas such as La Molina, Callao, La Punta, Chorrillos and Barranco, Alva [2].

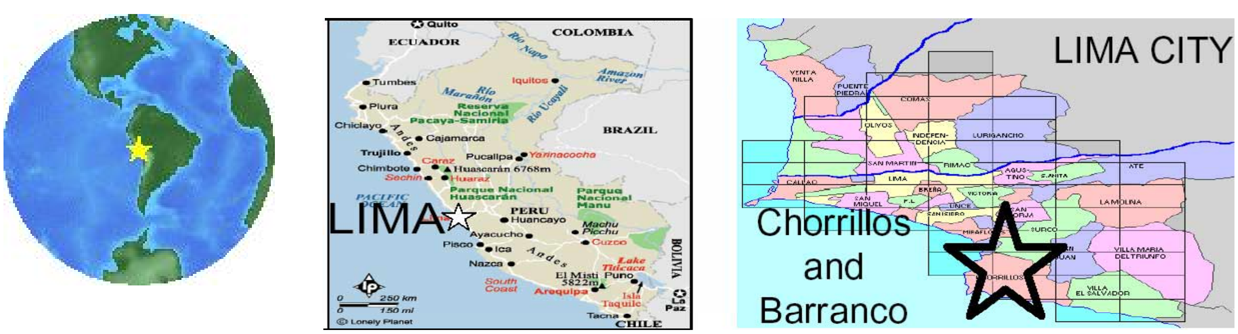

Fig. 1 Location of Peru, Lima, and Chorrillos and Barranco

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Recent earthquakes in Peru have revealed a high vulnerability of buildings and infrastructure, including school buildings. During the 1996 Nazca earthquake, even new school buildings were seriously damaged. As a result of this experience, a new earthquake-resistant design code was issued in 1997, which is more demanding than the former 1977 code. The seismic performance of school buildings compliant with the new code, made of concrete frames with unreinforced masonry infill walls (quite popular in urban areas of Peru), was successfully tested during the 2001 Arequipa earthquake. In this event, these structures did not present damage at all even though they where located in cities such as Moquegua, where the observed maximum seismic intensity was VIII on the Modified Mercalli scale, and where other similar structures designed and built with the 1977 code were severely damaged (Fig. 2).

Fig. 2 Different seismic performances of two school buildings during the 2001 Arequipa Earthquake. Left: School designed with the 1977 Code (see damage). Right: School designed with the 1997 code (no damage), Bariola [3]

Most school buildings do not meet the seismic requirements stated by the new earthquake-resistant design code, therefore, their seismic vulnerability need to be evaluated in order to develop earthquake risk mitigation measures. Since no method to evaluate the seismic vulnerability of a large number of structures has yet been developed in Peru, it is proposed in this study a methodology that includes a visual assessment of the structures, and an estimation of the expected earthquake behavior of the buildings. This visual evaluation is based on the Rapid Visual Screening of Buildings for Potential Seismic Hazards of the Applied Technology Council, ATC-21 [4], and the expected behavior is judged following the guidelines of the European Macroseismic Scale 1998, EMS [5].

As a pilot project the assessment of the seismic vulnerability of all school buildings located in Chorrillos and Barranco Districts in Lima, the capital city of Peru, was conducted using this methodology. These two districts out of the 43 existing in Lima were chosen for this study due to their: 1) large population, 2) large number of traditional buildings, and 3) high seismic intensities observed during past earthquakes. A total of 28 schools were evaluated in Barranco and 80 in Chorrillos, encompassing all kindergarten, primary, and secondary school buildings available in these two districts. This paper reports the main findings of the survey and proposes levels of seismic vulnerability for the surveyed school buildings.

METHODOLOGY

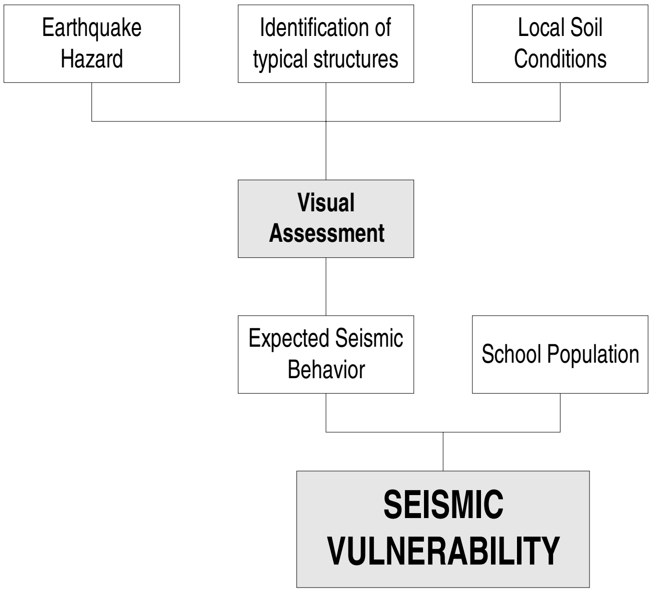


Fig. 3 Methodology for assessing seismic vulnerability

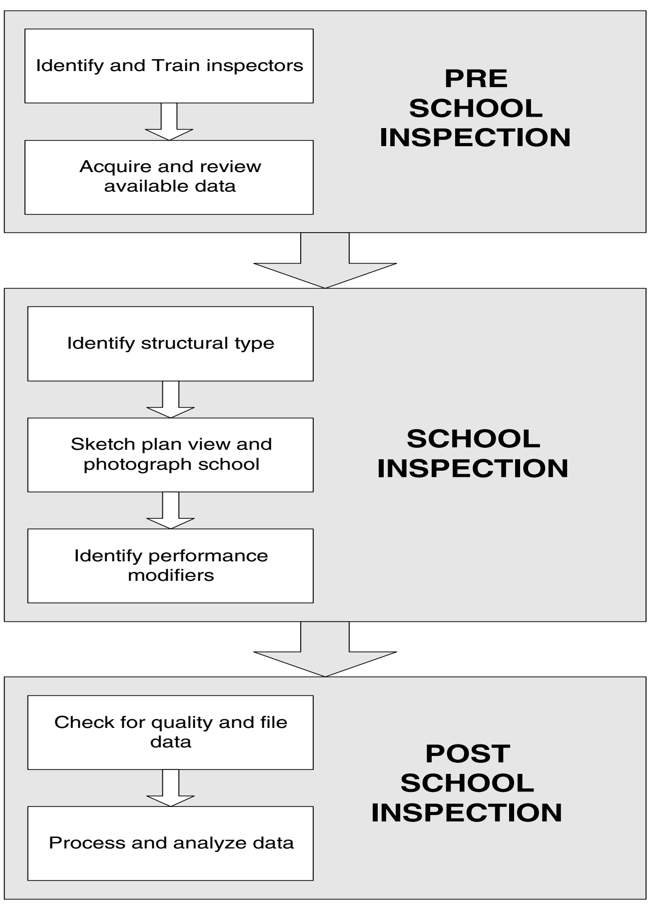


Fig. 4 Stages of the visual inspection

The methodology for the visual assessment of the seismic vulnerability of school buildings is schematically presented in Figures 3 and 4. This methodology intends to be suitable particularly for conditions where economic resources are scarce, the stock of school buildings is large, and establishment of intervention priorities is relatively urgent for implementation of earthquake risk mitigation actions.

Once a particular geographic area has been identified, earthquake hazard, local soil conditions and typical structures of the school buildings need to be identified and described. Evaluation of earthquake hazard includes identification of all possible sources of seismic activity and their potential for generating future strong ground motions. Earthquake sources may also be identified from records of historical (pre-instrumental) seismicity.

Once the earthquake hazard has been evaluated, information on local soil conditions has to be collected. Influence of local geological and soil conditions on the intensity of ground shaking and earthquake damage has been recognized for many years. Local site conditions profoundly influence amplitude, frequency content, and duration of strong ground motions. Schools located on sites where amplification of ground motions is very likely will be adversely affected in their seismic performance.

Identification of typical structures of the school building stock in the surveyed area should be based on a classification of the buildings according to their horizontal-force resisting system. Even for large school buildings stocks the number of building types to be considered in the assessment is small. Local construction and design practices, quality and description of typical construction materials, and observed past earthquake damage should be documented.

Assessment of the school buildings can be visually conducted from the exterior to accomplish two essential tasks: 1) identify the structural horizontal-force resisting system; and 2) identify features that can harm an acceptable seismic performance of the structure. This visual assessment is conducted aided by a form that has to be filled by trained inspectors. Figure 4 shows the stages of the visual procedure. The form collects information on building type identification, size, number and shifts of students, and attributes that modify seismic performance. Also a sketch of the general plan view should be included. Photos of the buildings from different sides and angles, of spotted structural attributes, and of features that illustrate the structural type should be taken. This photographic information will allow a later study of the buildings without returning to the school site.

Once the in-situ visual assessment of the buildings is conducted, the expected seismic behavior is estimated for each of the surveyed buildings. This estimation is guided by the European Macroseismic Scale 1998, EMS [5]. According to this scale "if two groups of buildings are subjected to exactly the same earthquake shaking, and one group performs better than the other, then … it can be stated that the buildings that were less damaged are more earthquake-resistant, and vice versa." The EMS includes six classes of decreasing *vulnerability* (A, B, C, D, E, and F). The first three classes A, B, and C represent the most *vulnerable* building types; and classes D and E represent building types with reduced *vulnerability*. Within the context of this methodology these classes express the expected seismic behavior; classes A, B, and C are expected to have poor seismic behavior, and classes D and E better behavior. Judgment should be used in assigning the expected seismic behavior to the school building types considering the identified structural features.

Number of students in the schools is critical information for the assessment of their seismic vulnerability. Overpopulated schools complicate implementation of earthquake preparedness actions. Proper evacuation of the school without risking the lives of students and teachers becomes more challenging and difficult to manage as the number of students increase. Also as the number of students increase, there are more demands to the building such as wider access stairs, aisles and escape routes. Most of the times these required changes are not performed and increase the vulnerability of schools. In addition overpopulation implies increase of the design live loads of the structure, and if this has not be taken into account in the structural design (that is most of the cases), the structure can be adversely affected even without the occurrence of an earthquake.

The expected seismic performance of the building and the number of students are combined and the seismic vulnerability for the school is established. Different degrees of seismic vulnerability are defined by cross-correlating ranges of school population with the classes of expected seismic behavior of the building. For two buildings with the same expected seismic performance, the one with the larger population would be more vulnerable than the one with lower population. And for schools with the same number of students, the one with poorer expected seismic behavior would be more vulnerable than the one with better expected seismic behavior.

Local expert knowledge provides valuable information on earthquake hazard (geologic and tectonic settings, fault activity, historical and instrumental seismicity), local soil conditions, and identification of typical structures. Also local expertise and experience is essential for judging the expected seismic behaviors and for establishing the degrees of vulnerability. The assessment of different degrees of vulnerability set the basis for the establishment of priorities for structural intervention. This intervention should not be limited to structural retrofitting or strengthening but total or partial replacement of the building, or change of use of the building.

LOCAL SOIL CONDITIONS AND GEOTECHNICAL SETTING

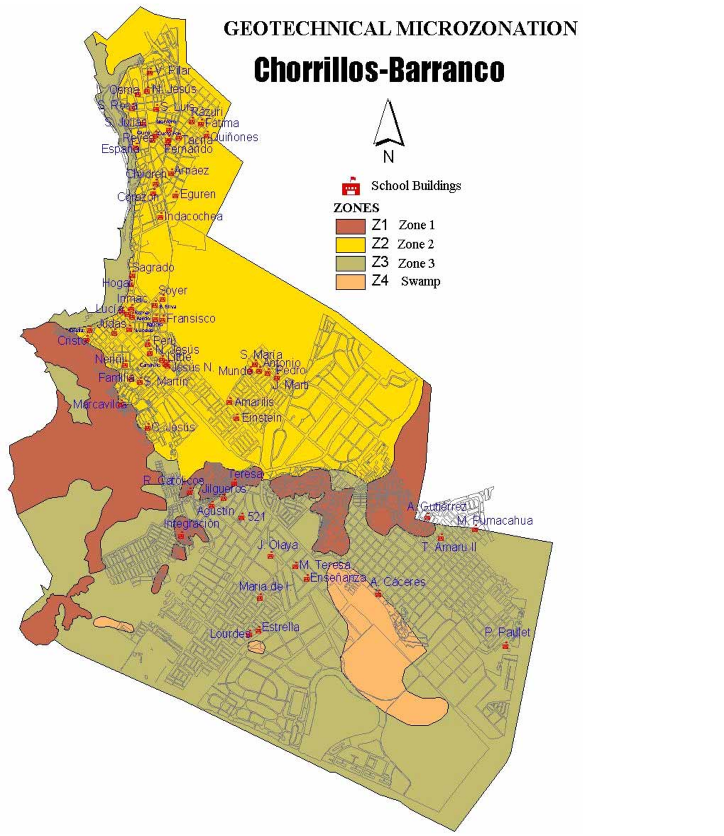


Fig. 5 Geotechnical Setting of Chorrillos and Barranco

Since local soil conditions are also Performance Modification Factors in the methodology, geotechnical information was gathered before starting the survey. Ayquipa [6] identified four geotechnical zones in a seismic microzonation study of Chorrillos and Barranco. The location of school buildings and corresponding geotechnical zones are shown in Fig. 5. Unlike most of the areas in Lima City that rest on a rigid, compacted gravel with predominant periods smaller than 0.1s (Alva [2]), Chorrillos and Barranco lay on soft soils and swamps. Fig. 5 shows that school buildings have been constructed on these soil deposits. Higher seismic intensities and severe structural damage observed in past earthquakes have been attributed to these particular local soil conditions. Description of each identified geotechnical zone is provided below.

Zone 1 (Z1)
It is a limited area located around the outcropping rock of *El Morro Solar* in Chorrillos district. The soil profile is composed by layers of poorly graded sand, clayey sand and silty sand with lens of clay. At an average depth of 2.00 m, a layer of medium dense gravel with silty sand matrix is found. The natural vibration periods, determined by microtremor or ambient vibration measurements, range from 0.08s to 0.25s. Due to topographical conditions, few school buildings are found in this zone.

Zone 2 (Z2)
It mostly covers the Barranco district and the northern part of Chorrillos district. Soil profiles randomly show mixed layers of sand, clay and silt, with different thickness. Underlying these materials at depths ranging from 2.0 to 8.0 m, a layer of gravel is found. Predominant natural vibration periods range from 0.25s to 0.40s. The ground water level ranges from 20.0 to 30.0 m in depth. Most school buildings are built in this zone.

Zone 3 (Z3)
It expands from the southern to the southwestern sectors of Chorrillos District. Soil profiles present clayey silt and silty clay layers of variable thickness. Layers of organic silt and clay appear at depths from 0.50 m to 1.70 m, with high water content and thickness of 2.00 m. Underlying these materials there are fine sands and silt with high organic content reaching depths of 5.0 to 7.5 m, where alluvial gravel is found. The ground water table depth ranges from 1.0 to 3.5 m. This zone also includes the beach area, composed by clean, loose and saturated sand. Predominant natural vibration periods range from 0.4s to 0.5s.

Zone 4 (Z4)
It includes a relatively small area located in the southern part of Chorrillos District. It is formed by marshy ground named "*Pantanos de Villa*." Soil profiles consist of a thin layer of clayey silt followed by a black to yellowish green peat with fetid odor. From 6.0 to 7.0 m in depth, there is a layer of compact sand with lens of peat. Ponds in the marshy area appear as a result of a shallow ground water level. The natural vibration periods in this zone are larger than 0.5s.

IDENTIFIED SCHOOL BUILDING TYPES

Five school building types are identified in Chorrillos and Barranco Districts. They include concrete frames with unreinforced brick masonry infill walls (C3), confined brick masonry (CM), unreinforced masonry (URM), adobe (ADB) and wooden (W) structures. A typical C3 structure consists of moment resistant concrete frames in the longitudinal direction and concrete frames with unreinforced masonry infill walls in the transversal direction. A CM structural type consists of oven-dried clay brick bearing walls confined by caste-in-place concrete columns and beams, which are conveniently distributed to increase the structure ductility. These elements slightly contribute to the structure bearing resistance. Figure 6 shows typical C3 and CM school buildings.

Fig. 6 "Virgen del Pilar" School (C3), and "Mi Peru" School (CM)

URM structures are those with clay brick bearing walls with no concrete columns confinement at all, or if they exist, they are so widely separated that do not contribute to the structure ductility. Adobe (ADB) buildings are walls made of sun dried earth bricks and jointed by mud mortar. Unreinforced ADB structures have shown in the past poor seismic performance, and therefore a poor seismic behavior is expected from these structures. Typically for a two-story building, the first story is made of adobe walls and the second story of "quincha." Traditional quincha buildings have wood plank frames infilled with smaller wooden planks and/or bamboo interwoven to make a matrix which is then plastered with one or more layers of mud or gypsum. W structures are traditional quincha structures. Figure 7 shows photos of typical URM, ADB and W school buildings.

Adobe and wood structures were constructed at the beginning of the last century; as seen in Fig. 7, it is apparent their deterioration due to aging and lack of maintenance. Some of these buildings have changed their use from classrooms into administrative office, reducing drastically the level of occupancy, and therefore their vulnerability.

Fig. 7 From left to right: "San Luis" School (URM); "San Fernando" School (ADB); and "San Julian" School (W)

Figure 8 shows the composition of the school buildings stock according to building types: 60% are C3, 32% CM, 3% URM and W respectively, and 2% ADB structures. C3 and CM structures comprise 92% of the school building stock. Figure 9 shows the distribution of school buildings according to the local soil conditions. Seventy-one percent of the school buildings are founded on soil type S2 which corresponds to zone 2 (Fig. 5), where soil conditions present adequately earthquake behavior. Twenty-two percent are founded on soil type S3 (zone 3, Fig. 5), where soil conditions are not seismically favorable. Just seven percent of school buildings are located on soil type S1 (zone 1, Fig. 5).

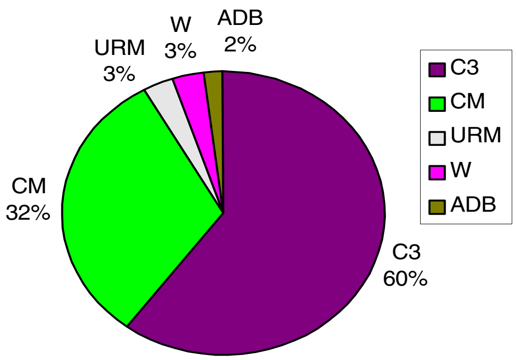


Fig. 8 School building types in Barranco and Chorrillos

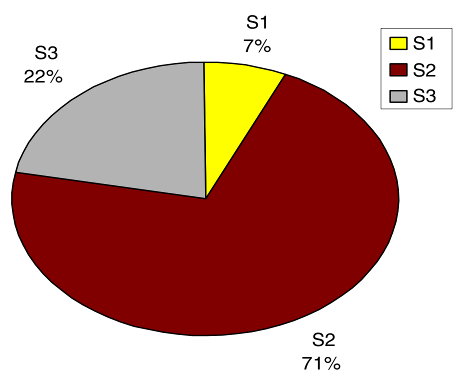
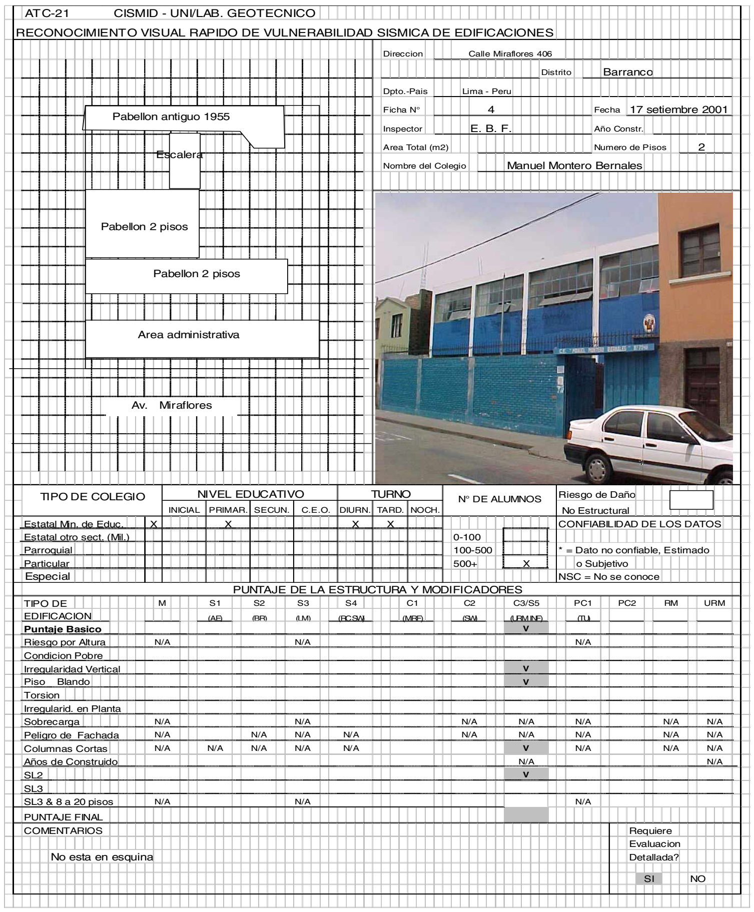


Fig. 9 Distribution of School Buildings by local soil conditions

VISUAL ASSESSMENT

Visual assessment of buildings to estimate their expected seismic performance is the most suitable approach when dealing with a large stock of buildings, economic resources are scarce, and there is urgency for implementing earthquake risk mitigation measures. By visually inspecting a building and identifying certain structural features, its expected seismic behavior can be reasonably predicted. Analysis of structural seismic vulnerability would require information of the structure that often is not available or does not exist. On the other hand, analysis would demand much more time and funding, and would be almost impractical to apply it to a large number of buildings. Implementation of the method needs a short training of the inspectors (who are not necessarily civil engineers or architects), and not much equipment but a digital camera.

Since no visual method has yet been developed in Peru for assessing seismic vulnerability of buildings, the method and data collection form developed by ATC-21 [4] were used. The data collection form includes besides the identification of the basic structure type, performance modification factors such as poor condition, vertical irregularity, soft story, torsion, plan irregularity, pounding, short columns, and soil types S1, S2, and S3 (Fig. 10). These structural features are assumed to affect the expected seismic performance of the buildings. The basic scores and its modifiers were not considered since they are not representative of Peruvian buildings.


ATC-21 CISMID - UNI/LAB. GEOTECNICO

RECONOCIMIENTO VISUAL RAPIDO DE VULNERABILIDAD SISMICA DE EDIFICACIONES

Direccion: Calle Miraflores 406
Distrito: Barranco
Dpto.-Pais: Lima - Peru
Ficha N°: 4
Fecha: 17 setiembre 2001
Inspector: E. B. F.
Año Constr.:
Area Total (m2):
Numero de Pisos: 2
Nombre del Colegio: Manuel Montero Bernales

TIPO DE COLEGIO		NIVEL EDUCATIVO: INICIAL	PRIMAR.	SECUN.	C.E.O.	TURNO: DIURN.	TARD.	NOCH.
Estatal Min. de Educ.	X		X			X	X	
Estatal otro sect. (Mil.)								
Parroquial								
Particular								
Especial								

N° DE ALUMNOS	
0-100	
100-500	
500+	X

Riesgo de Daño No Estructural

CONFIABILIDAD DE LOS DATOS
* = Dato no confiable, Estimado o Subjetivo
NSC = No se conoce

PUNTAJE DE LA ESTRUCTURA Y MODIFICADORES

TIPO DE EDIFICACION	M	S1 (AE)	S2 (BR)	S3 (LM)	S4 (RC SW)	C1 (MRF)	C2 (SW)	C3/S5 (URM INF)	PC1 (TU)	PC2	RM	URM
Puntaje Basico								V				
Riesgo por Altura	N/A			N/A					N/A			
Condicion Pobre												
Irregularidad Vertical								V				
Piso Blando								V				
Torsion												
Irregularid. en Planta												
Sobrecarga	N/A			N/A			N/A	N/A	N/A		N/A	N/A
Peligro de Fachada	N/A		N/A	N/A	N/A		N/A	N/A	N/A		N/A	N/A
Columnas Cortas	N/A	N/A	N/A	N/A	N/A			V	N/A		N/A	N/A
Años de Construido								N/A				N/A
SL2								V				
SL3												
SL3 & 8 a 20 pisos	N/A			N/A					N/A			
PUNTAJE FINAL												

COMENTARIOS
No esta en esquina

Requiere Evaluacion Detallada? SI NO

Fig. 10 Data Collection Form (Adapted from ATC-21 [4])

Since 92% of the school building stock is composed by C3 and CM structures, results of the visual assessment only for these two building types will be presented.

C3 buildings

Figure 11 summarizes the findings of the visual assessment. Short columns, poor soil condition and plan irregularity are the most frequent features that adversely affect an acceptable seismic performance.

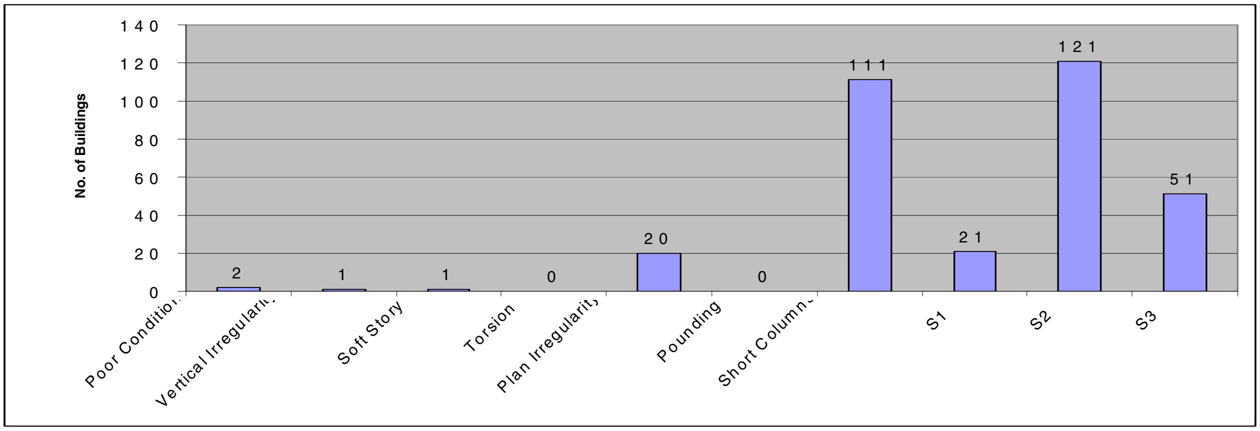


Fig. 11 Frequency of performance modification factors for C3 buildings

Short column is the major problem in these buildings (Fig. 12), this is true not only for existing structures but for new buildings being constructed without technical assistance. Figure 12 (left) shows a school under construction and encircled a short column.

Fig. 12 Short Columns in several C3 Buildings

CM Buildings

Figure 13 condenses the results of the visual assessment. Poor soil conditions and plan irregularity are the most common features harming an acceptable seismic behavior.

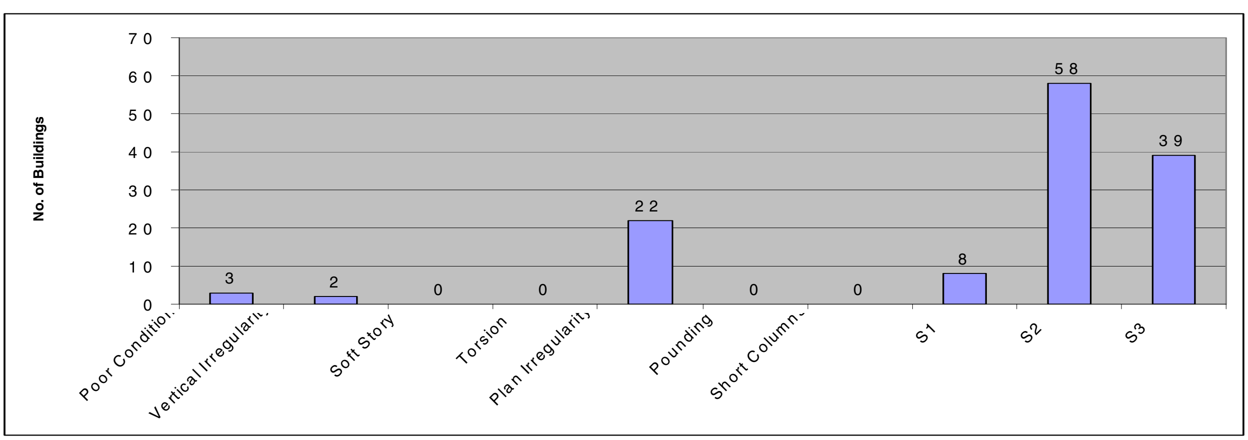


Fig. 13 Frequency of performance modification factors for CM buildings

EXPECTED SEISMIC BEHAVIOR

The guidelines provided by EMS [5] have been followed. These guidelines include five classes of structural vulnerability in decreasing order of vulnerability, from class A to F. Expected behavior A corresponds to adobe masonry or rubble stone masonry (poorest expected behavior); in the other end, class F corresponds to a structure with a high level of earthquake-resistant design (best expected behavior). The expected seismic behavior has been estimated from the results of the visual assessment considering the building type, performance modification factors, and past earthquake damage patterns. Thus expected seismic behavior for C3 and CM buildings ranges from C to D, depending upon the influence of the performance modification factors. Figure 14 shows that 58% of C3 school buildings are grouped into class C; and 15% into class D. Almost one fourth of the C3 buildings are estimated to be included into class E. For CM structures (Fig. 15), 43% are classified as E, 33% as D, and 24% as C. It is very likely that the amount of buildings for class E could be decreased if structural features such as wall density and adequate distribution of confinement elements had been introduced to the data collection form. Since the visual assessment was conducted from the exterior, these features could not be captured.

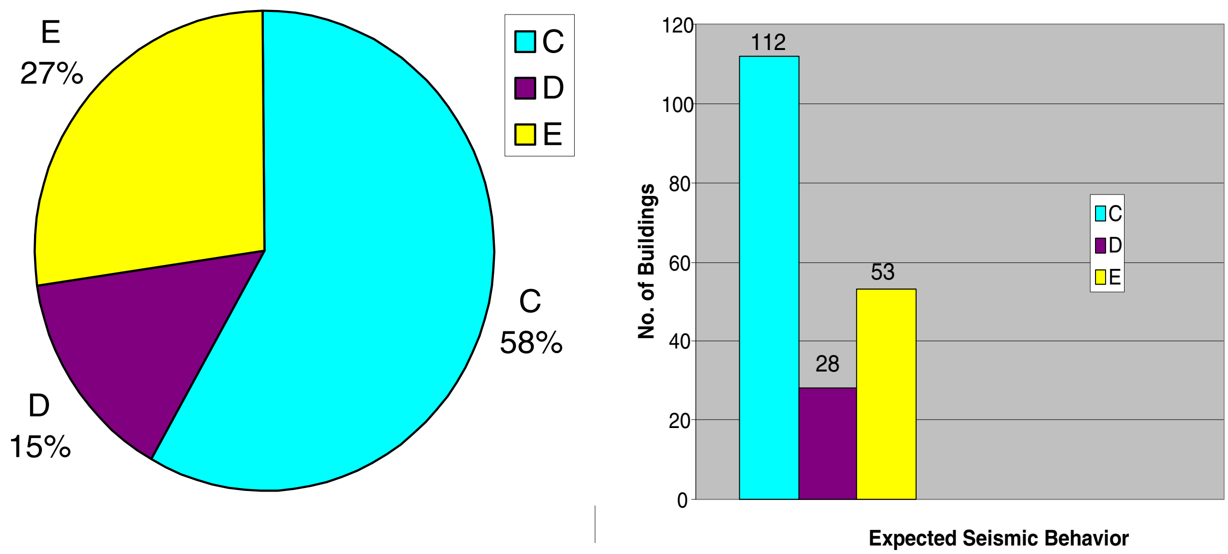


Fig. 14 Expected earthquake behavior for C3 buildings

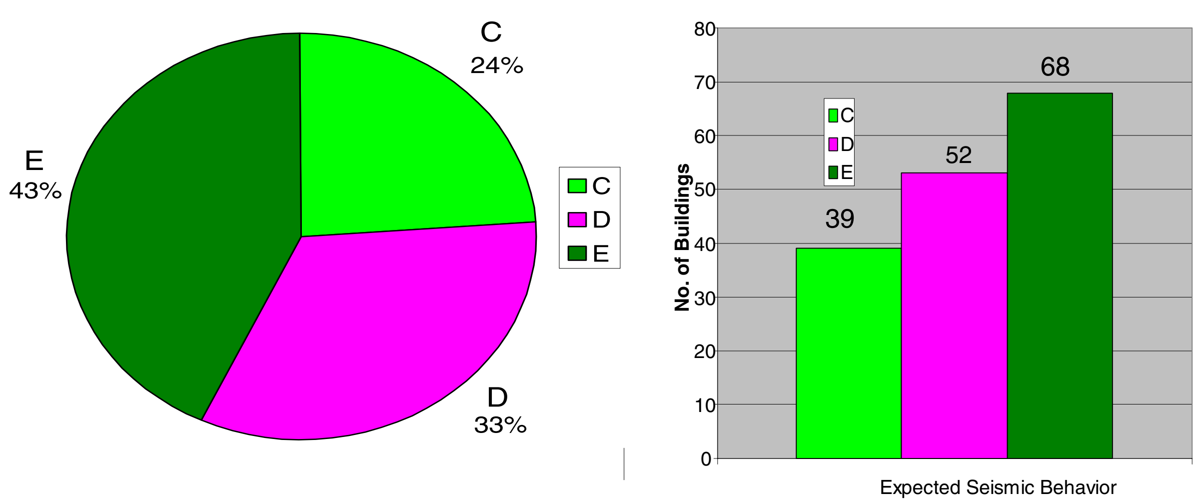


Fig. 15 Expected earthquake behavior for CM buildings

SCHOOL POPULATION

A total of 108 schools were evaluated in Barranco and Chorrillos. Several of them were composed by different buildings built in different years. Figure 16 and 17 show the number of schools (and percents) for three ranges of school population; i.e., greater than 500, between 100 and 500; and, less than 100. It is remarkable to see large school populations which imply overpopulation, and high occupancy density. For Chorrillos and Barranco the population distribution is practically identical.

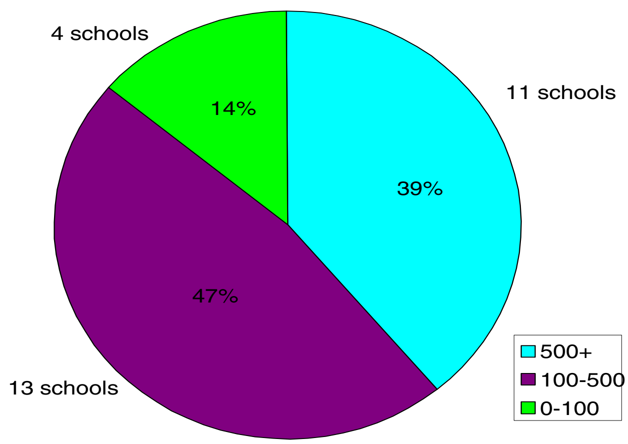


Fig. 16 School population for Barranco

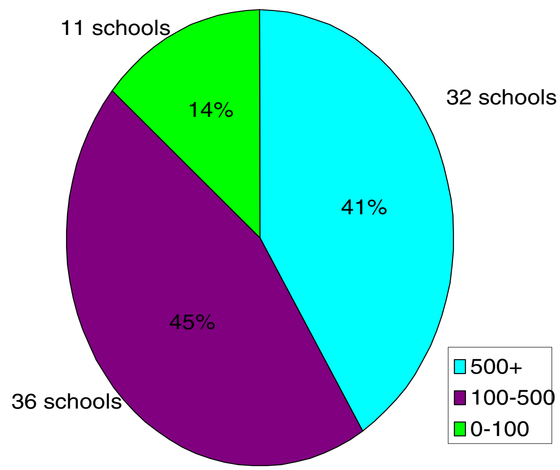


Fig. 17 School population for Chorrillos

SEISMIC VULNERABILITY

The seismic vulnerability of the school buildings is established after cross-correlating school population and expected seismic behavior. Table 1 shows four different degrees of vulnerability for C3 and CM structures (these structures are not only the most common in these two surveyed districts but all over the country). Thirty-five percent of the school buildings are regarded as very high vulnerable (VH), eighteen percent as high vulnerable (H), thirty-two percent as medium vulnerable (M), and fifteen-percent as low vulnerable (L). These degrees of vulnerability are the basis for establishing priorities for designing and implementing structural intervention, and earthquake risk mitigation actions.

Table 1. Seismic Vulnerability for C3 and CM school buildings

	School Population		
Expected Seismic Behavior	0 – 100	100 – 500	> 500
E	5% (L)	8% (L)	15% (M)
D	2% (L)	4% (M)	10% (H)
C	13% (M)	8% (H)	35% (VH)

Degree of Vulnerability	Very High	High	Medium	Low
	VH	H	M	L
Percent of school buildings	35%	18%	32%	15%

CONCLUSIONS AND RECOMMENDATIONS

A seismic vulnerability assessment methodology of school buildings is proposed and applied to two districts of Lima, the capital city of Peru. The methodology includes a visual evaluation of the structure, estimation of expected earthquake structural behavior and school population. The methodology has been capable of capturing basic features of the buildings for a rapid, reliable, and economical assessment of seismic vulnerability.

Two types of structures have been identified as the most popular, i.e., concrete frames with unreinforced masonry infill walls (C3), and confined oven-dried brick masonry (CM). Salient detected performance modification factors for these structures were short columns and plan irregularity respectively. However the data collection form was incapable of identifying factors such as wall density and spacing of confining elements. Unreinforced masonry and reinforced masonry are not commonly used for school buildings. Most of the few adobe and wood structures are old and in poor condition.

Cross-correlation of expected structural earthquake behavior and school populations defined different degrees of vulnerability for C3 and CM structures. This sets the basis for the establishment of priorities for the development and implementation of earthquake risk mitigation actions in the school system.

Given the advantages of the proposed methodology it is recommended to develop a standard visual approach that captures structural features of the typical school structures in Peru.

ACKNOWLEDGEMENTS

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