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SEISMIC VULNERABILITY OF INFORMAL CONSTRUCCION DWELLINGS IN LIMA, PERU: PRELIMINARY DIAGNOSIS

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ABSTRACT

This paper describes a study of the structural characteristics and the seismic vulnerability of informal construction dwellings in Lima, Peru, where the majority of the houses are built without professional advice or quality control. One hundred houses were surveyed in two districts of Lima where informal construction is prevalent, in order to gather information on their main architectonical and structural characteristics. A simple analysis revealed that most of them present significant structural deficiencies and thus are seismically vulnerable. The main problems observed were caused by bad quality of construction, poor location, insufficient wall density, and unstable parapets.

INTRODUCTION

In the last thirty years Lima, the capital of Peru, has not been subjected to severe earthquakes, even though it is located in a region of high seismic activity. During this period many brick masonry dwellings were built without any structural design and with poor quality of materials and workmanship. Are these houses prepared to resist a severe earthquake? No one knows for certain. It seems reasonable, therefore, to attempt to find out how these dwellings were actually built. This paper summarily describes a project developed to study the structural characteristics and to assess the seismic vulnerability of 100 houses built informally in two districts of Lima (Flores [1], Dueñas [2]).

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BACKGROUND & OBJECTIVES

The Peruvian coast has been subjected to severe earthquakes in the past, and will be in the future. Lima, the capital of Peru, is a coastal city of about 8 million people, which has suffered a tremendous population increase, mainly due to the migration of poor people from the provinces. The only way most of these people have to own a house is through informal construction, usually in lots that they have "invaded". The construction process usually takes several years, as the owner saves money to buy the materials needed to build each room of his house. The preferred construction material is clay brick masonry, confined with reinforced concrete beams and columns ("noble materials"). Construction is performed by the actual owner and his family, usually aided by local masons without any technical training. As a result, the quality of the construction is generally very poor.

The main objectives of this study are to collect preliminary information regarding the architectonical, constructive, and structural characteristics of informal dwellings in Lima, Peru, and to perform simple analyses to have an approximate assessment of their seismic vulnerability.

METHODOLOGY

1. **Literature survey.** Available literature was consulted to obtain information concerning social and technical issues of informal construction in the coastal cities of Peru. A list of the consulted bibliography (in Spanish) is given at the end of this document.
2. **Selection of study areas.** Two zones with different topographic and geological conditions were selected: Villa El Salvador, located in a flat, sandy area at the South of Lima, and Carabayllo, located in hilly, firm ground, located North of Lima. Fifty houses were surveyed in each location.
3. **Design of forms.** Two forms were designed using a known spreadsheet program: The survey form, used to collect the data of each house, and the report form, described below, used to process the information obtained.
4. **Field work.** This was the most difficult task of the project. The selected areas are very poor, with a high crime rate, and the inhabitants are reluctant to allow people into their houses. The students doing the survey had to contact local leaders to be able to access the dwellings.
5. **Data processing:** This involved transcribing the data of each dwelling from the survey form to the report form, adding a sketch of the structure, performing a seismic analysis, and assessing the seismic vulnerability of the dwelling.
6. **Final report**: The document is currently being edited (February 2004, Dueñas [2]).

REPORT FORM

The Report Form is a MS Excel spreadsheet organized as follows:

Background: Location, age, number of floors, type of soil, and general conditions of the house.
Technical Issues: Location problems, structural characteristics, quality of materials and workmanship, other degrading factors.
Seismic Analysis: Assessment of the seismic behavior of the house under frequent and rare earthquakes. This is done by comparing the existing shear wall area to the area required to withstand the analysis earthquakes. The stability of unrestrained parapets is also evaluated.
Seismic vulnerability: The diagnosis is based on the results of the seismic analysis and the constructive and deficiencies observed in the field.
Graphics and Photographs.

SEISMIC VULNERABILITY ANALYSIS

The seismic vulnerability of each surveyed dwelling was assessed through a simple seismic analysis, which consisted of comparing the existing masonry wall area, $\mathbf{A_e}$, to the area required to withstand seismic lateral loads, $\mathbf{A_r}$. The ratio $\mathbf{A_e/A_r}$ is computed for both frequent and severe earthquakes. If the wall area ratio is larger than 1,2, the structural walls have sufficient lateral strength, and the behavior of the structure under the selected design earthquake is considered to be good. If it is less than 0,8, the structure is deficient and the dwelling is vulnerable. For intermediate values, the structural strength is considered to be adequate.

The existing wall area $\mathbf{A_e}$ of each dwelling is the sum of the areas of all the structural walls. For frequent earthquakes, all masonry walls are considered to resist lateral loads. For rare earthquakes, only the walls confined with reinforced concrete elements on their four sides are considered to be 100% effective. Walls with confinement in three sides are considered to be 50% effective. The contribution of all other walls is ignored.

The required wall area $\mathbf{A_r}$ was calculated dividing the seismic lateral force **V** by the average shear strength of the structure, $\mathbf{v_r}$. Thus,

$$\mathbf{A_r = V / v_r}.$$

The seismic lateral force (kN) is given by the Peruvian Seismic Design Code [3] as

$$\mathbf{V = ZUSCP/R}$$

where

Z is the zone factor (**Z** = 0,2 for frequent earthquakes and **Z** = 0,4 for rare earthquakes);
U = 1 is the use factor for dwellings;
S is the soil factor (**S** = 1,0 for rigid soils, **S** = 1,2 for intermediate soils and **S** = 1,4 for flexible soils);
C = 2,5 is the seismic amplification factor selected for all dwellings;
P is the weight of the building in kN; and
R is the strength reduction factor. For rare earthquakes **R** = 3, accepting some damage in the structures. For frequent earthquakes the structures should remain elastic, thus **R** = 1 (Muñoz *et al.* [4]).

The shear strength of the masonry, $\mathbf{v_r}$ (kPa), was estimated by the following expression, derived from a formula proposed by San Bartolome [5]:

$$\mathbf{v_r = 0.5\ v'_m \alpha + 0.23 f_a}$$

where

$\mathbf{v'_m}$, is the characteristic shear strength of confined masonry. It was estimated, conservatively, at 820 kPa for masonry made with industrial clay bricks and at 510 kPa for masonry built with hand-made clay bricks;
α is a global strength reduction factor that depends on the shear/moment ratios of all resisting walls; and
$\mathbf{f_a}$ is the average axial stress acting on the walls (kPa).

Some of the dwellings had provisional roofs made with straw mats, cane, or wood covered with cement-asbestos sheets. In these cases, no rigid diaphragm was available to distribute lateral loads, and the seismic analysis consisted of estimating the potential overturning of the walls of the house under the design loads.

The vulnerability assessment of each dwelling was finally performed by complementing the results of the seismic analysis with the actual conditions of the dwelling, as observed in the field. For instance, if a building had adequate strength according to the analysis, but the quality of the construction was very poor, the seismic vulnerability could be assessed as high.

RESULTS

This section summarizes the main results obtained from the analysis of the 100 houses surveyed. Even though the results are not statistically significant, because the sample was very small and not uniformly distributed (only those houses that were accessible were surveyed), it is hoped that the information obtained will give a first impression of the main architectural, constructive and structural problems affecting the houses built informally in Lima.

Main problems observed

Location problems

Many dwellings are located in sloped terrains. In these cases builders need to cut and fill the ground to obtain a flat, horizontal surface (Figure 1). In many occasions this has resulted in failure of the foundation of the dwelling located right above the house being built.

a) Cutting the slope **b) Temporary straw dwelling on a fill**

Figure 1. Informal building on a hill

The majority of the houses in Villa El Salvador are located in loose sandy soils. Most of the dwellings have inadequate foundations and present extensive wall cracking due to ground settlement. The few dwellings with reinforced foundations do not present this problem. In Carabayllo, many dwellings are located over soft fills, and they also show many cracked walls (Figure 2). Also, since there are no water or drainage systems, water and sewage are dropped to the ground, and they filter down the slope, damaging the walls of the houses existing below (Figure 3). Many houses built in ravines are exposed to inundations during rainy seasons, and to falling rocks and debris caused by earthquakes.

Figure 2. Cracked wall **Figure 3. Humidity in wall**

Structural problems

The main structural problems are related to the number and distribution of structural masonry walls. Most houses in the surveyed districts are located in rectangular lots with the largest dimension perpendicular to the street. Usually, two “structural” walls are constructed on the long edges of the lot, and then rooms are created by placing infill walls in the short direction. The density of lateral resisting walls is therefore much larger in the long direction than in the short direction of the house. Since most infill walls are unconfined or made with hollow clay bricks, the houses are much more vulnerable to seismic damage in their short direction. This problem is exacerbated when the space at the front of the house is left open, to be used for commercial purposes, because in that case most of the transverse walls are located towards the back of the house, thus creating potential torsional problems.

There is a widespread misconception that the “structure” is composed only by the reinforced concrete beams and columns. Accordingly, these elements are generally overreinforced, even though reinforcement is very expensive, and the beams and columns mainly work as confinement to the masonry walls. In many cases load bearing walls are built with hollow clay bricks (they are cheaper than solid bricks) since they are not considered to be “structural” by the builders (Figure 4).

In order to take the most advantage of the available land, houses are generally built side by side, with no separation between them. In hilly areas, therefore, floor slabs of adjacent dwellings are at different levels. During a strong earthquake floor slabs could cause severe damage by punching the walls of adjacent houses (Figure 5).

Floor slabs are very expensive to build, and many owners decide to build them in two stages. Usually the second part of the floor slab is built several months or years after the first part, and the exposed surface of the old slab is dirty and the steel reinforcement is corroded. This generates inadequate adherence between the two parts of the slab, and as a result the slab is usually cracked.

Figure 4. Masonry walls **Figure 5. Floor slabs at different levels**

Many walls located on the upper floors of the house are usually built without any confining elements. This is especially prevalent in façade walls and roof parapets (Figure 6).

Figure 6. Unconfined masonry walls

Construction problems

Most surveyed dwellings had important construction problems, mainly due to lack of knowledge of proper building techniques, poor workmanship, or the use of materials of bad quality.

House owners and builders believe that the reinforced concrete beams and columns are the most important structural elements. Accordingly, they pay a lot of attention to their construction. The results, however, are usually very poor. Concrete is prepared with high water/cement ratio, large aggregate size, and inadequate mixing and vibration. Aggregates are usually bought from informal quarries, where there is absolutely no quality control in the cleanliness or the size of the material. Furthermore, curing is not considered to be important: beams and columns are almost never cured, and slabs are sometimes cured by pouring some water on the surface the day after they are built. As a result of these poor construction practices concrete is weak, porous, and full of honeycombs.

There is an understanding of the importance of reinforcement in the strength of the structure. Therefore, most elements are overreinforced, even though steel reinforcement is very expensive. Stirrups, however, are believed to be useful only to maintain the main reinforcement in place, and in most cases they have open hooks, or are made with small diameter rebar. In areas with access to welding factories, it is common to find welded steel bars, instead of overlapping rebar connections. Since safety is always a concern, many owners weld metal doors and windows to the reinforcement of columns or beams. A common problem observed is corrosion of the steel reinforcement. This happens because of poor quality of concrete with small covers or filtration of rain water.

The bricks used to build the masonry walls are usually hand made by local artisans, because these bricks are significantly cheaper less than industrial bricks. Clearly the quality of non-industrial bricks leaves much to be desired: they are irregular in shape and much weaker than the industrial bricks. Furthermore, the quality of the masonry is generally quite poor, since mortar joints are very thick and vertical joints are in many cases left empty. The photos in Figure 7, below, show many of the construction problems prevalent in most houses surveyed.

a) Open stirrups

b) Thick mortar joints

c) Exposed and corroded reinforcement

d) Honeycombs, exposed reinforcement, etc.

Figure 7. Construction problems

Seismic Vulnerability
Of the 100 dwelling surveyed, 71 had rigid floor slabs and the remaining 29 had provisional roofs made with straw mats, cane, or wood. Table 1 below shows the results of the seismic vulnerability analyses performed on all the houses.

Table 1. Results of seismic analysis

Predicted Seismic Behavior	Rare Earthquake (0,4 g)	Frequent Earthquake (0,2 g)
Good	35%	35%
Adequate	20%	18%
Deficient	45%	47%

Practically the same results are obtained for the two seismic conditions. This dual analysis has been therefore dropped in subsequent phases of this project. The results show that almost half of the dwellings surveyed are vulnerable, since they will suffer damage even in moderate earthquakes and could collapse during a large event. These preliminary results indicate that it is necessary to find out ways to improve the seismic characteristics of informal construction in Peru.

CONCLUDING REMARKS

Informal construction is prevalent in large cities in Peru and in other developing countries located in seismic regions. Non-engineered construction will continue as long as poverty exists in these regions. This means that many people will continue to live in seismically vulnerable (and many times unhealthy) homes. The safety problem of these poor people is not addressed by the professional community because it is not economically interesting, nor by the academic communities because it is not intellectually challenging, nor by the government because of lack of funds. The need to find solutions to this important problem, however, still exists. These solutions must be cheap and easy to apply. The research team is currently processing data obtained in other parts of Lima and in several other cities of the coast of Peru to have a better understanding of the technical and social problem and to develop recommendations for construction by house owners and local masons of safer and healthier houses, and to retrofit and reinforce existing homes.

BIBLIOGRAPHY (IN SPANISH)

1. Centro de Servicios de Pedagogía Audiovisual para la Capacitación, 1983. “Diagnóstico: Aspectos básicos de la autoconstrucción en Pueblos Jóvenes de Lima y Callao”, Ministerio de Agricultura, Lima, Perú.
2. Instituto Nacional de Desarrollo Urbano, 1983. “Diagnóstico sobre la vulnerabilidad y riesgo de las áreas críticas de Lima Metropolitana”, Ministerio de Vivienda, Lima, Perú.
3. Instituto de Transferencia de Tecnologías Apropiadas para Sectores Marginales y Consejo Nacional de Ciencia y Tecnología”, 1993, “Tecnologías apropiadas para la autoconstrucción de viviendas”, Lima, Perú.
4. Lázares, F., 1993. “Estudio de la vulnerabilidad sísmica de las edificaciones en las ciudades de Ilo, Moquegua y Tacna”. Anales del 8º Simposio Natural de Prevención de Desastres, Centro Peruano-Japonés de Investigaciones Sísmicas y Mitigación de Desastres (CISMID), Lima, Perú.
5. Vega-Centeno, P., 1992, “Autoconstrucción y reciprocidad: Cultura y solución de problemas urbanos”. Instituto de Desarrollo Urbano, Lima, Perú.

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REFERENCES

1. Dueñas, M., "Seismic Vulnerability of Informal Construction Dwellings in Lima", Master's Thesis, in Spanish. Catholic University of Peru, 2004.
2. Flores, R., "Preliminary Diagnosis of the Seismic Vulnerability of Informal Construction Dwelling in Lima", Civil Engineer Thesis, in Spanish. Catholic University of Peru, 2002.
3. Ministry of Housing, "Seismic Resistant Design Code E.030", in Spanish. SENCICO, Lima, Peru, 2003.
4. Muñoz, A., San Bartolomé, A., Rodríguez, C., "Seismic Forces for the Design of Housing Buildings", in Spanish. Catholic University of Peru, DI-SIC-2001-01, Lima, Peru, 2001.
5. San Bartolome, "Masonry Constructions: Seismic Behavior and Structural Design", in Spanish. Catholic University of Peru, 1998.

A REPORT FORM (IN SPANISH)

DIAGNOSTICO PRELIMINAR DE LA VULNERABILIDAD SISMICA
DE LAS AUTOCONSTRUCCIONES EN LIMA
FICHA DE REPORTE

Vivienda Nº : 009

Antecedentes:

Ubicación: Sector 2 - Grupo 8 - Mz."D" - Lote 7 - Distrito de Villa El Salvador

Dirección técnica: No recibió, maestro de obra Antigüedad de la vivienda: 19 años

Pisos construidos: 2 Pisos proyectados: 3

Geografía y geología: Pendiente media longitudinal a la vivienda, suelo de arena suelta Factor de Suelo S = 1.4

Estado de la vivienda: Se relleno para nivelar el terreno en la parte posterior del lote. La vivienda tiene dos pisos con techo de losa aligerada, algunos muros del primer y segundo piso tienen grietas verticales, algunas se proyectan al techo. Existen muros de aparejo de soga y cabeza, con ladrillos de arcilla. La mano de obra es de regular calidad. En la azotea, en la parte delantera, entre los ejes B y C existe un parapeto sin confinamiento.

Secuencia de construcción de la vivienda: Se construyo ambiente por ambiente.

Aspectos técnicos:

Elementos de la vivienda:

Elemento	Características
Cimientos	No se sabe
Muros	Ladrillo macizo artesanal, 9x13x23, juntas 2.5cm, muros soga y cabeza, h_1=2.50m
Techo	1er y 2do piso losa aligerada de 20cm
Columnas	Todas las columnas de 0.25x0.25m
Vigas	Peraltadas y chatas

Deficiencias de la estructura:

Problemas de ubicación:	Mano de obra:
Suelo de arenas sueltas / Asentamientos / Muros agrietados	De regular calidad
	Materiales deficientes:
Problemas estructurales:	Ladrillos artesanales
Estructura flexible	Factores degradantes:
Falta de juntas laterales entre viviendas	Grietas: en muros, en techos
Parapeto de azotea sin columnas	
Torsión en planta	Otros:

Análisis por sismo raro (Z=0.4g, U=1, C=2.5, R=3)

Fuerza permisible por corte (kN) = Ae(0.5v'm α+0.23· α_x=0.5 : α_y=1.0 Resistencia característica a corte (kPa): v'm = 510

Area	Cortante Basal		Fuerza permisible		Area de muros		Resultados		
Piso 1	Peso acum.	V=ZUSCP/R	fa	Fuerza	Requerida: Ar	Existente: Ae	Densidad	Ae / Ar	Estado
m^2	kPa	kN	kPa	kN	m^2	m^2	%	adimensional	
Análisis en el sentido "X"									
86	16	642	140	176	4.0	1.1	0.6	0.3	**Deficiente**
Análisis en el sentido "Y"									
86	16	642	260	1700	2.0	5.4	3.1	2.6	**Bueno**

Análisis por sismo frecuente (Z=0.2g, U=1, C=2.5, R=1)

Fuerza permisible por corte (kN) = Ae(0.5v'm α+0.23· α_x=0.5 : α_y=1.0 Resistencia característica a corte (kPa): v'm = 510

Area	Cortante Basal		Fuerza permisible		Area de muros		Resultados		
Piso 1	Peso acum.	V=ZUSCP/R	fa	Fuerza	Requerida: Ar	Existente: Ae	Densidad	Ae / Ar	Estado
m^2	kPa	kN	kPa	kN	m^2	m^2	%	adimensional	
Análisis en el sentido "X"									
86	16	963	140	287	6.0	1.8	1.0	0.3	**Deficiente**
Análisis en el sentido "Y"									
86	16	963	260	1889	3.1	6.0	3.5	2.0	**Bueno**

Estabilidad de muros al volteo - Sismo frecuente (Z=0.2g)

Muro	Factores				Mom.act.	Mom.res.	Resultado	Muro	Factores				Mom.act.	Mom.res.	Resultado
	m	P	a	t	$0.1 m P a^2$	$16 t^2$	Ma : Mr		m	P	a	t	$0.1 m P a^2$	$16 t^2$	Ma : Mr
	adim.	kN/m	m	m	kN-m	kN-m			adim.	kN/m	m	m	kN-m	kN-m	
M1	0.06	2.5	6.7	0.14	0.7	0.3	Inestable	M2							

FACTORES INFLUYENTES EN EL DIAGNOSTICO									DIAGNOSTICO			
Densidad de Muros	Sismo Fr.	Sismo R.	**Estabilidad de Muros**		**Mano de Obra y Materiales**		**Ubicación de la Estructura**		**Sismo Frecuente:** Nivel de desempeño		**Sismo Raro:** Riesgo sísmico	
Buena: Ae/Ar>1.:			Todos estables		Buena calidad		Buena ubicación		Buen desempeño		Riesgo sis. bajo	
Regular:0.8<Ae/Ar<			Algunos inestabl	X	Regular calidad	X	Regular ubicació	X	Regular desemp.		Riesgo sis. medio	
Deficiente: Ar/An<0	X	X	Muchos inestable		Mala calidad		Mala ubicación		Mal desempeño	X	Riesgo sis. alto	X

Diagnóstico:

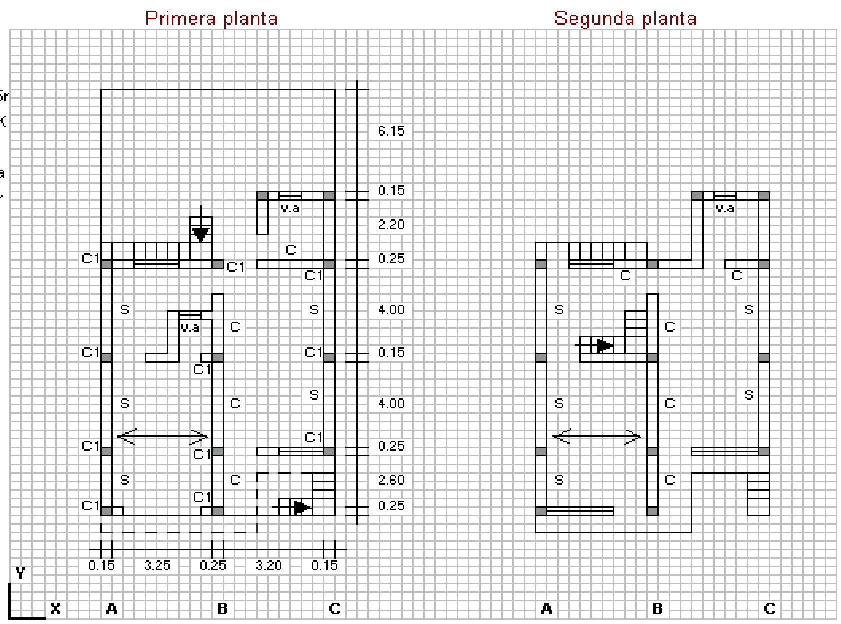
Sismo frecuente: La densidad de muros es deficiente en el sentido "X", los parapetos de la azotea que dan hac la calle no tienen confinamiento, la mano de obra es de regular calidad y los materiales son de baja calidad (ladrillos artesanales), la estructura se encuentra en una regular ubicación; zona con pendiente media y suelo de arenas sueltas. Algunos muros del segundo piso presentan grietas que pueden degradar su resistencia sísmica. La vivienda presenta un mal nivel de desempeño en el análisis por sismo frecuente.

Sismo raro: La vivienda presenta una densidad de muros deficiente y un riesgo sísmico alto.

Gráficos y fotografías:

Planta:

Lote: 7x20m
C1:0.25x0.25r
C: cabeza KK
S: soga KK
v.a.: vent.alta
X : sin techar



Elevación: