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Seismic evaluation for two rural housing prototypes Built with hollow concrete blocks, in Ocuilapa of Juárez, Chiapas, Mexico

Evaluación sísmica en dos prototipos de vivienda rural construidos con bloques de concreto hueco, en Ocuilapa de Juárez, Chiapas, México

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Abstract

In the rural areas of Mexico and Latin America, prevails the people of low income, living in unsafe and unhealthy, precarious housing that anchored to its inhabitants in the cycle of poverty. The academic team, with the purpose of contributing to the solution to the problem of rural housing, developed prototypes of low-cost housing were built by families living in conditions of high marginalization in the town of Ocuilapa Juárez, Chiapas. The construction used materials in the place; the foundation stone, sand with high clay content (22%) in the preparation of hollow concrete block and wood in the roof structure. This article presents the results of measurements made with accelerometers in two homes, to determine the level of vulnerability to seismic scenarios. The fundamental period of vibration obtained are from 0.08 to 0.12 seconds; range of values recommended by (Hernández et al.,1979), for structurally sound homes. Also, the analyses carried out prove that dwellings are in "low vulnerability" in the presence of some earthquakes.

Keywords: *Housing prototype, rural housing, blocks of sand soil cement, seismic vulnerability, earthquake*

Resumen

En el medio rural de México y Latinoamérica, prevalece la población de bajos ingresos económicos que habita en viviendas precarias, inseguras e insalubres, que anclan a sus moradores en el círculo de la pobreza. El equipo académico, con el propósito de contribuir en la solución al problema de vivienda rural, elaboró prototipos de vivienda de bajo costo que fueron construidos por familias que viven en condiciones de alta marginación en la localidad de Ocuilapa de Juárez, Chiapas. En la construcción se utilizaron materiales existentes en el lugar; piedra para la cimentación, arena con alto contenido de arcilla (22%) en la elaboración de bloques huecos de concreto y madera en la estructura de cubierta. En este artículo, se presentan los resultados de las mediciones realizadas con acelerógrafos en dos viviendas, para determinar el nivel de vulnerabilidad ante posibles escenarios sísmicos. Los periodos fundamentales de vibración obtenidos se encuentran entre 0.08 a 0.12 segundos; rango de valores recomendados por (Hernández et al., 1979), para viviendas estructuralmente sanas. También, los análisis efectuados comprueban que las viviendas están en condición de “vulnerabilidad baja” ante la presencia de sismos de cierta magnitud.

Palabras clave: Vivienda prototipo, vivienda rural, bloques de arena-suelo-cemento, vulnerabilidad sísmica, sismos

1. Introduction

In the rural areas of the state of Chiapas and other regions of Mexico, many homes are built with wood, reed, palm, stone and earth, among other natural raw materials. There are also homes built with low-cost industrial materials, such as cardboard sheets and waste materials (plastics, metal sheets, etc.). Rural community populations under poverty and extreme poverty social conditions generally live in this type of housing. However, they usually evidence a precarious condition, that is, they have walls and roofs made of bad-quality material, earth floors, they do not rely on proper spaces, they have little drinking water available and they lack drainage. These realities entail that families cram into unsafe and unhealthy dwellings, which prevent their economic and social development.

Consequently, the researches carried out by this work team have been guided by the search of solutions addressing the housing problem of low-income families, based on analyses and the construction of alternative housing prototypes that are economical, safe and offer hygienic environments for their residents. Additionally, they consider the typology of local properties and traditional uses and habits. These proposals aim at contributing to the improvement of rural areas and increasing the quality of life of the families.

The study was carried out in the town of Ocuilapa de Juárez of the Municipality of Ocozocoautla de Espinosa in Chiapas, located 13 km northwest of the city of Ocozocoautla and 31 km of the city of Tuxtla Gutiérrez, capital of the state of Chiapas, in Mexico (see Figure 1). The town has 3,921 inhabitants and 955 dwellings (INEGI, 2010 and 2013). According to data recorded in 2007 by the National Population Council (CONAPO), the population works mainly in primary activities and shows a high level of marginalization, referred to localities with lack of access to education, inadequate housing, and lack of consumer goods (CONAPO, 2007).

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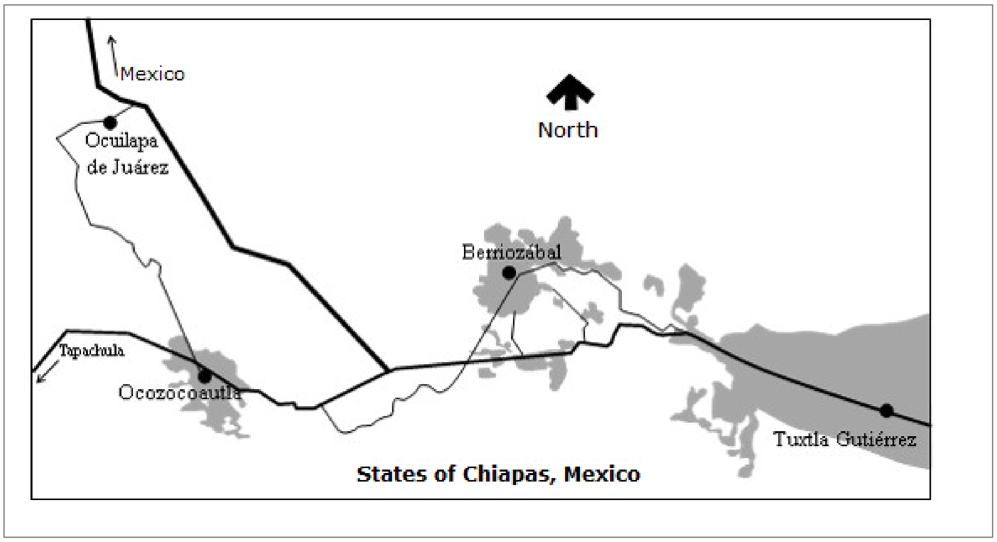


Figure 1. *Localization of Ocuilapa de Juárez, Municipality of Ocozocoautla, Chiapas*

The community houses are mainly built with a foundation of local stone masonry. The walls are built with two-cell hollow concrete blocks, with vertical steel reinforcement only in the corners and intersections, without considering door or window openings, and horizontal reinforcement in the reinforcing bar grid and the closure beam. The roofs have a wooden structure that supports the clay tile roof or zinc sheet. In general, constructions evidence inadequate constructive procedures, insufficient reinforcement steel, and use of local sand with high percentage of clay (22%), among other aspects, which contribute to the presence of considerable cracks and checking in the walls and makes the structural safety of the housing vulnerable.

The proposed housing prototypes were built by low-income families of the region, between 2007 and 2008, with on-site materials. Likewise, they considered the techniques usually employed by the inhabitants: stone masonry foundation; walls with a new approach of three-cell hollow concrete blocks and reinforced with steel on the inside; roofing with wooden structure and clay tile roof. The main purpose was to build low-cost housing and improve the structural elements to increase the safety, based on technical standards (Escamirosa et al., 2008).

Although the housing structure improved considerably, the average compressive strength of the three-cell blocks, obtained in the laboratory, was 19.30 kg/cm2, which is lower than the minimum strength required by technical standards (40 kg/cm2). However, the average compressive strength of concrete for the columns and closure beams reached the minimum requirement of 150 kg/cm2. The low compressive strength recorded in the blocks is a consequence of the high clay content in the locally found sand (22%), which was used in the concrete mix (Escamirosa et al., 2011). In this sense, it is technically undeniable that eliminating the clay in the sand would substantially improve the strength of concrete. Nevertheless, the water used for washing the sand or buying clean sand somewhere else would increase the cost of the works. In this regard, the work team decided to use the materials commonly used by the community during the housing construction.

This paper analyzes two housing prototypes built in Ocuilapa de Juárez with the aim of determining the vulnerability level in the event of earthquake scenarios. Therefore, measurements with accelerometers (acceleration sensors) were made in each dwelling and the fundamental periods of vibration were determined, which are within the value range recommended by (Hernández et al., 1979), for structurally sound housing. Additionally, analysis were made to prove that dwellings are under a "low vulnerability" condition in the event of earthquakes of a certain magnitude.

2. Background

Previous studies performed in the place (Escamirosa et al., 2006) provided information that allowed identifying the characteristics of the materials used and the existing conditions of the structural elements in 486 houses in the town of Ocuilapa de Juárez. The results indicate that floors are predominately made with a polished cement surface (70.37%), compared to earth with 16.67%. Regarding the walls, 79.42% are built with two-cell hollow concrete blocks, compared to 9.05% with thick partition. The remaining 11.53% of dwellings use: wood, adobe and mud construction, which correspond to vernacular constructions, and even waste materials such as cardboard and sheet. In relation to the roof, 41.14% of the homes use galvanized sheets, compared to 35.18% using concrete, and 20.57% use tiles made of clay of the region. Additionally, field inspections were made to specifically examine dwellings built with perishable materials (wood and cardboard), as well as those with earth floors, waste materials, and those built in the ancestral way with walls of traditional adobe, which are made with clay and straw, or mud. According to Moya (1988), the latter are built with rows of wooden posts driven into the ground to form the walls, with a framework of interweaved canes in between, which are later filled on both sides with a clay plaster mixed with forage or *straw. These two types of housing have a cultural and historical value in the region. All the houses described are in a very bad state of preservation and they evidence unsafe and unhealthy conditions.*

On the other hand, the structural elements of dwellings built with partition walls made of fired clay, solid or two-cell hollow concrete blocks, evidenced a better state of preservation; however, due to the following conditions, the structure does not guarantee the safety of their residents.

From the total number of dwellings, 62% have a stone masonry foundation and the rest is made of reinforced concrete. According to the region's type of rocky soil, both elements are adequate. However, 9.42% of the houses are built with walls of two-cell hollow concrete blocks, and 30.55% present cracks. The reason for this is that walls only have vertical steel reinforcement in the corners and horizontal steel reinforcement in door and window openings. In other words, they do not have reinforcement on the inner side of the cells, as stipulated in the technical standards. At the same time, laboratory analyses were carried out to determine the strength of hollow concrete blocks, which are generally built by inhabitants of Ocuilapa de Juárez with sand obtained from the sandbank "El Arenal", located 4 km from the town; it costs 50% less than the river sand, but it has a high content of soil (22% of clay). Results demonstrate that the simple compressive strength is 2.5 times lower than the one established in the standard (compressive strength of the hollow block = 16 kg/cm^2; minimum standard strength = 40 kg/cm^2; NTC, 2004) (Escamirosa et al., 2006).

The above conditions indicate that concrete blocks manufactured by the inhabitants do not comply with the minimum standard strength. Therefore, the housing walls are vulnerable to seismic effects, which are frequent in the state of Chiapas, since it is located in a region with high seismic activity, as a result of the subduction of the tectonic plate of Cocos under the North American plate (García and Suárez, 1996). Consequently, the damages identified in the housing walls could be aggravated, and the walls could partially or totally collapse as a result of telluric movements of a certain magnitude.

During the period of 2006-2008, through research projects financed by the Fondo Mixto CONACyT-Government of the State of Chiapas (FOMIX-Chiapas), as well as the Institutional Research System of the Universidad Autónoma de Chiapas, four housing prototypes were built for the community of Ocuilapa de Juárez (Escamirosa et al., 2008). The design of the spaces and functional elements of the houses considered the involvement of selected families, with the aim of knowing their opinions regarding the proposals, in relation to uses and habits, image and typology of the community, the natural environment, among other aspects (Figure 2).

In the wall construction, a new approach with three-cell concrete blocks was used, which included steel reinforcement on the inside. The dimensions of the blocks and the reinforcement characteristics were established based on the complementary technical standards (NTC, 2004).

The housing construction materials were those usually employed by the community inhabitants, and during the entire self-construction process of the houses, the selected families received technical assistance from the work team and students of the Faculty of Architecture. Training courses were given, as well as technical consulting, follow-up and quality control of the elements. The housing structure improved; however, the high content of clay (22%) contained in the sand used in the manufacture of three-cell concrete blocks produced an average compressive strength of 19.30 kg/cm^2, which is 50% lower than the standard average (NTC, 2004). On the other hand, the concrete used in the walls' closure beams and columns obtained a compressive strength of 150 kg/cm^2, corresponding to the minimum indicated by the standard (Escamirosa et al., 2011).

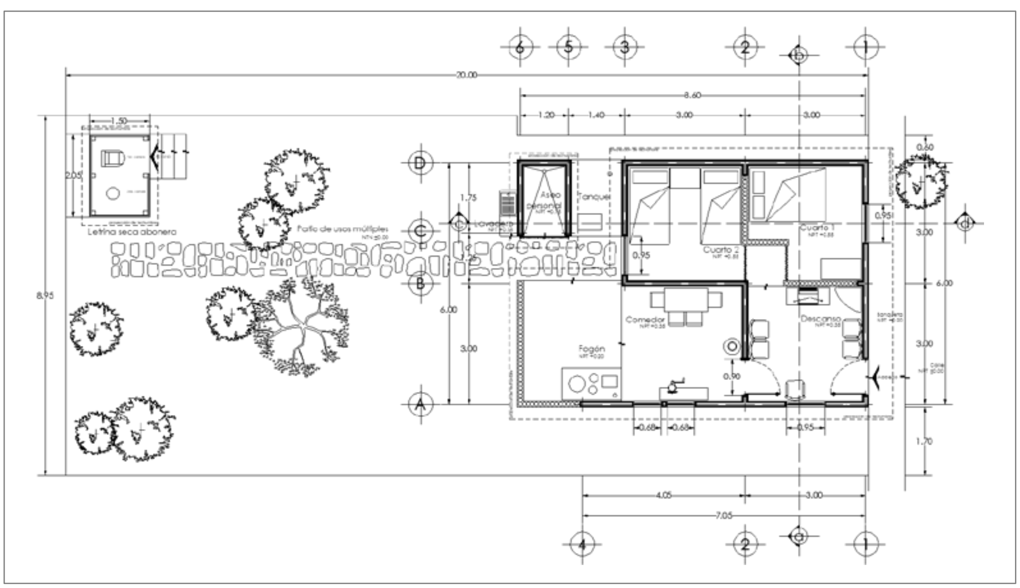


Figure 2. *Architectural plan of a rural housing prototype (Escamirosa et al., 2011)*

3. Prototype Characteristics

The structural elements of housing prototypes were designed and built based on the Mexican building regulations, specifically the Complementary Technical Standards for Masonry Structures and Seismic Design (NTC, 2004). Therefore, the location of Ocuilapa de Juárez was considered in the "C" high-risk seismic zone, according to the seismic regionalization of Mexico (CFE, 2008) and the type of rocky soil of the study area. The following paragraphs describe the structuring of the housing prototypes, whose construction ended in August 2008, in compliance with the specific details described in the Manual for Self-construction of Housing and Sanitary Services (Escamirosa et al., 2011).

The foundation is made of masonry prepared with stones extracted from areas surrounding the construction and settled with local cement-sand mortar, with a rectangular section of 40 cm wide and a variable depth depending on the site topography. Likewise, during the constructive process, the anchoring of the vertical steel reinforcement of the columns was made, and a reinforced-concrete reinforcing bar grid with a section of 15x20 cm was placed on the foundation.

The walls were built with hollow concrete block masonry of 15x19x40 cm, with three cells (cell section of 9.67x9.67 cm), reinforced with steel on the inside, both in the vertical and horizontal direction, and distributed crosswise and lengthwise of the walls, according to the standard (NTC, 2004) (Figure 3).

The columns in the wall ends employ three cells and four in the wall intersections, in addition to two consecutive cells in the ends of the door and window openings. In the case of walls without door or window openings, a 3/8" steel rod was placed every 75 cm with one cell. The reinforcement consisted in corrugated steel rods with fy = 4.200 kg/cm^2 and concrete of f'c = 150 kg/cm^2, manufactured on site with local sand.

Finally, a gabled roof was built with a structure made of local wood. Studs of 10x10 cm were placed at the end of the external perimeter walls, including the ridge boards, which support the rafters installed every 70 cm, which in turn support the furring strips of 2.5x10 cm fixed every 35 cm, according to the size of the local, colonial–type earthen tiles of 6x18x46 cm. Furthermore, rafters of 5x15 cm were placed at the center of the span and perpendicular to the rafters, in order to reduce the deformations of the wood and improve the safety.

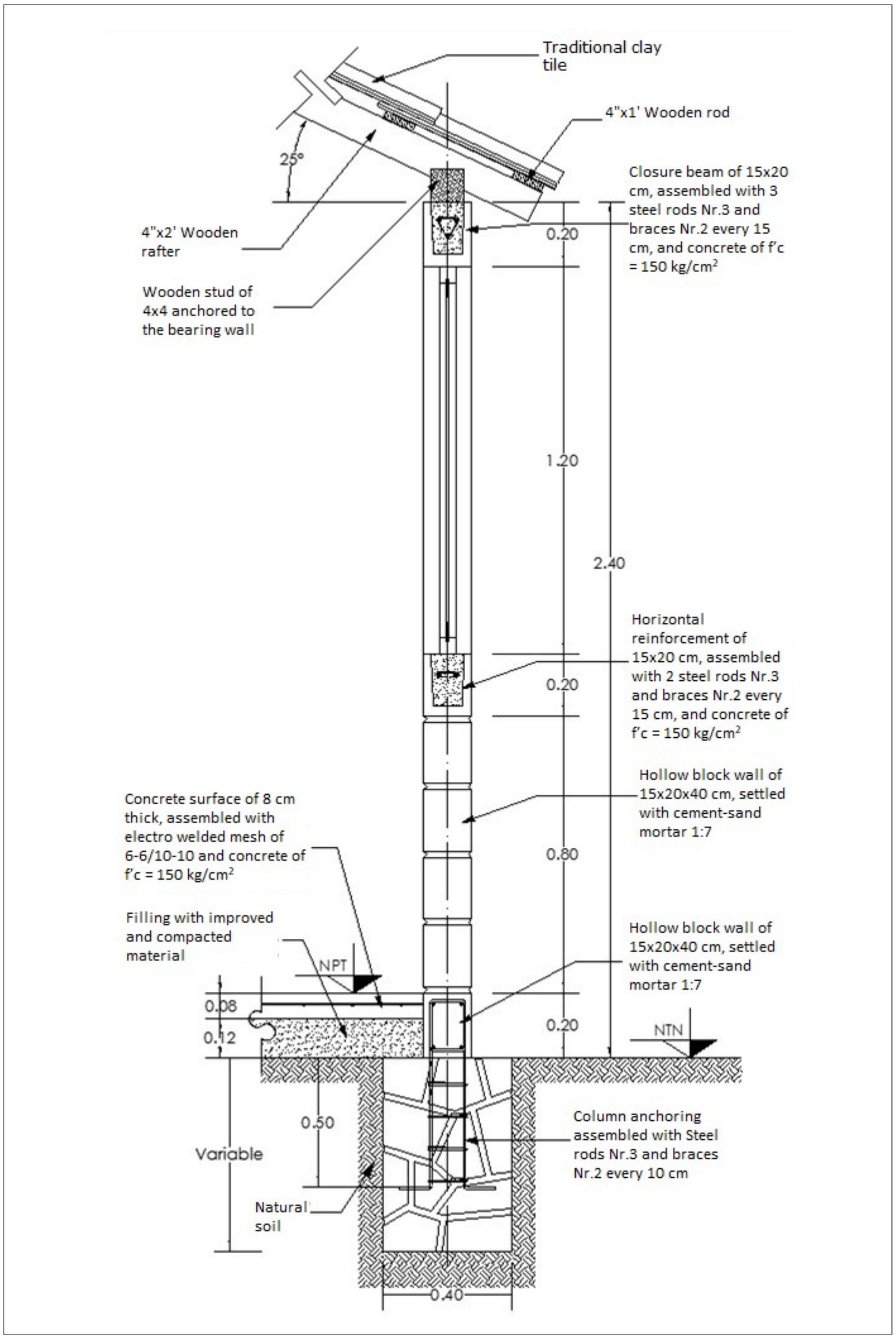


Figure 3. *Structure of the housing prototypes; cross section (Escamirosa et al., 2011)*

4. Results of the Housing Prototype Analyses

Field works were performed in Oculapa de Juárez in two of the selected dwellings (V1 and V2), according to the low-income condition of the residents (INEGI, 2010) and (INEGI, 2013). The accelerometer measurements were initiated on October 3, 2014, with the aim of conducting the corresponding study to determine the fundamental periods of vibration of the structure and the soil. An accelerograph sensor was used and, based on the results, the necessary analyses to determine the structural dynamic properties were carried out.

The V1 dwelling, with geographic coordinates: 16°51'28.99" N and 93°24'53.62" O, is located on the 16 de Septiembre street and its owner of Mr. Crescencio Pérez Pérez. The house was built approximately 6 years ago (Figure 4 and

Figure 5). The V2 dwelling, with geographic coordinates: 16°51'30.52"N y 93°24'43.96"O, is located on the Ignacio Allende street and it is owned by Mrs. Norbel Jiménez Pérez (Figure 5 and Figure 6).

Figure 7 shows the positioning of the accelerograph in the V2 dwelling at the indicated P3 point, which corresponds to the geometrical center. The obtained recordings were made in three orthogonal directions with a duration of 30 seconds. The results of the study establish that the average fundamental periods of vibration per housing, are the following: dwelling V1 with 0.1280 seconds and dwelling V2 with 0.1067 seconds. Moreover, the corresponding soil measurements in the analyzed zones are: V1 with 0.1164 seconds and V2 with 0.1219 seconds.

Figure 8 and Figure 9 show the positions of the acceleration sensor in the structure of each dwelling (P2, P3 and P4) and in the free field (P1; soil).

***Figure 4.** Location of the V1 dwelling (Reyes B., 2015)*

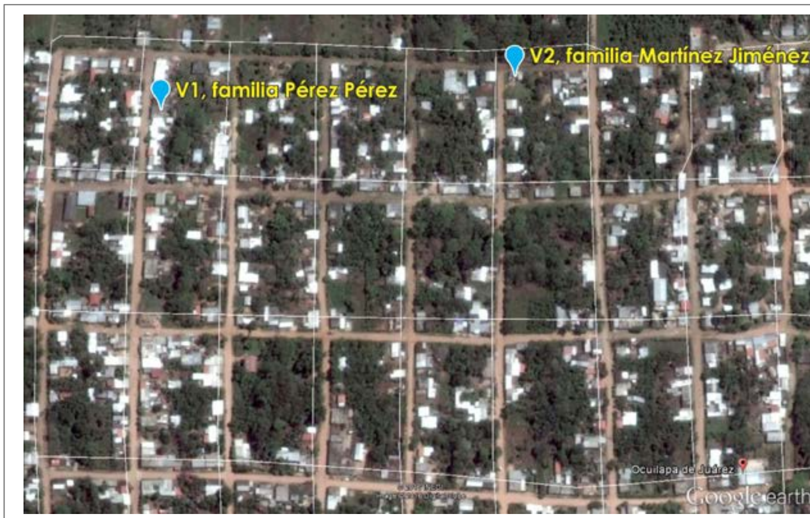


***Figure 5.** Satellite photograph of the location of V1 and V2 (Cortesía de Google Maps©, 2010)*

Figure 6. *Location of the V2 dwelling (Reyes B., 2015)*

Figure 7. *Positioning the sensor in the geometric center P3 of V2 (Reyes B., 2014)*

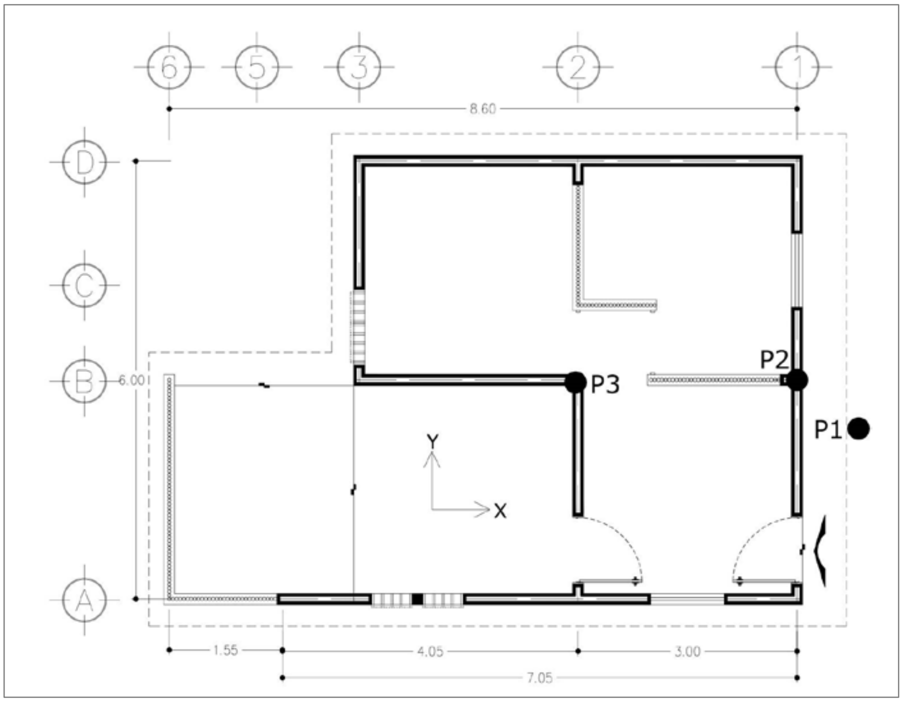


Figure 8. *Sensor position in the V1 dwelling*

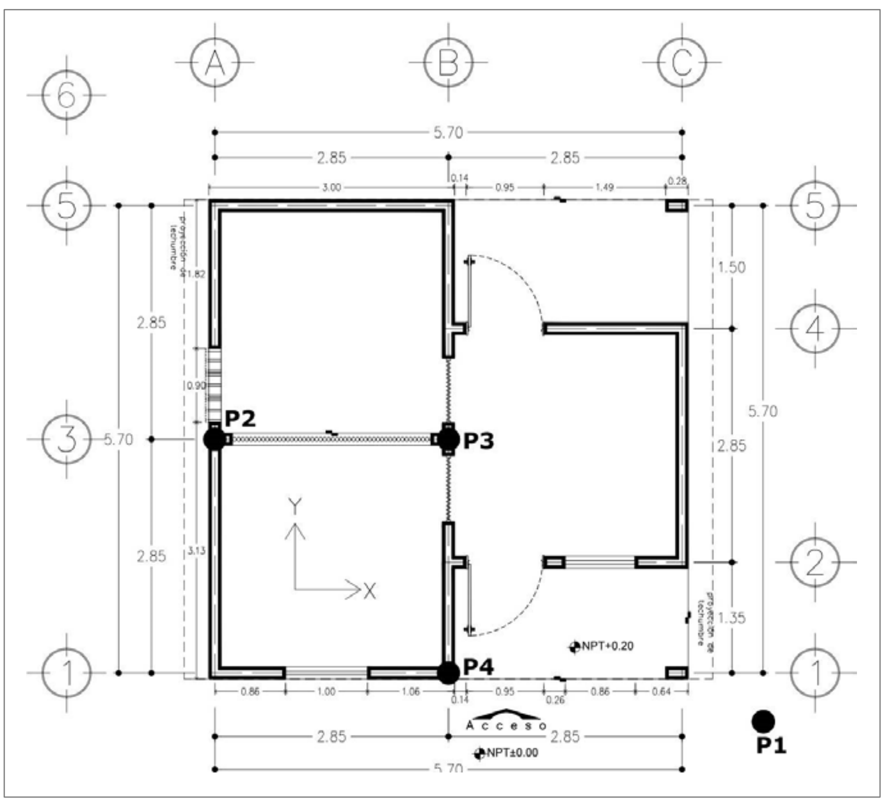
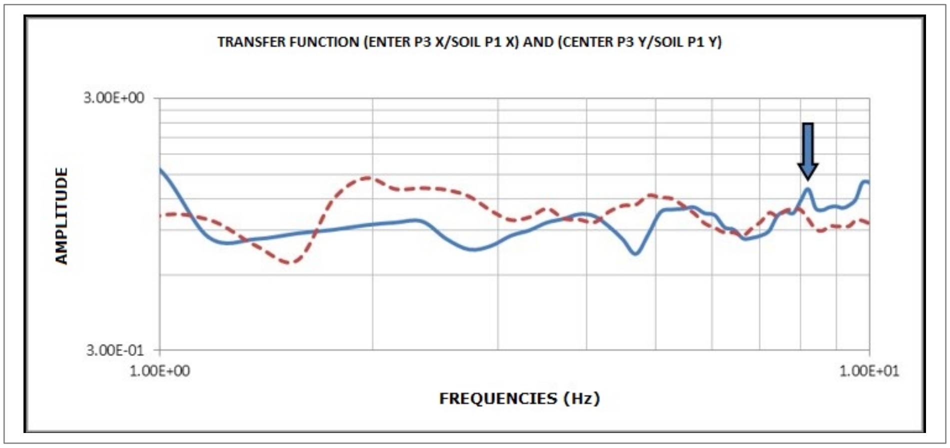


Figure 9. *Sensor position in the V2 dwelling*

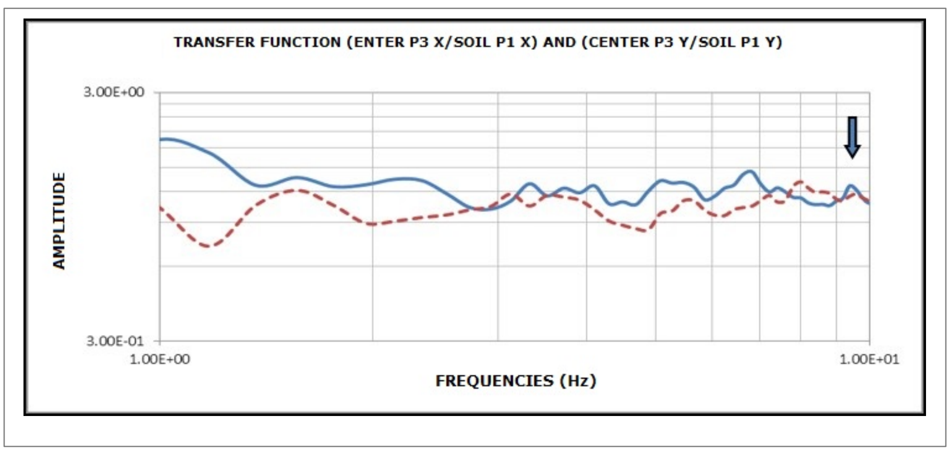
Charts 1 and 2 show the transfer functions in each dwelling. The continuous function corresponds to the short direction of the house (x) and the discontinuous function corresponds to the long function (y). These functions where obtained by dividing the Fourier spectra calculated from the accelerometer recordings at the center of each dwelling (Point P3), and the soil (Point P1). The relationship between both recordings allows establishing how the response is amplified in point P1 in relation to point P3. The charts highlight the frequencies that generate a wider amplitude of the spectral response. Next, the transfer function, or spectral ratio, was determined using the technique of (Nakamura, 1989).

Chart 1. *Transfer function of the V1 dwelling*



Note: *Continuos line-X, discontinuous-Y*

Chart 2. *Transfer function of the V2 dwelling*



Note: *Continuos line-X, discontinuous-Y*

5. Discussion of the Results of the Structural Analysis

The results demonstrate that the average fundamental period of the V2 dwelling, with 0.1067 seconds, complies with the recommended range for a structurally sound house, between 0.08 to 0.12 seconds, established by (Hernández et al., 1979) in studies with instrumentations made in dwellings of the state of Guerrero, Mexico, in 1979, and by Arroyo et al. in 2010. However, they show that the V1 dwelling, with 0.1280 seconds, exceeds that range.

With the purpose of confirming the results obtained in the analysis of the dynamic properties of the V1 dwelling, where a high period was recorded, an alternative was applied to find out the contribution of the walls' strength in the event of seismic actions, based on the geometrical and physical characteristic of the prototype. In this perspective, a seismic analysis was made on the house structure, based on the static analysis method that is applicable to buildings whose height is below 30 m. The method consists in calculating the lateral force acting on the center of mass of the dwelling, which in turn will produce the effect equivalent to the seismic action (CFE, 2008).

Table 1 and Table 2 show the results of the analysis concerning the total load in the dwelling (Wi) and the acting shear force (Va). Table 3 shows the results obtained in the inspection of each structural axis of the V1 dwelling, which indicate that the masonry walls have a low vulnerability. Therefore, the safety degree of the V1 housing prototype is considered adequate and it does not require a detailed assessment for a potential structural reinforcement in the short term.

Table 1. *Total load calculation for the V1 dwelling; Wi*

Floor	Roof Load				Masonry Walls				Fc [(1)]	Wi
	Area	DL (Dead load)	LL (Live load)	W1 (Load 1)	WA (Wall area)	H (Aver. height)	W. V. (Weight volume)	W2 (Load 2)	1.10	ton
	m^2	kg/m^2	kg/m^2	ton	m^2	m	ton/m^3	ton		
1	52.16	56.74	20	4.00	3.68	2.70	1.50	14.92		20.82

Note: (1) Load factor for combination with seismic load (NTC, 2004).

Table 2. *Calculation of the acting shear force; Fi and Va*

Floor	Wi	Hi (1)	WH	C/Q (2)	Fi	Va
	ton	m	ton-m		ton	ton
1	20.82	2.70	56.20	0.43	8.88	8.88
Sum	20.82		56.20			

Source: *CFE, 2008 (Seismic Analysis-Static Method).*
Note: (1) *H = Average height of 2.70 m.*
(2) *C = 0.64 (Seismic Coefficient, Zone C, Type II Soil.*
Q = 1.5 (Seismic compartment in masonry with hollow concrete blocks with internal reinforcement); Parameters q1 to q5 and S define the geometry and the physical conditions of the structure by visual inspection (correction factors).

Table 3. *Seismic vulnerability by axis*

Inspection in axis X										Qx = 1.5
Floor	Vr (ton)	Va (ton)	Vr/Va	S	Ki = S(Vr/Va)	KQ (1)	KZ (2)	Condition	Category	Vulnerability
1	46.50	8.88	5.24	0.41	2.14	3.22	0.64	KQ ≥ KZ	1	Low
Inspection in axis Y										Qy = 1.5
Floor	Vr (ton)	Va (ton)	Vr/Va	S	Ki = S(Vr/Va)	KQ (1)	KZ (2)	Condition	Category	Vulnerability
1	27.18	8.88	3.06	0.41	1.25	1.88 t	0.64	KQ ≥ KZ	1	Low

Note: (1) *Strength coefficient of the structure.*
(2) *Seismic coefficient (NTC, 2004).*

6. Conclusions

The fundamental periods of vibration obtained in dwellings V1 and V2 are acceptable for a new structure; 0.1280 and 0.1067 seconds respectively. However, since the V1 dwelling slightly exceeded the range of periods for a structurally sound home, between 0.08 and 0.12 seconds maximum, according to (Hernández et al., 1979), an additional inspection was undertaken with the purpose of evaluating the contribution of the masonry walls' strength and, thereby, determining the dwelling's seismic vulnerability, which turned out to be of "Low Vulnerability". This indicates that the walls have a good resistance in the event of seismic actions and there is no risk in the V1 housing prototype.

Likewise, accelerometer recordings were obtained to determine the fundamental periods of the soil in each prototype, which were 0.1164 and 0.1219 seconds in the V1 and V2 dwellings, respectively. As observed, the fundamental periods of the soil are low and they confirm the rocky soil composition in the study area, with high resistance and low compressibility.

In conclusion, the results of the prototype analyses indicate that the structural efficiency in both dwellings is satisfactory. Likewise, the visual inspections did not evidence damage or degradation of the materials used in the construction of the masonry walls. Without a doubt, the elimination of the clay contained in the sand used in the block manufacture will improve the compressive strength of concrete. However, the washing procedure to separate the clay requires a large amount of water, which is not available in the sandbank, and its use would increase the cost of this construction material. Moreover, buying river sand in the city of Ocozocoautla, located 13 km from Ocuilapa de Juárez, means a 50% additional cost in relation to the local sand.

Furthermore, the study shows that the housing prototypes built by low-income families of the community of Ocuilapa de Juárez, based on a new proposal with walls made of three-cell concrete blocks, manufactured with local sand and reinforced with steel on the inside, fulfilling the current regulations (NTC, 2004), are within the range of structural safety, as their low seismic vulnerability was verified. Consequently, the prototypes constitute an alternative to increase the structural confinement level in the housing walls in this locality, and thus the residents can build their houses with improved safety conditions. Among other special features of the prototypes, their low construction cost stands out, given the materials used and the constructive procedures that are easily executed.

Finally, the scientific-technological proposal will contribute to solve the structural unsafety evidenced by housing with similar characteristics and, therefore, it will allow reducing the potential risks that residents could face due to telluric movements of a certain magnitude, thus benefiting low-income families living in rural communities of the state of Chiapas, Mexico or other Latin American countries.

7. Acknowledgements

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