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SEISMIC VULNERABILITY ASSESSMENT OF TWO RURAL HOUSING PROTOTYPES BUILT WITH CONCRETE HOLLOW BLOCKS, IN OCUILAPA DE JUÁREZ, CHIAPAS

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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 anchoring 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 that were built by families living in conditions of high marginalization in the town of Ocuilapa Juárez, Chiapas. The construction used existing materials in the place; stone in foundations, sand with high clay content (22%) in the preparation of concrete hollow blocks 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 common values for structurally 'healthy' dwellings. Also, the analyses carried out prove that dwellings are in 'low vulnerability' condition in the presence of medium magnitude earthquakes.

Keywords

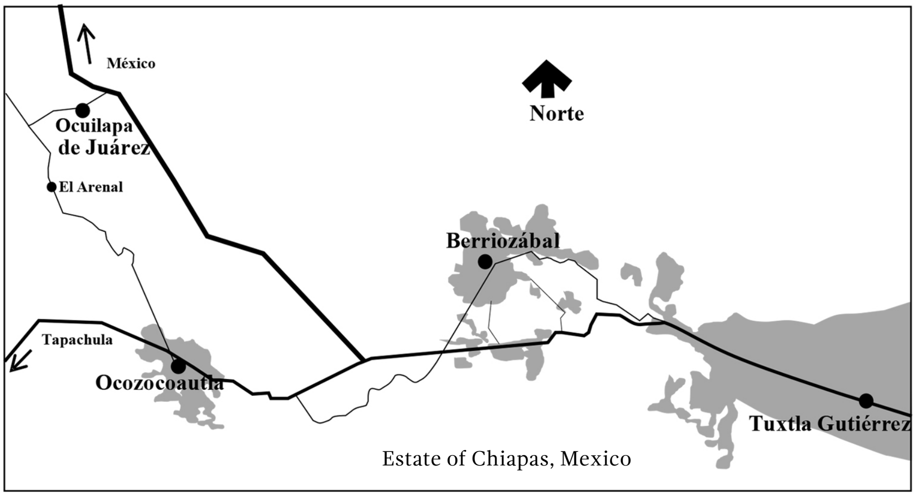
Housing prototype; rural housing; concrete hollow blocks; seismic vulnerability; earthquakes.

In the rural areas of the state of Chiapas and other Mexican entities, as well as in Latin America, there are houses built with wood, reed, palm, stone and soil, among other raw materials from nature; also, houses made with low-cost industrialized materials are identified, such as cardboard sheets and waste products: plastics, metal sheets, etc. The rural population, in a social condition of poverty and extreme poverty, builds their own homes with these characteristics, and in most cases, they have walls and roofs made of poor quality materials, dirt floors, do not have adequate spaces, they obtain little water for consumption and do not have drainage. These realities lead families to live crowded and in unhealthy and insecure conditions that prevent their economic and social development.

Consequently, the search for solutions that address the problem of rural housing for low-income families, has guided the research conducted by this working group to the analysis and construction of alternative housing prototypes, economically affordable, safe and with elements that offer hygienic environments for the inhabitants; in addition, consider the typology of local properties and traditional customs and uses. These housing proposals are intended to contribute to the improvement of rural habitat and to raise the families' quality of life.

The study presented was conducted in the town of Ocuilapa de Juárez in the municipality of Ocozocoautla de Espinosa, Chiapas, which is located 13 km northwest of the city of Ocozocoautla and 31 km from the city of Tuxtla Gutiérrez, capital of the state of Chiapas (image 1). The town has 3,921 inhabitants and 955 homes (INEGI, 2010 and 2013), and according to the figures of the National Population Council (2007), the majority of the inhabitants carry out primary activities and register a degree of "high" marginalization, referred to localities with lack of access to education, inadequate housing and lacking consumer goods.

Image 1. Location of Ocuilapa de Juárez,
Municipality of Ocozocoautla, Chiapas



In previous works (Escamirosa *et al*., 2006), it was identified that about 79.4% of the total housing in the locality are built with stone masonry foundation of the place; the walls of hollow blocks of concrete with two cells with vertical reinforcement only in the corners and intersections (without reinforcement in the openings of doors or windows), and in the horizontal sense, have reinforcement in the enclosure at the height of doors and windows, and, in some cases, in the rebar of walls; the roofs are structured with wood that supports the mud tile or zinc sheet roof. In general, there are houses built with inadequate procedures, they have little reinforcing steel (insufficient structural confinement); and, in addition, the mortar and concrete is made with sand from the place that contains 22% clay (without organic matter and with very high plasticity). These aspects directly influence the fissures and cracks present in the walls of a high percentage of homes and, consequently, allow to assert that they have a high level of vulnerability (Calvi *et al*., 2006 and Tesfamarian and Goda, 2013).

Between 2007 and 2008, five low-income families from Ocuilapa de Juárez built alternative housing prototypes. The existing materials were used in the locality, which due to their low cost, are commonly used by the inhabitants; likewise, it was considered to take advantage of their skills and experiences acquired in the traditional techniques that they have applied from generation to generation, for the construction of their own homes: Stone masonry foundation; walls with a new proposal of hollow blocks of concrete with three cells and reinforced with steel inside; roof with wooden structure and covered with clay tile. In the mortar for the elaboration of the hollow blocks and the concrete in the filling of castles and slabs, local sand was used, which due to the high clay content, is suggested as a mixture of sand-soil-cement.

Although the structure of the dwellings improved considerably, the average compressive strength of the hollow blocks of sand-soil-cement with three cells, obtained in the laboratory was 42.93 kg/cm², lower than the average resistance established in the standards NMX-C-404-ONNCCE-2012 and N-CMT-2-01-002/02 (SCT, 2002), which are respectively 100 and 60 kg/cm²; however, the average compressive strength of concrete for castles and slabs reached the minimum established resistance of 150 kg/cm² (NTCM, 2004). The low resistance to compression registered in the blocks is a consequence of the high content of clay in the sand of the place (22%) (Escamirosa *et al.*, 2016). In this sense, it is technically indisputable that the removal of the clay in the sand used would significantly improve the strength of the concrete; however, the water used to wash the sand or acquire clean sand from another place increases the cost of this material by 100%. For this reason, the work team decided to use the materials commonly used by the community for the construction of the houses.

This paper presents the analysis carried out in two prototypes built in Ocuilapa de Juárez, to determine the level of vulnerability of homes in the face of possible seismic scenarios. The measurements were made in each dwelling with accelerant-metric sensors and the average fundamental vibration periods were established, which are in the range of values recommended by Hernández, *et al.* (1979), corresponding to structurally sound housing (0.08 to 0.12 seconds). The above indicates that the system has the rigidity equivalent to a one-level system, with a "sufficient" wall density. It is important to add that the fundamental period obtained through environmental vibration override the results reported in the structure, since it includes the interrelation of structural and non-structural elements.

2. BACKGROUND

2.1 Field research

As already mentioned, in 2005 the first studies were carried out in Ocuilapa de Juárez. The field works allowed to identify the characteristics, the materials used and the conditions of the existing structural elements in 486 homes. The results show that out of the total homes, 70.37% have polished cement floors and 16.67% of ground; the walls, 79.42% are made of hollow concrete blocks with two cells, 9.05% with annealed mud partition and the remaining, 11.53% use: wood, adobe and bajareque (vernacular constructions), and even waste materials such as cardboard and sheet. Regarding the roofs, 41.14% of the houses have galvanized sheet, 35.18% are concrete and 20.57% are tile from the region. In a detailed way, the houses built with wood, waste materials, dirt floors and those built ancestrally with adobe or *bajareque*[1] walls were examined. Without exception, these houses are in a very poor state of conservation and present unsafe and unhealthy conditions.

On the other hand, in homes built with annealed mud walls, solid blocks or concrete hollows with two cells, it was observed that their state of conservation is greater; nevertheless, the structure does not guarantee security for its occupants due to the following conditions: Of the total of the houses, 62% have masonry foundations with local stone and the rest of reinforced concrete. In both cases the elements are suitable for the type of rocky soil in the area; however, 79.42% of the houses are built with hollow concrete block walls with two cells and of these, 30.55% have cracks as a result of which the walls only have vertical reinforcement steel in the corners and intersections, without considering the spans of doors and windows, and in the horizontal sense, most only have a slab of enclosure at the height of doors and windows. The houses were built with few confining elements in their walls (images 2 and 3), which are insufficient according to current technical standards (NTCM, 2004). In fact, they do not comply with what is specified in the reinforcement section for structural integrity for rural housing and the materials that give rise to the system do not comply with the specifications of said norm.

Image 2. Inside of a hollow block house

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[1] According to Moya (1988), the bajareque is built with rows of wooden horcones driven into the ground that form the walls and between these a network of interwoven rods is placed, which are then filled on both sides with mud flat, mixed with grass or straw.

Image 3. Typical house with hollow block walls.

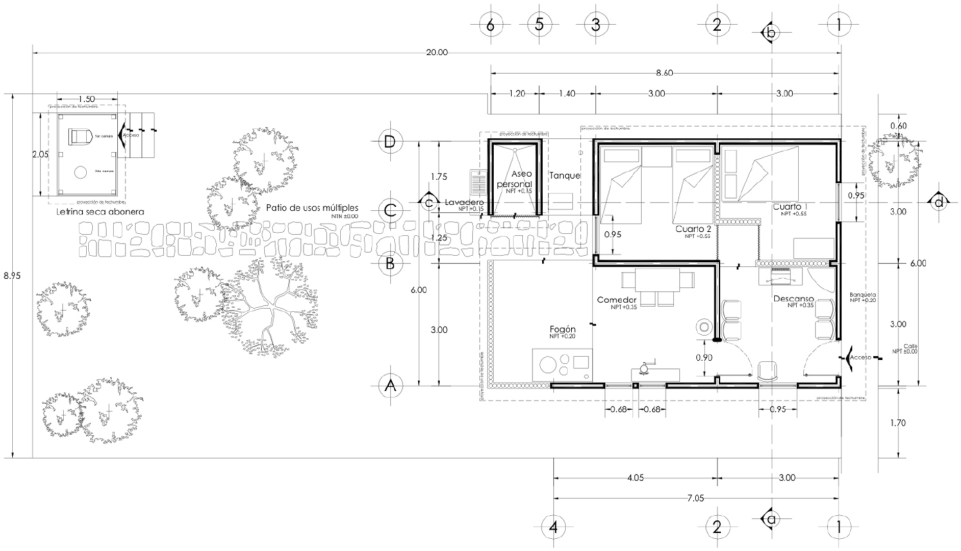
Analyzes were made in the Materials Laboratory of the Faculty of Architecture of the Universidad Autónoma de Chiapas, to determine the physical and petrographic properties of the sand used, in addition to the resistance to simple axial compression, the specific weight and the absorption of the concrete hollow blocks with two cells, commonly manufactured by the inhabitants of Ocuilapa de Juárez. The results show that the local sand, obtained from the "El Arenal" material bank, located 4km from the town (image 1), contains 22% clay without organic matter with very high plasticity; this sand has a cost 100% lower compared to the river sand that can be obtained in the city of Ocozocoautla. The analyzes indicated that the average resistance to simple axial compression of the mortar made with this type of sand was 30.19 kg/cm^2, lower than that established in the standards (Minimum resistance = 60 kg/cm^2: NCMT-2-01-002/02 (SCT, 2002) and 100 kg/cm^2: NMX-C-404-ONNCCE-2012).

The previous conditions allow to notice that the houses can be vulnerable to the seismic effects. These are frequent in the state of Chiapas, because it is located in an area with high seismic activity, mainly due to the subduction of the Cocos tectonic plate under the North American plate (García and Suárez, 1996). This is only one of the five seism genic sources that occur in this region. For this reason, and because the seismic-resistant system of this type of housing is based solely on vertical load-bearing elements, there is a risk that the damages identified in the walls of dwellings built with hollow concrete blocks will become more acute, and may even cause partial or total collapses, as a result of seismic movements.

2.2 Characteristics of rural housing prototypes

During the period from 2006 to 2008, through research projects financed by the Mixed Fund of CONACYT and the Government of the State of Chiapas (FOMIX-Chiapas) as well as by the Institutional Research System of the Universidad Autónoma de Chiapas, four housing prototypes in Ocuilapa de Juárez were built. In the design of the spaces and functional elements of the houses, the participation of the low-income families selected was considered in order to know their comments in relation to the proposals, to uses and customs, image, typology of the community and natural environment, among other aspects (image 4).

Image 4. Architectural plan of a rural home prototype



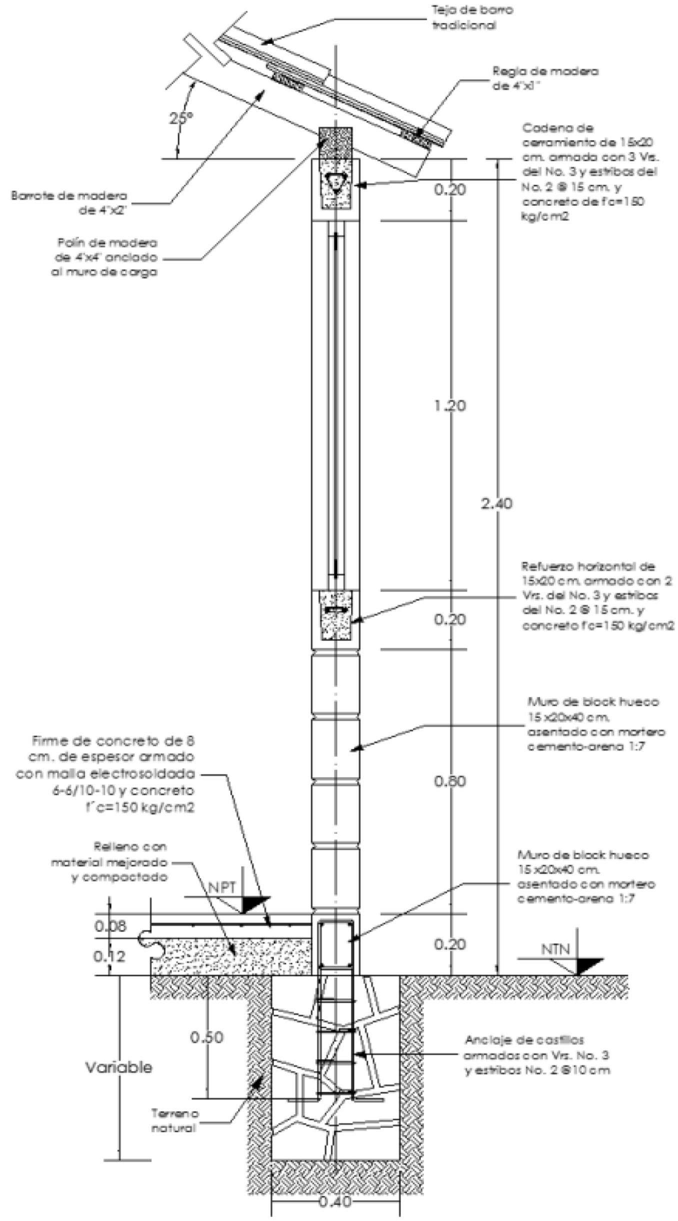
In the construction of the walls, a new proposal of a three-cell hollow block made of sand-soil-cement concrete was used (sand from the location was used), which included the placement of reinforcing steel in the interior, both in the vertical as horizontal direction and distributed to the top and the length of the walls, in accordance with the standards for masonry walls with hollow concrete blocks (NTCM, 2004). The dimensions of the hollow blocks were 15x19x40 cm (600 cm^2 of gross area), with three section cells each of 9.67x9.67 cm, obtaining 319.47 cm^2 of net area (53.25%). The internal and external thicknesses of the walls of the blocks were on average 2.5 cm (images 5 and 6).

Image 5. Mold for the manual elaboration of blocks

Image 6. Hollow block pieces with three cells

For the prototypes, the existing materials were used: sand, stone and wood; also, the procedure applied was assisted self-construction, which consisted of offering technical assistance to the selected families. In this regard, training courses, technical advice, monitoring and quality control were given during construction. These activities were carried out by the work team and the architecture students of the University.

Image 7. Structure of housing prototypes; cross-section



In general, the structure of the dwellings improved; however, the high content of clay (22%) contained in the sand used for the manufacture of the three-cell concrete blocks, resulted in obtaining an average resistance to simple compression of 42.93 kg/cm². This result is lower than 60 kg/cm² established in standard N-CMT-2-01-002 / 02 (SCT, 2002), at 100 kg/cm² of the standard NMX-C-404-ONNCCE-2012, and at 40 kg/cm², which is the value specified by the NTC of masonry of the RCDF (NTCM, 2004) for a typical mortar II; for its part, the concrete used in the castles and walls' slabs, recorded an average compressive strength of 150 kg/cm², which corresponds to the minimum indicated in the current standard (NTCM, 2004).

The walls of the houses were designed and constructed as structural elements, based on Mexican standards, specifically the "Normas Técnicas Complementarias para Estructuras de Mampostería y para Diseño por Sismo" (NTCM, 2004). For this, the location of Ocuilapa de Juárez was considered in the seismic zone "C" of high risk, according to the seismic regionalization of Mexico (CFE, 1993), and the type of soil in the study area.

The following is a description of the structuring of the houses' prototypes whose construction was completed in August 2008; the specific details are described in the Manual for the Self-Construction of Living and Sanitary Services (Escamirosa *et al.*, 2016).

2.3 Structure of prototypes

The foundations were built with stone masonry extracted in areas surrounding the building and was joined with mortar based on cement and sand from the place with a 1:4 ratio, with a simple average compressive strength of 92.30 kg/cm². This was higher than the minimum resistance established in the NTCM 2004 (40 kg/cm²) and lower than the maximum (125 kg/cm²). According to these standards, in masonry foundations the slope of the inclined faces, measured from the edge of the wall or slab, should not be less than 1.5 (vertical): 1 (horizontal). However, in the area it is common to find foundations with a rectangular prism shape (without screw hooks), so the section used in the foundations of the houses was rectangular, 40 cm wide, with a variable depth according to the topography of the work site.

In the constructive process, the anchoring of the vertical reinforcement steel was made in the castles of the corners and in the intersections of walls; likewise, on the foundation, a slab or chain of reinforcement was placed with a section of 15x20 cm, concrete of 150 kg/cm² and reinforcement with ARMEX 10x15x4" (image 7).

The walls were built based on the standard (NTCM, 2004), reinforcing the hollow blocks, with steel bars in both the vertical and horizontal directions. The vertical reinforcement (castles), located at the corners of the walls, occupied three cells of the block, and four at the intersections. In addition, two consecutive cells were reinforced at the ends of the door and window openings. In the case of walls without openings (doors or windows), a 3/8" rod was placed and the cell was filled with mortar every 75 cm. The reinforcement used was with corrugated steel rods DA-42 with fy = 4,200 kg/cm² and concrete made in situ with local sand with a f'c = 150 kg/cm² (images 8 and 9).

Image 8. Construction of reinforced walls

Image 9. Intermediate horizontal reinforcement

The roofs were built gabled, with wood structure of the place; 10x10 cm bricks were placed in the external perimeter walls, including the ridge walls, which supported the 5x10 cm bars, in order to reduce the possible deformations of the wood and offer greater safety.

3. ANALYSIS OF THE HOUSING PROTOTYPES' VIBRATION PERIODS

Field work was carried out in Ocuilapa de Juarez in two housing prototypes (V1 and V2), inhabited by selected families with low income. The accelerometer measurements started on October 3, 2014, proceeding to perform the corresponding study to determine the fundamental vibration periods of the structure and soil. The equipment used was a triaxial Episensor accelerometer and an Altus K2 recorder, both from kinemetrics. Based on the results obtained, the necessary analyzes were carried out to determine the structural dynamic properties (images 10 and 11).

Image 10. Location of house V1

Image 11. Satellite photograph of the location of V1 and V2

Source: Courtesy of Google Maps ©, 2010

House V1, with geographic coordinates: 16°51'28.99" N and 93°24'53.62" W, is located on 16 September street and is owned by Crescencio Pérez Pérez. The house was built approximately six years ago. House V2, with geographic coordinates: 16°51'30.52" N and 93°24'43.96" W, is located on Ignacio Allende street and its owner is Norbel Jiménez Pérez (images 10 and 12).

Image 12. Location of the house V2

Image 13. Placement of the sensor in P3 of V2

Figure 13 shows the placement of the accelerograph in the house V2 at the indicated point P3, which corresponds to the geometric center. The records obtained were in three orthogonal directions of 30 seconds duration and the results obtained in the analysis made, allowed to establish that the periods of fundamental vibration in average per dwelling are the following:

Housing V1 with 0.1280 seconds and housing V2 with 0.1067 seconds; the corresponding floor in the analyzed areas: V1 with 0.1164 seconds and V2 with 0.1219 seconds.

Images 14 and 15 show the locations of the acceleration sensor in the structure of each dwelling (P2, P3 and P4) and in the free field (P1; floor).

Image 14. Location of the house V1 sensor

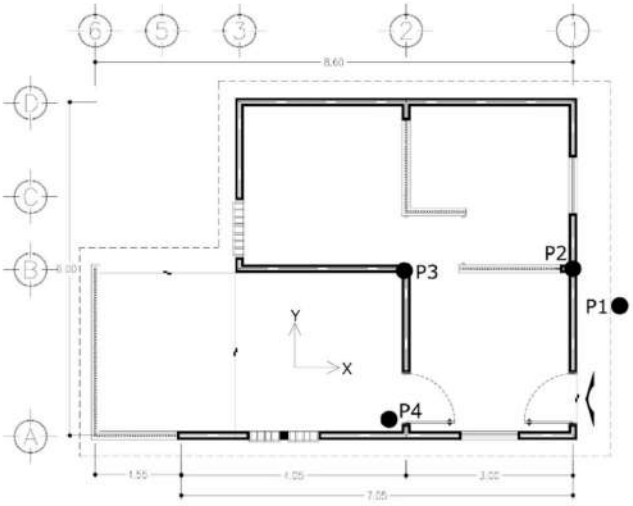
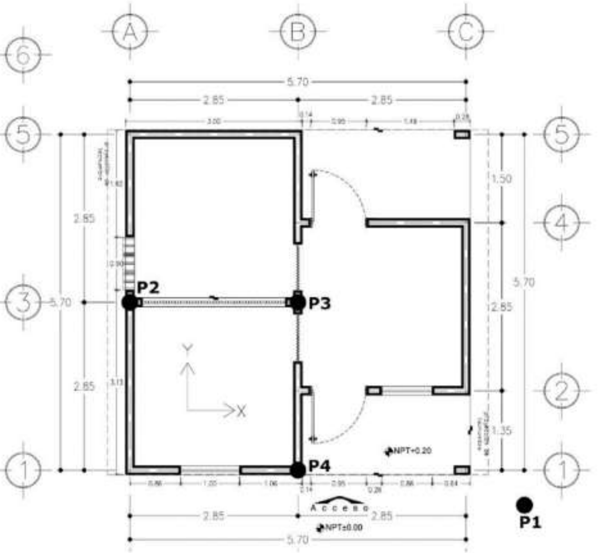


Image 15. Location of the house V2 sensor



Next, Images 16 and 17, show the transfer functions in each dwelling; the continuous function corresponds to the short address of the dwelling (x), and the dotted function for the long function (y). These functions were obtained by dividing the Fourier spectra calculated from the accelerometer records in the center of each dwelling (point P3), among the ground ones (point P1). The relationship of both registers allows to establish how the response at point P3 is amplified with respect to point P1. In the images, the frequencies that generate the greatest amplification of the spectral response are highlighted. Right after, the Transfer Function, or spectral ratio, was determined using the Nakamura technique (1989) and the procedure for determining the transfer functions suggested by Lermo and Chávez-García (1994). Finally, the graphs of the transfer functions of houses V1 and V2 indicate the frequencies that, according to the technique applied, respectively represent the fundamental vibration frequencies for said dwellings, of 7.81 Hz (0.128 s) and 9.3 Hz (0.1067 s). It is important to note that according to Lermo (1994), the values of the fundamental period of the structures do not necessarily correspond to the crest of greater amplitude, but depend on the form they take.

Image 16. Transfer function of house V1
(Continuous line-X, discontinuous-Y)

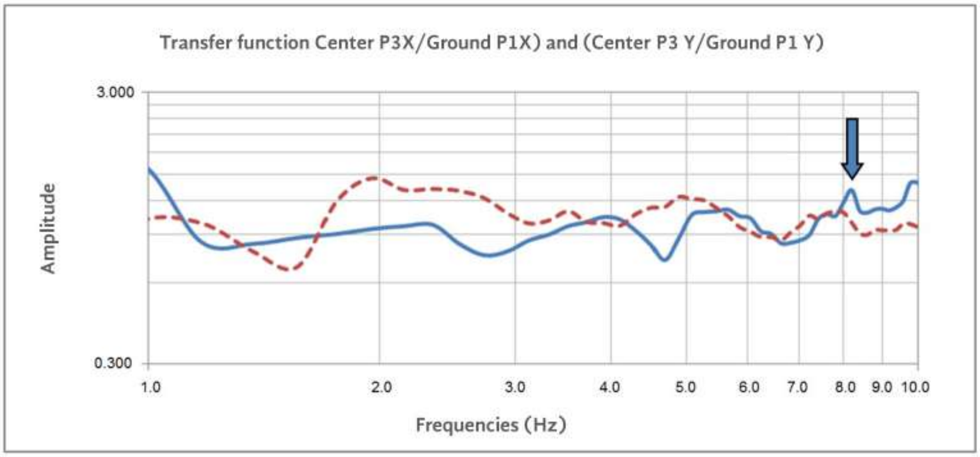
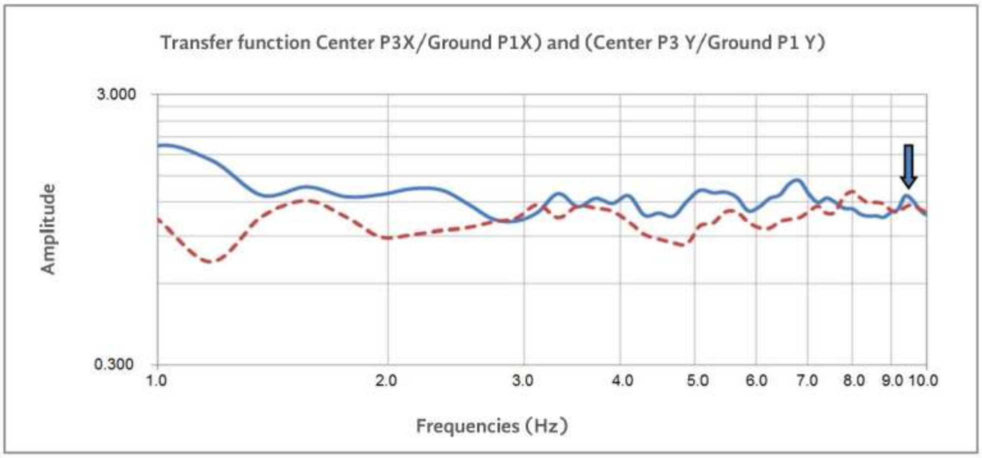


Image 17. Transfer function of house V2
(Continuous line-X, discontinuous-Y)



4. DISCUSSION OF THE STRUCTURAL EVALUATION RESULTS

The results obtained show that the average fundamental period of housing V2, with 0.1067 seconds, is within the recommended range for a dwelling considered structurally healthy, between 0.08 to 0.12 seconds, a parameter established in 1979 by Hernández, *et al*., and by Arroyo, *et al*., in 2010; both studies for instrumentation carried out in homes in the state of Guerrero, Mexico. On the other hand, housing V1 with 0.1280 seconds is slightly above that range. It is important to clarify that these values are an indirect generalization of the rigidity of the structural system. Additional elements must be used to be able to affirm if the vulnerability is low or not, especially when the period of construction and soil are similar. However, in this work the periods detected in both houses were taken as parameters indicative of the existence of an adequate walls density in the dwellings.

With the intention of confirming the results obtained in the evaluation of the dynamic properties of housing V1, because it registered a high period, an alternative was applied to know the contribution of the resistance of the walls to seismic actions, based on the geometric and physical characteristics of the prototype. For this, the seismic analysis was carried out on the house structure, based on the static analysis method, applicable to buildings with a height of less than 30 m, and which consists of calculating the lateral force acting in the mass center of the dwelling, which in turn will produce the equivalent effect to the seismic action. This analysis does not consider the effects of torsion, and can only be applied when the eccentricities are less than 10%, because it ignores the deformations by shear (CFE, 2008).

Tables 1 and 2 present the results of the analysis of the total load in the house (Wi) and the acting shear force (Va). Table 3 shows the results of the review of each structural axis of housing V1, and show that, according to the seismic hazard specified by the Civil Works Manual (CFE, 1993) for the study area, the masonry walls have "low vulnerability", so the degree of security of the V1 housing prototype is adequate, and does not require a detailed evaluation for possible structural reinforcement.

Table 1. Calculation of the total load of the house V1; Wi

Between floor	Cargo on deck				Masonry walls				Fc (1)	Wi
	Area	CM (Dead weight)	CV (Live load)	W1 (Load 1)	Am (Wall area)	H (Average height)	P. V. (Weight volume)	W2 (Load 2)	1.10	ton
	m2	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

Notes: (1) Load factor for combination with seismic load (NTCM, 2004).

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

Between 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
Amount	20.82		56.20			

Source: CFE, 1993 (Seismic analysis-static method)

Note: (1) H = average height of 2.70 m;
(2) C = 0.64 (Seismic coefficient, Zone C, Type II terrain, according to the Civil Works Manual of the CFE (CFE, 1993).
Q = 1.5 (Seismic behavior factor in masonry with hollow concrete blocks with internal reinforcement); Parameters q1 to q5, and S define the geometry and physical conditions of the structure by visual inspection (correction factors).

Table 3. Seismic vulnerability per axis

Review on the X axis — Qx = 1.5

Btw. floor	Vr (3) (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

Review on the Y axis — Qy = 1.5

Btw. floor	Vr (3) (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	0.64	KQ ≥ KZ	1	Low

Notes: (1) Resilient coefficient of the structure.
(2) Seismic coefficient (CFE, 1993).
(3) In the analyzes, a design shear stress vm* = 3.0 kg / cm^2 was considered, criterion for masonry based on hollow blocks joined with type II mortar.

On the other hand, the fundamental periods of the soil in each prototype based on the accelerometer records, were of 0.1164 and 0.1219 seconds in dwellings V1 and V2, respectively. As it is observed, the fundamental periods are low and confirm that the composition of the soil in the study area is of high resistance and low compressibility. However, it is important to mention that the periods of soil and the structures studied are very close to each other, which may not be favorable during the response to intense seismic excitation.

CONCLUSIONS

The fundamental periods of vibration obtained in housing prototypes V1 and V2; 0.1280 and 0.1067 seconds, respectively, are acceptable for new structuring; however, as prototype V1 slightly exceeded the range of periods in a structurally healthy housing, considered between 0.08 to 0.12 seconds maximum. In that house an additional revision was carried out which purpose was to evaluate the contribution of the resistance of the masonry walls and with it, to determine the seismic vulnerability. This was "low", which indicates that the walls have good resistance to seismic actions.

In conclusion, the results obtained in the evaluation of the seismic behavior carried out in the prototypes V1 and V2, indicate that the structural efficiency in both houses is satisfactory, which shows that the housing prototypes built by low-income families in the community of Ocuilapa de Juárez, from a new proposal with concrete block walls with three cells, made with local sand and reinforced with steel in the interior according to current regulations (NTCM, 2004), are within the range of adequate structural security when verified that they register low seismic vulnerability.

Therefore, the prototypes presented are a good option that exemplifies how the level of structural confinement can be increased in the dwellings' walls of that locality. Following this alternative and disseminating it, it could be possible for the inhabitants to build their homes with better security conditions. Other peculiarities of the prototypes are: The low cost of its construction, for the materials used; and constructive procedures, easy to execute.

Finally, the raised technological proposal could contribute to solving the structural insecurity presented by homes with similar characteristics. Its application, therefore, would allow reducing the possible scenario of seismic risk that could be suffered by the inhabitants of popular housing, constituted by low income families living in rural communities of the state of Chiapas, Mexico or Latin American countries.

THANKS

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