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DAMAGE CURVES FOR NON-ENGINEERING CONFINED MASONRY BUILDINGS

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Abstract

Masonry buildings are the mostly used structures in urban areas of Peru. Most of these buildings has been built using non engineering techniques, and they are considered weak buildings against earthquake. Since Peruvian coastal areas have more than 60% of non-engineering buildings, the development of damage curves to estimate earthquake response of building from seismic demand is required.

For that purpose characterization of masonry capacity of walls is estimated using the CISMID database of masonry walls test collected in 20 years. Damage limits proposed in the database are used for two kinds of masonry units: horizontal hollow bricks (is called also tubular bricks) and handmade solid bricks. Both of these masonry units have lower resistant capacity, and represents lower limit values from the recommended for bearing walls by NTE-070 Peruvian standard. Structural modeling were performed developing nonlinear earthquake response analysis for 1563 models of non-engineering buildings. Seismic demands of five Peruvian earthquakes are used to compute maximum seismic response of these models that represents typical masonry buildings which are likely used on urban emerging areas for cities in the coastal of Peru.

From the results of the nonlinear earthquake response, ratios between peak ground acceleration and drift response were evaluate. These data produce a series of damage curves as PGA function to find drift response. Then for the evaluation of the seismic risk as function of peak ground acceleration (PGA), a process of regression of various types of damage masonry buildings developed by the authors previously, was used. In this way, the quantifying of the repair costs relate with the seismic demand, generate damage amount curves in terms of percentage of repair cost of the building and PGA. In order to check damage amount curves, comparison between damage survey of Pisco city and simulation using the curves was performed, with good agreement.

Keywords: non engineering masonry, fragility curves, damage curves

1. Introduction

Non engineering buildings in Peru represents 60% of the stock of buildings in urban areas. This kind of building is characterize by non-confine elements on wall boundaries and non-collar beam in their story level. In addition there are buildings who presents confinement but use as material horizontal hollow bricks which are fragile in resistance of gravity and seismic loads. The reason, the low cost of these bricks. Under this scenario, the generation of damage curves for seismic demand to be used in the evaluation of seismic risk is an important tool for the evaluation of seismic response, and prediction of seismic risk especially in emerging zones in the country. In this paper damage curves using the damage limits proposed by CISMID database of masonry walls test collected in 20 years [1], are developed using two kinds of masonry units: horizontal hollow bricks and handmade solid bricks (see Fig. 1), both of them have lower resistant capacity and represents lower limit values from the recommended for bearing walls by NTE-070 Peruvian standard.

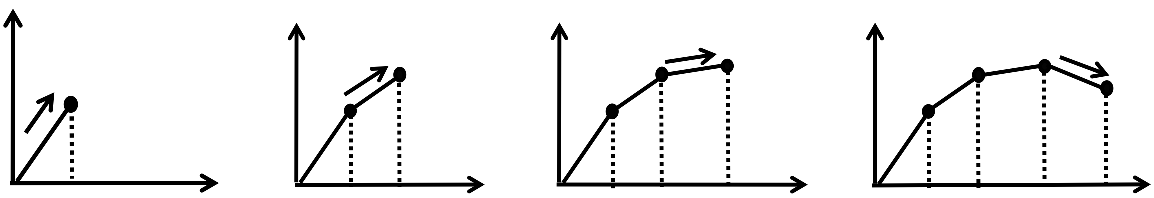
(a) (b)

Fig. 1 Horizontal hollow brick (a) and handmade solid brick (b)

2. Behavior of Masonry Walls

2.1 Failure sequence of masonry

The behavior of masonry wall is obtained from cyclic test through experimental behavior curves who provide us the idea of the evolution of structural damages (cracks) on confined masonry walls. For an incremental loading the damage is defined according to the following stages (Fig. 2).



(a) (b) (c) (d)

Fig. 2 Process of limit states on confined masonry walls

(a) Elastic Stage: That occurs when the wall has elastic behavior with an initial stiffness (K_0) until the first cracks are found on confined masonry walls, which is called Cracking Point (PC). When the small displacements and strength are given by the cyclic lateral loading test, the horizontal cracks appears in columns.

(b) Post-Elastic Stage: After the first cracks, there are an increment of the cracking until the initial diagonal cracks appears, which is called Yielding Point (PY). Then the confined masonry wall shows a slope post–elastic stiffness (K_1). This stiffness has less value than the initial.

(c) Yielding Stage: During this stage, the large deformation with a slight strength increment, with a huge stiffness reduction (K_2) until reach the Maximum resistance (PM) and try to keep constant until the stiffness and resistance goes down at the same time there are an increment of the diagonal cracks.

(d) Ultimate Stage: The stiffness decreases with a negative slope (K_3) with a drastic reduction of the resistance until reach the failure of wall, for this research is considered 20% of the strength reduction, which is called Ultimate Point (PU).

In Fig. 3, the states of the confined masonry and stiffness degradation is presented, obtaining stiffness for each stage (K_0, K_1, K_2 and K_3).

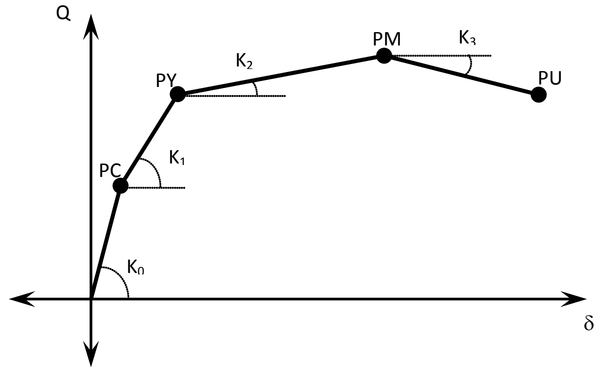


Fig. 3 Limit States and Stiffness Degradations

Table 1 Ratios of Stiffness Parameters of Masonry [1]

RATIOS	K_0 (tonf/cm)	K_1/K_0	K_2/K_0	K_3/K_0
Minimum	12.745	0.052	0.000	-0.322
Maximum	265.344	0.696	0.200	0.000
Average	94.757	0.314	0.051	-0.051
Stand. Dev.	49.789	0.149	0.040	0.068

2.2 CISMID Database of Confined Masonry Walls

In the last 20 years the structural laboratory of CISMID-FIC-UNI had investigate masonry walls from materials likely used in Peru such factory made bricks, handmade solid bricks, horizontal hollow bricks among others from different locations in the country. The experimental results has been collected and are share online on web page www.cismid-uni.org/wallx [1] where behavior curves and parameters from confined masonry walls test are presented. Experimental results are collected from 30 typical masonry walls subjected to axial load (simulating weight of upper floors) and lateral loads (simulating seismic loads). These specimens are subjected to reversal lateral loading (cyclic), the predominant behavior of these walls was the flexural-shear failure, because the initial cracks appear on columns (Flexural Failure), then increase with the increment of the lateral displacement; then, cracks are expanded onto the wall, and diagonal cracks appear (Shear Failure). In Fig. 4 is presented a sample of this database of results conducted at CISMID. Details of the capacity model for masonry wall area presented in Table 1 and Table 2 from experimental data base of CISMID. More details are presented in reference [1].

Table 2. Ratios of Drifts of Typically Masonry Walls [1]

RATIOS	$\delta c/h$	$\delta y/h$	$\delta m/h$	$\delta u/h$
Minimum	0.0001	0.0001	0.001	0.004
Maximum	0.004	0.009	0.015	0.016
Average	0.001	0.002	0.007	0.011
Stand. Dev.	0.001	0.002	0.003	0.003

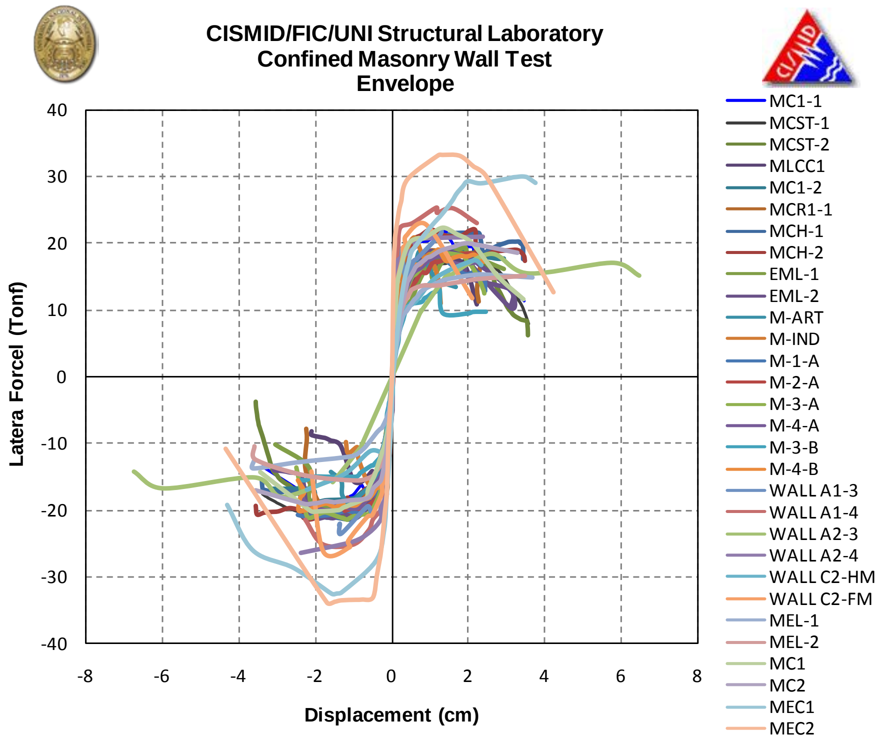


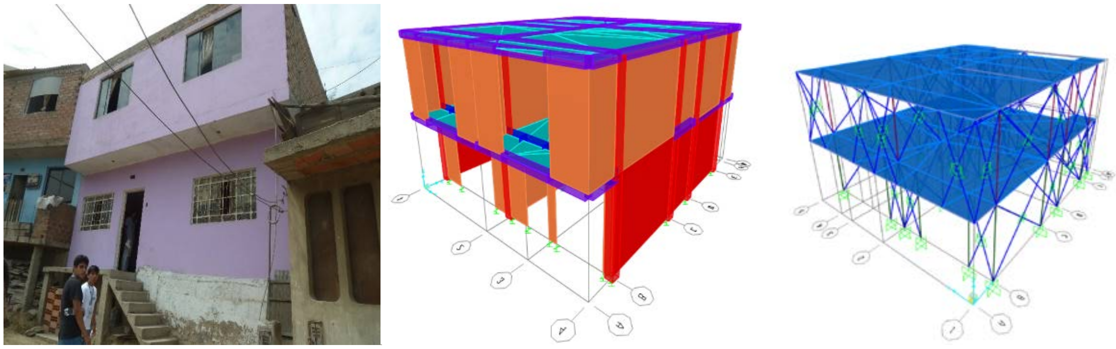
Fig. 4 Sample of database behavior curves

3. Generation of Damage Curves

For the generation of damage curves structural models from representative dwellings of emerging zones in Lima city has been considered for the estimation of the response by nonlinear seismic analysis. In each evaluation, the skeleton curves obtained from the CISMID database has been considered for the representation of the masonry walls, which are reduced to nonlinear spring model, taken into account the variation of the materials, number of stories (Np), and amount of walls (DM %). Here two kind of brick units for the walls has been considered: walls with handmade bricks and walls with horizontal hollow bricks.

3.1 Numerical models for two kinds of masonry

Numerical simulation are carried out by nonlinear time history analysis of tridimensional model using a computing program of structural analysis. Masonry walls are idealized spring skeleton curves using the CISMID data base of two kinds of masonry (walls with handmade bricks and walls with horizontal hollow bricks) where parameters were investigated by Cardenas et al. 2014 [1]. Then shear springs were considered to represent the inelastic behavior of confined masonry on these non-structural buildings as the example presented in Fig. 5 where it is possible to observe the diagonal springs that represented the walls as diagonal struts in the (c) right side figure.



(a) Example dwelling (b) Elastic Model (c) Inelastic Model

Fig. 5: Non-structural building and its representation

Models were demands by five records of Peruvian seismic ground motions [2, 3] which are presented in Table 3:

Table 3 Records of Peruvian seismic ground motions used on time history analysis

Record	**Date**	**PGA (g)**
Atico	24/11/2001	0.295
Lima	17/10/1966	0.269
Lima	03/10/1974	0.192
Pisco	15/08/1997	0.488
Satreps	Synthetic 28/10/1746	0.900

In order to use the records on the simulated earthquake demand to the structural model, the signal was normalized from 0.150g to 0.600g, to produce a range of seismic responses of the building.

3.2 Seismic responses and damage criteria

CISMID database and discussions among the authors produce average damage range set as drift values for two kinds of masonry walls: horizontal hollow brick wall and handmade brick wall. Initial cracking on the walls appears in a range between zero and 0.00125. Yield point produce by opening of diagonal cracks and yield on the reinforcement of confined elements, appears by a drift 0.002 to 0.0025. Maximum capacity on this kind of walls is likely produce in a drift range between 0.004 and 0.005, when the diagonal crack opens more than 3 mm. Finally the failure appears for maximum range between 0.01 and 0.015, when the slope of the capacity curve (stiffness) became negative.

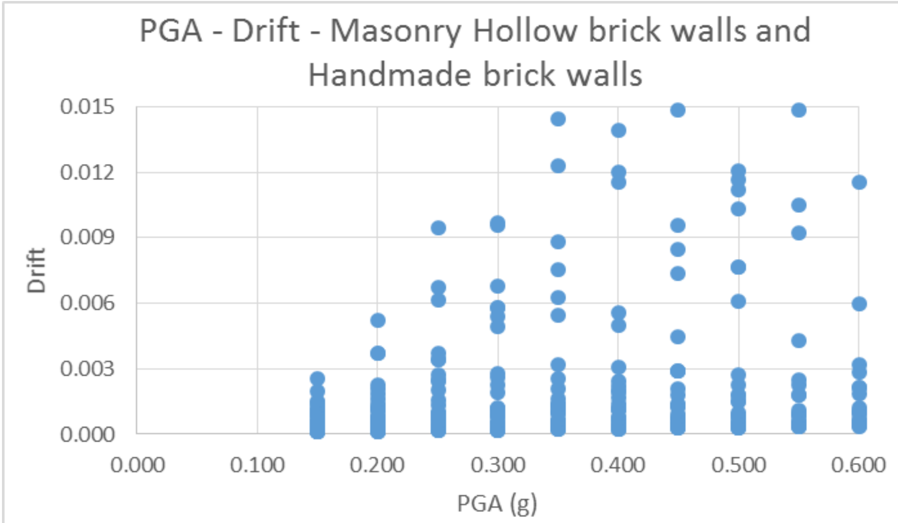


Fig. 6: Horizontal hollow bricks and handmade bricks masonry models nonlinear earthquake response

Considering the failure sequence presented in item 2.1, and the damage criteria adopted on this section, nonlinear earthquake response analysis was developed for 1563 models of non-engineering buildings as was the example presented on 3.1. Maximum drift on each model ratio with the peak ground acceleration (PGA) for the 5 models normalized from 0.150g to 0.600g are presented on Fig. 6. Review of this results was performed for re-analyze those models where responses gave out of range.

4. Damage Curves for horizontal hollow bricks and handmade bricks non-engineering structures

The results from time history analyses in terms of PGA and drift are plotted to produce damage curves for non-engineering buildings models with weak masonry materials. These curves represents the earthquake response on horizontal hollow bricks structures and handmade bricks structures, providing damage curves in terms of ratio between PGA and maximum drift. In Fig. 7 a selected number of maximum drift of the model and PGA is presented. Here parameters such number of stories (Np), wall density (DM) and type of brick (Handmade or Horizontal hollow).

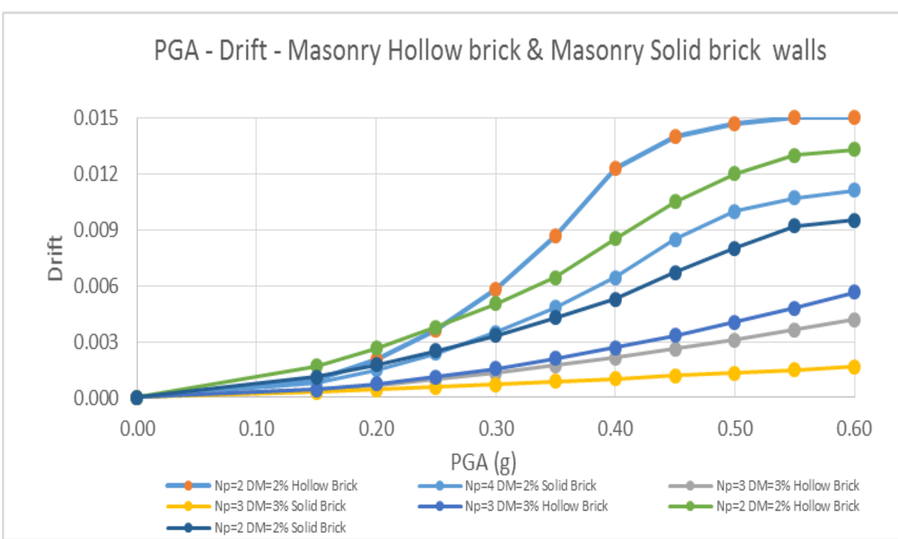


Fig. 7: Damage Curve PGA – Drift on non-engineering structures

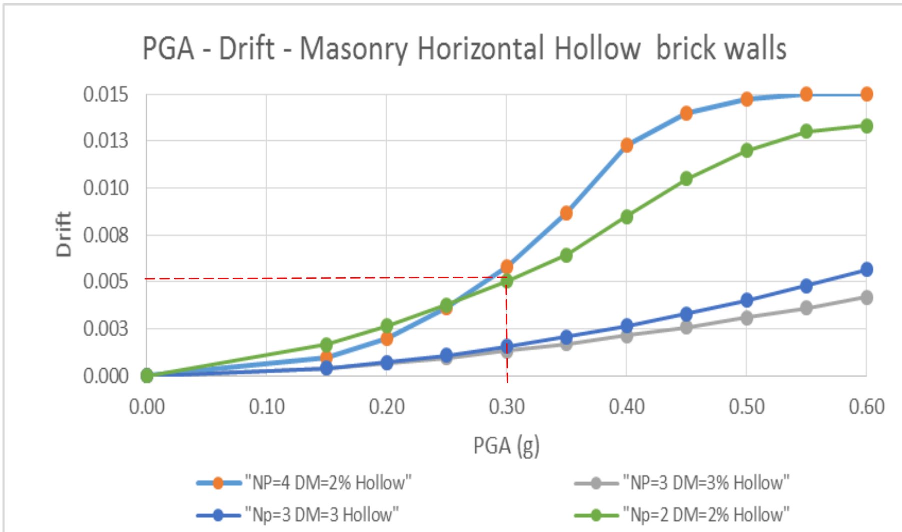


Fig. 8: Damage Curve PGA – Drift on non-engineering structures with horizontal hollow bricks

Fig. 8 and Fig. 9 present the damage curves for masonry models with handmade brick walls and masonry models with tubular brick walls respectively. Here the split of the curves shows that handmade brick models are better than tubular brick wall models due to their responses are small during earthquakes. Also, after 0.300g horizontal hollow walls increase considerable the drift response on the models reaching 1/150 at 0.600g. On the other hand, masonry handmade brick models after 0.400g increase softly the drift response reaching drift of 1/100 at 0.600g. Therefore horizontal tubular brick walls are weaker than handmade brick wall on the models.

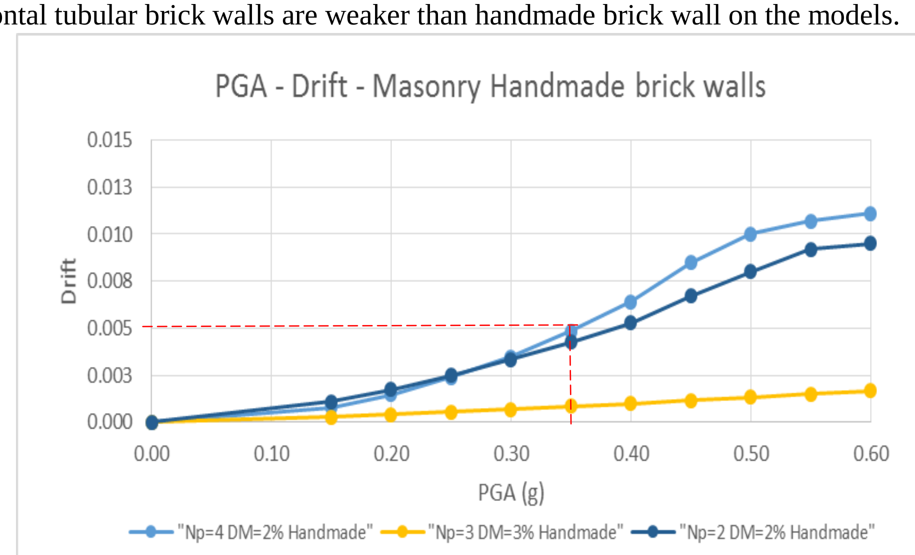


Fig. 9: Damage Curve PGA – Drift on non-engineering structures with handmade bricks

5. Estimation of Seismic Response with Damage Level Estimation

A seismic response simulator with damage level estimation (Simulador Respuesta Sísmica y Nivel de Daño SRSND in Spanish) is used implementing the developed damage curves. Details of the development of this software are presented in reference [5]. This simulator is used as predictor of the repair cost for a damage level as a consequence of an input acceleration of the ground (PGA).

For the estimation of the seismic response is computed by an approximate method based on equivalent single degree of freedom system under the demand of peak ground acceleration of the soil where the structure has been build. For that purpose seismic hazard of the location is used as a first input. Next a catalog of building types that represent the study zone is needed. Therefore a field survey for typify the buildings must be developed. On the survey several variables are consider: seismic demand acceleration, material of the building, number of stories, structural predominant system, state of conservation, irregularities of plant, height and shape. With these data the appropriate damage curve is selected for a deterministic value of PGA to compute the inter story drift response for the building.

A process of regression of various types of damage and quantifying the repair costs relate with the distortion of the seismic response (Δδj/hj) in each building. This repair cost (Cr) is expressed as the percentage of the cost of the structure, considering λ and ε parameters of structural vulnerability for the structural system and the type of repair involved for the materials involved.

$$C_r = \left[\left(\frac{\Delta\delta_j}{h_j}\right)/\lambda\right]^{\varepsilon}/100 \tag{1}$$

Considering the curves with larger drift response, the risk evaluation curves in term of damage amount express as percentage of repair cost (retrofitting cost estimation) for the models [4, 5], which is a function of the evaluated maximum drift earthquake response, are presented on Fig. 10 for the case of models with masonry walls with tubular brick. Here the two curves express the larger probable response for models, one for confined masonry and another for unconfined masonry walls. It is possible to read that in these models will start the condition of heave damage after 0.350g for unconfined walls and for confined walls after 0.500g.

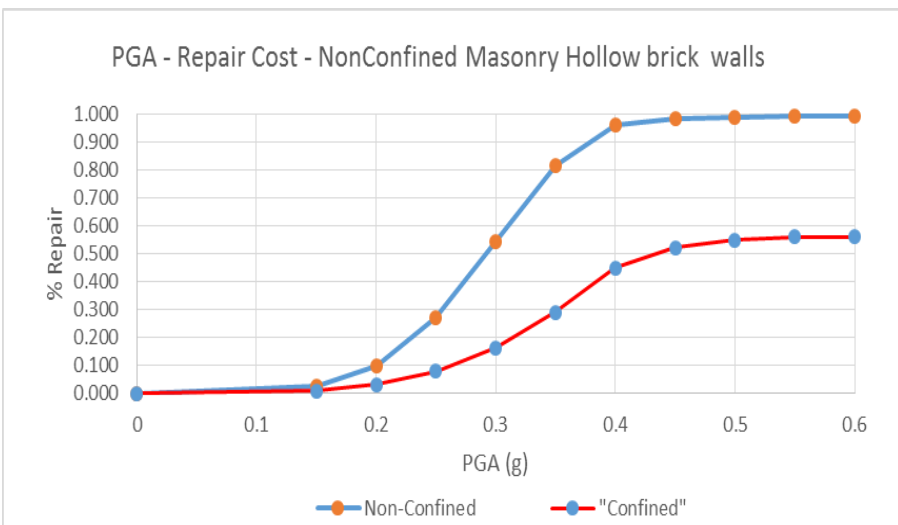


Fig. 10: Risk Curve PGA – Drift on non-engineering structures with horizontal hollow bricks

Better behavior is expected when models use handmade brick walls, as is presented in Fig. 11, were curves for non-confined walls and confined walls are presented. On non-confined walls repair cost increase substantially for demands over 0.375g. For confined walls behavior reach a maximum value of 40% of the cost for 0.600g such number of stories (Np), wall density (DM) and type of brick (Handmade or Horizontal hollow).

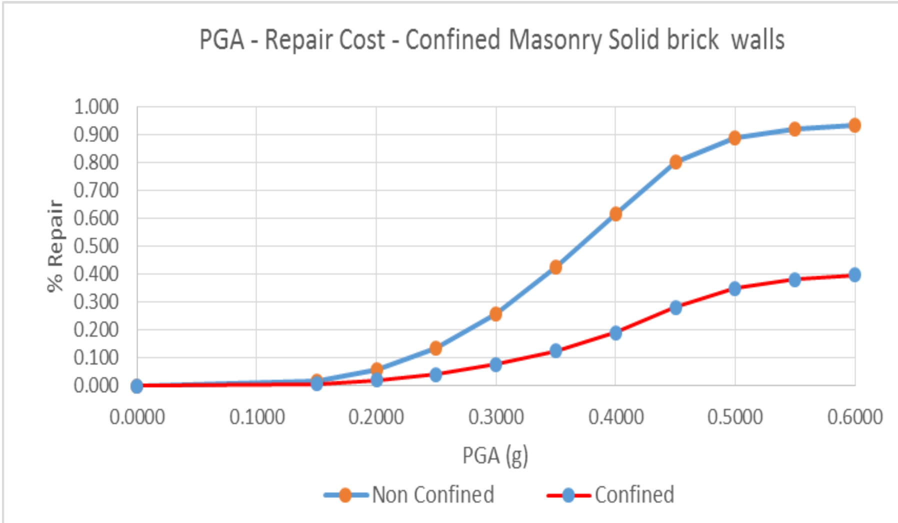


Fig. 11: Risk Curve PGA – Drift on non-engineering structures with handmade bricks

6. Estimation of Damage on Urban Areas with non-engineering buildings

For the verification of the results of the risk curves presented in Fig. 10 and Fig. 11, damage survey of Pisco city due to Pisco earthquake 15/8/2007, was used for comparison with the simulation results. In Fig. 12, damage survey generated by [6] developed for each building is used a pattern figure for the simulation.

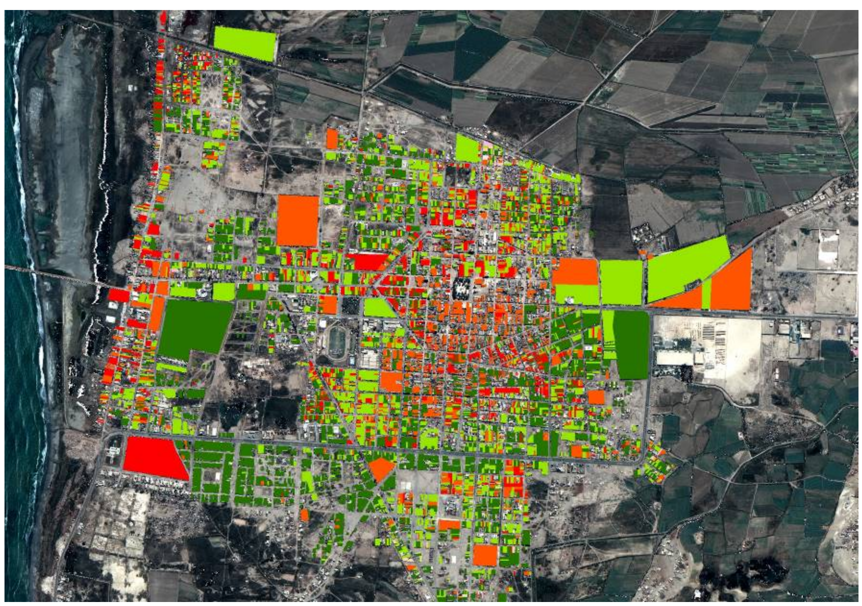


Fig. 12: Damage survey after Pisco earthquake 15/8/2007

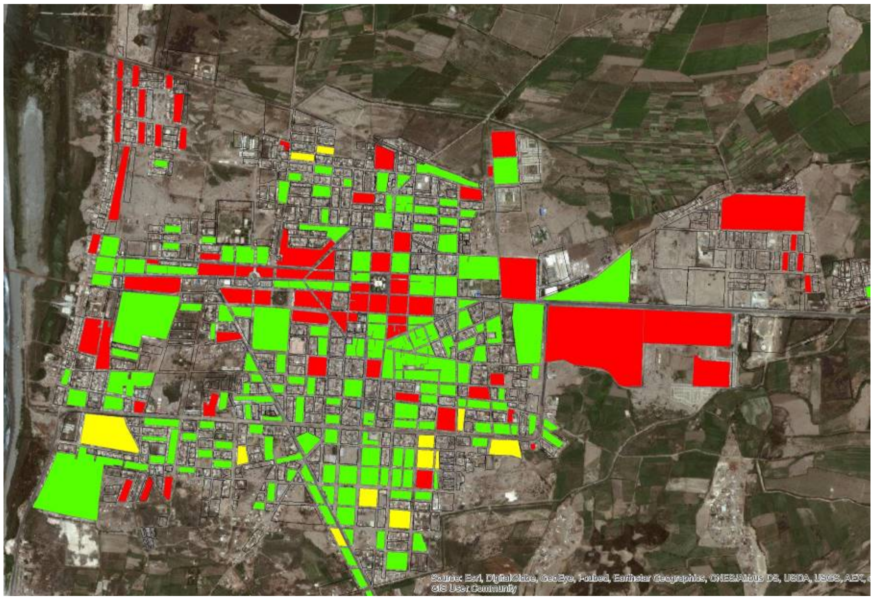


Fig. 13: Simulation with risk curves for Pisco earthquake 15/8/2007

Simulation analysis using the risk curves, are used for the estimation of damage in terms of the percentage of repair cost of the buildings. In this case due to the availability of data set, the estimation is perform for block of buildings, consider as representative the likely built structure on the block. Fig. 13 presents the results where dark green color represents a repair cost of between 0 to 15%, light green color represents repair cost between 16% to 30%, yellow color a repair cost between 31% to 60%, orange color repair cost between 61% to 85% and red color values between 86% to 100% of the repair cost.

7. Conclusions

Non-engineering masonry buildings represents almost 60% of the housing in emerging areas of Peru. These buildings use two kinds of masonry units: horizontal hollow bricks and handmade solid bricks, both with the low capacity to resists earthquakes.

For these non-engineering systems, identification of masonry walls capacity parameters using database of CISMID experimental database of masonry walls test was presented. This skeleton curves are used to developed non-linear earthquake response analysis on 1563 structural models.

The results of the non-linear earthquake response analysis were grouped by selected parameters such number of stories (Np), wall density (DM) and type of brick (Handmade or Horizontal hollow). Curves of maximum earthquake response in terms of story drift, was plotted for five representative earthquakes, presented in Table 3, generating a universe of results presented on Fig. 7. Considering a selection of responses of Fig. 8 and Fig. 9 damage curves for models with horizontal hollow brick walls and handmade brick walls were displayed. From these two figures is possible to read that horizontal hollow brick walls models produce larger responses than handmade brick wall models.

From the results of Fig. 8 (horizontal hollow brick structure) if the drift limit value (0.005 in red dashed line) of Peruvian Standard NTE-070 is reached first at 0.30g, therefore after this limit reparability became difficult. Also the curves show a substantial drift increment (0.006 to 0.015) for PGA between 0.30g to 0.60g. Therefore for PGA over 0.30g, models will not be reparable.

Also analyzing the results presented in Fig. 9 (handmade brick walls models), if drift limit value (0.005 in red dashed line) of Peruvian Standard NTE-070 is reached at 0.35g, therefore after this limit reparability became difficult. Also curves presents a substantial drift increment 0.009 to 0.011, for PGA between 0.40g to 0.60g. In this case behavior of these models are better than tubular brick walls models.

Repair cost estimation has been computed in terms of percentage repair cost using a model presented in [1] implementing the damage curves from this research. Results are presented in Fig. 10 and Fig. 11 for horizontal hollow brick walls models and handmade brick walls models. Here the curves with larger drift were used in the computing of the cost of repair. For the verification, results were implement to a GIS system using damage curves and risk curves to compute the repair cost on urban area. The results of the simulation on Pisco city due to earthquake of 15/8/2007, Fig. 13, show good agreement with the damage survey presented on Fig. 12. It is possible to read that results depends of the PGA, therefore if better accelerometer network on urban area the results of the simulation could be improve and will be near to the survey. Also if indirect method from dynamic characteristic of soil could provide distribution of PGA in urban zone, the propose curves could be a good tool for the estimation of damage on non-engineering masonry buildings.

8. Acknowledgements

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