Vulnerability functions for buildings due to liquefaction

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SUMMARY
Recently, the occurrence of seismic events with large magnitudes around the world have generated significant damage to houses and infrastructure due to ground acceleration and liquefaction of sands, generating important losses to the public and private sectors; some examples are the Christchurch, Mexicali and Tohoku earthquakes on March 11th and April 4th in 2010 and February 22nd, 2011 respectively.
In this paper several vulnerability functions defined by permanent vertical ground displacement are proposed. The proposed vulnerability functions are obtained as a result of a combination of those defined as empirical with those obtained through statistics of damage from a database of buildings affected by liquefaction during earthquakes. This information is a compilation of geocoded damage during the Mexicali, New Zealand and Japan earthquakes. This approach can be applied throughout the world to point out where are the areas with potential soil liquefaction to help decisions makers to mitigate thru code improvements and land use regulations, among others.

Keywords: Vulnerability functions, Soil liquefaction, Risk assessment

1. INTRODUCTION

The occurrence of seismic events with important magnitudes during past years around the world like those occurred in Mexico, New Zealand, Chile on 2010 and Japan on 2011 have generated important damage on dwellings and infrastructure in the region, not only due to ground acceleration, but also to the occurrence of sand liquefaction. The reconstruction cost of Mexican damages was around four hundred million dollars, for New Zealand situation, extensive damage occurred over more than 50% of the city, leaving more than 10,000 people homeless and the economic losses were more than four billion dollars. The Tohoku earthquake in Japan generated damages over 300 billion dollars.

Unfortunately, in several areas where the liquefaction phenomenon may occur, there are human settlements and civil infrastructure. This situation settle a large number of people, buildings and infrastructure in a potential risk due to the generation of liquefaction. Situation that must be taken into account when territorial planning are being formulated.

In order to create plans for prevention and mitigation of damage due to the occurrence of this type of events, it is necessary to carry out a risk assessment at regional level. One widely accepted way to perform risk analysis is, on one hand, the use of probabilistic scenarios that represent the environment hazard and on the other, the use of vulnerability curves that reflect the behavior of the infrastructure under certain intensity by mean of a expected damage.

For this reason, some vulnerability curves are proposed in this paper employing real data collected from damages on dwellings affected during the Mexicali earthquake (Mexico), Christchurch (New Zealand) and Tohoku (Japan). The vulnerability curves proposed in this paper are a combination of those defined as empirical and statistics curves, since the employed damage levels are based on expert opinion and intensity of liquefaction and characteristics of dwellings were obtained from real events.

1.1. Liquefaction

Liquefaction is not a rare phenomenon since there are several records about it occurrence. Table 1 shows a compilation of the most significant events that took place just during the last two years.

Table 1. Seismic events where soil liquefaction has occurred.

ID	Date	Magnitude	Latitude	Longitude	Depth (km)	Distance (km)	Region
1	01/12/2010	7.0	18.45	-72.571	13	25	Port Au Prince (Haiti)
2	02/27/2010	8.8	-35.90	-72.73	35	95	Maule (Chile)
3	04/04/2010	7.2	32.28	-115.08	10	50	Mexicali (Mexico)
4	09/03/2010	7.1	-43.53	172.120	5	45	Danfield (New Zealand)
5	02/22/2011	6.2	-43.59	172.68	5.9	6	Chistchurch (New Zealand)
6	03/11/2011	9.0	38.297	147.372	30	129	Tohoku (Japan)
7	08/23/2011	5.8	37.936	-77.933	6	8	Central Virginia (USA)
8	10/23/2011	7.1	38.69	43.49	20	16	Tabanli (Eastern Turkey)

2. STATISTICAL VULNERABILITY FUNCTIONS

2.1. Methodology

Several authors have proposed functions to determine the state of damage of buildings and bridges associated with soil liquefaction (Bird *et al.*, 2006; Aygün *et al.*, 2011; Brandenberg *et al.*, 2011) One existing philosophy to generate vulnerability functions has it bases on statistical information. Besides the fact that like any other philosophy to estimate vulnerability curves through defining or categorizing the expected behavior of different structural systems that are in the region, this philosophy reduce the uncertainty associated to assessment of damage since real data are employed in the evaluation.

In this methodology, it is assumed that damage from a number of dwellings with the same characteristics is known once the perturbing event has occurred (earthquake, hurricane, flood, etc.). In the same sense, the hazard intensity to which dwellings are subject. The employed database must be as objective as it is possible regarding the estimation of the damage and it must include all levels of damage that have been reported and not just those with collapse or seriously damaged, but also, those dwellings that did not suffer damage.

It is important to use an intensity measure that reflects in a proper manner the actions that are imposed to the structure; in the case of estimating the expected damage for buildings due to the occurrence of liquefaction, vertical displacement of the soil are considered as a measure of intensity.

Once the above characteristics are defined, we proceed to calculate the frequency of damage by dividing the number of dwellings that have a certain level of damage by the total number of structures that conform the database for this category of structural system in J discrete ranges. A regression analysis is performed taking into account the mean intensity associated to the frequency of damage for a specific range. Results of regression analysis are assumed as a capacity cumulative distribution. In other words, it is considered that each considered building is a discrete point defined by coordinates (Δ, β), where Δ is the vertical soil displacement due to liquefaction and β is the damage present in the structure due to that displacement.

Then, the vulnerability function is defined by minimizing the objective function expressed by

$$g(\phi) = \sum_{i=1}^{N} \left(F_{\varDelta}(\varDelta_i) - \beta_i \right)^2 \tag{2.1}$$

where $F_{\varDelta}$ ($\varDelta_i$) is the vulnerability function for a given structural system.

3. DATABASE FOR BDWELLINGS DUE TO SOIL LIQUEFACTION

3.1. Damage database

Since the base of vulnerability functions proposed in this paper is statistical in nature, it is necessary to have a database containing information about different housing damage due to soil liquefaction events. During the occurrence of earthquakes in Mexico, New Zealand and Japan, information related to damage in several infrastructure sectors has been recorded, such as the cases of damage on buildings, roads and irrigation channels. It is important to point out that for this paper, only the information related to damage on dwellings and buildings of 2 or 3 levels caused by soil liquefaction is employed.

Fig. 1 shows the statistics of dwellings that suffered damage in the municipality of Mexicali, Mexico. The information contained in this database was obtained from field visits by the Ministry of Social Development (SEDESOL) staff in order to carry out a reconnaissance of affected areas and to provide the necessary assistance.

It is important to note that it was not the only place where liquefaction damage occurred, however, it was the area that had the largest number of dwellings that were damaged by this phenomenon.

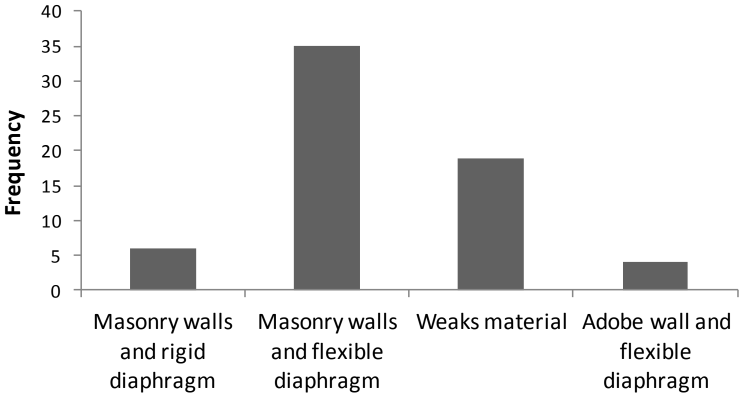

Figure 1. Statistics of dwelling that suffer damage due to April 4th in 2010 earthquake in Mexicali, Mexico

It is important to mention that the employed damage levels are associated exclusively to soil liquefaction phenomenon and those damages occurred for soil shaking are not considered.

Similarly, we used a database of damaged buildings by liquefaction due to earthquake in the city of Christchurch in New Zealand (CERA, 2011, Orense, 2010) in the area where this phenomenon was presented (Jacka and Murahidy, 2011). Statistics of the different structural systems are shown in Fig. 2. The employed damage index associated to each building was assigned using the damage level assigned by the local government of Christchurch associated to the damage intervals proposed by Cazares (2011) for a quick and rough estimate of damage in homes before the occurrence of a natural phenomenon disturbing in Mexico.

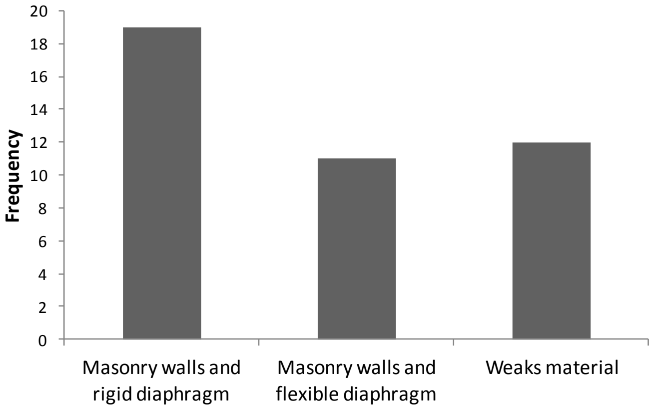

Figure 2. Statistics of dwelling that suffer damage due to February 22th in 2011 earthquake in Chistchurch, New Zealand

In the same sense, Fig. 3 shows the information collected of damage caused by liquefaction in the city of Tohoku, Japan. This information was obtained from the GEER (2011) and the damage index was assigned employing the same methodology as that used for New Zealand and Mexicali cases.

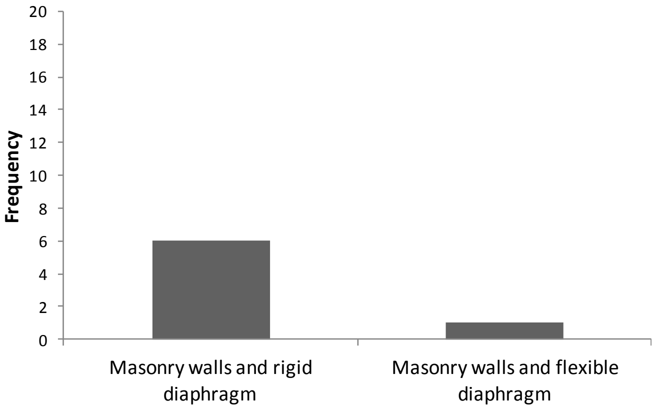

Figure 3. Statistics of dwelling that suffer damage due to March 11th in 2011 earthquake in Tohoku, Japan

The information shown in the previous figures are the statistics of the different types of dwellings and buildings according to the structural system that it is assumed like a identifier for the behavior that they may have at the occurrence of liquefaction. This behavior is represented by the expected damage given a vertical displacement of the ground.

4. VULNERABILITY FUNCTIONS DUE TO LIQUEFACTION

As a result of the collected data, Fig. 4 shows the distribution according to the suffered damage by the presence of liquefaction in the area where these are located. In this figure it is observed that about 14% of homes had no damage, 22% had minimal damage and another 29% had minor damage, similarly, 19% had partial damage and a percentage similar to above, the households had total damage.

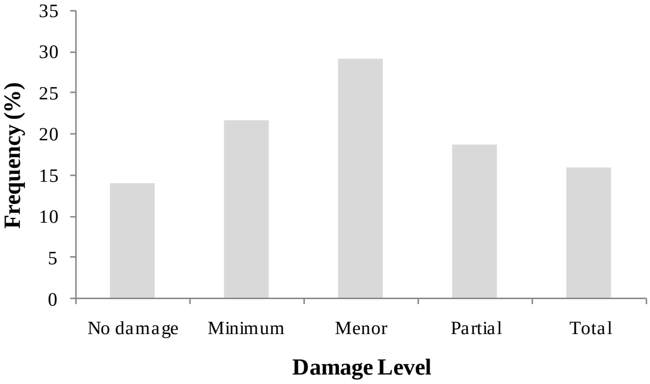

Figure 4. Distribution of dwellings according to the occurred damage

In the same sense, in order to determine the physical damage of a structural system when a vertical displacement due to soil liquefaction occurs, it is necessary to know the intensity of the hazard associated with that damage. For this reason, Fig. 5 shows the distribution of damage in dwellings associated to an intensity of vertical displacement. This distribution corresponds to the total surveyed structures regardless of the structural system.

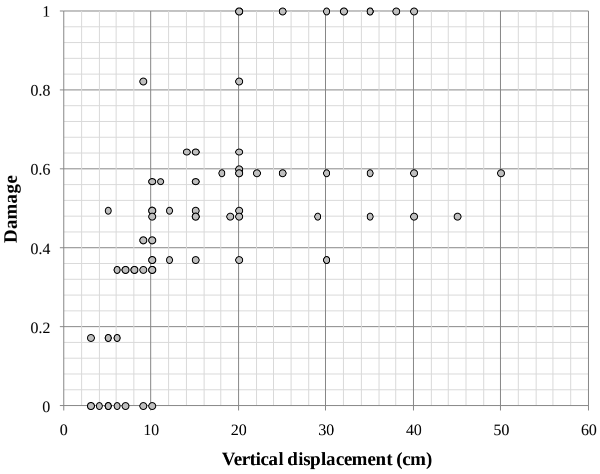

Figure 5. Damage distribution of dwellings as functions of a vertical displacement

After employing the Eqn. 2.1, a vulnerability curve was obtained for the total records included in the employed database (Fig. 6). It is important to express that the obtained curve corresponds to all structures (dwellings and buildings) regardless the structural system employed in their construction, or material from which they are built.

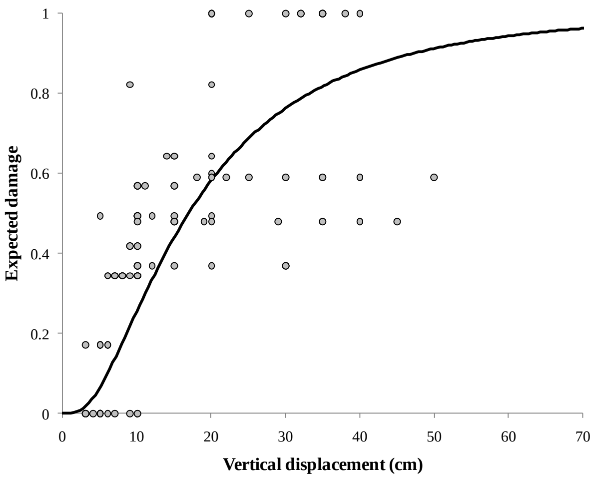

Figure 6. General vulnerability curve

As is shown in the above figure, a wide dispersion of data is presented, since the fact that fitting a single vulnerability curve increase the dispersion in estimating the damage associated with liquefaction. For this reason, to conduct a segregation of information considering the structural system and the construction material is proposed.

As a result of the above, the following classification was obtained:

- Dwellings with masonry walls and rigid diaphragm
- Dwellings built with weak material in walls and roof
- Dwellings with adobe walls and flexible diaphragm
- Dwellings with masonry walls and flexible diaphragm
- Masonry buildings 2 or 3 levels

Fig. 7 shows the vulnerability curve obtained with Eq. 2.1 for dwellings built with masonry walls and rigid diaphragm. The correlation factor between the data used and the proposed curve is 82%.

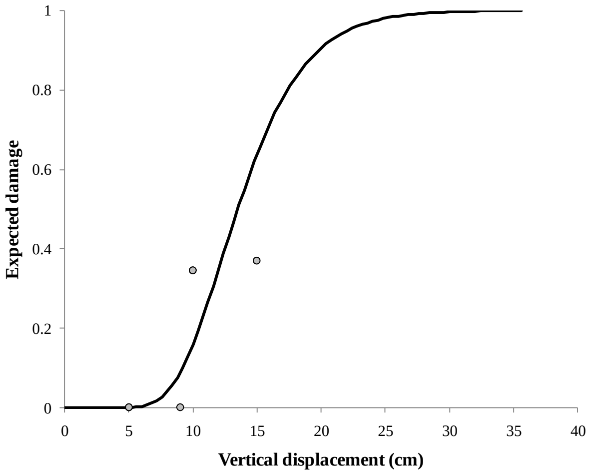

Figure 7. Vulnerability curve for dwellings with masonry walls and rigid diaphragm

Similarly, Fig. 8 shows the vulnerability curve for those houses that are built with weak materials such as wood, reeds, cardboard and general waste materials. The correlation factor between the employed data and the proposed curve is greater than 95%.

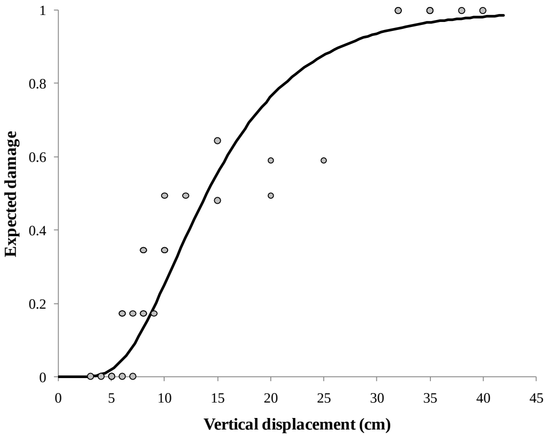

Figure 8. Vulnerability curve for dwellings with weak material

Unfortunately, for dwellings built with adobe walls and flexible diaphragm, the used database does not have as many records as that one employed for masonry walls and rigid diaphragm dwellings. Regardless the above, the proposed vulnerability curve presented in Fig. 9, has a correlation factor greater than 98%.

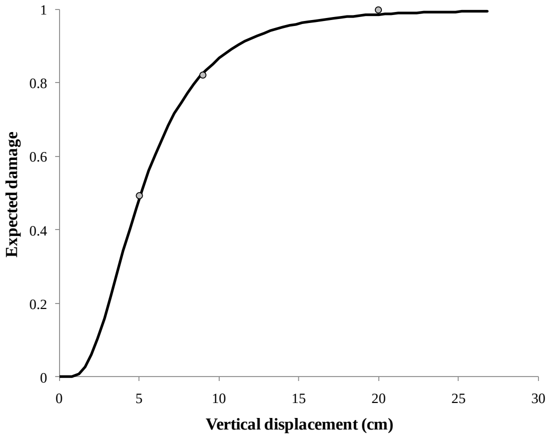

Figure 9. Vulnerability curve for dwellings with adobe walls and flexible diaphragm

For those masonry walls and flexible diaphragm structures the proposed vulnerability curve is shown in Fig. 10. It is important to mention that this structural system is the most used in the region of Mexicali, Mexico. At first glance, it is observed a large scatter between used data and the proposed curve, however, the resulting correlation factor is nearly 90%, which is considered as an acceptable value.

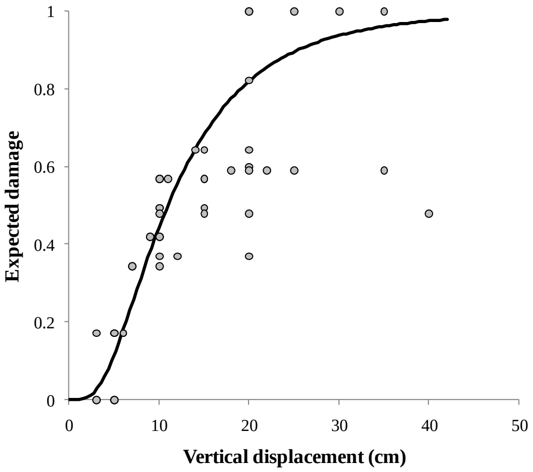

Figure 10. Vulnerability curve for dwellings with masonry walls and flexible diaphragm

Regarding the two and three level buildings it was observed that damages are associated to a larger vertical displacement intensities if they are compared with those required in dwelling for the same damage level. Despite the fact that there are no an important number of records, the correlation factor of the obtained vulnerability curve is around 90% (Fig. 11)

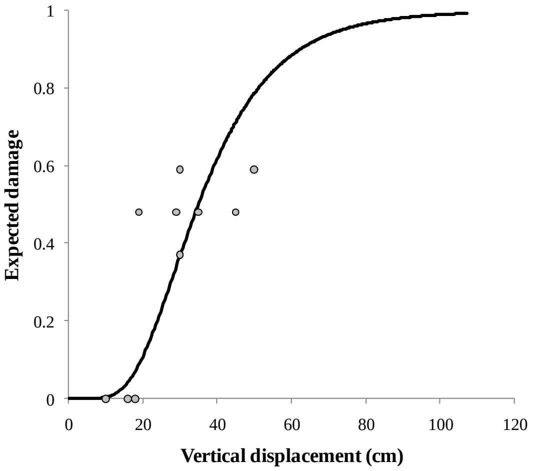

Figure 11. Vulnerability curve for two and three story masonry buildings

From the figures presented above, and as it is expected, buildings are less susceptible to damage than those with masonry walls and rigid diaphragm dwellings, this situation may be due to the provision employed for their construction.

Despite the fact that the proposed vulnerability curves shows an acceptable correlation factor with the observed damages, it is important to create a more robust data base so that important characteristics like foundation or type of damage can be taken into consideration.

5. CONCLUSIONS

This paper proposes vulnerability curves for dwellings and buildings due to soil liquefaction considering, on one side, the threat intensity parameter defines by the permanent vertical soil displacement associated to liquefaction and on the other side, the structural system and material of dwellings and buildings. The proposed functions are based on different damage reports of houses affected by the phenomenon of liquefaction in the municipality of Mexicali, Mexico, the city of Christchurch, New Zealand and the city of Tohoku, Japan.

In order to reduce the uncertainty in estimating the damage from soil liquefaction, it is necessary to improve the databases used in this paper, collecting as many records of houses that have suffered damage from the effect of this phenomenon.

With the proposed vulnerability curves, it is possible to carry out probabilistic risk studies due to liquefaction in dwellings and short buildings that are useful to create plans for prevention, mitigation and damage reduction to help institutions and governments to focus resources for risk management.

AKCNOWLEDGEMENT

This research is part of the project “Creation of an instrument to evaluate and determine the structural damage level in dwellings due to disasters” sponsored by the Ministry of Social Development (SEDESOL) in Mexico. Authors thank to SEDESOL for the employed databases

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