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Seismic vulnerability of Mexico City buildings

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ABSTRACT: After the 1985 Mexico City earthquake, an extensive study of the damage was carried out, as a result, the resistant coefficient was obtained for 429 concrete buildings by means of a simplified method. Based on this data, vulnerability curves are constructed for medium reinforced concrete buildings, showing the percentage of damaged buildings as a function of the seismic intensity, for three different areas in the lake zone of Mexico City. The relationship between the seismic intensity and the rehabilitation costs involved is also given as a first aproximation to the problem.

1 INTRODUCTION

An evaluation of the building seismic capacity is required in order to estimate vulnerability curves. There are different ways to achieve this: analytical analysis of typical buildings to calculate the resistance of a group of structures for some scenarios; engineering judgment supported on the actual practice design and code requirements; experimental models of typical buildings; and the analysis of damaged buildings after an earthquake. Obviously, the best information is that one arised from a big earthquake; nevertheless, not all the earthquake's and damage's information is available, since strong ground motion recording instruments have been recently installed and past earthquakes damage observations are very limited.

A research team of the Universidad Autónoma Metropolitana analyzed many of the damaged buildings by the 1985 Mexico City earthquake, in order to obtain their seismic resistance by means of a simplified method. Vulnerability curves for the most affected areas in the city were ths obtained using the calculated seismic capacity of 200 affected structures, considering four damage levels and up to 13 stories height. The methodology applied could also be used to relate cost rehabilitation to seismic intensity.

2 RESISTANT COEFFICIENTS

The procedure for estimating the resistant coefficients (k) is an adaptation by Iglesias, *et al.* (1987), of the first level procedure of the Japan Building Disaster Association Guidelines (Japan, 1979 and Umemura, 1980), for the conditions prevaling in Mexico City buildings, and was used to draw a map of intensities for the 1985 Mexico City earthquake. This method was calibrated with the damage observed and with detailed analysis (Iglesias, *et al.* 1987).

The resistant coefficients for each floor were obtained under the assumption that the actual seismic shear is equal to the resistant shear force calculated with a simplified method. If the actual seismic shear is estimated from static analysis:

$$VRi*Si = ki*Ai*W \qquad (1)$$

where:
VRi = resistant shear force in the ith floor
Si = reduction factor for structural configuration and deterioration
ki = shear base coefficient reduced by ductility
Ai = shear force distribution with heigth
W = total weigth of the structure
hence:

$$ki = VRi*Si/Ai*W \qquad (2)$$

Assuming that failure ocurrs in the vertical structural elements of each story, the resistant shear force is evaluated as the combination of the resistance of these elements, according to their relative stiffness. Element resistances were determined from average stresses chosen conservatively after studying typical designs adopted in medium rise concrete buildings in Mexico. The value of ki corresponding to the weakest story (failure condition) is adopted as the resistant coefficient of the building k, which can also be used as a seismic intensity measure (K) in those buildings that suffered severe damage.

Information of 429 buildings was obtained, but it was possible to apply the method in 200 only. The rest of the structures were disregarded because of

the following reasons:

1. The damage was not concentrated in the vertical structural elements.
2. Undamaged buildings with more than 10 stories.
3. The weakest floor according to the method was not the most damaged story.
4. The compiled information was not enough or was unreliable.

3 DAMAGE LEVEL

If the damage classification proposed in table 1 is considered, the damage distribution of the 200 analyzed buildings is: 81 for damage level 3, 22 for damage level 2 and 97 for damage levels 1 and 0.

Table 1. Damage classification.

Damage level	Description of damage
3 (serious)	Crushed concrete, broken ties and/or buckled rebars in columns, beams or shear walls
2 (medium)	Cover spalling in concrete or cracks from 0.5 mm to 1.0 mm width in concrete elements
1 (light)	Cracks less than 0.5 mm and no structural damage
0 (none)	No damage

The 200 buildings that constitutes the sample were located in different areas of the lake-bed zone of the city. The first zone considered for obtaining vulnerability curves was Delegación Cuauhtémoc (Figure 1), since was most affected area during the 1985 earthquake and 167 buildings of the sample were ubicated there. The mean k values and variation coefficients obtained for the 167 structures are given in table 2 for each damage level.

Table 2. Seismic capacity mean values and variation coefficients for buildings located in Delegación Cuauhtémoc.

Damage level	k mean value	Variation coefficient
3	0.083	0.30
2	0.110	0.33
1	0.161	0.35
0	0.184	0.35

As it was expected, the seismic capacity is smaller of the most seriously affected structures. The high variation coefficients are explained because of the different seismic intensities ocurred in this zone during the 1985 earthquake, producing similar damage level to buildings with different seismic capacity.

4 VULNERABILITY CURVES

Three different areas were considered for the vulnerability analysis: the first one is the Delegación Cuauhtémoc; the second is contained into the first area and is classified as high seismicity zone by the new Mexico City code (Normas, 1987); the last one is the highest intensity zone during the 1985 earthquake and is contained into the second area, as can be seen in Figure 1.

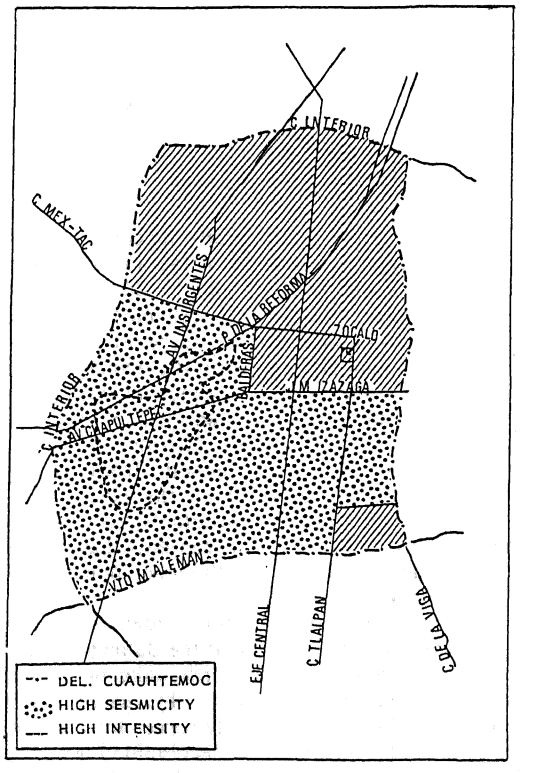

Figure 1. Areas of lake-bed zone of Mexico City under study.

Considering K as a seismic intensity measure, the percentage of buildings whose resitance coefficient k is less than a given K value represents the expected seriously damaged buildings (damage level 3) in the sample, produced by the seismic intensity chosen. This value is corrected taking into account the relationship between the building's and damage's type for the sample and the total population of buildings. In order to get the relationships for other damage levels, an empirical damage conversion fac-

tor, calibrated with the damage observed (Guerrero, 1991), is introduced. This factor is the relationship between the mean resistance of buildings with different damage levels, for example: the damage factor to transform damage 3 to damage 2 is F23 = 0.110/0.083 = 1:325, thus, the percentage of buildings with at least damage 2 is achieved finding the buildings whose resistance is less than the selected intensity multiplied by 1.325.

According to the building census of the city carried out by the authorities (Noreña, *et al* . 1989), the incidence of damage depends on the number of floors; buildings from 5 to 8 floors suffered serious damage or collapse in 7.4% of the total buildings located in Delegación Cuauhtémoc, while structures from 9 to 13 floors were affected in 40.6% of the cases, in the same area. The different performance is explained because the 9 to 13 stories buildings period proximity to the soil's period (around 2 sec for the lake-bed zone of the city). Therefore the buildings were classified in low rise buildings (5 to 8 floors) and medium rise buildings (9 to 13 floors) for the vulnerability analysis. The influence of the building's height could be observed in Figure 2 which represents the vulnerability for low and medium rise buildings for damage 3 in Cuauhtémoc Distrit.

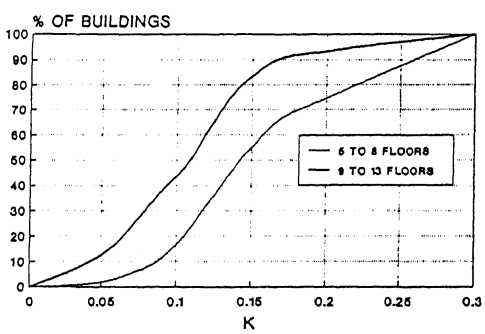

Figure 2. Vulnerability comparison between low and medium rise buildings for damage level 3.

Figure 3 shows the vulnerability curves for medium rise concrete buildings, located in Delegación Cuauhtémoc, for three different damage levels. As mentioned above, 40% of the buildings from 9 to 13 stories suffered serious damage according to reported statistics, from this amount of damage a seismic intensity K = 0.093 is obtained from the vulnerability curve. If the ductility factor Q is taking as 4 (the most common value used for this type of buildings in Mexico), the seismic coefficient resulting from this condition is c= 0.093*4 = 0.37g, as an average for the total area considered, which coincide with the intensity map drawn for the 1985 earthquake (Iglesias, 1989).

Vulnerability curves for medium rise buildings, located in the high seismicity zone defined in the new

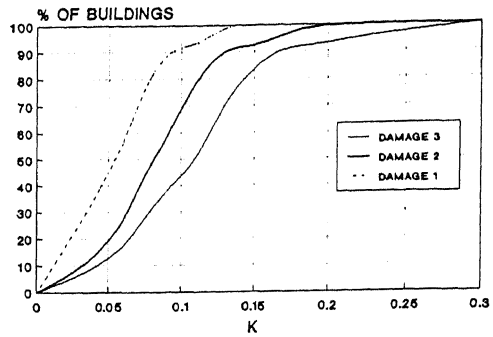

Figure 3. Vulnerability of medium rise buildings located in Delegación Cuauhtémoc.

Mexico City code, are illustrated in figure 4. Taking the same K value of 0.093 as for Delegación Cuauhtémoc, the severe damaged buildings percentage is 21%, showing higher seismic capacity than the buildings located in the first area analyzed; in spite of that, the amount of damage observed after the 1985 earthquake was quite similar for both areas, this situation can be explained by the major intensity ocurred in the high seismicity zone during this event. A 36.5% of seriously damaged buildings was reported in the census for this area which lead to an intensity K equal to 0.115 according to the vulnerability curve shown in Figure 4, very similar to the seismic intensity obtained by Iglesias (1989) for this zone.

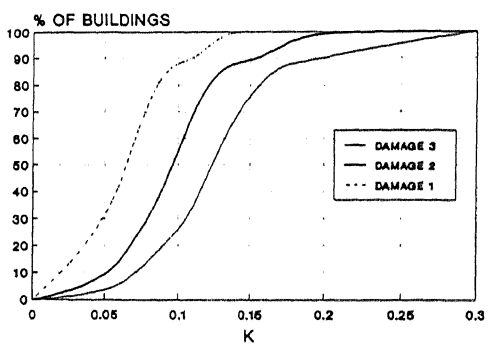

Figure 4. Vulnerability of medium rise buildings located on the high seismicity zone.

The sample for the high seismicity zone contains 129 structures, the mean k values and variation coefficients for these buildings are presented in table 3.

The seismic capacity of the buildings in this zone is higher than the first sample, because of the better quality of construction (due to a more concentration of modern buildings). The variation coefficients are smaller than those presented in table 2, suggesting a more similar structure resistance for the same damage level, since the seismic intensity during the

1985 earthquake was more homogeneous than in the first zone studied. The high variation coefficient obtained for damage level 1 and 0 is due to the high resistances attained in some non structural damaged buildings.

Table 3. Seismic capacity mean values and variation coefficients for buildings located in high seismicity zone.

Damage level	k mean value	Variation coefficient
3	0.090	0.23
2	0.137	0.14
1	0.165	0.34
0	0.187	0.36

The last area considered is the highest intensity zone for the 1985 earthquake. Unfortunately, the information available was scarce and the number of buildings in this sample was limited to 53. For that reason, the vulnerability comparison presented in Figure 5 for the three areas do not distinguish the influence of building's height in the vulnerability, and is constructed for buildings from 5 to 13 stories and for damage level 3. From the available data, higher resistances were obtained for the buildings on this zone than in the others, as it can be seen in the figure. More information is needed in order to get more reliable conclusions in this area.

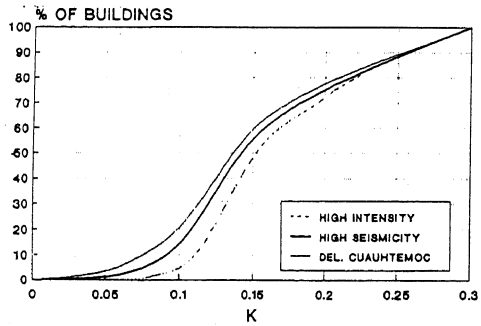

Figure 5. Vulnerability comparison between the three areas considered for buildings from 5 to 13 stories and damage level 3.

The plotts shown until now were constructed for accumulated damage, for example, damage 2 curve represents the expected damaged buildings for damage levels 2 and 3. The vulnerabilty of buildings from 9 to 13 floors located on the high seismicity zone, for non accumulated damage, are presented in Figure 6. For a seismic intensity K = 0.11 the distribituion of each damage level is: 36% for level 3, 25% for level 2, 16% for level 1 and 23% for no damage, giving a total of 100%. This type of curves could be useful for evaluating the rehabilitation cost according to damage distribution after a strong ground motion.

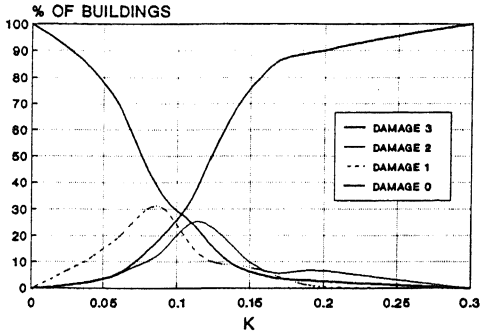

Figure 6. Vulnerability for medium rise buildings located in the high seismicity zone for non accumulated damage.

5 INFLUENCE OF BUILDINGS REHABILITATION IN VULNERABILITY

The resistant coefficients were initially calculated considering building properties from the original drawings; neverthless, the earthquake vulnerability was afterwards reduced because of the city rehabilitation. The main modifications that affected the vulnerability are:

1. Demolition of the buildings in worst conditions.
2. Reinforcement of severe and light damaged buildings.
3. Strengthening of important buildings such as schools, hospitals, fire stations and others, since the owners of these buildings were required by the authorities to demonstrate that their buildings comply with the new code specifications.

The principal techniques adopted for the repair and retroffiting of buildings in Mexico City were identified after the inspection of a file containing more than 100 building rehabilitation projects (Aguilar, *et al.* 1989 and Jara, *et al.* 1989). The increment of the resistant coefficients was estimated for the most typical used techniques: jacketing of beams and columns with reinforced concrete, and concrete shear walls addition, in order to estimate their influence on the vulnerability. For buildings retroffited by means of reinforced concrete jacketing, the mean k value resulted 100% higher; when shear concrete walls were added, the mean increment in the k coefficient was 50%.

Buildings demolished or strengthened by other techniques which were less commonly used were eliminated of the sample, reducing the buildings located in the Delegación Cuauhtémoc to 108.

A vulnerability comparison in the high seismicity

zone, before and after the buildings were retroffited, is plotted in figure 7 for structures from 9 to 13 levels and damage level 3. It can be seen the great vulnerability reduction produced by the retrofitting process. As an example, for the same seismic intensity K = 0.11 of 1985, 13% of the structures in this area are expected to be seriously damaged now, instead of the 36% resulting from the original population. This change represents a 64% reduction of the buildings collapsed or seriously damaged for this event. It is important to notice that this result does not consider the reinforcement of undamaged buildings, neither the new buildings designed according to the 1987 code specifications.

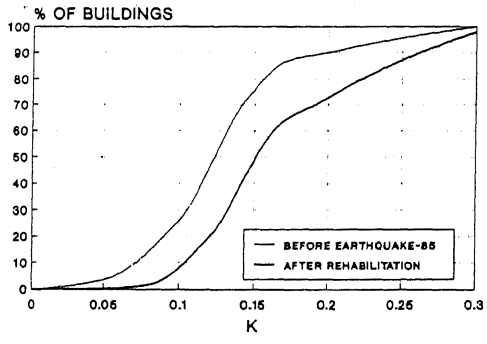

Figure 7. Vulnerability before and after the rehabilitation process for buildings located in the high seismicity zone and damge level 3.

6 REHABILITATION COST CURVES

An evaluation of the rehabilitation costs for several buildings damaged by the 1985 earthquake was attained in order to establish the amount of money necesary to reinforce earthquake damaged structures. A mean cost was proposed for the two strengthening techniques most commonly applied in Mexico's buildings: reinforced concrete jacketing and concrete shear walls addition. The superstructure retrofitting cost was evaluated from the strengthening projects available on the Universidad Autónoma Metropolitana file. Finishing's, installation's and foundation's costs were extrapolated using the percentages proposed by Robles and González-Cuevas (1984). Figure 8 shows the seismic intensity-cost relationship. From this figure, an intensity K = 0.11 involves a rehabilitation cost of 180 million dollars in the high seismicity zone. If vulnerability reduction after buildings were retroffited is considered, the rehabilitation cost for an earthquake as strong as the 1985 one, would be reduced to 100 million dollars. The costs are evaluated according to 1989 prices in Mexico City.

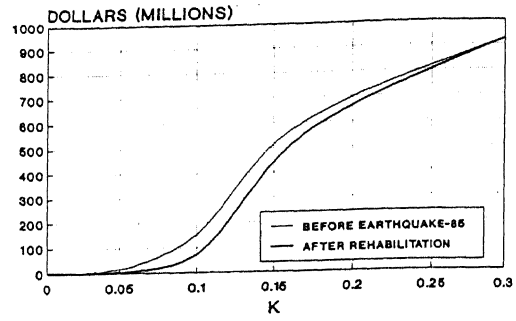

Figure 8. Rehabilitation costs for different seismic intensities in the high seismicity zone.

7. SEISMIC INTENSITY MEASURES

The severity of the ground motions is usually measured by Modified Mercalli intensity scale (MMI), peak ground acceleration (PGA) and peak spectral acceleration (PSA). A relationship between these quantities and the K coefficient is given in tables 4 and 5, as a first approximation to the problem. The considerations followed to obtain these relationships are:

1. MMI. Based on the intensities map for the 1985 Mexico City earthquake proposed by Iglesias (1989), and on the MMI map drawn by the authors for the same event (Guerrero, 1991), a direct correlation between these measures was proposed.

2. PGA. Fundación ICA (1988), Iglesias (1989), and Singh, *et al.* (1988), suggested that the relative amplification, of the seismic intensities in the lakebed zone of Mexico is quite similar for the 1985, 1986 and 1988 earthquakes. Thus, a linear regression from the K values, obtained for the elaboration of the intensities map for the 1985 earthquake, and the 1986-1988 peak ground accelerations recorded by the Fundación ICA accelerometer network, was attained.

3. PSA. An estimation of response spectra for the 1985 earthquake was carried out by Ordaz, *et al.* (1988), for several parts of the city. A linear regression based on those results and on the intensity map was calculated.

A plot showing building vulnerabilty for the three zones considered and damage level 3 for different seismic measures is given in figure 9.

Table 4. Modified Mercalli Intensity and seismic intensity K relationships.

K coefficient	MMI
K<0.06	VI
0.06<K<0.08	VII
0.08<K<0.11	VIII
0.11<K<0.14	IX

Table 5. Peak ground acceleration, peak spectral acceleration and seismic intensity K relationships.

K coefficient	PSA	PGA
0.05	0.27g	0.04g
0.10	0.80g	0.13g
0.15	1.32g	0.21g
0.20	1.85g	0.30g
0.25	2.37g	0.38g
0.30	2.80g	0.47g

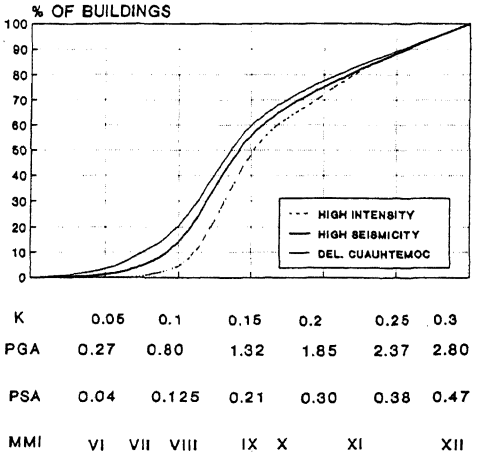

Figure 9. Vulnerability related to typical seismic measures.

8 CONCLUSIONS

A methodology to estimate the vulnerability and the rehabilitation cost from the analysis of a strong earthquake's damage is given. From the results obtained for Mexico City, vulnerability curves are proposed for implementing mitigation plans for the city. It should be noticed that the curves are limited to the studied areas and are based on the damage produced by only one earthquake.

The curves obtained shows that buildings located in the high seismicity zone have more seismic capacity than the ones located in Delegación Cuauhtémoc. In spite of that, the amount of damaged buildings in both areas are quite similar confirming the bigger intensity produced by the 1985 earthquake in the high sesimicity zone proposed by the mexican code.

Structures from 9 to 13 floors are the most vulnerable for the zones under study.

City rehabilitation reduce the vulnerability in the studied scenario around 64% for an earthquake as strong as the 1985 .

Rehabilitation-cost curves were obtained for different seismic intensities based on the vulnerability curves. More complete studies on this topic are needed in order to improve the reliability of the results.

These curves can be incorporated in decisions making in seismic risk analysis and could be used in expert systems programs for structural damage assesment and evaluation of existing structures.

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