INFLUENCE OF STRONG GROUND MOTION DURATION IN SEISMIC DESIGN OF STRUCTURES

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SUMMARY

A study of the duration of strong ground motion using accelerometric data of subduction and normal faulting Mexican earthquakes is presented. Duration is obtained based on the time between 2.5 and 97.5 percent of the Arias intensity. An expression to predict this duration in terms of the magnitude, distance to the rupture area and site period is proposed. This expression is used together with the random vibration theory to predict response spectra. Three dimensional response spectra of seismic coefficient, structural period and number of inelastic cycles are obtained. Finally, the inelastic structural response of a concrete structure built over the lakebed zone in Mexico City is studied. A synthetic accelerogram in terms of strong motion duration and site period that yields the same inelastic response as the real accelerogram is proposed as a simplified tool to model inelastic behaviour in lakebed zone sites.

INTRODUCTION

Nowadays most seismic design codes are based on maximum amplification parameters such as peak and spectral acceleration. But these parameters not only do not exhibit a straight correlation with loss and damage but also do not consider damage due to hysteretic behaviour or several earthquake excitations in high seismicity zones. Although strong motion at some sites as Mexico City has low peak acceleration compared to other sites with smaller epicentral distances, motion there exhibit long harmonic duration with long dominant periods and for very frequent large earthquakes. The interest of integrating in some way the duration as a design parameter is due to cumulative structural damage and hysteretic behaviour. Structural damage depends not only on the earthquake maximum intensity but also on the whole history of demands before and after this maximum intensity. A lot of research is now in progress in order to study and include such concepts. This paper deals with the study of the duration capable of yielding structural damage which may be helpful in the use of some seismic damage models (Fajfar and Gaspersic, 1996).

It has been shown that for a wide set of accelerograms recorded over the rupture area of subduction Mexican earthquakes, maximum response parameters have a poor correlation with damage, while duration of motion is a parameter well correlated with earthquake effects on structures (Reinoso et al, 1996). When attenuation is taken into account, duration of strong ground motion is not relevant anymore unless large accelerations due to local site amplification effects such as those as the Mexico City Valley are present.

The amount of digital accelerometric data recorded during the last 15 years allow us to formulate a regression that predicts the duration in terms of the earthquake magnitude, distance to the rupture area and dominant period of the site. This predicted duration is used to obtain response spectra via random vibration theory (Udwadia and Trifunac, 1975 and Reinoso et al. 1990).

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COMPUTING STRONG MOTION DURATION FROM ACCELEROGRAMS

There are many ways to measure strong motion duration from accelerometric records. A recent review was made by Bommer y Martínez-Pereira (1996) who compared different ways of measuring the duration and proposed a new one. In this work we use the duration between the times where the 2.5 and 97.5 of the Arias intensity is computed. In order to compare data of different stations during different earthquakes, accelerograms have been carefully selected and revised, so records with short duration due to thresholds have been omitted. Additionally, accelerograms were all set to the same threshold filtering them in the time domain as a typical digital accelerometer. This fixed threshold was 20 cm/s2 at the epicentral area and 4 cm/s2 in Mexico City.

Results shown here are for subduction earthquakes originated at the contact of the Northamerica and Rivera and Cocos plates, and also for normal faulting ones caused by the subduced Cocos plate. The earthquakes have magnitudes between 4.9 and 8.1. Accelerometric stations are located over the epicentral area (16 km) and as far as 550 km. They are also located either over rock or lakebed zone sites with dominant periods as large as 5.2 seconds. Figure 1 shows the location of some of these earthquakes together with their magnitude and date. Apart from the May 22, 1994 event that occurred at a depth of 45 km, all earthquakes are superficial with depths between 12 and 27 km.

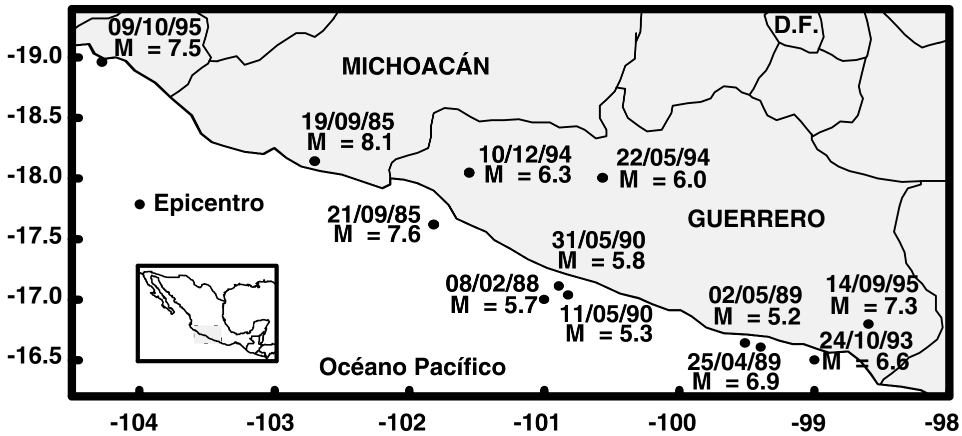

Figure 1 Earthquakes used in this study

The whole set of data was obtained during 15 earthquakes recorded at more than 400 accelerometric stations. Figure 2 shows some free-field accelerograms either over rock and soft soils recorded during the 1995 Colima earthquake (M=8.0); this figure exhibits the diversity of strong ground motion in terms of amplitude, frequency content and duration. In Figure 2 is clear the influence of attenuation and soil effects in Mexico City. Dots in this figure indicate the location of accelerometric sites.

Duration with respect to magnitude, distance to the rupture area and dominant site period

There have been some important works on the prediction of strong motion duration. Esteva and Rosenblueth (1964) described the duration in terms of the earthquake magnitude and source to station distance. Dobry et al (1978) obtained a linear regression with respect to magnitude and discussed the variation of duration for different soils. Trifunac and Brady (1975) obtained a linear regression with respect to site classification, earthquake magnitude and epicentral distance, so the total duration is the sum of the duration of the earthquake source. The time interval between the fastest and the slowest wave arrival at the station and the duration caused by repeated wave scattering from material discontinuities and surface topography. They found that the average duration is about twice as long on soft alluvium as on hard-base rock. Herrmann (1985) proposed duration in terms of the source duration and the epicentral distance. Trifunac and Westermo (1982) and Novikova and Trifunac (1994) obtained regressions in the frequency domain of duration in terms of magnitude, epicentral distance and site characteristics at the station.

Accelerograms recorded over the rupture area of an earthquake exhibit large acceleration and short duration. It has been long recognised that neither maximum ground acceleration nor response spectra are strictly correlated with structural damage. Using accelerometric data recorded over the rupture area of recent Mexican subduction earthquakes with a wide range of magnitudes, Reinoso et al (1996) have shown that a parameter that correlates better with observed damage is the duration of strong ground motion. Reinoso et al (1996) also compared the duration computed with two different Aria's intensities and for two sets of earthquakes (M ≥ 5.7 and M ≥ 6.9) with the theoretical duration obtained with Brune's model. Results showed that duration obtained between the 2.5 and 97.5 of the Aria's intensity was closer to the theoretical results.

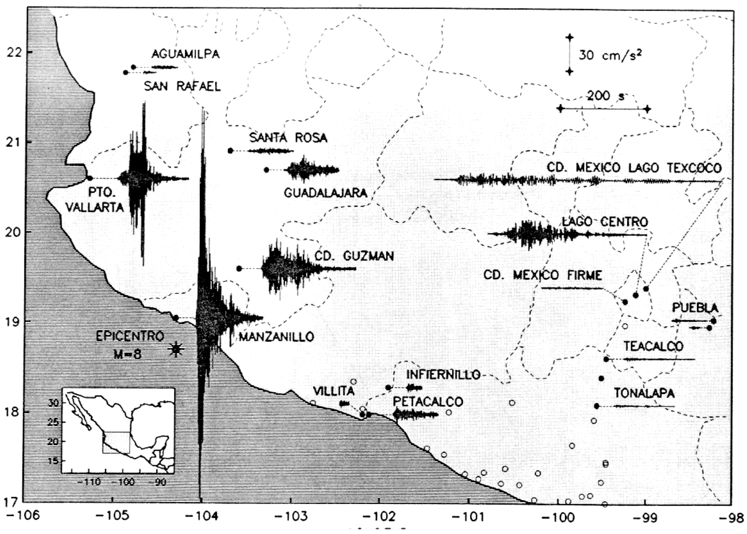

Figure 2 Accelerations recorded along central Mexico during the 1995 earthquake

Contrary to what happened to the attenuation of intensity, duration grows with distance. This is particularly hazardous for soft soils as the seismic energy for long periods, which attenuate less than short ones, amplifies notoriously. Seismic waves from subduction earthquakes need to travel more than 250 km to hit Mexico City. Because of regular patterns of radiation and attenuation, these waves arrive with low amplitude and long duration, and soil amplification at lakebed zone sites cause damage or even collapse to some structures. Although there are evidences that at hill zone sites strong ground motion is already amplified of one would expect at similar epicentral distances (Ordaz and Singh, 1991) this effect may be neglected in this work as no evidences have been found that duration is also affected.

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It has been shown (Guerrero, 1997; Reinoso et al 1997) for Mexican subduction and normal fault earthquakes that strong motion duration, D, depends on magnitude, M, distance to the rupture area, R' and dominant period, Ts, as

$$D(R',M,Ts) = 1.4\times10^{-4}\left(e^{1.52M} + 185\,(R' - 24)\,e^{0.28M} + 5680\,(Ts - 0.5)\,e^{0.44M}\right) \qquad (1)$$

Valid for R' ≥ 24 km and Ts ≥ 0.5 sec (for firm and hard rock sites Ts=0.5 sec). The soft sites that were employed to obtain equation 1, with a very large data collection, have been those of Mexico City. It should be noticed that D increases notoriously with Ts: for an earthquake with M=5 motion is 18 sec longer for Ts=5sec than Ts=0.5s, and for the same periods duration is 72 sec longer for M=8.1 than for M=5. This considerable increase in duration could be due simply to 1D propagation (Singh and Ordaz, 1993) rather than complicated 2D and 3D scattering (Reinoso et al 1997). Figure 3 shows a comparison of the computed duration for each component of motion (symbols), the trend computed for each earthquake and the trend obtained with equation 1. All of the nine earthquakes shown in Figure 3 have roughly the same distance to the rupture area.

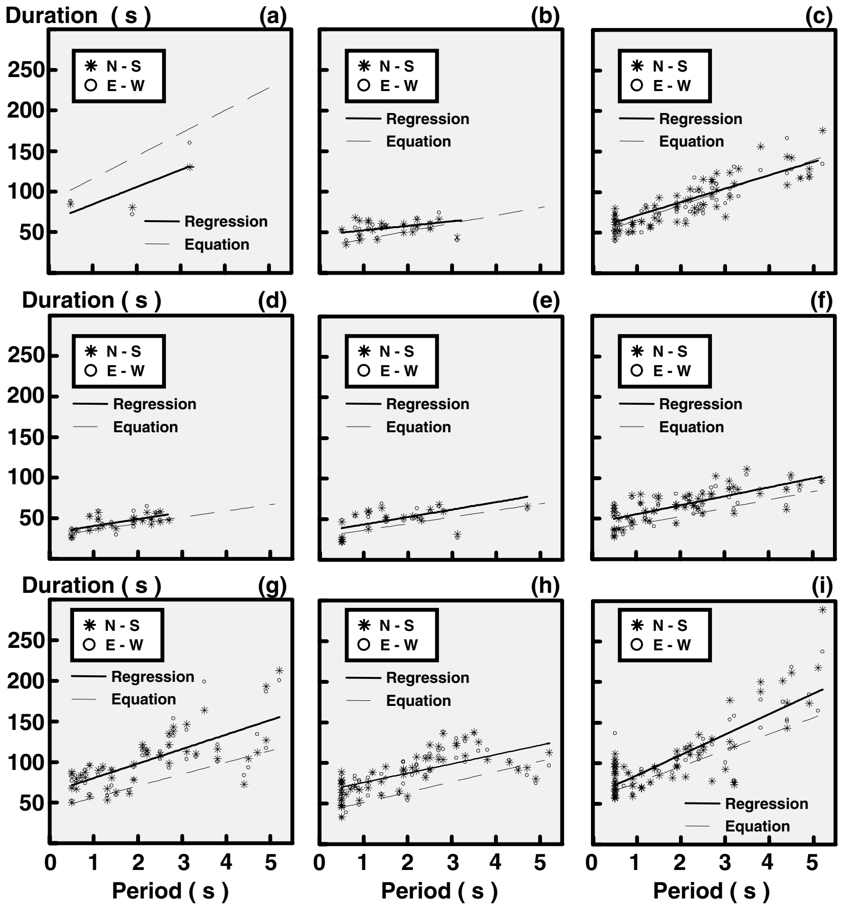

Figure 3 Computed duration (symbols), regression for each earthquake and computed trend with equation 1. Earthquakes: a) 19/09/85, 8.1; b) 08/02/88, 5.7; c) 25/04/89, 6.9; d) 02/05/89, 5.2; e) 11/05/90, 5.3; f) 31/05/90, 5.8; g) 24/10/93, 6.6; h) 10/12/94, 6.3; i) 14/09/95, 7.3

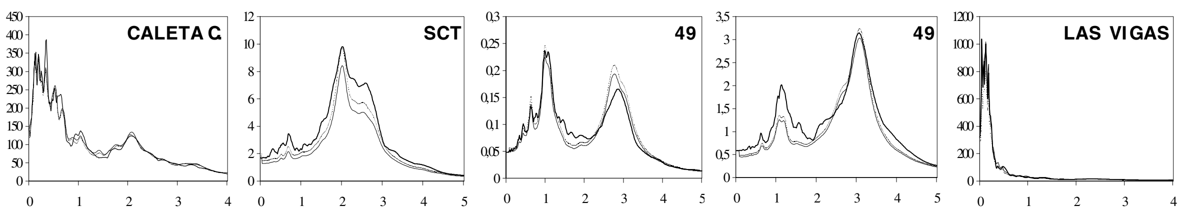

Figure 4 Comparison of response spectra for different earthquakes, epicentral distances and soil conditions. Dark line: exact spectra; discontinuous line: RVT and computed duration; dotted line: RVT and duration given by equation 1

Predicting response spectra using the random vibration theory and strong motion duration

Duration predicted with equation 1 could be used to obtain response spectra together with the random vibration theory, RVT (Udwadia and Trifunac 1974). RVT is helpful to predict response spectra using only a theoretical or empirical spectrum. An estimation of the strong ground motion duration is needed for computing RVT response spectra, although this duration does not reflect damage or deterioration to the structure. These expressions have been already tested for Mexico City (Reinoso et al, 1990, Guerrero, 1997). Figure 4 shows some examples of response spectra obtained using RVT and the duration of equation 1 and the comparison with the exact spectra.

INELASTIC CYCLES AND DURATION FOR SDOF SYSTEMS

Zahrah and Hall (1984) defined the number of equivalent cycles, N, as the relation of the total dissipated energy per unit mass of a SDOF system, EH, with respect to the area bellow the monotonic strength-displacement curve. The maximum yield strength, Fy, and the maximum displacement, Dm, define this curve.

SDOF oscillators with different strength, Cs, and Period, To, were submitted to the SCT 1985 accelerogram. Using a hysteretic elastoplastic model, the inelastic number of cycles and the respective duration plots were obtained. These plots are shown in Figure 4. According to this figure, those SDOF systems with To ~ 2 sec experienced more inelastic cycles, and even oscillators with strength (seismic coefficient) close to 1.0 but with To=2 sec observed non linear behaviour. Figure 5 shows clearly how structures with low strength have an increase of inelastic cycles and duration, jumping up when Cs < 0.15.

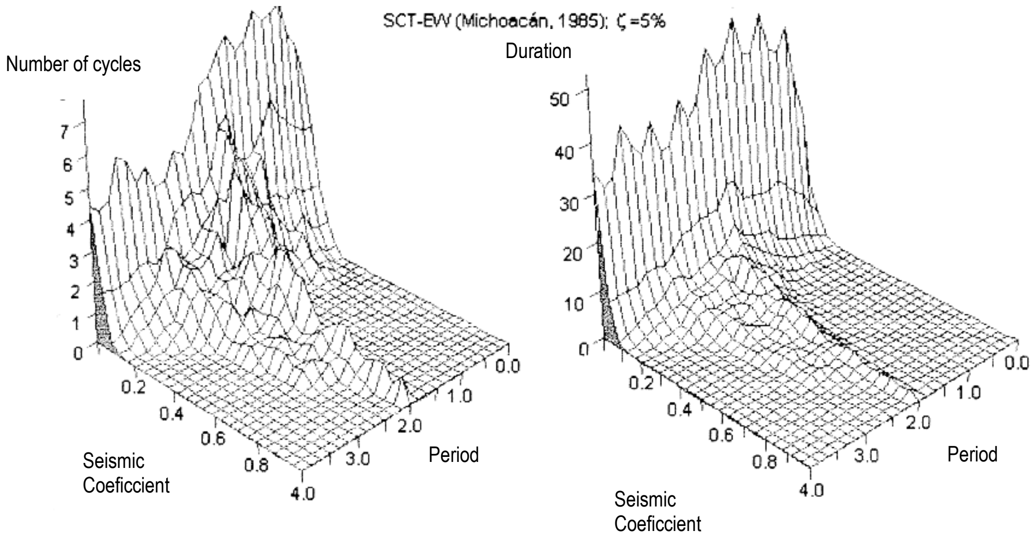

Figure 5 Three-dimensional response spectra for site SCT during the 1985 earthquake: Number of cycles (left) and inelastic duration (right)

STRUCTURAL RESPONSE OF A 13-STOREY BUILDING

Buildings in Mexico City are shacked on average every two years by an earthquake with magnitude 7 or larger. As was mentioned before, these earthquakes occur at epicentral distances between 250 and 500 km and, although amplification is low, duration is long and the motion is rich in low frequency. This traduces in constant and large shaking for medium rise buildings. It is expected that Mexico City structures be badly affected by degradation not only during one earthquake but of accumulated damage during several ones, since the safety of the structure is a function of the entire history of cyclic oscillations (Jeong and Iwan, 1988). It is clear that, at least for Mexico City, buildings have collapsed after dozens of seconds of strong shaking; there are several testimonies of survivors who took long time to escape through emergency exists.

The behaviour of a 13-storey high concrete-frame building located at the lakebed zone in Mexico City is studied. Building's design follows rigorously the 1993 code (Guerrero 1997, Reinoso et al, 1997). The accelerogram used in the study is the EW component of the SCT 1985 earthquake. Degradation was considered using Park's model with three parameters.

Results obtained were Park's damage index, interstorey drift and displacements. Computed Park and Ang's index using the whole accelerogram were 0.206 and 0.226 according to nominal and severe degradation. It was noticed that same results were obtained if only the intense part of the accelerogram was employed: the central pulses that last 10 seconds (5 pulses). This means that, apparently, only this intense part is causing the damage. Then, building's response was obtained due to the intense part of the SCT accelerogram and Park and Ang's index were 0.199 and 0.269 for nominal and severe degradation, respectively, practically the same results as the whole accelerogram. The same was observed for interstorey drift and ductility demand (Guerrero 1997).

Synthetic accelerogram

These results lead to propose a synthetic accelerogram similar to the intense part of the SCT motion. This monotonic motion last 10 sec and its amplitude is also 168 gal. Using this synthetic accelerogram, Park and Ang's index were 0.194 and 0.262 according to nominal and severe degradation, almost identical to the short accelerogram. The same was observed for interstorey drift and ductility demand (Guerrero 1997). The synthetic accelerogram (Figure 6) is given by

$$A_s(t) = \quad A_{máx} * \sin \left[\frac{2\,\pi\, t}{T_1} \right] * \sin \left[\frac{\pi\, t}{T_2} \right] \tag{2}$$

where As(t) is the ground acceleration, Amax is the peak acceleration, T1 is the dominant soil period and T2 is the strong motion duration; t needs to be smaller than T2.

Ductility demands were similar although variations of 30 per cent were observed for upper levels since synthetic accelerogram is monochromatic. Obtained ductility demands varied between 5 and 6 for storeys 1, 7, 8, 9, and 10, and between 4 and 5 for other storeys. The similitude of results between the whole accelerogram and the synthetic one could be explained with results from O´Connor and Ellingwood (1992) who used Californian earthquakes and SDOF oscillators showing that duration of motion has a significant influence on the hysteretic energy dissipation and rms displacement of the inelastic system, but not on its peak inelastic response or ductility demand. The same was found by Lam et al (1996) who using an elastic perfectly plastic model without strength degradation concluded that earthquake duration has a much more pronounced effect on the hysteretic ductility demand than both the cinematic ductility demand and Park and Angs´s damage index. Comparison of interstorey drift is shown in Figure 7.

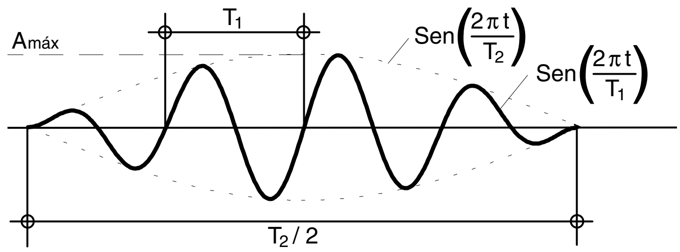

Figure 6 Synthetic accelerogram built with peak acceleration, duration (T2/2) and soil period (T1)

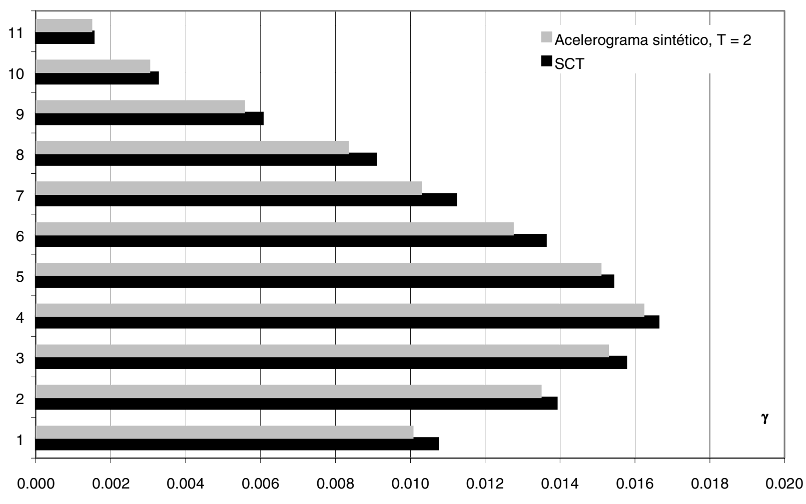

Figure 7 Interstorey drift obtained for the synthetic and for the actual accelerogram

Results shown in Figure 7 prove that the synthetic accelerogram could be used with reasonable accuracy to design structures since the obtained interstorey drift is the same compared to the drift computed with the whole accelerogram (see dots for CD, SCT and VIV, Figure 7).

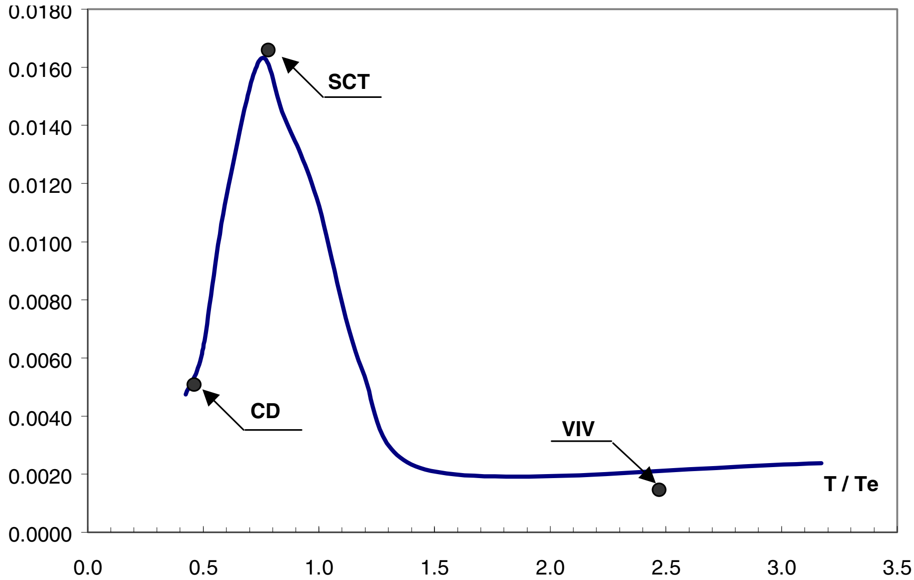

Figure 8 Interstorey drift obtained for the synthetic and for three actual accelerograms. T=1.48 sec is the period of the structure and Te is the site dominant period

Finally, the concrete building was "moved" along the lakebed zone in the city in order to find its earthquake response at different sites with different soil periods. Site periods varied from 0.5 sec (considered firm soil in Mexico City) and 3.3 sec; Amax varied according to the observed peak acceleration during the 1985 earthquake at SCT, VI and CD stations. The inelastic study was carried out with synthetic accelerograms computed with equation 3. Interstorey drift results are shown in Figure 8 with solid line. Maximum interstorey drift (0.0165) was obtained when the ratio of the site period and the structural one is 0.7. As the dominant period of the structure is 1.48 sec it means that the worst place to build this structure is where soil period is 2.1 sec.

CONCLUSIONS

The study of strong ground motion duration during subduction earthquakes based on the times between 2.5 and 97.5 of the Arias intensity was presented. Based on accelerometric data, an expression to predict the strong motion duration is proposed. This expression is in terms of magnitude, distance to the rupture area and dominant soil period. The expression has been successfully tested obtaining response spectra using the random vibration theory and the predicted duration.

On the other hand, response spectra relating seismic coefficient, structural period and number of inelastic cycles allow us to predict better the inelastic response of a structure given by its period and seismic coefficient. The study of the inelastic response of a 13-storey concrete structure in Mexico City shows the influence of duration and degradation in its response. Using the analytical accelerogram with different duration but characterised with the same maximum amplitude and dominant period as the actual accelerogram, shows clearly that interstorey drift, Park and Ang's index and ductility demand are the same for the analytical and actual accelerograms.

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