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STRONG GROUND MOTION PREDICTION AT MEXICO CITY

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SUMMARY

After the 1985 Michoacan earthquake became mandatory to predict seismic ground motion at Mexico City. Nowadays, most of source, path and site effects can be accounted for because quantitative descriptions of them are available. In fact, hundreds of accelerograms have been recorded at the hill, transition and lake-bed zones of the valley. Their Fourier amplitude spectra allow to point out peculiarities for motions produced by earthquakes of different origin. On the other hand, an interpolation scheme based upon Bayesian statistics and theoretical considerations was developed in order to infer the dynamic amplifications of ground motion at soft soil sites, relative to the hill zone. The objective is to postulate possible earthquakes and make predictions of seismic intensities at any site of the valley. Apparently, in the near future, the most damaging earthquake to the structures at Mexico City will come from the Guerrero coast. If a major earthquake strikes there, it is likely that most of the energy of the incoming field would correspond to the resonant frequencies due to soil conditions.

INTRODUCTION

Almost 15 years ago, the September 19, 1985 Michoacan (Ms=8.1) earthquake, which originated in the subduction zone along the Mexican coast, caused unprecedented destruction to Mexico City. The motion at the city was smooth and gentle, yet destructive as the predominant periods of the ground oscillations in the most severed areas of the city were between 2 to 3 secs. In order to understand what happened, simultaneous consideration was paid to source, path, and site conditions. Apparently, most of the factors that control the damage scenarios coincide at the 2 to 3 sec period band. In fact, teleseismic seismograms (recorded in Europe and North America) revealed an enhanced source radiation for waves around a period of 3 sec. On the other hand, such a period could also be seen in near-source records which showed the rupture process as the growth of a smooth crack and have been explained as due to changes in the rupture front velocity. Meanwhile, the seismograms (obtained from double integration of recorded accelerations) in Mexico City reveal that vertical motions were nearly identical throughout the valley of Mexico regardeless if the recording site was on the lake sediment or on hard rock. These vertical seismograms showed ripples with 2 to 3 sec period, superposed to long-period waves, that are features of the incoming field due to the source and path characteristics. Besides significant source and path effects, it is well known that the lacustrine formations of the basin underlaying Mexico City greatly amplify ground motion. It became clear that the bulk of seismic motion at the top of lacustrine origin soils was related with amplification due to the vertical resonance of shear waves. That explained, grosso modo, observed damage distribution. Therefore, source, path and site effects account for the what happened during the 1985 Michoacan earthquake, especially on a variety of structures located at sites with dominant period between 2 and 3 sec.

At present, the most significant source, path and site effects can reasonably be accounted for because quantitative descriptions of them are available. Empirical transfer functions (ETF) have been computed from hundreds of accelerograms recorded at dozens of sites placed at the hill, transition and lake-bed zones of the valley. Records of several earthquakes (including the ones at CU, a site in the hill zone, that has been in operation for almost 35 years) have been useful to discriminate between source-path and site effects. We use this information as a seismic data-base to predict the strong ground motion levels (maximum response spectra

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ordinates) in Mexico City for some future large earthquakes. To accomplish such a task we rely on (1) an improved assessment of Fourier amplitude spectra (FAS) that represent the input motion to the valley of Mexico and (2) an interpolation scheme of ETF that allows to account for site effects in response spectra calculations. For a variety of possible large earthquakes, we present our results as contour maps of response spectral ordinates. Likely scenarios of high risk are controlled by the trilogy: (1) source-path effects, (2) site response and (3) building characteristics.

STRONG GROUND MOTION ASSESMENT

One of the highest seismicities worldwide is observed in Mexico, particularly along the Pacific coast, from Jalisco to Chiapas. Earthquakes there, are produced by the subduction of the Cocos and Rivera oceanic plates beneath the North American plate. As in other seismic zones, Mexican subduction earthquakes follow an ocurrence process composed of alternating episodes of build-up and release of energy. The later appears to be produced once a certain strength treshold is reached. A segment of an identified subduction zone for which no recent earthquakes have occured is called seismic gap (Kelleher, et al., 1973; Singh et al., 1981). Thus, it is usual to assign large probabilities to the occurrence of an earthquake in the near future in such gaps. In agreement to this consideration, large events have actually occurred in zones previously identified as seismic gaps. Large earthquakes also occur in the continent at depths larger than about 40 km. They are caused by normal fault mechanisms within the subducted ocean plate (Singh et al, 1985b). Although relatively infrequent, some of such earthquakes have caused great damage. More rare are the crustal earthquakes ($M_s<7$) which occur within the continental plate. Such events can cause considerable damage.

The current building code of Mexico City takes into account the tectonic origin and the estimated recurrence period of the earthquakes that were assumed to represent the most important threat to the city (Rosenblueth, et al. 1988) in agreement with a catalog large earthquakes that occurred during the last two centuries in the country (Singh and Suárez, 1988). The postulated events were of the following types: (1) subduction, (2) intermediate deep, (3) intraplate thrust and (4) local. The former was represented by observed Fourier spectra, the others were inferred using a theoretical source model (Aki, 1967; Brune, 1970; Boore, 1983). Site effects were accounted for from damage observations and the response spectra of the available records at the time. The adopted seismic zonation of the city was based in the pioneering work of Marsal and Mazari (1959). It distiguishes essentially three zones: hill, transition and lake-bed. After 1985, an extense accelerometric network was deployed in Mexico City covering a significant part of the hill, transition and lake bed zones. Records of more than ten earthquakes, with magnitudes between 5.0 and 8.1, have allowed to built a full-fledged empirical model for strong ground motion assesment. This model is based upon the proposals of Singh et al. (1988), Ordaz et al. (1989) and Pérez-Rocha et al. (1991). The former accounts for site effects by means of ETF. The second is a procedure to compute site elastic response spectrum from the ETF and a postulated earthquake, which is especified by its FAS at hill zone. The last one is a spatial interpolation scheme for seismic data recorded in a plane. Our aim is to compute response spectra ordinates for virtually any site at Mexico City.

A brief description of the basis of this approach, as well as preliminary results for a postulated large earthquake, were presented in Reinoso et al. (1992). In this work we use, in addition, a theoretical source model to scale the FAS of some significant earthquakes recorded at the University City, a site in the southern part of the hill zone within the valley of Mexico (CU is the acronim in Spanish). Besides regional amplification, our approach allows to account for peculiarities due to source and path. Also, we introduce a Bayesian interpolation scheme for the ETF in order to improve the stability of computations. Our scheme is based upon theoretical wave propagation considerations as well.

FOURIER AMPLITUDE SPECTRA (FAS) AT HILL ZONE IN MEXICO CITY

Since 1965, a dozen of large subduction earthquakes [$6.9 \leq M \leq 8.1$] has been recorded at CU. Horizontal acceleration records, the approximate extension of the rupture areas, date and magnitude of these earthquakes are shown in Figure 1. These records reveal important source and path effects for Mexico City. These effects, not pointed out before with quantitative detail, are significant for strong ground motion predictions. The Fourier Amplitude Spectra of earthquakes originated at the Michoacan, Petatlan, Guerrero-San Marcos, and Ometepec gaps are compared in Figure 2. The events of the gap indicated at the top of each frame are enhanced with heavy lines. Each FAS is the average of the horizontal components of motion at CU. All spectra are reliable in the middle frequency band (between 0.3 and 3 Hz, approximately). The September 19, 1985 Michoacan earthquake, with Ms=8.1, is the most energetic event that has been recorded at CU. Note that the spectra of events from Petatlan gap show high frequency content that decrease somewhat slower than the ones from other regions. This fact helps to explain the concentrated damage near the transition zone due to the March 14, 1979 earthquake. On the other hand, although the Ometepec's earthquakes have magnitudes Ms=7.0, 7.3 and 7.4, they show similar amplitudes which follow a conspicuous peak around 0.5 Hz. Finally, the April 25, 1989 San Marcos earthquake with Mw=6.9, as well as the FAS of events of 1962 (with Ms=7.0, 7.1; inferred at CU by using ETF) have amplitudes that can be larger than the ones due to the earthquakes generated in the Michoacan, and Ometepec gaps, particularly for periods between 2 and 3 sec. Also, amplitudes of events from San Marcos are similar to the ones of events from Petatlan [with Ms=7.5, 7.6] for periods between 2 and 5 sec. These comparisons, and the evidences from the July 28, 1957 Guerrero earthquake [Ms=7.7] suggest that large amplitudes between 2 and 3 sec can be a typical feature of earthquakes from this region, covered by the Guerrero and San Marcos gaps.

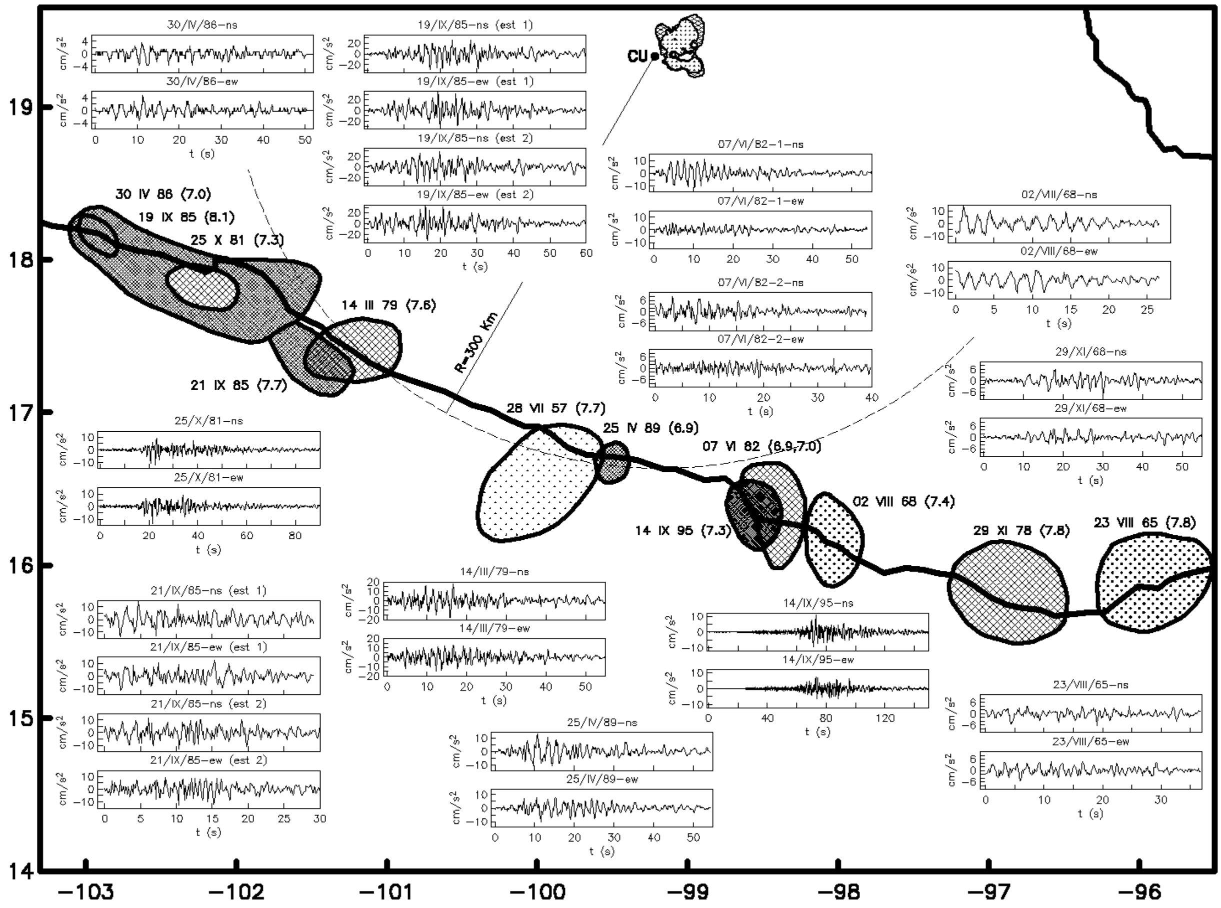

Figure 1 Horizontal accelerations produced by subduction earthquakes at the University City (CU)

It is very likely that most of these source-path characteristics will be present in future subduction earthquakes. Therefore, in order to preserve such characteristics, we propose to correct them using scaling laws based on a theoretical source model of radiated Fourier spectra. There is a method for earthquake simulation in which a record of a small earhquake is used as empirical Green functions (Hartzel, 1978; Irikura, 1986). It is based on the assumption that the record is related to one simple dislocation of the seismic source. In addition, large earthquakes are idealized as the superposition of several simple dislocations. This means adecuate superposition of the record several times. Instead, we scale its FAS according to the ω^2 theoretical source model (Aki, 1967; Brune, 1970; Boore, 1983). Figure 3 shows two San Marcos-Guerrero spectral realizations, scaled to Ms=8.1 and Ms=7.7, respectively. In both cases, the April 25, 1989 [Ms=6.9] earthquake was used as empirical Green function. We also include in our assessment a postulated normal earthquake [Ms=7.0] which depth is about 80 km beneath Mexico City. It was obtained after a distance correction of the accelerations recorded at CU caused by the October 24, 1980 Oaxaca earthquake. In this figure, solid and dashed lines indicates NS and EW components. Michoacan gap, represented by the September 19, 1985 earthquake, was included for comparison.

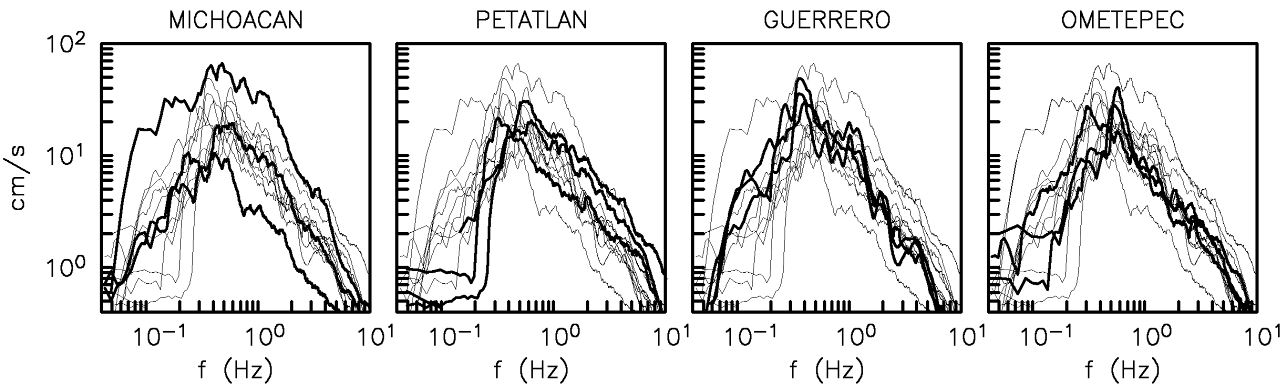

Figure 2 Comparison of FAS of subduction earthquakes recorded at CU

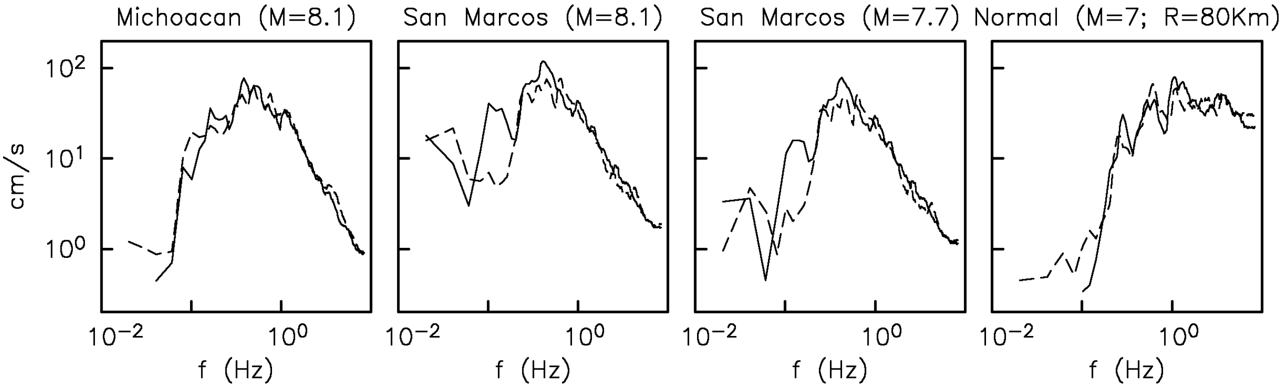

Figure 3 FAS of horizontal ground motion components at CU for postulated earthquakes

EMPIRICAL TRANSFERT FUNCTIONS (ETF) FOR SITE EFFECTS

A moderate subduction earthquake, with Ms=5.8, was the first event extensively recorded by the Mexico City accelerometric array. With the data written by this earthquake, Singh et al (1988) computed spectral ratios of FAS, called ETF, in order to obtain empirical amplifications of the lake bed zone relative to CU. Later on, using additional data from coastal events, Reinoso (1991) found that the stability of these ETF is increased if the average of the motion recorded at several hill zone sites, is taken instead of the one recorded at CU. He found that the amplification level is always the same, regardless earthquake's size, distance or azimuth.

To obtain the ETF of non-instrumented sites we rely on the self-similarity of scalar shear wave propagation in an elastic wedge with a moving rigid base (Sánchez-Sesma and Velázquez, 1987). The dynamic amplifications on the free surface of this model, written in terms of a non-dimensional frequency, are the same regardless the distance to the corner of the wedge (or the local depth of the soft soil). A normalized frequency description of the one-dimensional response of a single layer yields the same property if the thickness is changed. On the assumption that the spatial variation of the soil conditions is reasonably smooth, we interpolate the amplitudes of ETF for normalized frequencies, written in terms of the dominant period of the ground. We set this reference period as the inverse of the frequency where the largest amplification of the ETF occurs. For all available records of each instrumented site, ETF and dominat periods were computed and averaged as variables of random processes. The coefficients of statistical variation were used as weigths of the data in a spatial interpolation scheme. It is based on the Bayes theorem to adjust the coefficients of a two-dimensional polynomial function (Lancaster and Salkauskas, 1986; Pelto et al., 1988). The effective coefficient of variation is a quadratic combination of two parts, one related with the statistics, namely uncertanties of data, and other raletad with the geometry, spatial distribution of data. Because of the inverse quadratic relation, the lower coefficient of variation, the more is the weight of the datum in the interpolation.

Most of the ground periods obtainded from microtremors (Lermo et al, 1988) were included in the ground periods data-base. Large coefficients of variation, relative to the ones of strong ground motion data, were assumed for these data. We believe that periods obtained from strong ground motion records are more reliable. In order to enclose the interpolation area, called control points were also placed located along the boundary between the hill and transition zones. The value Ts=0.5 sec, sligthly less than the lowest period mesured at the transition zone, has been set as the dominat period for the hill zone. The coefficient of variation to this period was calibrated in order to constrain the solution at the hill zone. Periods from a variety of sources were successfully combined following the Bayessian least square matching. Figure 4 shows the map of dominant periods of the ground of Mexico City. Also, geotechnical zonification, main avenues and all strong grund motion accelerometric stations are presented. Dominant periods reach values larger than 5 sec.

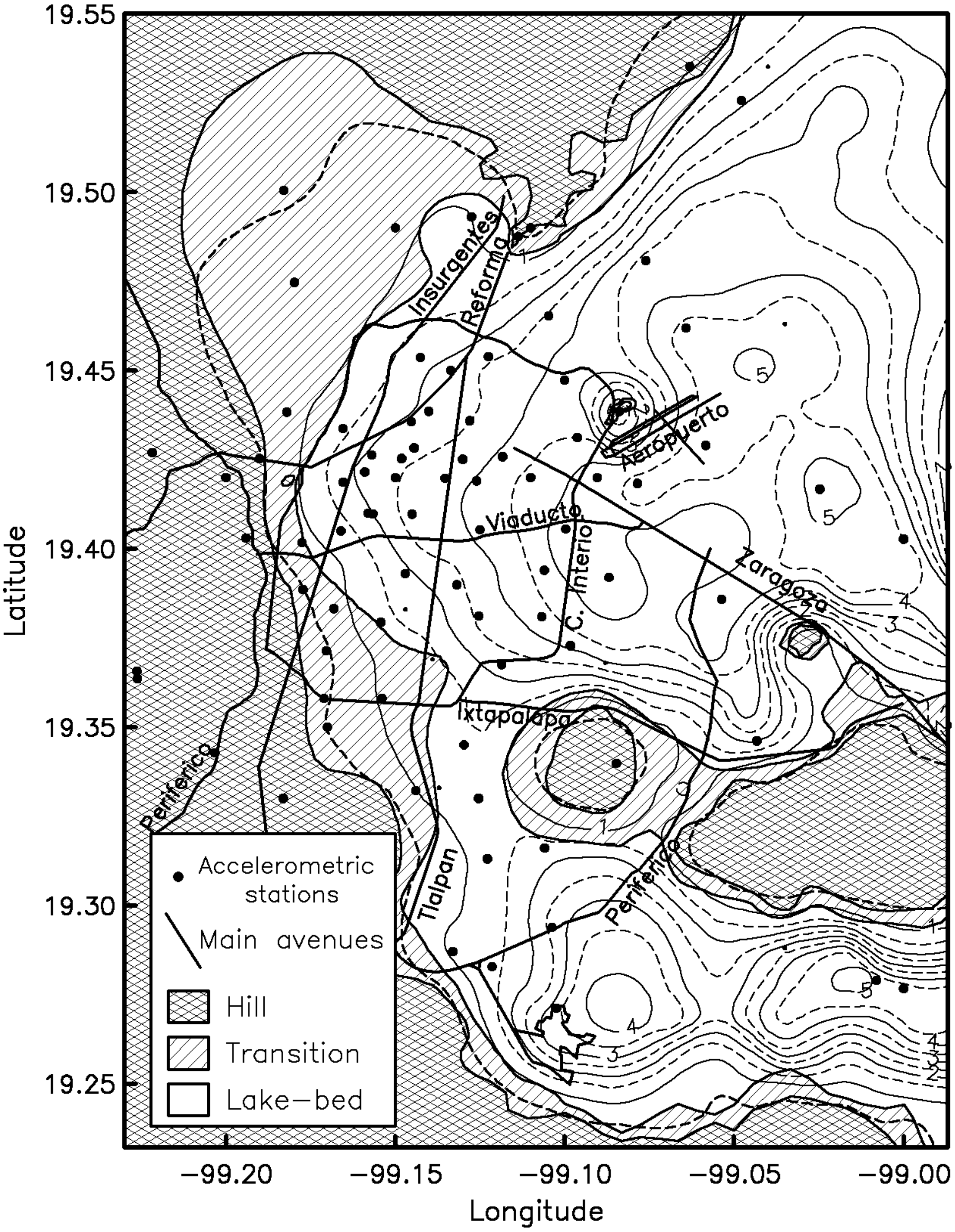

Figure 4 Isoperiods curves of dominant ground period in the Valley of Mexico

For the spatial interpolation of the ordinates of the ETF, we have followed a similar approach in which prior information is accounted for by means of the Bayes theorem. Only ETF from strong ground motions are available. As these ETF are relative to the average of the ground motion at the hill zone, unitary ETF for all non-dimensional frequencies can be impossed at the control points. However, these information is not enough for interpolation purposes in a significant part of the valley, especially if the density of data is insufficient to describe the spatial variation of the soil conditions. Given the dominant period of the ground at a given site, an interpolation in the normalised ground's period domain is performed in order to get a prior ETF. In this domain, the available data allow to interpolate ordinates for periods between 0.5 and 5 sec. This function is used within the Bayesian scheme of spatial interpolation. In fact, such function is an excellent prediction of the relative dynamic amplifications because it comes from real ETF and only the dominant period of the ground is required for computation. Besides the period, this spatial interpolation yields a function which takes into account the local particularities of amplifications.

RESPONSE SPECTRA ASSESSMENT

Following the proposal by Ordaz et al. (1989), we take the FAS of a desired site as the product of the ETF at there and the FAS of a postulated earthquake at CU. Since ETF are referred to as the average of the ground motion at hill zone, the FAS at CU is smoothed to partially account for this fact. On the other hand, random vibration theory was used to compute response spectra ordinates (Cartwrith and Longett-Higgins, 1956; Boore, 1983). In such a way, a duration of motion is required. Using Arias duration as the time between the 5 and 95% of the Arias intensity (Arias, 1969), Ordaz and Reinoso (1987) found that random vibration theory gives suitable results for typical ground motion of Mexico City. To account for postulated earthquakes, we used well-recorded data of several earthquakes to obtain an empirical relationship for Arias duration against magnitude of earthquake and dominant period of the ground.

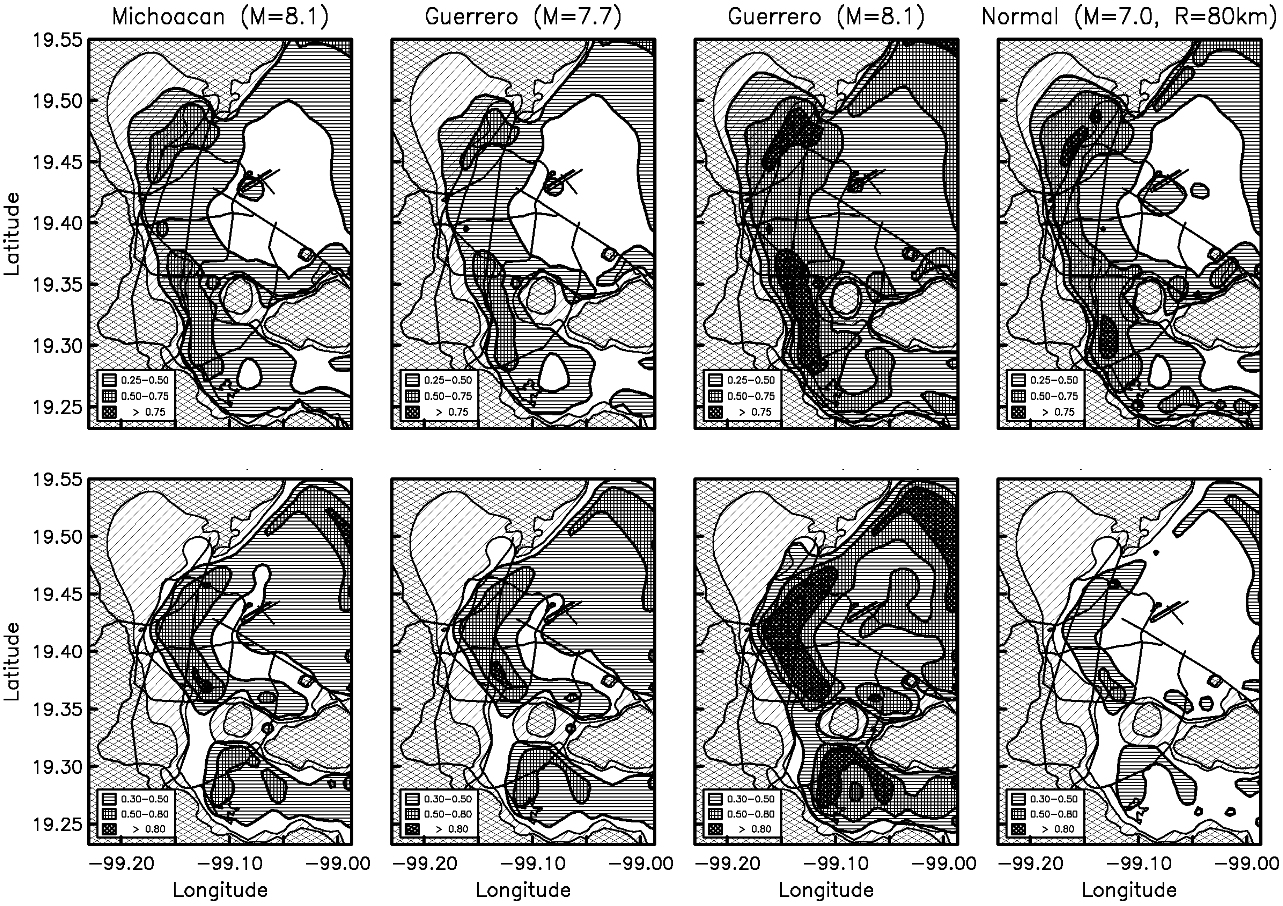

Figure 5 Spectral ordinates (Sa/g) for periods Te=1.0±0.25 s (top) and Te=2.0±0.5 s (bottom)

Seismic forces for structural periods in the ranges Te = 1.0 ± 0.3 s and 2 ± 0.5 s were computed for each postulated earthquake. Spatial distributions of such forces are detailed in figures 5 and 6. In both figures, the Guerrero M=8.1 postulated earthquake yields the heighest seismic intensities. However, these intensities can be reached for structural periods near 1 sec, if an intermediate deep earthquake, with M=7, take place at 80 km beneath the valley. Note that the Guerrero M=7.7 earthquake produce intensities much alike the ones due to the Michoacan M=8.1 earthquake.

CONCLUSIONS

A method for the reliable prediction of seismic response spectra at any site within Mexico City was presented. This empirical approach considers possible events of various origins. In fact, most of source-path and site effects are accounted for because quantitative descriptions of them are available. They come from hundreds of accelerograms recorded at many sites at the hill, transition and lake-bed zones of the valley. Most of the used data was collected after the great 1985 Michoacan earthquake. Moreover, an interpolation scheme based upon Bayesian statistics and theoretical considerations was developed in order to infer the dynamic amplifications of ground motion within the lake-bed zone at non-instrumented sites.

This allowed us to predict seismic risk scenarios for Mexico City. In the near future it is likely that a damaging earthquake to the structures at Mexico City will come from the Guerrero coast. A prediction of ground motion characteristics is given here if a major earthquake strikes there. Results clearly illustrate that seismic forces are strongly dependent upon the characteristics of seismic source, the path of seismic waves towards Mexico City, the effects of local surface geology and the structure dynamical properties.

The varius scenarios illustrate the most significant aspects that contribute in the structural design and allow to identify zones with higher risk within the valley. Results may have its bearing in practical design, planning and decisions for land use, structural repair and retrofiting. Moreover, the knowledge of accurate forecasts of seismic risk scenarios may be helpful to implement emergency plans in the short and long terms.

ACKNOWLEDGMENTS

Most of the developments reported herein have been stimulated and followed by the late Prof. E Rosenblueth (1926-1994). His insigth and suport were crucial to deal with this problem. We thank J Avilés, D Murià Vila and L Vieitez for their keen critical comments. This has been the product of many efforts aimed to instrument Mexico City valley and the Mexican coast. Data from the networks installed by Instituto de Ingeniería-UNAM, Centro Nacional de Prevención de Desastres and Centro de Instrumentación and Registro Sísmico are gratefully acknowledged. For their help in this regard we thank specially to L Alcántara, R Quaas and J M Espinosa-Aranda. This research has been partially supported of the Government of Mexico City (supervised along several years by D Ruiz and C Buenrostro) and DGAPA-UNAM under Grant IN104998.

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