Ground motion variability in the virgin Texcoco Lake area, Mexico

Luis Osorio & Juan M. Mayoral
Instituto de Ingeniería, Universidad Nacional Autónoma de México, Mexico City, Mexico

ABSTRACT
Spatial ground motion variability observed in the Texcoco lake region, in the surroundings of Mexico City, has been studied through the generation of sets of site specific response spectra developed performing several 1-D stochastic site response analyses. The studied zone has an area of 19.0 by 5.5 km^2, and has been instrumented with four seismological stations, which have recorded strong ground motions over the past years. This area presents unique geotechnical subsoil conditions consisting on very soft clays deposits, with low shear strength and high compressibility, randomly interbedded by sand lenses. The subsurface conditions prevailing at the instrumented sites, including shear wave velocity distribution with depth, were characterized using standard penetration, SPT, and cone penetrations, CPT, tests, combined with selective sampling of undisturbed soil specimens. Uncertainties associated with shear wave velocity measurements were considered allowing a random variation of +/-30% around the mean values. Series of resonant column and cyclic triaxial tests were carried out to obtain the dynamic soil properties. From this work, response spectra for the studied area were proposed. These can be used in future updates to the Mexico City building code.

RESUMEN
En el pasado, en estudios realizados de análisis de respuesta de sitio estocásticos unidimensionales, se han observado variaciones espaciales de los movimientos de suelo en la región del ex Lago de Texcoco. Para evaluar este fenómeno en este trabajo se consideró una zona de estudio de 104.5 km^2, que se instrumentó con cuatro estaciones sismológicas, que cuentan con registros de sismos fuertes. Esta región presenta condiciones geotécnicas difíciles debido a la presencia de depósitos de arcillas blandas lacustres altamente compresibles, de espesores importantes, intercalados aleatoriamente con lentes de arenas y limos. De esta zona se tiene información de la distribución de la velocidad de onda de cortante con la profundidad, obtenida a partir de la caracterización con pruebas de penetración estándar, SPT, y penetración de cono, CPT, combinado con muestreo de suelo inalterado y alterado. Las incertidumbres asociadas con la velocidad de onda de cortante se tomó en cuenta variando aleatoriamente el valor de la velocidad media +/-30%. Además se realizaron series de pruebas de columna resonante y triaxial cíclica para obtener las propiedades dinámicas de los suelos. De este trabajo se obtuvieron los espectros de respuesta para el área de estudio, que en el futuro podrían ser incorporadas en el código de construcción de la ciudad de México.

1 INTRODUCTION

Driven by the extensive damage observed during the 1985 Michoacan earthquake, several studies were launched to reduce the seismic risk in Mexico City valley, which ranged from dynamic soil property determination (e.g. Romo et al. 1986; Ovando et al. 1991; Romo, 1995), as well as global seismicity evaluations (e.g. Rosenblueth,1987; Esteva et al. 1989), and amplification studies (e.g. Romo, 1976; Seed et al. 1988; Seed et al. 1989). However, most of these studies have been focused on downtown Mexico City where the damage was more notorious. Even considering the large amount of information gathered from this effort, the nearby area in the so-called virgin Texcoco Lake, towards the north east of downtown, is still limitedly explored, as stated in the Mexico City building code (RCDF, 2004), Figure 1, and thus, its seismic parameters are not available for engineering design. In addition, this area poses an even more difficult subsoil conditions than downtown due to the important ground motion spatial variability observed during several earthquakes, as depicted in Figure 2, which shows the response spectra measured at stations TXSO and TXCH during the Costa de Guerrero and Puebla earthquakes, as can be seen, there are clear changes both in frequency content and spectral ordinates. This variation in ground motions can be associated with rapid changes in the depth to bedrock-like layers and thicknesses of sand and silt lenses, which are commonly found at this area interbedding the clay deposits. The bedrock-like term refers to a geological formation typically found in Mexico City´s soil profiles and usually called second hard layer. This is a very dense layer of partially cemented sandy silts and silty sands, which exhibits a larger shear wave velocity than the overlaying layers (i.e. presents a larger impedance ratio). Thus, it can be considered as a half space for 1-D wave propagation analysis. This paper presents field, laboratory and analytical studies aimed at characterizing ground motion variability, from a practical standpoint, to reduce the seismic risk in the area. Both subsurface exploration and laboratory testing was conducted at selected sites to determine the dynamic properties of the materials found at the site. The seismic environment of the region was established from empirically-derived response spectra, and local amplification effects were determined using 1-D stochastic site response analysis, on randomly generated soil profiles. The information gathered from this research can be used in future works to develop a seismic microzonation of the aforementioned area in order to minimize the seismic risk in structures located in the Texcoco lake region.

2 DESCRIPTION OF THE STUDIED SITE

The studied site is instrumented with four seismological stations (Texcoco Sosa, TXSO, Texcoco Site 1, TXS1, Texcoco Site 2, TXS2, and Texcoco Chimalhuacan, TXCH) as depicted in Figure 3. The site is nearly flat, has an area of 104.5 km^2, and is located to the North-East of Texcoco Lake, at about 12.6 km away, in average, from the Mexico City International Airport. The closest station to the Airport (TXCH) is located approximately 10.0 km to the East, whereas the further station (TXSO) is about 16.5 km to the North-East. Regarding the geology, the region is associated with Pleistocene lakes that existed in the valleys that are part of the Mexican Volcanic Belt. These lakes have being drained out due to water extraction and now they have formed clayey deposits randomly interbedded by sandy silts and silty sands.

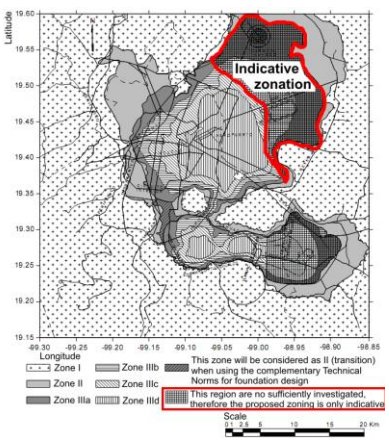

Figure 1. Location of the area of interest with respect to the seismic zoning proposed by RCDF

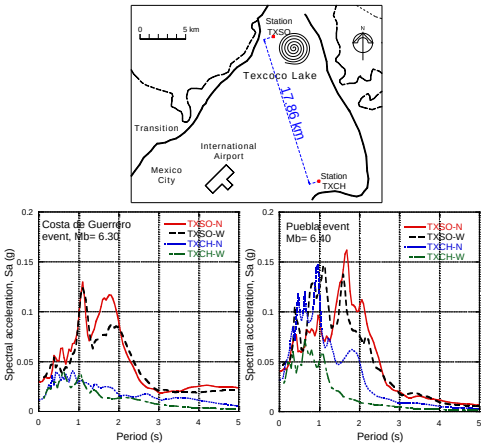

Figure 2. Ground motion variability observed in the area for station TXSO and TXCH

3 SUBSURFACE INVESTIGATION

An exhaustive subsurface exploration was carried out along with an experimental program where series of laboratory tests were conducted to establish the soil profile, hydraulic conditions, index and mechanical properties, including the stress-strain behavior during monotonic and cyclic loading (Mayoral et al. 2008a). This paper only focuses on research work related to the dynamic aspects of the ground response.

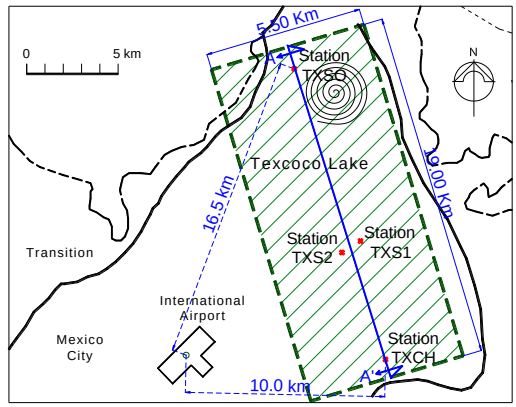

Figure 3. Studied area location

3.1 Field exploration

The field exploration consisted on four, standard penetration test, SPT, borings combined with undisturbed sampling recovery, and four cone penetration tests, CPT, conducted at each seismological station (Mayoral et al. 2008a). The location of the exploration borings is presented schematically in Figure 4. These corresponds to the theoretical location of each seismological stations selected, as reported in the Mexican strong ground motion database. Their locations were corroborated in the field except the corresponding to TXCH, which was not found where was supposed to be placed. In addition, two piezocone tests, PZC-1 and PZC-2, were carried out at stations TXSO and TXCH, to characterize in-situ pore water pressure distribution. With the information gathered, the cross section of the studied zone, shown at Figure 5, was developed. This idealized representation of the subsoil conditions allows verifying that the soil layers are fairly horizontal, and the depth to bed rock-like. Thus, 1-D wave propagation analysis can be used to obtain the dynamic response of the soil deposits. It can be clearly noticed that the effect of water withdraw is starting to modify the hydrostatic pore pressure distribution, in particular below 22 m. This condition can led to a change in dynamic soil properties for long term conditions due to consolidation of the clayey soils (Ovando, 2007), especially if the urban growth in the area demands the construction of deeper wells for water supply to meet local needs. The cone penetration tip resistance, q_c, and the number of blow counts corrected by energy and overburden pressure, $(N_1)_{60}$, distributions with depth measured at each studied station, are presented in Figure 6.

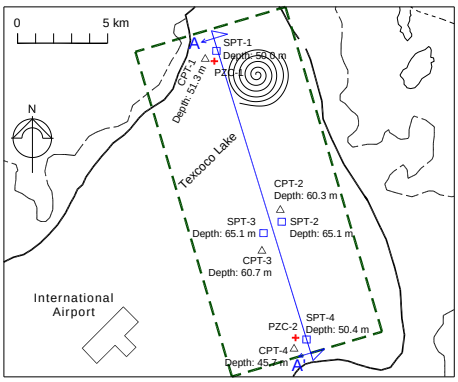

Figure 4. Layout of subsoil exploration borings

3.2 Estimation of shear wave velocity profiles

3.2.1 Clays and silts

Shear wave velocities for clays and silts were estimated using the expression proposed by Ovando et al. (1991) in terms of the tip penetration resistance, q_c, measured with CPT.

$$V_s = \eta \sqrt{\frac{q_c}{N_{kh}\,\gamma_s}} \qquad [1]$$

where: Vs is the shear wave velocity, in m/s; q_c is the tip cone penetration resistance in ton/m^2; γ_s is the unit weight of the soil, in ton/m^3; N_{kh} and η are parameters that depend on the soil type and are compiled in Table 1. These values were determined for the subsoil conditions prevailing at the site in a previous work (Mayoral et al. 2008b).

Table 1. Values N_{kh} and η

Soil Type	Values for N_{kh} Max.	Average	Min.	η
Texcoco Lake clays	14	9.5	6.7	23.33
Sandy silts found at the so-called hard layers in Mexico City Valley	16	11.1	8	40
Clay (studied area)		7.70		37.5

3.2.2 Sands

The estimation of shear wave velocities for sands was carried out using the empirical expression proposed by Seed (Seed et al. 1983), which provided the closest values to the measured response.

$$V_s = \alpha (N_1)_{60}^{\beta} \qquad [2]$$

Where: Vs is the shear wave velocity, in m/s; $(N_1)_{60}$ is the number of blow counts, measured with SPT, corrected by energy and overburden pressure. The parameters α and β were determined elsewhere for this zone (Mayoral et al. 2008b) and are equal to 61 and 0.5 respectively.

Both empirical expressions were used to obtain the shear wave velocity profiles that appear in the Figure 10, for each studied site.

3.3 Laboratory testing

Disturbed and undisturbed samples were recovered and taken to the laboratory to determine their index and dynamic properties respectively. Index properties included water content, liquid and plastic limits, soil densities, grain size distribution, and fine percentage. Prior to the determination of the dynamic properties, the undrained shear strength was obtained in several undisturbed samples, for three different in-situ stress levels. Series of resonant column and cyclic triaxial tests were conducted to study the dynamic behavior of the geomaterials found at the site.

3.4 Normalized modulus degradation and damping curves

With the results obtained from the cyclic traxial and resonant column tests, normalized modulus degradation and damping curves were generated (Figure 7). This figure also shows idealized curves presented by Romo et al. (1988) for the virgin Texcoco Lake. It can be observed that the effect of time (i.e. about 20 years) has not changed significantly the modulus reduction curve and that the experimental data nicely falls within the upper and lower bound proposed by Romo et al. (1988). This fact however, was not possible to verify for the damping curves, because only the average curve was reported by Romo et al. (1988). It is important to point out that Romo and his coworkers obtained these curves in their original work by fitting independently sets of experimental data.

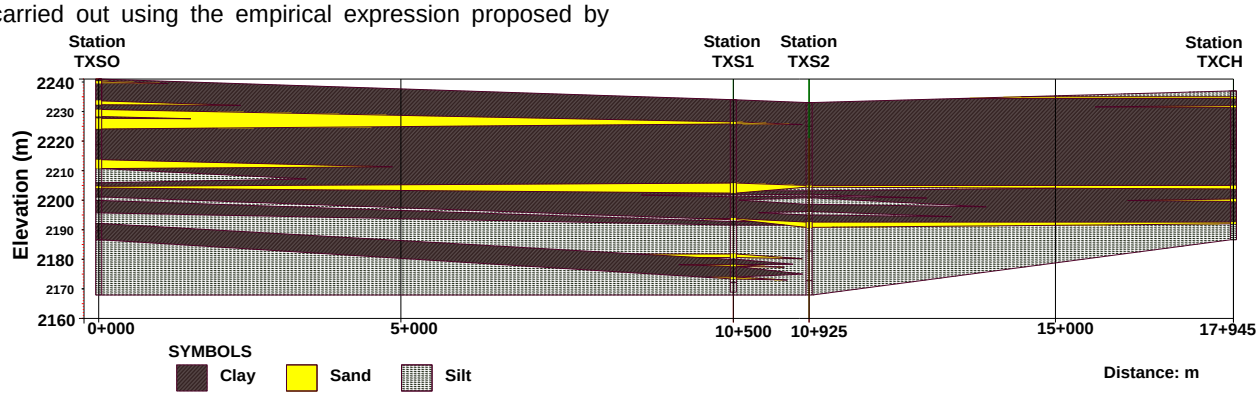

Figure 5. Schematic cross section (A-A') of the subsoil conditions prevailing at the studied zone

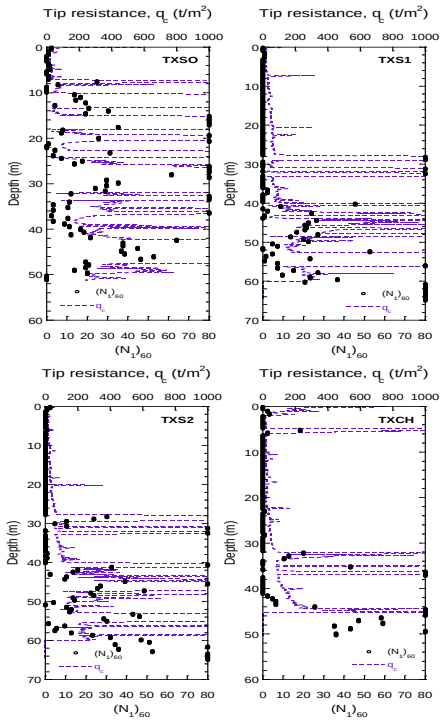

Figure 6. Cone penetration tip resistance, (N1)60 values for sites TXSO, TXS1, TXS2 and TXCH

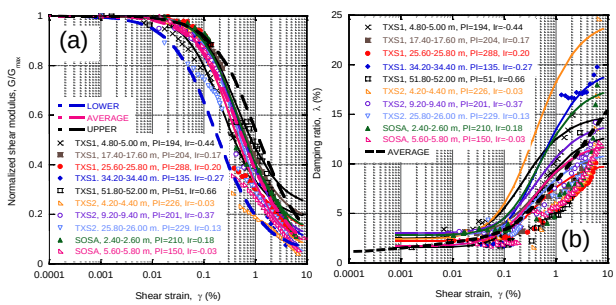

Figure 7. Estimated (solid line) and measured (dots) modulus degradation (a) and damping (b) curves for soft clay

For completeness, the experimental results were fitted with a Massing type model proposed by Romo (1995), defined by the following expressions:

$$G = (G_{\min} - G_{\max}) H(\gamma) + G_{\max} \quad [3]$$

$$\lambda = (\lambda_{\max} - \lambda_{\min}) H(\gamma) + \lambda_{\min} \quad [4]$$

$$H(\gamma) = \left[\left(\gamma / \gamma_r \right)^{2B} \Big/ 1 + \left(\gamma / \gamma_r \right)^{2B} \right]^{A'} \quad [5]$$

$$A' = I_r + A \quad [6]$$

$$I_r = \frac{w_L - w_N}{PI} \quad [7]$$

where: G_{max} is small strain stiffness (i.e. 10^{-4} %). The model described by equations 3 to 7 was developed within the equivalent linear analysis framework. The parameter G_{min} is a cutoff stiffness associated to a maximum experimental strain usually taken on the order of 10% for Mexico City clays (Romo, 1995; Romo et al. 1988). The parameter λ_{min} is the value of the damping ratio for small angular deformations (i.e. 10^{-4} %); λ_{max} its value for large deformations (i.e. near dynamic failure); $H(\gamma)$ is a function that depends on soil angular deformation; A and B are soils parameters that define the geometry of the curve G-γ, which are a function of the plasticity index of the soil; γ_r is a fixed reference value of the shear strain corresponding to 50% of modulus degradation; I_r is the relative consistency, which can be expressed in terms of the liquidity index, Li, as $I_r=1-Li$; w_L, w_N and PI are the liquid limit, water content and plasticity index of the soil respectively. A comparison between experimental data and the model predictions is included in Figure 7. Noticed how the model captures overall the experimental G/G_{max} curves but systematically over predict the damping values.

Due to the practical difficulty in sampling the sand layers, the upper and lower bounds proposed by Seed and Idriss (1970) for normalized modulus degradation and damping curves respectively, were deemed appropriated, considering that they had been used in 1-D wave propagation analysis (Romo et al. 1988; Seed et al. 1988), which predictions were in good agreement with the measured response during the 1985 Michoacan earthquake.

4 SEISMIC ENVIRONMENT

The seismic environment was characterized through an empirically-derived response spectra obtained from strong ground motions recorded at TXSO station, which measured among others events the Michoacan 1985 earthquake. This spectrum corresponds to an envelope of the observed responses, scaled to the peak ground acceleration, PGA, observed during the 1985 earthquake at the site (i.e. 0.1g). Acceleration time histories generated from time domain spectral matching as suggested by Lilhanand and Tseng (1988) and modified by Abrahamson (1993) were obtained from this spectrum and deconvolved to bedrock-like layers by means of a one dimensional site response analysis considering linear soil properties to ovoid the non-uniqueness of the solution when non-linear soils are involved. The details of this process have been presented elsewhere (Mayoral et al. 2008b). Figure 8 show the acceleration time history of the input ground motion selected for analysis, which corresponds to the strong ground motion for bedrock-like layers proposed by Mayoral et al. (2008b) exhibiting the largest duration. Figure 9 shows a comparison of the spectral shape used to characterize the seismicity at the studied sites in bedrock-like layers with the corresponding response spectra of both horizontal components of the ground motion recorded at UNAM in station CUMV, which is placed on rock, during the Michoacan 1985 earthquake. The north component was used by Seed et al. (1988) to analyze the observed response in several locations in the city. Several researches in the past have proven that assuming one dimensional SH waves propagating vertically yield to good results that compare well with the measured response. Thus the potential effect of surface waves is negligible. It can be seen a

good agreement in the frequency content of both ground motions.

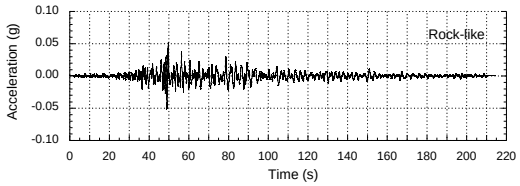

Figure 8. Acceleration time history in bedrock-like

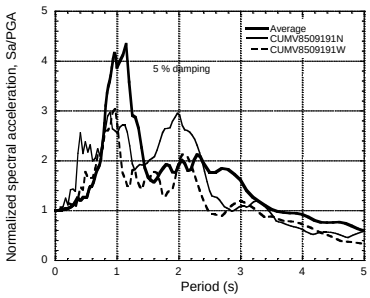

Figure 9. Response spectrum of input motion and the corresponding to CUMV Station recorded during the Michoacan, 1985 earthquake

5 IDEALIZED PROFILES FOR ANALYSIS

From the geotechnical information gathered at the studied sites, two idealized soil profiles for analysis were constructed (Figure 10). It can be clearly seen the presence of thick clay layers, randomly interbedded with sand and silt lenses. In general, the soil profile at this zone presents a desiccated crust of clay at the top extending up to a depth of 1.0 m approximately, which is underlain by a soft clay layer 25.0 m thick in average, with a large number of lenses of sandy silt, sandy clays and silty sands randomly interbedded, and with variable thickness. The water content of these materials usually ranged from 190 to 399 %, and plasticity index vary from 135 to 288%. Underlying the clay there is a 4.0 m average thick layer of very dense sandy silt (number of blow counts corrected by energy and overburden pressure, $(N_1)_{60}$, larger than 65) combined with volcanic ashes, which rests on top of a stiff clay ($(N_1)_{60}$ about 9) layer which goes up to about 60 m depth. The water content of this layer generally goes from 100 to 139 % and the plasticity index from 50 to 106 % approximately. Underneath this elevation a competent layer of very dense sandy silts with $(N_1)_{60}$ greater than 100 is found.

6 MEASURED RESPONSE

The four seismological stations located in the studied area (TXS1, TXS2, TXS0 and TXCH) have monitored strong ground motions over different periods of time, associated to several seismic events. According to the Mexican Strong Ground Motion Database (1996), MSGD, stations TXS1 and TXS2 were installed after the 1985 Michoacan earthquake, and have registered motions since 1998 to date, and station TXS0 operated since 1973 until 1985. Station TXCH starting recording in 1979, and stopped operating in 1982. Using the measured responses for the seismic events reported in the MSGD, the spectral shapes that characterized the response in each site were obtained, normalizing the spectral acceleration by the corresponding peak ground acceleration, PGA. These normalized shapes, obtained from the mean, μ, mean plus one standard deviation, $\mu+\sigma$, and the envelope, are presented in Figure 11. From these plots, it is evident the differences in frequency content and amplification factors in each site. Because of the low intensity of the motions developed in the hard layer during the 1985 Michoacan earthquake, the response does not involve any large non-linear effects, thus equivalent linear properties are considered sufficiently accurate for the analyses present herein.

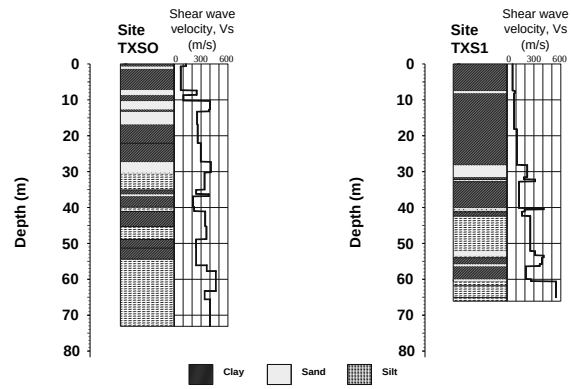

Figure 10. Idealized soil profiles and shear wave velocity distributions

7 MODEL CALIBRATION

The seismic response of each idealized soil profile, sites TXSO, TXS1, TXS2 and TXCH, was obtained with the program RADSH (Barcena et al. 1994). The program RADSH was developed to compute the probabilistic site response of horizontally stratified soil deposits subject to two dimensional SH waves propagation in the frequency domain, assuming equivalent linear soil properties. It uses the Thompson-Haskell solution (1953). The input motion is defined in terms of a response spectrum from which the equivalent power spectrum of the excitation is computed. The response is obtained in terms of power spectra using the random vibration theory. The accelerations, strains and response spectra in different points of the system are computed from the corresponding power spectrum and the extreme value theory. The main hypothesis of the program is that the seismic movements are stationary and assumed as a Gaussian process with zero mean. Thus, this random process is completely characterized by its power spectra. Using the random vibration theory, the maximum responses of a linear system excited by a stochastic process can be computed for a given confidence level. Physically this characterization of the seismic environment is equivalent to consider an infinite number of acceleration time histories with the same mean frequency content but with randomly distributed phases.

As part of the software validation, its predictions for each point were compared with those obtained from a deterministic analysis using the program SHAKE

(Schnabel et al. 1972). The acceleration time history used in the SHAKE analysis was already presented in Figure 8. The results and comparisons of RADSH and SHAKE are presented in Figure 12. As can be seen in this figure, there is a very good agreement between the results obtained with RADSH and SHAKE. The program RADSH was used in the next analysis stage to obtain the stochastic site response for each site.

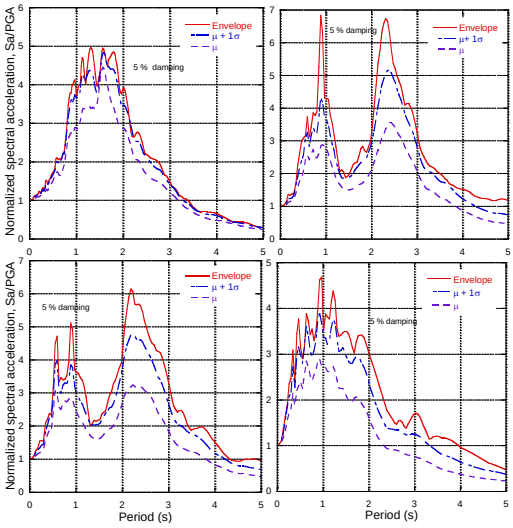

Figure 11. Representative ground motions, μ, μ + 1σ, and envelope of measured responses for sites TXSO, TXS1, TXS2 and TXCH

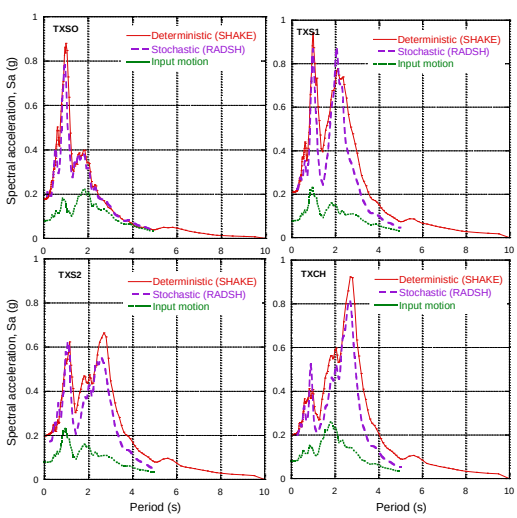

Figure 12. Computed response spectra using RADSH and SHAKE for sites TXSO, TXS1, TXS2 and TXCH

8 STOCHASTIC SITE RESPONSE ANALYSIS

Perhaps the most important sources of uncertainty in a site response analysis are: 1) characteristics associated to source-path travel mechanism and seismogenic zone, 2) dynamic soil properties (i.e. shear wave velocity profiles and modulus degradation and damping curves), 3) soil profile configuration (e.g. layers thicknesses, sloping angles of layering), and 4) input ground motion used for analysis. To account for these uncertainties, both the input motions as well as the soil properties were considered as suggested by Seed et al. (1988). In order to take into account uncertainties associated with the determination of shear wave velocities of the soil, the shear wave velocity was assumed to vary with a normal distribution within a ± 30 % range from the average value estimated using empirical expressions based on CPT and SPT measurements. A normal distribution was considered to represent the spatial variability of the shear wave velocity in each layer. Random shear wave velocity profiles, *Vs (i)*, were generated using random numbers, *R* (generated from 0 to 1), assuming a normal distribution an applying expression 8 each layer *i*

$$Vs(i)= R(i)\,(Vsmax(i) - Vsmin\,(i))+Vsmin(i) \qquad [8]$$

Where: Vs_{max} and Vs_{min} are the maximum and minimum shear wave velocities. These were obtained increasing and decreasing 30% the measured shear wave velocity respectively. This variation was considered appropriated based on the dispersion observed in shear wave velocity estimations in Mexico City clays from empirically derived equations as a function of cone penetration resistance, q_c, (Romo, 1995; Mayoral et al. 2008a) and the number of blow counts, measured with SPT, corrected by energy and overburden pressure, $(N_1)_{60}$ (De Alba et al. 1992).

Thus, twenty five random soil profiles were generated for each studied site, assuming a normal distribution for the shear wave velocity. The errors resulting from applying a single ground motion for representing the seismic environment with only one time history was overcome by using a response spectrum as input motion and the random vibration theory (Romo et al. 1977). The uncertainties associated with the shear modulus degradation and damping curves, and soil profile were considered secondary, taking into account that especial care was exercised during the field work, soil sampling and testing, which led to an small dispersion in the experimental data obtained (see Figure 7). Figure 13 shows the results of these analyses for two sites, as well as the mean, μ, and mean plus one standard deviation, μ+σ.

9 REGIONAL SUBSIDENCE EFFECTS IN THE SITE RESPONSE

Water withdrawn from relatively shallow aquifers has led to regional subsidence in Mexico City, which implies consolidation of the clay deposits and led to changes in their small strain dynamic properties (Ovando et al. 2007). To exemplify the effect that these changes can have on the dynamic ground response at the studied area, the response spectra for year 2008 (current conditions), 2018 and 2028 were compared in Figure 14, for site TXS1. A potential increase on the order of 10% in the small shear strain stiffness, G_{max}, and a reduction of 12 %, in the damping was assumed to occur about every ten years as reported by Ovando et al. (2007) for downtown areas. It can be seen clearly the importance that the effect of regional subsidence can have in the soil

response at site TXS1, being able to reduce the fundamental period of the soil deposit in about 20 % in 20 years.

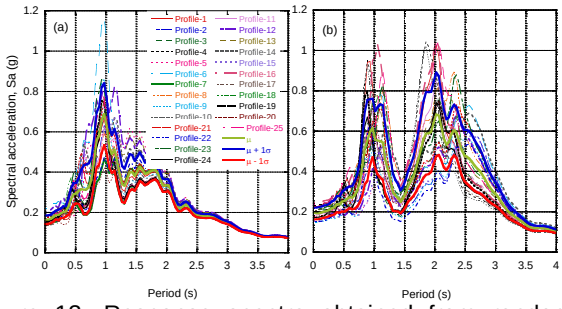

Figure 13. Response spectra obtained from randomly generated soil profiles for sites (a) TXSO and (b) TXS1

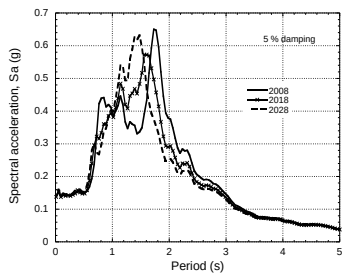

Figure 14. Effect of change in dynamic soil properties with time due to regional subsidence

10 PROPOSED RESPONSE SPECTRA

Ground motion variability was established in terms of four response spectra, one for each studied site, as it is presented in Figure 15, which shows a comparison between the mean, μ, mean plus one standard deviation, μ+σ, and measured envelope and computed response spectra. A reduction of 60 % of the spectral amplitude μ+σ is deemed appropriate for design purposes. This completely covers the measured response. The suggested design response spectra are depicted in Figure 16. The shape of the response spectra follows the one presented in the Mexican building code, changing only the parameters of the equations. A common practice in Mexico is to reduce the maximum spectral accelerations obtained from site response analysis in 40% (Rosenblueth, 1990). However, the authors consider60% of the spectral amplitude of mean plus one standard deviation more appropriate in this case taking into account the uncertainties observed in the analysis. It is warrant to mention that to date there is a lack of recommendations in the Mexican code regarding design spectra for the specific area investigated in this work. These suggested spectra are given by the following equations:

$$Sa = a_0 + (c - a_O)\frac{T}{T_a} \;;\; \text{if } T < T_a \qquad [9]$$

$$Sa = c \;;\; \text{if } T_a \le T \le T_b \qquad [10]$$

$$Sa = c\left(\frac{T_b}{T}\right)^r \;;\; \text{if } T > T_b \qquad [11]$$

The parameters to be used in these expressions are summarized in Table 2.

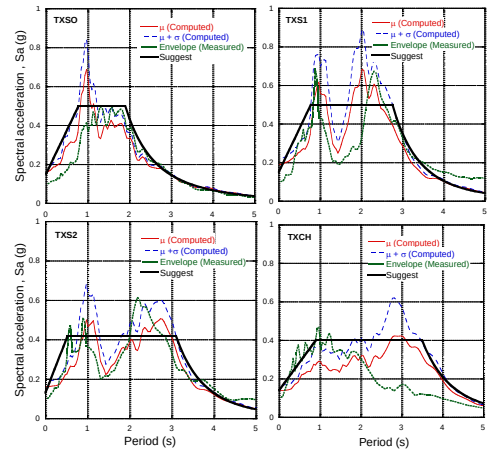

Figure 15. Design response spectra proposed for the sites TXSO, TXS1, TXS2 and TXCH

Table 2. Parameter values to computed the proposed design spectra

Studied sites	C	a_0	T_a[1]	T_b[1]	R
TXSO	0.50	0.15	0.78	1.90	2.7
TXS1	0.50	0.15	0.78	2.76	4.2
TXS2	0.42	0.13	0.53	3.10	4.6
TXCH	0.40	0.14	0.90	3.50	4.8

[1]Periods in seconds

11 CONCLUSIONS

Spatial ground motion variability observed at the virgin Texcoco lake region is related to changes on thicknesses of the compressible clays layers found at the area, due to presence of sandy silts and silty sands lenses randomly distributed in the subsoil, and rapid changes on depth to bedrock-like layers materials. One-dimensional wave propagation analyses using randomly generated soil profiles, to account for shear wave velocity variability, and random vibration theory, to define the seismic environment, appears to capture relatively closely the measured response at the studied area. Errors in the determination of ground motion response associated with scatter of the experimental modulus degradation and damping curves and soil profile configuration (e.g. layer thickness, layer sloping angles) seems to be secondary when especial care is exercise during field and laboratory works. Although pore pressure distributions measured at the area reveal a small deviation from the hydrostatic one, leading to conclude that local subsidence rates are small, the rapid urban growing and the construction of pumping wells to meet local water supply needs can trigger a modification in the small strain dynamic soil properties. This effect appears to reduce the predominant period of the soil about 10 % every ten years in average, for the worst case scenario. This potential variation was approximately accounted for when shear wave velocities were varied during the stochastic site response analyses.

REFERENCES

Abrahamson N., 1993. “Non-stationary spectral matching program”, unpublished.

Barcena A. y Romo M. P., 1994. “RADSH – Programa de computadora para analizar depósitos de suelos estratificados horizontalmente sujetos a excitaciones dinámicas aleatorias”, Informe Interno, Instituto de Ingeniería, UNAM

De Alba, P.A., Benoit, J., Pass, D.G. y Carter J.J., 1992. “Low-strain shear modulus from penetrometer tests”, Meeting of the International Committee on Foundation Performance During Earthquakes and its Influence on Building Codes, ISSIVIIFE y SMMS, August 20, Mexico City, pp 1-7.

Esteva L. y Ordaz M., 1989. “Riesgo sísmico y espectros de diseño en la República Mexicana”, Informe Interno, Instituto de Ingeniería, UNAM

Lilhanand K, Tseng W. S., 1988. “Development and application of realistic earthquake time histories compatible with multiple damping response spectra”. In: Proceedings of the 9th world conference on earthquake engineering, Tokyo, Japan, vol. II; p. 819–824.

Mayoral J. M., Osorio L. y Romo M. P., 2008a. “Microzonificación sísmica de la zona del Ex-Lago de Texcoco”, Informe Interno, Instituto de Ingeniería, UNAM.

Mayoral J. M., Romo M. P. and Osorio L., 2008b. “Seismic parameters characterization at Texcoco lake, Mexico”. Soil Dynamics and Earthquake Engineering, Volume 28, Issue 7, Pages 507-521, July

MSGD (BMDSF), 1996. “Base Mexicana de Datos de Sismos Fuertes”. Actualización de los Catálogos de Estaciones a 1995 y Acelerogramas a 1994. Catálogo de los registros de los temblores del 14 de septiembre, 9 y 21 de octubre de 1995, SMIS, CD.

Ovando E. y Romo M. P., 1991. “Estimación de la velocidad de ondas S en la arcilla de la ciudad de México con ensayos de cono”, Revista Sismodinámica, 2, 107 123

Ovando E., Ossa A. and Romo M., 2007. “The sinking of Mexico City: Its effects on soil properties and seismic response”. Soil Dynamics and Earthquake Engineering 27, 333–343

RCDF, 2004. “Reglamento de Construcciones para el Distrito Federal”, Administración Pública del Distrito Federal, Jefatura de Gobierno, Normas Técnicas Complementarias para el Diseño por Sismos, México

Romo M. P., 1976. “Soil-structure interaction in a random seismic environment”, PhD dissertation, University of California, Berkeley

Romo M. P., Lysmer J. and Seed H. B,, 1977. “Finite element random vibration method for soil structure interaction”, Proceedings of the 4th International Conference on Structural Mechanics in Reactor Technology, Vol K (a), paper K 2/3, San Francisco, Calif., August

Romo M.P. y Jaime A., 1986. “Características dinámicas de las arcillas del Valle de México y análisis de respuesta de sitio”, Reporte Interno, Instituto de Ingeniería, UNAM, Abril

Romo M. P., Jaime A. and Reséndiz D., 1988. “General soil conditions and clay properties in the Valley of Mexico”, Journal Earthquake SPECTRA, Vol 4, No 2, pp 731 752, November

Romo M. P., 1995. “Clay Behavior, Soil Response and Soil Structure In-teraction Studies in Mexico City”. Proceedings of the Third Interna-tional Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics. San Luis Missouri, USA, Vol 2, pp 1039-1051

Rosenblueth E., 1987. “Modelos probabilísticos de la ocurrencia de temblores”, Memorias del Simposio Generación, Propagación y Efectos de Temblores, SMMS, SMIS, SMF, UGM, abril

Rosenblueth E. y Ovando E., 1990. “Riesgo sísmico en el Valle de México: una perspectiva geotécnica”, El subsuelo de la cuenca del Valle de México y su relación con la ingeniería de cimentaciones a cinco años del sismo, Sociedad Mexicana de Mecánica de Suelos, S. C. , México, D. F.

Schnabel P. B., Lysmer J. and Seed H. B., 1972. “SHAKE - A computer program for earthquake response analysis of horizontally layered soils”. Report No. EERC-72/12, University of California, Berkeley.

Seed H.B., Idriss I. M., 1970. “Soil moduli and damping factors for dynamic response analysis”. UCB/EERC-70/10. Berkeley: University of California.

Seed H. B., Idriss M. I. and Arango I., 1983. “Evaluation of liquefaction potential using field performance data”. Journal of the Geotechnical Engineering Division, ASCE 109(3): pp 458-82

Seed H. B., Romo M. P., Sun J., Jaime A. and Lysmer J., 1988. “Relationships between soil conditions and earthquake ground motions”. Journal Earthquake SPECTRA;4(2):687–730

Seed and Sun, 1989. “Implications of site effects in the Mexico City earthquake of Sept. 19, 1985 for earthquake-resistant design criteria in the San Francisco Bay area of California”, Report No UCB/EERC-89/03, march

Thomson-Haskell N. A., 1953. “The dispersion of surface waves on multilayered media”, Bull Seism Soc Am, vol. 43, pp 17-34.