Characterization of the seismic environment prevailing at Texcoco Lake, Mexico

Caractérisation de l'environnement séismique prévalent dans le lac de Texcoco, Mexico

Luis Osorio
Instituto de Ingeniería, UNAM   Email: LOsorioF@iingen.unam.mx
Juan M. Mayoral
Instituto de Ingeniería, UNAM   Email: JMayoralV@iingen.unam.mx
Miguel P. Romo
Instituto de Ingeniería, UNAM   Email: mromo@pummas.iingen.unam.mx

ABSTRACT

Texcoco lake area, in the valley of Mexico, presents particularly difficult geotechnical conditions due to the presence of thick deposits of soft, highly compressible lacustrine clay, randomly interbedded with sand lenses. In contrast to other sites in the valley, there is a lack of information regarding geotechnical subsoil conditions, dynamic properties, and earthquake recordings at rock sites. Thus, the seismic environment is not completely identified. This paper describes field and laboratory investigation as well as analytical studies, aimed at characterizing the ground response this region. In-situ measurements of shear wave velocity, using suspension PS logging, along with cone penetration, CPT, and standard penetration, SPT, resistance values, and results from series of resonant column and cyclic triaxial tests were used to obtain a representation of the subsoil characteristics found at the site, and the variation of dynamic properties with strain level. Predicted shear wave velocity profiles derived from empirical correlations compare well with measured values. Ground motion definition was achieved indirectly through empirically derived response spectra obtained from sets of earthquake ground motions recorded by four seismic stations located in the area. Acceleration time histories representative of the design earthquake were obtained using time-domain spectral matching. 1-D shear wave deconvolution was used to obtain the corresponding ground motions in rock. With this information, probabilistic analyses of site response were carried out at several points. The response of the system was obtained in terms of power spectrum using the random vibrations theory. In order to consider the potential variability in the subsoil dynamic properties, a random variation of the shear wave velocity was also accounted for in this study, taking the mean and plus one standard deviation values. Finally, a set of response spectra that defines the spatial variation of dynamic response the studied area was obtained.

RÉSUMÉ

Le territoire du lac de Texcoco, dans le val de Mexico, présente particulièrement des conditions géotechniques difficiles. Comment un effet de l'existence de dépôts profonds d'argiles lacustres, doux et hautement comprimables, aléatoirement intercalées avec des verres de sable. Au contraire d'autres lieux dans le val, il y a une absence d'information entre les relations et les conditions géotechniques du sous-sol, les propriétés dynamiques et les enregistrements de tremblements sous roc. Ensuite, le comportement sismique n'est pas reconnu complètement. Ce texte décrit l'investigation dans champ et laboratoire même que les études analytiques, visés à la caractérisation de la réponse de ce territoire. Des mesures in-situ de la vélocité des ondes de coupe, en utilisant du PS logging suspension, avec pénétration de cône, CPT, pénétration standard, SPT, valeurs de la résistance, et les résultats des séries des colonnes résonantes et des test triaxial cycliques ont été utilisés pour obtenir une représentation des caractéristiques du sol trouvés dans le site, et la variation des propriétés dynamiques avec un niveau de tension. Les profils de vélocités des ondes de coupe prédit à partir des corrélations empiriques font une bonne comparaison avec les valeurs mesurées. La définition du mouvement du terrain a été obtenue indirectement à travers le spectre de réponse empirique obtenu à partir des systèmes de mouvement de tremblement enregistrés par quatre stations sismiques localisées dans l'endroit. Des histoires représentatives des temps d'accélération du tremblement de conception ont été obtenues en utilisant un correspondant spectre dans le domaine du temps. La déconvolution des ondes de coupe en 1-D ont été employées pour obtenir les mouvements correspondent sous roc. Avec cette information, des analyses probabilistes de la réponse en site ont été effectuées dans beaucoup de positions. La réponse du système a été obtenue grâce aux termes du spectre de potence, en utilisant la théorie des vibrations aléatoires. A la fin, on considère la variation potentielle dans les propriétés dynamique du sol, une variation aléatoire des ondes de coupe a été également examinée ici, on remarque des valeurs moyennes et maximales de la déviation standard. Finalement, un système de spectres a été obtenue afin d'obtenir un résultat qui a définie la variation spatiale de la réponse dynamique du territoire.

Keywords : Lacustrine clay, Texcoco lake, ground motions, seismic.

1 INTRODUCTION

Due to the particular characteristics of Mexico City clay having high plasticity index, no significant reduction in shear modulus is observed even for shear strains as high as 0.1 %. Similarly, there is not a significant increase in the damping ratio until angular distortions of the order of 0.3% are reached (e.g., Romo et al. 1988). Thus, the response of clayey soil deposits is nearly elastic even for shear strains as high as 0.3 %, which leads to a high potential of amplification of the seismic waves. Indeed, amplification factors up to 5 were observed during the 1985, Michoacan earthquake. Spectral ordinates for 5% structural damping of measured ground acceleration at the surface ranged from about 0.4 g to 1.0 g at periods of 2 sec (e.g., Seed et al. 1988, Maroyal et al. 2006). Despite the amount of knowledge gathered for the main clay deposits found in Mexico City, surrounding areas, such as the Texcoco Lake still remain poorly explored, and in consequence the seismic parameters, including dynamic soil properties and representative site specific ground motions for geotechnical earthquake engineering analysis are unavailable. This paper describes a field investigation and laboratory testing program as well as analytical studies, aimed at characterizing the ground response of a particular area located at the Texcoco Lake region.

2 DESCRIPTION OF THE STUDIED SITE

The studied site is approximately 110 m wide and 120 m long, and nearly flat. It is located to the west of an old solar evaporator no longer in operation, within the old Texcoco lake, at about 16.5 km to the northeast of the Mexico City International Airport, as depicted in Figure 1. Seasonal desiccation cracks are often observed at the upper clay layers,

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which usually do not reach depths higher than 1.5 m, but that may extend up to 10 to 12 meters, or being randomly interconnected.

3 SOIL SITE INVESTIGATIONS

An extensive field and laboratory investigation was conducted to define soil stratigraphies, hydraulic conditions, soils index properties, and static and dynamic stress-strain soil behavior (Mayoral et al. 2008). This paper focuses only on research work related to the dynamic behavior of the materials found at the studied site.

3.1 *Field Tests*

For the characterization of the subsoil conditions, one Standard Penetration Test, SPT, nine Cone Penetration Test, CPT, and one PS suspension logging test were used. The depth of the CPT ranged from 25 to 100 m. At those depths where the hardness of the ground exceeded the applicability of this subsoil exploration technique, standard penetration tests, SPT, was applied instead. In addition, a 60 m depth SPT (i.e. SPT-1) was conducted for soil identification purposes. Figure 2 shows the location and depths of each exploration boring, from which also were retrieved disturbed and undisturbed soil samples at selected depths. Figure 3a summarizes the results obtained from standard and cone penetration tests, in terms of the variation of penetration resistance with depth. The suspension PS logging technique was used to determine in situ values of shear wave velocity, V_s (Figure 3b). The hydraulic conditions of site pore water were established based on piezocone measurements taken at the center of the site, conducted in the proximity (about 0.5 m away) of CPT-1.

3.2 *Subsoil conditions*

Based on the subsurface characterization it was found that the soil profile at the studied site 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 of about 25.0 m thick, with a high number of interbedded lenses of sandy silt, sandy clays and silty sands. The water content of these materials ranged from 190 to 295 %, and plasticity index ranging from 139 to 265%. 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 goes from 100 to 112 % and the plasticity index from 60 to 106 % approximately. Underneath this elevation a competent layer of very dense sandy silts with $(N_1)_{60}$ greater than 100 is found.

3.3 *Estimation of shear wave velocity profiles*

For clays and silts: Shear wave velocities for clays and silts were estimated using the expression proposed by Ovando and Romo (1990) in terms of the tip penetration resistance, q_c, measured with CPT.

$$V_s = \eta \sqrt{\frac{q_c}{N_{kh}\gamma_s}} \tag{1}$$

Where: V_S is the shear wave velocity, in m/s; q_c is the tip cone penetration resistance in kPa; γ_s is the unit weight of the soil, in kNm^{-3}; N_{kh} and η are parameters that depend on the soil type, which were determined for the particular conditions of the site. Typical values of these parameters are presented elsewhere (Ovando & Romo 1990). This expression was properly recalibrated, obtaining values of N_{kh}= 7.70 and $\eta = 37.5$ for the soil conditions prevailing at the site using the results obtained with suspension logging.

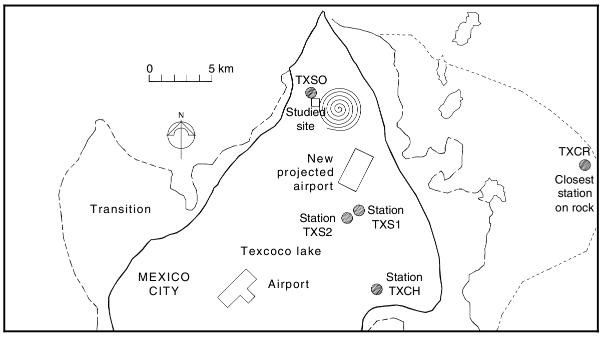


Figure 1. Studied Site location at Texcoco Lake Valley

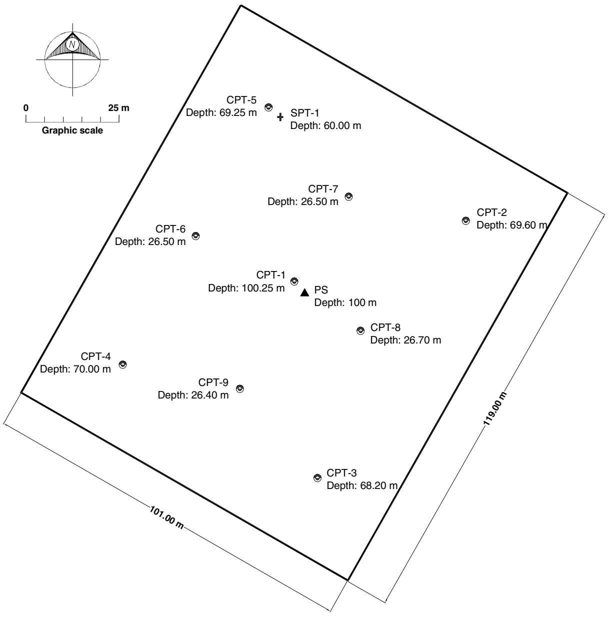
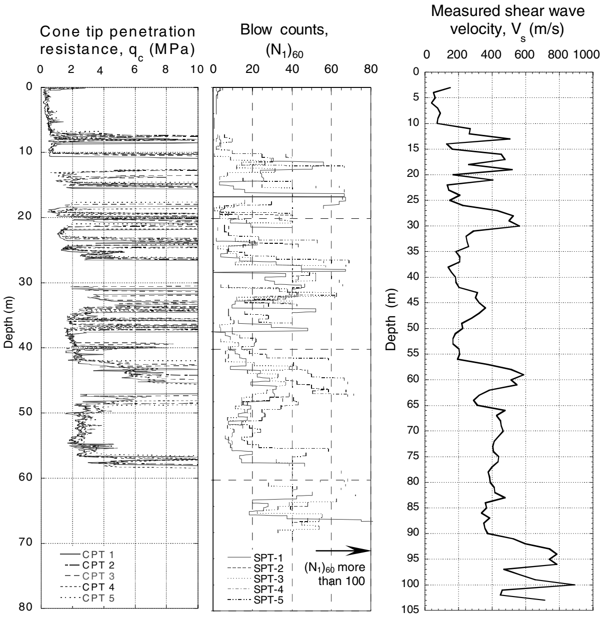


Figure 2. Layout of subsoil exploration borings



(a) (b)

Figure 3. Results from standard and cone penetration tests (a) and in-situ shear wave velocity measured at the site with suspension logging (b)

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

$$V_s = \alpha N^{\beta} \tag{2}$$

Where: V_s is the shear wave velocity in m/s; N is the number of blow counts corrected by energy and overburden pressure; $\alpha = 61$ and $\beta = 0.5$.

Once the empirical expressions were validated for the conditions prevailing at the site, they were used to develop mean and mean plus and minus one standard deviation shear wave velocity profiles, it was found that the average representative values of shear wave velocity of clayey materials, V_s, are about 70 m/sec approximately, at the upper soft clay layers (from 0 to 10 m) and from 200 to 400 m/s in the stiff clay layers. In the deep hard deposits and sand lenses, V_s ranged from 400 to 800 m/s.

4 DYNAMIC PROPERTIES

In the work presented herein, it was deemed appropriate to used twin samples, considering the high plasticity of the soil tested, and the homogeneity of the material. Therefore, series of resonant column tests and cyclic triaxial tests were conducted in twin samples retrieved at the site. Five series of resonant column tests were conducted, each sample with three different confining pressures ranging from the in-situ effective stress to twice this value, to properly reproduce, in a practical way, the field conditions and other loading scenarios. Thus, a total of ten twin samples, two for each resonant column, were tested (Mayoral et al. 2008). From these tests, the small to large deformation stiffness and damping variation of the clayey soils was established. Due to the practical difficulty in sampling the sand layers, the upper and lower bounds proposed by Seed e Idriss (1970) for normalized modulus degradation and damping curves respectively were deemed appropriated, considering that they had been used in 1D wave propagation analysis (Romo et al. 1988, Seed et al. 1988), which predictions were in good agreement with the measured response during the 1985 Michoacán earthquake.

4.1 *Normalized modulus degradation and damping curves*

With the results obtained from the resonant column and triaxial tests, normalized modulus degradation and damping curves were developed for the clay found at the site. These experimental results were fitted with a Masing type model, which is able to account for soil nonlinearities associated with the shear strain level generated during an earthquake (Romo 1995, Flores and Romo 2001).

Figure 4 shows a comparison between the experimental and fitted response as a function of plasticity index (PI) and relative consistency (I_r). The parameter PI has been found to influence significantly the shear modulus and, to a lesser degree, the damping ratios, λ, of clayey materials (i.e. Romo et al. 1989). The parameter I_r seems to affect mostly the small strain soil stiffness, G_{max}, but also may influence the geometry of the curves. As can be seen in Figure 4, there is a very good agreement between the predicted (P) behavior and the experimental (E) data.

5 SEIMIC ENVIRONMENT

It is common practice to characterize site-specific ground motions for earthquake design of structures on the basis of empirically derived response spectra. The travel-path influence on the seismic waves characteristics as they propagate from the source to the particular rock site is approximately accounted using recordings taken at seismological stations near the studied site during seismic events located at potentially active sources. The response spectrum, normalized with respect to peak ground acceleration (PGA) eliminates the intensity factor of the motions recorded on rock sites during several events. Any difference observed between the spectral curves reflects the effect of the energy-release source and wave path trajectories (followed from the epicenter to the site) specific for a given earthquake. For the case studied, the lack of seismological stations located at rock sites makes difficult the ground motion determination, due to the effect that the soil profile may have in the dynamic response. This was resolved by obtaining synthetic acceleration time histories using time domain spectral matching targeting directly the soft soil response spectra derived from seismic records, using the method proposed by Lilhanand and Tseng (1988) as modified by Abrahamson (1993). These time histories were, in turn, used in deconvolution analyses to bring the soft soil ground motions down to the stiffer materials that appear at the bottom of the soil profile, hereafter referred as rock-like, obtained using the synthetic ground motions, 1, 2 and 3 (Figure 5).

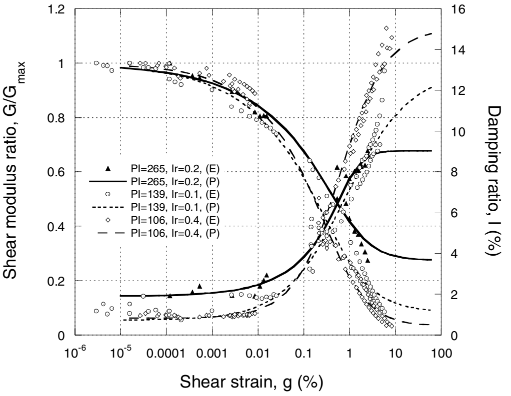


Figure 4. Predicted and measured modulus degradation and damping curves (Mayoral et al. 2008)

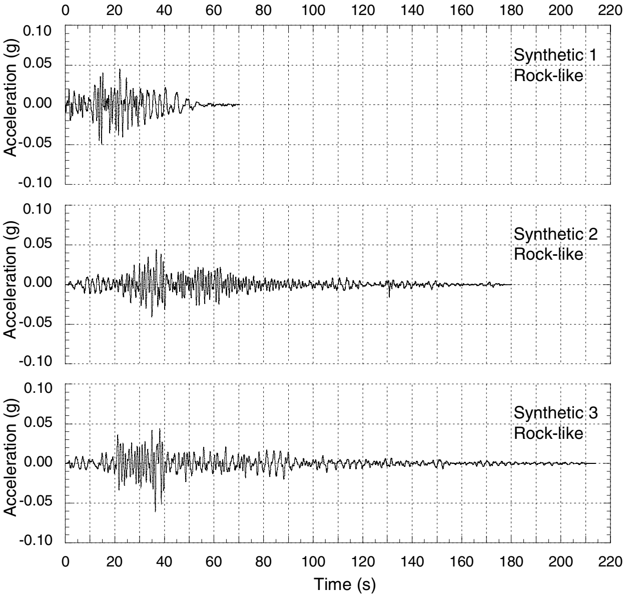


Figure 5. Acceleration time histories in rock-like

5.1 *Recommended ground motions*

The response spectrum corresponding to the synthetic time history 1, is a good representative average of the three ground motions considered, as can be notice in Figure 6. Thus, this can be used as input motion directly, for site response or soil structure interaction analyses, using random vibration theory (e.g. Barcena & Romo 1994, Romo 1980). For nonlinear time domain analyses it would be recommended to use both synthetic time histories 2 and 3, to include the effect of long duration events in the structural fatigue. The analysis included herein does not account for potential changes on the dynamic properties at the site due to regional consolidation, which may lead to a reduction in the natural period of the site approximately 15 to 20 % of its original value (Ovando et al. 2007). This could affect structures with predominant periods ranging from 0.7 to 0.9 sec.

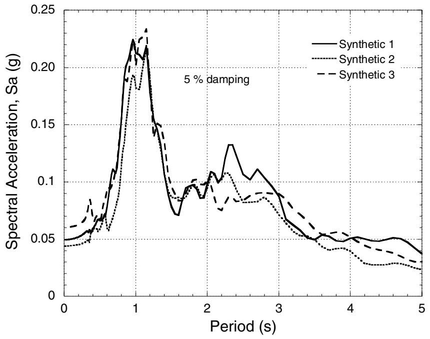


Figure 1. Acceleration response spectra in rock-like

6 PROPOSED RESPONSE SPECTRA

Finally extending the area of investigation to the sites where they are located seismological stations TXS1, TXS2 and TXCH (Figure 1), proposed movements of design for the studied sites are established in terms of response spectra (Figure 7), which are defined by the following equations:

$$\mathrm{S}a = a_0 + \left(c - a_O\right)\frac{\mathrm{T}}{\mathrm{T_a}} \text{ ; if } T < T_a \tag{3}$$

$$Sa = c \text{ ; if } T_a \le T \le T_b \tag{4}$$

$$\mathrm{S}a = c\,\frac{T_b}{T}^{\,r} \text{ ; if } T > T_b \tag{5}$$

The values taken by the parameters found in these expressions are obtained from Table 1.

Table 1. Response spectrum

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.

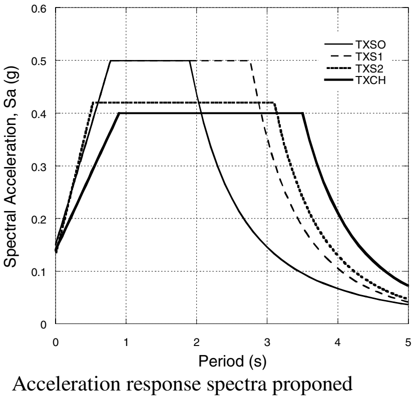


Figure 2. Acceleration response spectra proponed

7 CONCLUSIONS

This paper describes the framework used to establish the seismic environment of a particular area located within the Texcoco lake region. This involved field and laboratory investigation. In particular, CPT and SPT were applied to generate a representation of the subsoil conditions. Parameters N_{kh} and η, which allows correlating CPT tip resistance measurements with reference values of shear wave velocity, were obtained for the Texoco lake clays and silts. The benchmark data were determined through PS suspension logging. Normalized soil stiffness and damping relationships were constructed performing resonant column and triaxial tests in twin samples. The experimental data appears to be susceptible to modeling with Masing type hyperboilic models. Time domain spectral matching was used to obtain a representative set of synthetic acceleration time histories for soft soil, which, in turn, were deconvolved to deeper stiffer layers that can be used in seismic soil structure interaction analyses. Finally design spectra for four different sites were proposed.

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