IDENTIFICATION OF MEXICO CITY CLAY DYNAMIC PROPERTIES

Victor M TABOADA-URTUZUASTEGUI[1], Hernán MARTINEZ[2], Miguel P ROMO[3] And Carlos D ARDILA[4]

SUMMARY

The surface and downhole acceleration records of the “Central de Abasto Oficinas (CAO)” array at Mexico City have been analyzed to determine the soil stiffness as a function of shear strain amplitude. The 3/31/93, 24/10/93, 23/05/94, 10/12/94 and 09/10/95 seismic events have been used for this purpose. The shear stress-strain histories have been evaluated directly from the field downhole acceleration records, employing a technique of system identification, and used to obtain the variation of shear modulus with shear strain amplitude. A shear-beam model, calibrated by the identified properties, is found to represent the site dynamic response characteristics. The results have been compared with values obtained by previous authors using field and laboratory tests.

INTRODUCTION

Experimental data are the keystone to the identification of the behavior of real systems. There are three main sources of experimental data: (1) laboratory testing, (2) in situ testing, and (3) observation of existing systems subjected to natural excitations. In situ testing procedures and laboratory tests have been the main tools to obtain the soil stress-strain relationships. The field testing procedures are restricted to small amplitude response which make them useful only to provide the means of measuring soil low-strain dynamic properties, such as shear wave velocity [Stokoe and Nazarian 1985; Nazarian and Desai 1993]. The laboratory techniques are often used to evaluate the soil properties at larger strain levels; however, its applicability is somewhat restricted due to disturbance introduced during soil sampling, and difficulties in reproducing the in situ stress state and the seismic loading history [Elgamal et al 1995].

Observation of instrumented systems that experienced a broad variety of natural excitations ranging from mild to severe are, in the abstract, the best set of data, and they usually cover a wide range of amplitude response. Under earthquake conditions any system, in general, may sustain unpredicted damage or may display unanticipated strengths; such information is not available through other means. However, it must be taken into account that real earthquake data suffer several limitations too. They are of transient nature, characterized by short duration, and they are single non-repeatable events. Nevertheless, earthquake response data enclose information not available elsewhere.

In the last few years, some attempts have been made to evaluate shear stress-strain histories directly from acceleration records using the technique of system identification. This identification procedure, originally proposed in basic form for shake-table studies [Koga and Matsuo 1990], was further developed and used earlier for analyzing downhole site response at Lotung, Taiwan [Zeghal and Elgamal 1994, 1995]. Recently, [Elgamal, 1996] this technique was used to study the dynamically induced liquefaction of a saturated loose sand stratum in centrifuge model simulations.

The valley of Mexico City is frequently affected by strong ground motions due to a combination of high rate of subduction-related seismicity at regional distances, and unique soft clay site materials conditions. Although the dynamic stress-strain behavior of Mexico City clays has been thoroughly studied and a Massing-type model has been developed [Romo 1995], the accelerometer-vertical arrays yield an unique opportunity to study the characteristics of shear stress-strain and their evolution with time during actual ground motions.

[1] *Research Professor, Geotechnical Department, Institute of Engineering, UNAM.*
[2] *Research Professor, Mine and Engineering Department,Civil Eng. School, National University of Colombia at Medellin*
[3] *Research Professor and Head, Geotechnical Department, Institute of Engineering, UNAM, Apartado Postal 70-472, 04510 Méx*
[4] *Assistant Researcher, Geotechnical Department, Institute of Engineering, UNAM*

CENTRAL DE ABASTOS OFICINAS (CAO) SITE

The CAO site is located not far from the downtown of Mexico City, within the central lacustrine deposit zone of the valley (figure 1). From a geotechnical point of view, Mexico City has been divided in three regions (see figure 1): a) the lake zone, which consists of a 20 to more than 100m highly compressible deposit, high water content clay underlain by the so-called deep deposits formed by very stiff layers of cemented silty sands, b) the hill zone formed by volcanic tuffs and lava flows and c) the transition zone composed by erratic stratifications of alluvial sandy and silty layers interlaced with clay layers. The building collapses and severe damage produced by the earthquake of September 19, 1985 were essentially located within the lake bed zone. Their distribution lie within the zone bounded by the chain-dot line in figure 1. The CAO downhole acceleration array is located near the central part of the valley within the lake zone (figure 1).

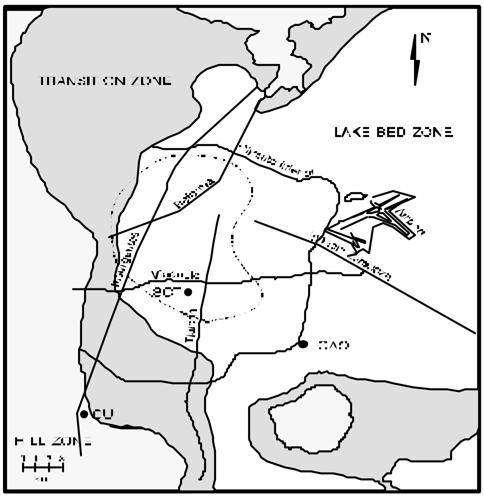


Figure 1. Mexico City Geotechnical Zoning [Seed 1988].

At the CAO site, the geological material consists of quaternary soft clayey and silty soil over a partially cemented gravel and sandy alluvial stratum. The clayey deposit is 40-50m thick and it contains not only important fractions of silt, but also some thin layers of fine sand and volcanic glass at various depths. Figure 2 shows the stratigraphic column and includes the unit weight (g), natural water content (w) and shear wave velocity (Vs) continuous profiles. It may be observed that w varies from 50 to 200% for the top 10 meters; and reaches 350 to 450% between 10m and 40m.

The downhole array of the site includes one superficial accelerometer and three more located at 12m, 30m and 60m below ground surface. Tables 1 and 2 present, respectively, the basic information about the five seismic events used in this study, and the most important characteristics of their acceleration records.

Table 1. General Characteristics of the five seismic events used in this study.

Date	Time (GMT)	Lat.N	Long.W	Depth (km)	Mb	Mw
31/03/93	10:18:15.5	17.18	101.02	8.0	5.3	
24/10/93	7:52:16.0	16.63	98.97	35	6.2	6.7
23/05/94	1:41:46.0	18.00	100.59	50		5.7
10/12/94	16:17:41.0	17.98	101.52	55	6.3	6.6
09/10/95	15:35:51.0	18.75	104.50	20	6.5	7.9

Table 1. General Characteristics of the CAO downhole array acceleration records.

Event	Station	Length (s)	Max. Acceleration (cm/ s^2)	
			EW	NS
09/10/95. Time (GMT):15:35:51.0	Surface	348.75	-19.37	13.83
	CAO 12m	320.00	18.20	13.33
	CAO 30m	320.00	7.76	8.40
	CAO 60m	320.00	2.17	2.56
10/12/94 Time (GMT):16:17:41.0	Surface	210.64	-19.64	13.17
	CAO 12m	210.63	13.31	11.51
	CAO 30m	211.50	14.34	8.08
	CAO 60m	-	-	-
23/05/94 Time (GMT):1:41:46.0	Surface	151.71	-8.38	8.14
	CAO 12m	141.55	8.69	8.28
	CAO 30m	141.55	7.66	8.08
	CAO 60m	141.34	2.77	2.64
24/10/93 Time (GMT):7:52:16.0	Surface	200.27	-9.57	-13.40
	CAO 12m	211.07	9.42	9.83
	CAO 30m	243.23	7.15	6.87
	CAO 60m	185.63	2.17	2.06
31/03/93 Time (GMT):10:18:15.5	Surface	36.69	2.15	2.87
	CAO 12m	34.01	2.03	2.33
	CAO 30m	30.83	1.59	2.13
	CAO 60m	22.60	0.37	0.41

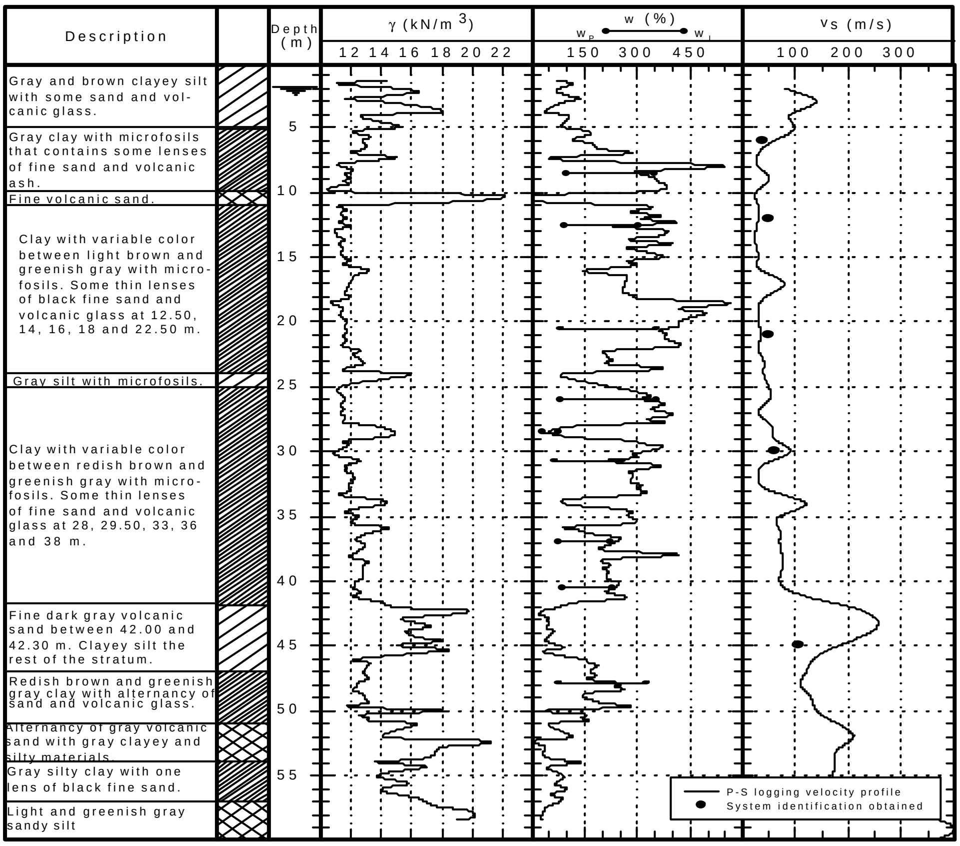


Figure 2. Stratigraphic Description and Soil Properties at the (CAO)" Site [After Jaime et al, 1987].

EVALUATION OF SHEAR STRESS-STRAIN HISTORIES

System Identification Description.

On the basis and results included in Romo, 1995, about some important free field response studies in Mexico City; it is concluded that the one-dimensional model is adequated enough to evaluate the response of the deposits found within the lake and transition zones of Mexico City. It is assumed that the soil deposit at the CAO site, subjected to seismic excitation, presents a response pattern similar to that of a one-dimensional shear beam (figure 3). Therefore, the following quotation may be used: $\frac{\partial \tau}{\partial z} = \rho \frac{\partial^2 u}{\partial t^2}$ (1)

with the following boundary conditions: $u(h,t)= u_g$, and $\tau(0,t)=0$ (2)

Where: t is time, z=depth coordinate, $\tau = \tau(z,t)$ is the horizontal shear stress, $\partial^2 u / \partial t^2 = \partial^2 u(z,t) / \partial t^2$ is absolute horizontal acceleration, u=u(z,t) is the absolute horizontal displacement, $u_g = u_g(t)$ is the input (or bedrock) absolute horizontal displacement, $r = 1200\ kg/m^3$ is the mass density, and h is soil stratum depth. Integrating the equation of motion (1) from surface to depth z, with the stress free surface boundary condition (eq. 2), shear stress at any level z may be expressed as:

$$\tau(z,t) = \int_0^z \rho \frac{\partial^2 u}{\partial t^2} dz \qquad (3)$$

Employing linear interpolation between downhole accelerations, the discrete counterpart of the shear stress at depth z_i reduces to:

$$\tau_i(t) = \tau_{i-1}(t) + \rho \frac{a_{i-1} + a_i}{2} \Delta z_{i-1} \text{, with } i=2,3\ldots \qquad (4)$$

Where the subscript i refers to level z_i, $\tau_i = \tau(z_i, t)$, $a_i = a(z_i, t)$ is the acceleration history at level z_i, and Δz_i is the spacing interval between the sensors involved in the analysis as shown in figure 4. At midway between levels z_i and z_{i-1}, the shear stress may be expressed as: $\tau_{i-1/2}(t) = \tau_{i-1}(t) + \rho \frac{3a_{i-1} + a_i}{8} \Delta z_{i-1}$ with i=2,3 (5)

Where $\tau_{i-1/2}(t)$ is the shear stress at depth $(z_{i-1} + z_i)/2$. A corresponding second-order accurate shear strain γ_i at level z_i may be expressed as [Pearson, 1986]:

$$\gamma_i(t) = \frac{1}{\Delta z_i + \Delta z_{i-1}} \left((u_{i+1} - u_i) \frac{\Delta z_{i-1}}{\Delta z_i} + (u_i - u_{i-1}) \frac{\Delta z_i}{\Delta z_{i-1}} \right) \text{, } i=2,3.. \qquad (6)$$

The shear strain $\gamma_{i-1/2}$ at level $(z_{i-1} + z_i)/2$ may be expressed as [Elgamal, 1996]:

$$\gamma_{i-1/2}(t) = \frac{u_i - u_{i-1}}{\Delta z_i} \text{, } i=2,3.. \qquad (7)$$

where $u_i = u(z_i, t)$ is the absolute displacement evaluated through double integration of the corresponding recorded acceleration histories.

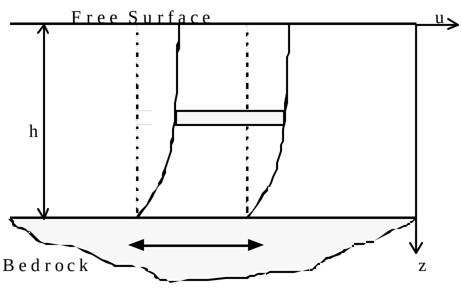


Fig 3. Model for Site Shear Behavior.

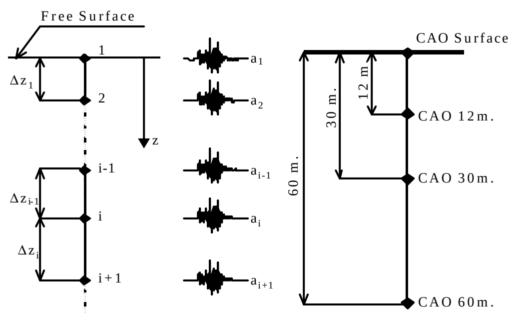


Fig 4. CAO Downhole Acceleration Array.

Application to CAO site.

In view of instrument and digitization inaccuracies, shear strain histories (evaluated using integrated accelerations) include baseline drifts in the form of spurious very low frequency components. These drifts in shear stress estimates (eq. 6) and minor high frequency stress components (eq. 4) were eliminated using low- and high-pass filters [Oppeinheim and Shafer, 1989]. Zero-phase time domain FIR filters (Finite duration impulse response) with the characteristics mentioned in table 3, were used. This filtering procedure introduces no phase shifts. As shown in table 3, the filter bandwidths were selected to be wide enough to conserve the site shear stress and strain characteristics. In order to maintain simplicity, first order linear interpolation between accelerations was employed to estimate stresses (eq. 4 and 5); and second order interpolation between displacements was used to evaluate strains (eq. 6 and 7). Both interpolation schemes yield second-order accurate shear stress and strain estimates [Elgamal, 1996].

Table 3. Characteristics of filters used to process the CAO site recorded accelerations.

Earthquake	Freq. range of significant acceleration response (Hz)	Low frequency cutoff. (Hz)	High frequency cutoff. (Hz)
10/09/95 EW	0.30-1.00	1.30	0.20
10/09/95 NS	0.25-1.20	1.70	0.20
10/12/94 EW	0.30-1.10	1.50	0.20
10/12/94 NS	0.30-1.20	1.50	0.20
23/05/94 EW	0.30-1.20	1.30	0.20
23/05/94 NS	0.30-1.20	1.30	0.20
24/10/93 EW	0.30-1.70	2.00	0.25
24/10/93 NS	0.30-1.60	2.00	0.25
31/03/93 EW	0.25-2.00	2.20	0.20
31/03/93 NS	0.25-2.50	3.00	0.20

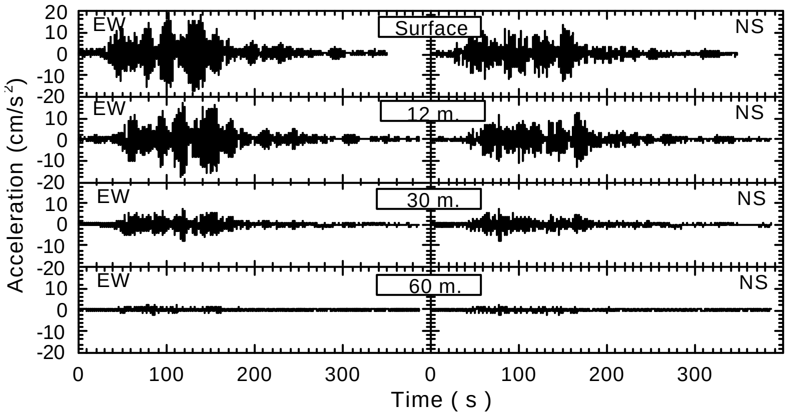


Figure 5. Horizontal Acceleration Histories at Surface, 12, 30 and 60m Depth for 09/10/95 Earthquake.

It was decided to estimate the shear stress and strain histories at midway between sensors (6m, 21m and 45m) and the same sensors levels (12m and 30m, see figure 6). Assuming an average mass density equal to 1200 kg/m3, the stress (in kPa) and strain (in %) equations for the CAO site were obtained directly applying equations 4 to 7. Note in Figure 5 the long duration and the drastic amplification of motions from deep deposits up to the ground surface. It is important to note that it is only used the initial half part of the acceleration time histories, which exclusively includes the body waves arrivals.

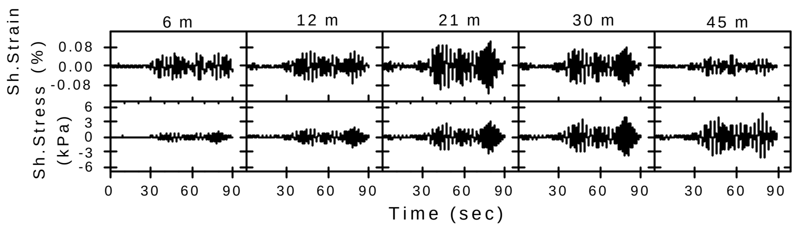


Figure 6. Shear Stress and Strain time Histories for 09/10/95 Earthquake (EW component).

4. ANALYSIS OF SOIL SHEAR STRESS-STRAIN RESPONSE

Evaluation of Soil Non-Linear Properties

The estimated shear stress and strain seismic histories are related to the soil shear stiffness characteristics at each accelerometer level z_i (figure 4). Consequently, soil behavior at the CAO site was assessed through analysis of the seismic shear stress-strain histories at levels mentioned before. In order to qualitatively illustrate the reduction of soil shear stiffness with strain amplitude, figure 7 depicts the EW shear stress-strain histories at 6m, 12m, 21m, 30m, and 45m depth during 09/10/95 seismic event.

A simple approach was used to quantify the information provided by the shear stress-strain histories. Soil stiffness properties were assessed in terms of the conventional equivalent shear modulus. The rationale behind equivalent stiffness is summarized as follows [Seed and Idriss, 1970]: ellipses, which represent a linear viscoelastic response [Lazan 1968] were fitted to the estimated stress-strain cycles; and fitting was based on reproducing the same energy dissipation, and shear stress at peak shear strain [Abdel-Ghaffar and Scott 1978]. Thus, the equivalent shear modulus during a shear stress-strain cycle may be evaluated in the form presented in figure 8.

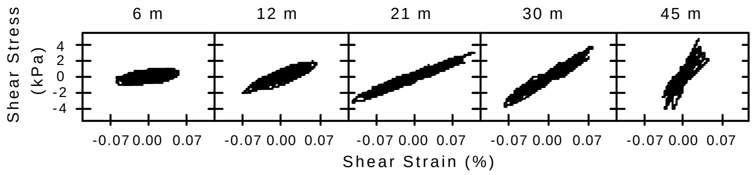


Figure 7. Shear Stress-Strain Histories During 09/10/95 Seismic Event (EW component).

Figure 9 shows a series of isolated stress-strain cycles obtained at different times during the 09/10/95 seismic event (EW component). In this figure the drastic increase of shear moduli is clearly appreciated with depth variation because of their strong dependence on the confining pressure. In view of the inherent irregularities observed in most of the isolated stress-strain cycles, it was decided to fit ellipses to groups of similar cycles, instead of only isolated cycles. In this way, the soil dynamic response is estimated as the average behavior of the group, and not as the behavior of only one cycle. It seems that the most reasonable selection criterion is the strain amplitude. Then, it was considered that two or more cycles might be grouped if they had similar strain amplitudes (see figure 10).

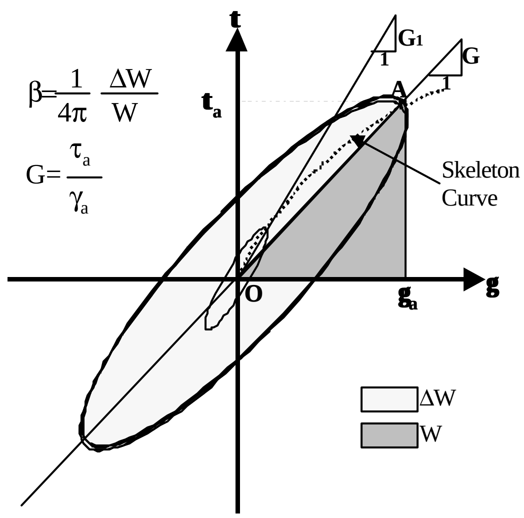


Fig 8. Equivalent Stiffness During a Loading Cycle.

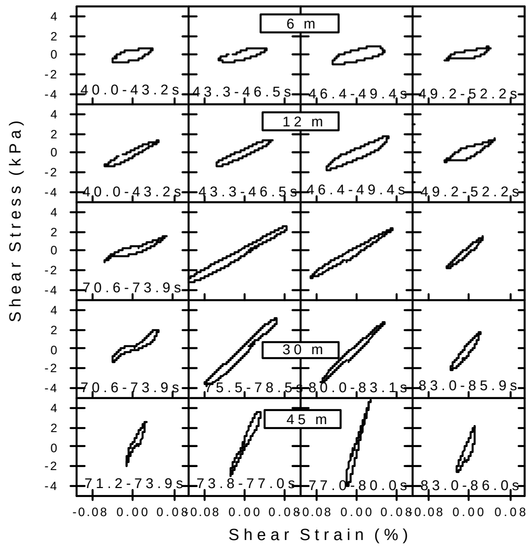
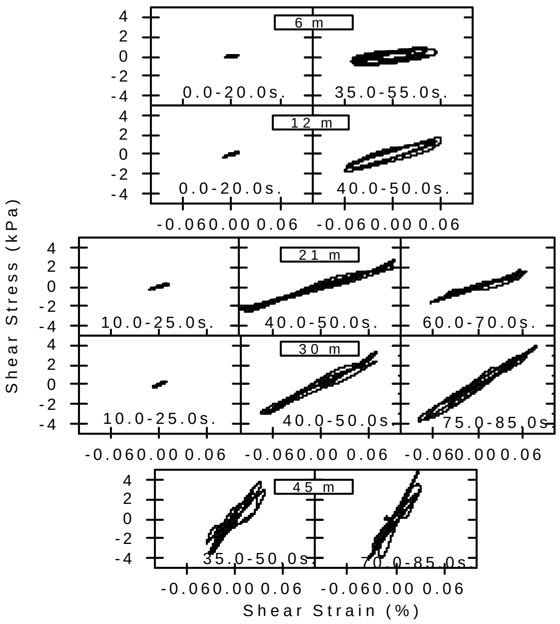


Fig 9. Selected Stress-Strain Isolated Cycles for 09/10/95 Earthquake (EW component).

Comparison with Laboratory and Field Data.

Figure 11 depicts the variation of normalized modulus, G/Gmax, with the strain amplitude, for all the seismic events analyzed (solid and hollow circles). The dotted curves included in this figure, correspond to the upper and lower limits currently accepted for the Mexico City clay having plasticity indexes larger than 150% [Romo, 1995]. The low strain ($\gamma \leq 10^{-4}$%) shear modulus, Gmax, obtained are: Gmax=16MPa at 45m depth; Gmax=5.5MPa at 30m depth; Gmax=3.5MPa at 21 and 12m depth; and finally, Gmax=2.0MPa at 6m depth. Assuming an average mass density equal to 1200 kg/m^3, the corresponding shear wave velocities evaluated are: 105m/s at 45m depth; 62m/s at 30m depth; 49m/s at 21 and 12m depth, and finally, 37m/s at 6m depth. These identified shear wave velocities are presented in figure 2, together with the site stratigraphic description, (solid circles) and labeled as “system identified obtained” and some important soil properties profiles. In general, the evaluated shear moduli exhibit low scatter, and the shear wave velocities presented here are in good agreement with those obtained for the CAO site by Jaime et al, 1987, using suspension p-s logging procedures (fig. 2). It is well known that both the shape of the modulus reduction curve and the magnitudes of the threshold strain are strongly affected by the plasticity index and the confining effective stress. These two factors are especially important for the Mexico City clay. Note in figure 11 that the shear modulus values estimated at 12m and 30m



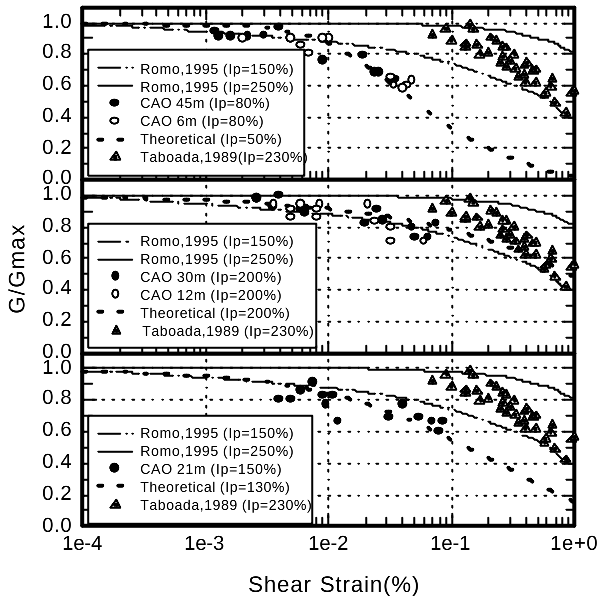


Fig 10. Selected Groups of Shear Stress-Strain Cycles for 09/10/95 (EW component) Earthquake.

Fig 11. Normalized Shear Modulus versus Cyclic Shear Strain at Various Levels.

depths are in good agreement with the lower Mexico City clay band limit. The values estimated for 21m depth present some scatter and a little tendency to fall below the lower band limit. In addition, note (fig. 11) the good agreement between CAO obtained points for 6m and 45m, and the theoretical curve obtained by applying the Massing-type model equation presented by Romo, 1995, using Ip=50%. Similar appreciation may be applied for 30m, 12m and 21m values; which were compared with the same theoretical curves (eq. 13) using Ip=200% and Ip=130%. These Ip values are in accordance with those observed for Mexico City clay at the CAO site for the corresponding depths. Table 4 shows that, while large, the shallow estimated shear strains (6m and 12m) underestimate those that occur at deeper levels (21m). There is an approximate depth range between 15m and 25m, where the maximum shear strains occur for the CAO site. This observation may be extended to other sites within the “Lake Zone” taking into account some variation in depth range. Singh et al, 1997, reported, for 1985 Michoacan earthquake, large vertical deformation gradients in the depth range of 10m to 20m.

Table 4. Maximum shear strains (%) observed at the CAO site.

Event.	6 m	12 m	21 m	30 m	45 m
31/03/93 EW	0.0103	0.0094	0.0125		
31/03/93 NS	0.0083	0.0092	0.0192		
24/10/93 EW	0.0433	0.0325	0.0460	0.0309	0.0127
24/10/93 NS	0.0492	0.0357	0.0746	0.0512	0.0207
23/05/94 EW	0.0134	0.0113	0.0182	0.0108	0.0083
23/05/94 NS	0.0144	0.0117	0.0163	0.0111	0.0073
10/12/94 EW	0.1037	0.0919	0.1213		
10/12/94 NS	0.0560	0.0409	0.0657		
09/10/95 EW	0.0590	0.0686	0.1128	0.0781	0.0451
09/10/95 NS	0.0453	0.0474	0.1009	0.0832	0.0557

This is partially supported by the observation that there was generalized obstruction, at depths exceeding 5 to 10m, in flexible-tube piezometers [Durazo, 1994]. As mentioned earlier, the 1985 earthquake caused extensive damage to the Mexico City's water supply system but didn't affect neither the subway nor sewage system, which are located at depths that vary between 10 and 25 m.

CONCLUSIONS

The estimated shear stress-shear strain histories were used to evaluate soil shear at different levels and compared with the currently accepted curves for the Mexico City clay. The normalized modulus G/Gmax, at 6m and 45m levels, only fit well with documented laboratory results, for shear strains below 0.005%. The main cause of this behavior is the presence, at mentioned depths, of a silty clay material with low natural water content (average w=100%) and consequently low plasticity index (about 80%). In contrast, the values of G/Gmax found for levels 12m (Ip=200%), 21m (Ip=150%), and 30m (Ip=200%) are, in general, in good agreement with the accepted lower limit band for the Mexico City clay (Ip=150%). When the normalized modulus was compared with a theoretical curve obtained by applying the Massing-type model equation using Ip values in accordance with those observed at the corresponding depths, a good agreement was found. This seems to support the generally accepted idea that the plasticity index significantly affects the stiffness of clayey soils. All the identified values of average shear wave velocity are in good agreement with the in-situ measured shear wave velocity using suspension p-s logging procedures. Observation of the estimated shear strains at different levels allows concluding that there is a depth range of approximately 15m to 25m, where large strains occur. Theoretical analyses [Romo, 1988] had shown this phenomenon. This is due to the existence of a soft clay layer between 12m and 20m, having high water contents (>450%) and plasticity indexes of the order of 300%.

REFERENCES

1. Abdel-Ghaffar, A. M., and Scott, R. F. (1978). "Investigation on the Dynamic Characteristics of an Earth Dam". Rep. No. EERL 78-02, Earthquake Engrg. Research Lab., California Institute of Techn, Pasadena, Calif.
2. Durazo, J. (1994). "Corrimiento dentro del Subsuelo lacustre de la Cuenca de México". Geofisica Internacional, 33, 625-634.
3. Elgamal, A-W., Zeghal, M., Tang, H. T., and Stepp, J. C. (1995). "Evaluation of Low Strain Site Characteristics using the Lotung Seismic Array". J. Geotech. Engrg., ASCE, 121(4), 350-362.
4. Elgamal, A.-W., Zeghal, M., Taboada, V., and Dobry, R. (1996). "Analysis of Site Liquefaction and Lateral Spreading Using Centrifuge testing Records". Soils and Found., 36(2), 111-121.
5. Jaime, A., Romo, M.P., and Ovando, E. (1987). "Carácterísticas del suelo en el sitio Central de Abastos Oficinas." Instituto de Ingeniería, UNAM, México.
6. Koga, Y. and Matsuo, O. (1990). "Shaking table tests of embankments resting on liquefiable sandy ground." Soil and Foundations, 30(4), 162-174.
7. Lazan, B. J. (1968). "Damping of Material and Members in Structural Mechanics", Pergamon Press Ltd., Oxford, United Kingdom.
8. Nazarian, S., and Desai, M. (1993). "Automated Surface Wave Method: Field Testing". J. Geotech. Engrg., ASCE, 119(7), 1094-1191.
9. Oppenheim, A. V., and Shafer, R. W. (1989). "Discrete-Time signal Processing". Prentice Hall.
10. Pearson, E. C. (1986). "Numerical Methods in Engineering and Science". Van Nostrand Reinhold Co.
11. Romo, M.P. (1998). "Personal Files"
12. Romo, M. P. (1995). "Clay behavior, Ground response and Soil-Structure interaction studies in Mexico City" 3rd Int Conference on Recent Advances in Geotech Earthquake Engrg. And Soil Dynamics, St. Louis Missouri.
13. Seed, H. B., and Idriss, I. M. (1970). "Soil Moduli and Damping Factors for Dynamic Response Analyses". Rep. EERC 70-10, Earthquake Research Center, U. of California, Berkeley, Cal.
14. Seed, H. B., Romo, M. P., Sun, J. I., Jaime, A. and Lysmer, J (1988). "The Mexico Earthquake of September 18, 1985-Relations Between Soil Conditions and Earthquake Ground Motions". Earthquake Spectra, Vol. 4, No. 4, November, 687-729.
15. Singh, S. K., Santoyo, M., Bodin, P., and Gomberg, J. (1997). "Dynamic Deformations of Shallow Sediments in the Valley of Mexico, Part II: Single-Station Estimates". Bull. of the Seis. Soc. Of Am., 87(3), 540-550, June/97.
16. Stokoe, K. H., and Nazarian, S. (1985). "Use of Rayleigh Waves in Liquefaction Studies". Proc. Measurement and Use of Shear Wave Velocity for Evaluating Soil Properties, Geotech Engrg Division, ASCE, N.Yk,1-14.
17. Taboada, V. M., (1989). "Cycle Behaviour of the Mexico City Caly at CAO Site". MSc Thesis, DEPFI, UNAM, México D.F.
20. Zeghal, M., and Elgamal, A.-W. (1994). "Analysis of site liquefaction using earthquake records." J. Geotech. Engrg., ASCE, 120(6), 996-1017.
22. Zeghal, M., and Elgamal, A.-W. (1995). "Lotung downhole array. II: Evaluation of soil nonlinear properties." J. Geotech. Engrg., ASCE, 121(4), 363-377.