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ANALYSIS OF SOME DOWNHOLE ACCELERATION RECORDS FROM "CENTRAL DE ABASTO OFICINAS" SITE AT MEXICO CITY

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ABSTRACT: The surface and downhole accelerations records of "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 09/10/95 seismic event (NS component) has 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 in previous investigations from 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. Field testing procedures are restricted mainly to small amplitude responses which make them useful to provide the means of measuring soil low-strain dynamic properties. The laboratory techniques are often used to evaluate the soil properties at larger strain levels; however, its applicability is somewhat restricted due to disturbance induced during soil sampling, and difficulties in reproducing the in situ stress state and the seismic loading history.

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 analyses of downhole site response at Lotung, Taiwan (Zeghal and Elgamal, 1995).

In this paper, a simple and powerful identification procedure was employed to obtain the shear stress-strain histories for CAO site at various elevations, directly from the acceleration records. These histories are used to evaluate the variation of soil shear stiffness with shear strain. The main aspect of this investigation is that we examine the dynamic shear stress-strain histories associated with earthquake ground motions for Mexico City clays, and estimate its dynamic characteristics directly from acceleration records.

CENTRAL DE ABASTO OFICINAS (CAO) SITE

The site is located not far from Mexico City downtown, within of the central lacustrine deposits zone of the valley (figure 1). The stratigraphy of the Valley of Mexico consists of Miocene and Oligocene volcanics with a total thickness of about 2 km. These volcanics overlie a 4 km of Cretaceous limestones, which, in turn, rest on Mesozoic metamorphics. The Miocene volcanics are overlain by about 100 m of tuffs and sands, gravels and recent lava flows, forming the so-called "Hill Zone" which is located at the periphery of the valley enclosing it. In extensive areas of the central part of the valley, clays 10 to 100 m thick lie atop the stratigraphic column forming the "Lake Zone" where the CAO site is located.

At 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 40-50 m 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 it includes the volumetric weight (γ), natural water content (ω) and shear wave velocity (Vs) continuous profiles. It may be seen that ω varies from 50% to 200% for the top 10 meters; and reaches 350% to 450% between 10 m and 40 m.

The downhole array of the site includes one superficial accelerometer and three more located at 12 m, 30 m and 60 m below ground surface. The superficial station operates independently of the downhole array station, and unfortunately, the timing of the downhole instruments is not synchronized with that of the surface sensor. Table 1 presents basic information about the seismic event used in this study, and the most important characteristics of their acceleration records. Note the significant difference between the first sample time registered at surface and downhole sensors. This situation imposes the need to realize a time devise synchronization process over all the acceleration records used, to guarantee the existence of a common time origin.

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

Station	First Sample Time (GMT)	Length (s)	Max. Acceleration (cm/s^2)
Event: 09/10/95 (NS component). Time (GMT): 15:35:51.0			
Surface	15:38:05.5	348.75	13.83
CAO 12m	15:37:52.0	320.00	13.33
CAO 30m	15:37:52.0	320.00	8.40
CAO 60m	15:37:51.0	320.00	2.56

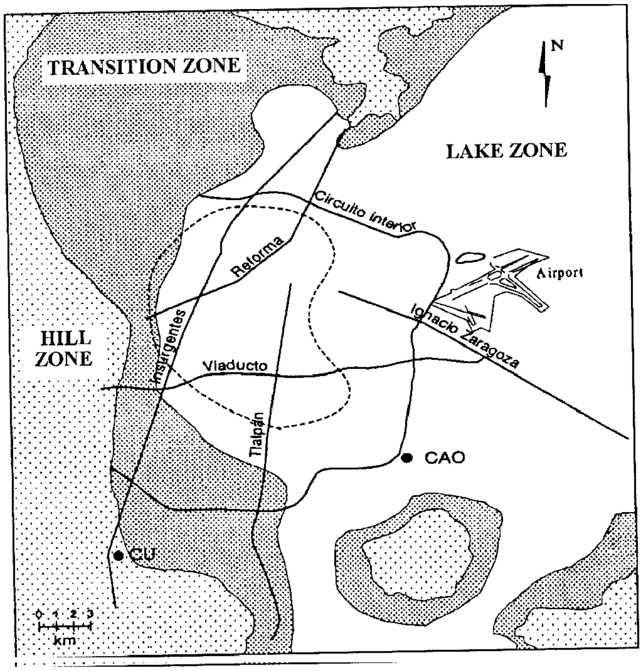

Figure 1. General location map of CAO site.

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 adequate 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 CAO site, subjected to seismic excitation, presents a response pattern similar to that of a one-dimensional shear beam (figure 3). Then it may be used the next equation:

$$\frac{\partial\tau}{\partial z} = \rho\frac{\partial^2 u}{\partial t^2} \quad (1)$$

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 the 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, $\rho = 1.2$ kN.s^2/m^4 is the mass density, and h is the soil stratum depth.

Integrating the equation of motion (1) from surface to depth z, with the stress free surface boundary condition (eq. 2), shear stresses at any level z may be expressed as:

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

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

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

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:

$$\tau_{i-1/2}(t) = \tau_{i-1}(t) + \rho\frac{3a_{i-1}+a_i}{8}\Delta z_{i-1}\text{, with } i=2,3 \quad (5)$$

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):

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

The shear strain $\gamma_{i-1/2}$ at level $(z_{i-1}+z_i)/2$ may be expressed as (Zeghal and Elgamal, 1995):

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

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

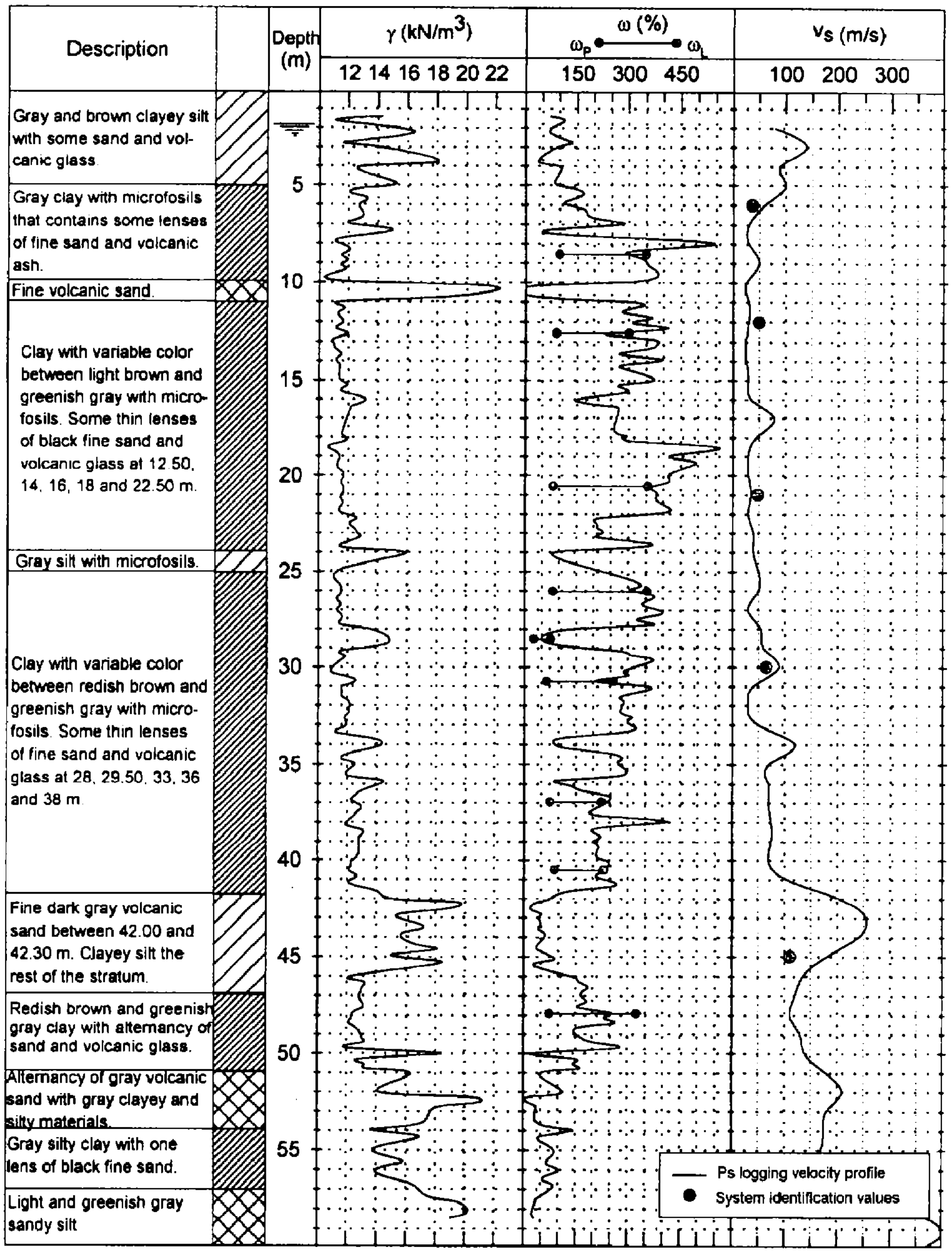

Figure 2. Stratigraphic description of the "Central de Abasto Oficinas" site.

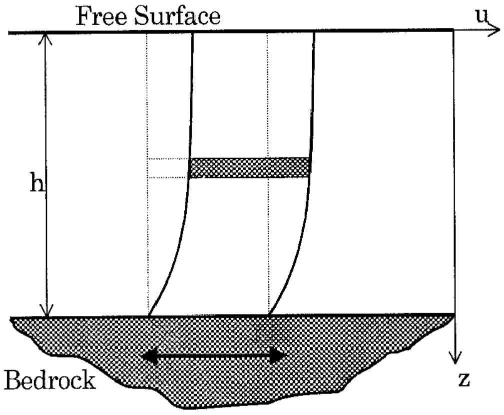

Figure 3. Model for site shear behavior.

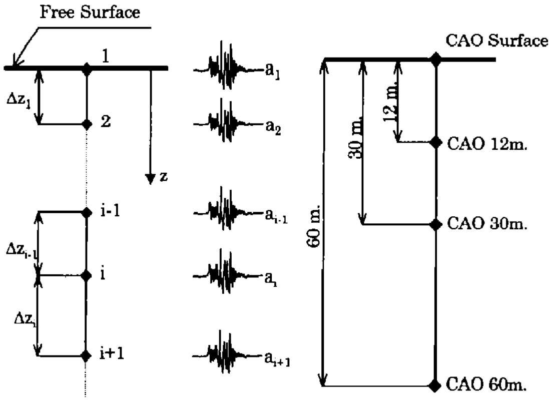

Figure 4. CAO downhole acceleration array and site discretization.

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 and minor high frequency stress components were eliminated using low- and high-pass filters. The zero-phase time domain FIR (Finite duration Impulse Response) filter with the characteristics mentioned in table 2, was utilized. This filtering procedure introduces no phase shifts. As shown in table 2, 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 (eqs. 4 and 5); and second order interpolation between displacements was used to evaluate strains (eqs. 6 and 7). Both interpolation schemes yield second-order accurate shear stress and strain estimates.

Table 2. 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 NS	0.25-1.20	0.2	1.7

In view of the position of the accelerometers (surface, 12 m, 30 m and 60 m), it was decided to estimate the shear stress and strain histories at midway between sensors (6 m, 21 m, and 45 m) and at the same sensors levels (12 m and 30 m). Assuming an average mass density equal to 1.2 $kN.s^2/m^4$, stresses (in kPa) and strains (in %), equations for CAO site were obtained by directly applying equations 4 to 7.

Figure 5 presents the original horizontal acceleration time histories for 09/10/95 (NS component) seismic event. Note its long duration and the drastic amplification of motions from deep deposits up to the ground surface. Figure 6 depicts the NS shear stress and strain histories, at considered levels, during the 09/10/95 seismic event. It is important to note that we only use the initial part of the acceleration time histories, which exclusively includes the body waves arrivals.

ANALYSIS OF SOIL SHEAR STRESS-STRAIN RESPONSE

Evaluation of soil non-linear properties

The estimated shear stress and strain seismic histories are related by the soil shear stiffness characteristics at each accelerometer level z_i (figure 4). Consequently, soil behavior at 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 NS shear stress-strain histories during 09/10/95 (NS component) seismic event.

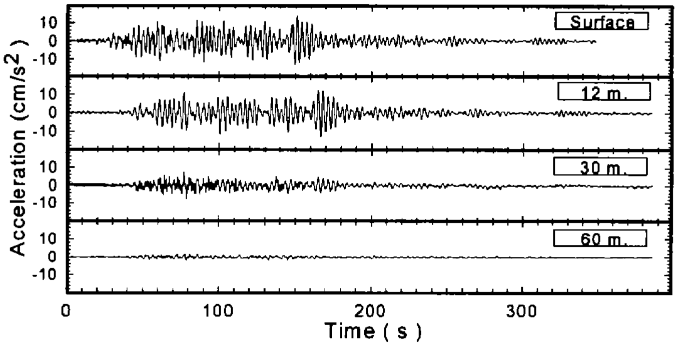

Figure 5. Horizontal acceleration histories at surface, 12 m, 30 m and 60 m. depth for 09/10/95 (NS component) earthquake

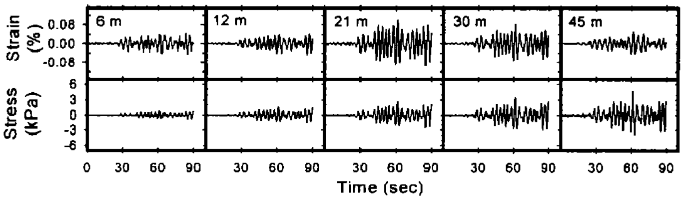

Figure 6. Shear stress and strain histories for 09/10/95 earthquake (NS component)

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, 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 G, during a shear stress-strain cycle may be evaluated by computing the slope of the line formed by the extreme points of the loop in the shear stress-strain cycle. Figure 8 shows a series of isolated stress-strain cycles obtained at different times during the 09/10/95 seismic event (NS component). In this figure it is clearly appreciated the drastic increase of shear moduli with depth because the strong dependence on the confining pressure and lower shear strain induced by the seismic motion. 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 loops, instead of only to 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. For the 09/10/95 (NS component) earthquake, the following time periods were selected to lump similar stress-strain cycles (see figure 6):

- At 6 m depth, two groups of cycles were selected. One between 30.00 sec-60.00 sec. The second between 60.00 sec-90.00 sec. They present strain amplitudes of 0.035% and 0.045%, respectively.

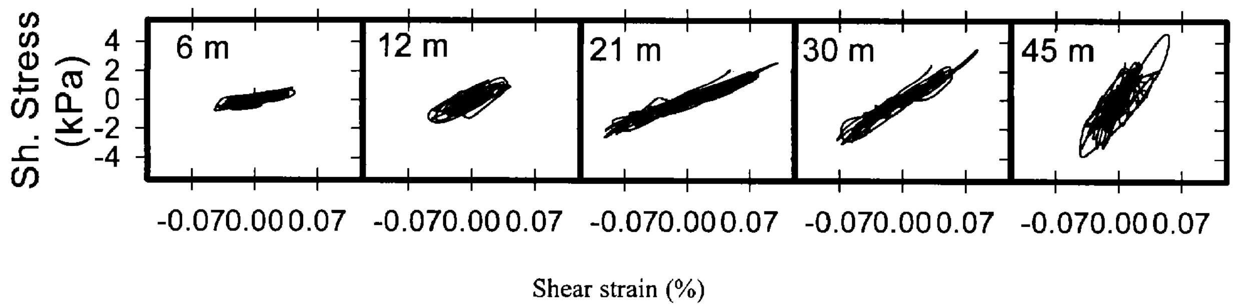

Figure 7. Shear stress-strain histories during 09/10/95 seismic event (NS component).

- At 12 m depth there are two groups of cycles. The first of them between 0.00 sec-20.00 sec. The second between 30.00 sec-60.00 sec. They have average strain amplitudes of 0.005% and 0.04%, respectively.

- At 21 m depth, two groups were selected with time intervals and strain amplitudes of: 0.00 sec-20.00 sec for 0.008%, and 40.00 sec-60.00 sec for 0.08%.

- At 30 m depth, two groups were selected again. Their time intervals and strain amplitudes are: 5.00 sec-20.00 sec for 0.008%; and 40.00 sec-60.00 sec for 0.055%.

- Finally, at 45 m depth, two groups were selected. The first of them between 0.00 sec-10.00 sec, and the second between 25.00 sec-80.00 sec. They have average strain amplitudes of 0.02% and 0.025%, respectively. All these shear stress-strain cycles groups are included in figure 10.

Comparison with laboratory and field data

Figure 10 depicts the variation of normalized modulus, G/G_{max}, with the strain amplitude, for the seismic event analyzed. The dotted curves included on this figure, correspond to the upper and lower limits actually accepted for the Mexico City clay having plasticity indexes larger than 150% (Romo, 1995).

The low strain shear modulus, G_{max}, obtained are: G_{max}=14.6 MPa at 45 m depth; G_{max}=5.1 MPa at 30 m depth; G_{max}=2.8 MPa at 21 m, G_{max}=3.0 MPa at 12 m depth; and finally, G_{max}=1.3 MPa at 6m depth. Assuming an average mass density equal to 1.2 kN.s^2/m^4, the corresponding shear wave velocities evaluated are respectively: 110.3 m/s; 65.2 m/s, 48.3 m/s, 50.0 m/s, and finally, 37 m/s. These velocities are presented in figure 2, together with the site stratigraphic description, and they appear to fall within the range of values expected for the soils and the conditions of Mexico City. In general, the evaluated shear modulus exhibit low scatter, and the shear wave velocities presented here are in good agreement with those obtained for CAO site by Jaime et al., (1987), using p-s logging and downhole procedures (figure 2).

It is well known that both the shape of the modulus reduction curve and the magnitude 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 modulus values established from earthquake data analysis appear to fall below the Mexico City band especially for strains larger than 0.005%.

The stratigraphic description presented in figure 2 shows that soil at 6 m and 45 m depth is a silty clay material with lower natural water content (average ω=100%) and consequently low plasticity index (about 80% or less). In contrast, soil at 21 m, 12 m and 30 m, presents lesser silt content and higher natural water and plasticity index values. Figure 11 also contains three theoretical curves obtained by applying the Masing-type model equation presented by Romo (1995), using Ip=50%, 130% and 200%. This Ip values are in accordance with those observed for Mexico City clay at CAO site for the corresponding studied depths. Note the good agreement between CAO obtained points at different levels and the corresponding theoretical curves.

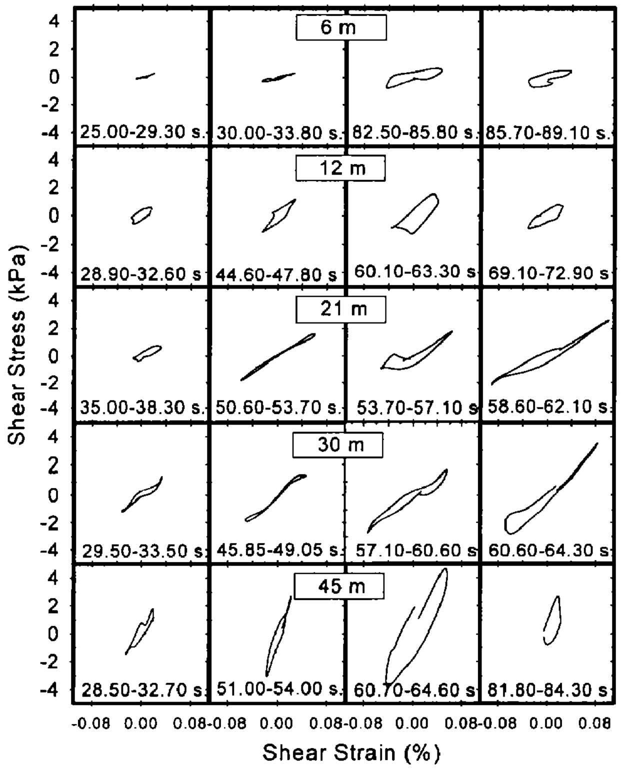

Figure 8. Selected stress-strain isolated cycles

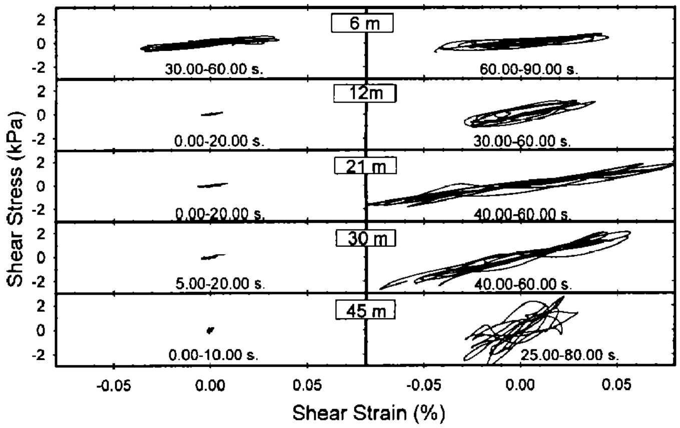

Figure 9. Selected groups of shear stress-strain cycles for 09/10/95 (NS component) earthquake.

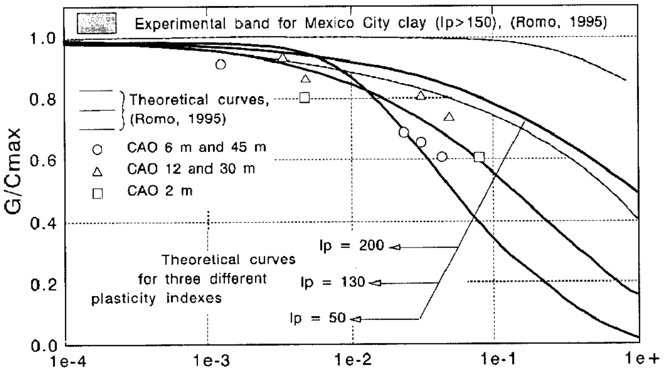

Figure 10. Normalized shear modulus versus cyclic shear strain at various levels.

CONCLUSIONS

A simple but powerful technique of system identification was employed to directly evaluate site shear stress-strain histories from downhole and surface acceleration records. This technique is based on an interpolation procedure between downhole accelerations, and it is assumed a one-dimensional shear beam model behavior for the soil.

The estimated histories were used to evaluate soil shear stiffness at different levels and they were compared with the actually accepted curves for Mexico City clays. Although all the estimated values of average shear modulus are in good agreement with the in-situ measured s-wave velocity, it seems that they only fit well with documented laboratory results, for strains below 0.005%. The main cause of this behavior is the presence, at certain depths (6 m and 45 m), of a silty clay material with low natural water content (average ω=100%) and consequently low plasticity index (about 80% or less). In contrast, if we compare the system identification results against the Masing-type theoretical curves calculated with acceptable Ip values, it is found an excellent fit between them. This observation emphasizes the importance of taking into account the plasticity index when interpreting the dynamic response of soft clayey soils, and especially when the soil under observation is the Mexico City clay.

The observation of instrumented systems is one of the best sources of experimental data, because do not interfere with the system response and allow to make observations in a wide range of strain amplitudes and frequency contents of ground motions.

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