ELSEVIER

Soil Dynamics and Earthquake Engineering 27 (2007) 333–343

SOIL DYNAMICS AND EARTHQUAKE ENGINEERING

www.elsevier.com/locate/soildyn

The sinking of Mexico City: Its effects on soil properties and seismic response

Efraín Ovando-Shelley*, Alexandra Ossa, Miguel P. Romo

Instituto de Ingeniería, UNAM, Ciudad Universitaria, Coyoacán 04510, DF, Mexico City, Mexico

Received 16 June 2006; received in revised form 23 August 2006; accepted 29 August 2006

Abstract

Extensive pumping to extract water from Mexico City's subsoil has caused regional sinking. Water pumping produces regional consolidation which increases effective stresses acting on the subsoil modifying its static and dynamic properties. As the soil properties change, so does their dynamic response. Approximate expressions to estimate the future changes in soil properties are proposed. Also, this paper puts forth new evidence to illustrate these changes and presents estimates of future settlements in central Mexico City, using a soil consolidation model that overcomes some of the limitations of Terzaghi's theory. Results of an analysis to estimate the effects of the evolution of the subsoil's dynamic properties are illustrated by means of seismic analyses performed on a couple of sites in an old lake bed in Mexico City.

Keywords: Mexico City; Evolution of soil properties; Regional subsidence; Seismic response

1. Introduction

The larger part of Mexico City lies on what used to be a shallow lake, the lowest portion of a basin surrounded by volcanoes. Prevalence of a lacustrine environment during long periods propitiated the deposition of large volumes of fly ash and other pyroclastic materials that were driven into the lake by water flows running from the higher lands and by the winds. In time, the chemical degradation of these materials formed clays and clayey silts. These soils are geologically very young and are notorious for their extremely high water content and compressibility.

As urban expansion took off in the XVIth century, the old lake was desiccated progressively and nowadays it has almost completely disappeared. The desiccation of the lake, mainly by diverting inflowing rivers and by land reclamation, induced a regional consolidation process which was enhanced in the mid XIXth century when water began to be pumped from the aquifers that underlie the clayey soils, as population increased. From 1900 to 1920 the settlement rate in downtown Mexico City was 3 cm/year; by the 1940s the rate was 13 cm/year and in the early 1950s it reached 26 cm/year [1,2]. Wells in downtown Mexico City were banned in the 1960s and settlement rates decreased to 5 cm/year. In the late 1970s and early 1980s new wells were put into operation in the outskirts, mainly near the hills that surround the city in the north and the south. Settlement rates increased again and in central Mexico City they now amount to 7–10 cm/year but at some sites near the newer wells they exceed 30 cm/year [3]. The total subsidence over the last 100 years with respect to a reference point outside the lake zone is now more than 8 m in some areas. Water pumped from the aquifers provides about two-thirds of the city's supply and it is highly unlikely that pumping be stopped or even reduced in the future, given the trends of urban expansion observed over the last decades.

2. Changes in geotechnical conditions

Geotechnical engineers in Mexico City have studied systematically its subsoil for many decades. In most of the area formerly occupied by the lakes, main soil formations are ordered in a sequence of soft clay strata interspersed with lenses and layers of harder clayey silts with sands. As

*Corresponding author. Fax: +52 55 56 16 0784.
E-mail address: eovs@pumas.ii.unam.mx (E. Ovando-Shelley).

0267-7261/$ - see front matter
doi:10.1016/j.soildyn.2006.08.005

seen in the stratigraphical cross-section of Fig. 1, the main soil strata are (a) archaeological debris and fills, the uppermost materials; (b) a crust of desiccated low plasticity silty clays; (c) the Upper Clay Formation having the most compressible soils, designated as FAS in Fig. 1; (d) the first Hard Layer that appears at an average depth of about 40 m, formed by sands, gravelly sands and thin lenses of softer silty clays; (e) the Second Clay Formation, about 10 m thick and referred to as FAI in Fig. 1; (f) the so called Deep Deposits—very consistent silts and sandy silts interspersed with hard clays—appear at the base of the stratigraphical column (50 m deep or so).

In response to water extraction and the ensuing consolidation process, effective stresses will increase and, consequently, the properties of the clay strata that underlie the former lake bed will change. In what follows we present evidence of these changes, taken from the results of soundings performed in different dates at several sites in the city and from the results of tests performed on soil samples retrieved from several places within the former lake bed. Effective stress increments also affect dynamic soil properties and the seismic response of the soft lacustrine clays will also change, as discussed here.

2.1. Evolution of pore pressures

Piezometric readings taken over a 10 year period illustrate the gradual depletion of pore pressures at a site in the central part of the city (Fig. 2). Pore pressures were measured with open-head piezometers installed in the permeable layers (mainly fine sand and volcanic ash) that intersperse the upper clay formation. Pore pressure decay rates varied from 0.002 to 0.014 kPa/year at different depths and at different times, over the 1990–2002 period (Fig. 3). Pore pressures diminish faster in the permeable layers that confine the two main clay formations.

2.2. Water content, volumetric weight and undrained strength

Profiles for these parameters at two different dates (1952 and 1986) are given in Fig. 4 for a site located within a densely urbanized zone where earthquake related damages

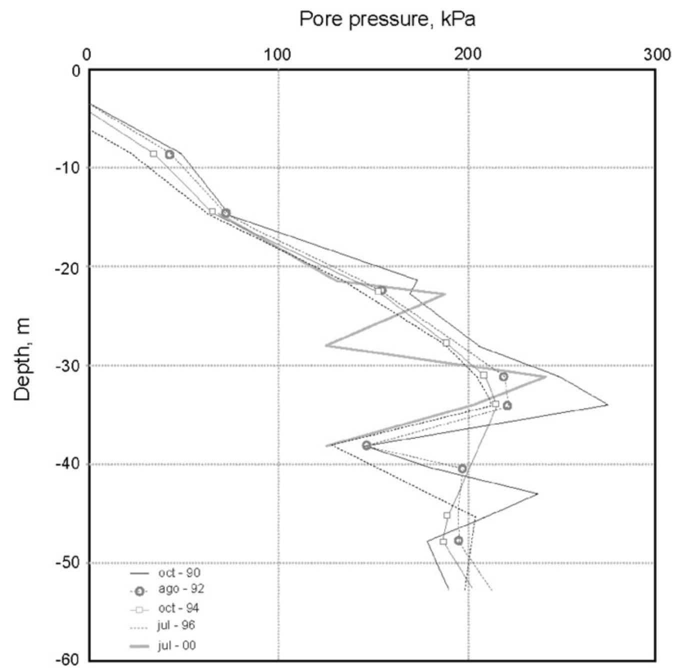

Fig. 2. Piezometric readings taken over a ten year period at a site in the central part of Mexico City.

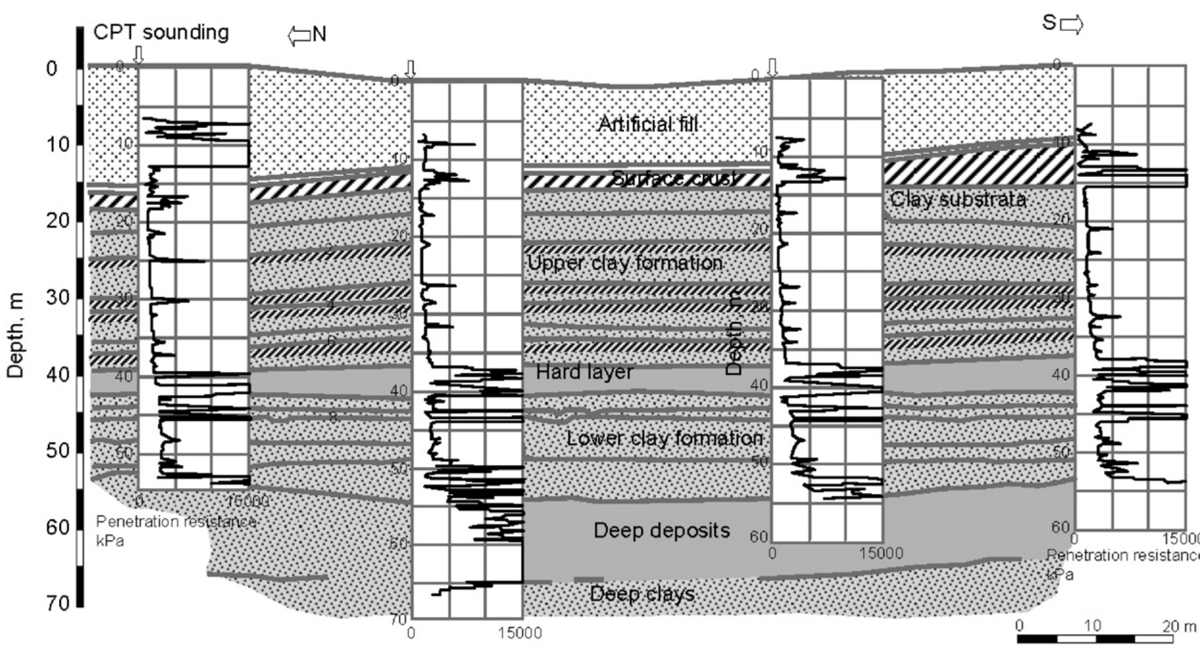

Fig. 1. Stratigraphical cross-section in central Mexico City.

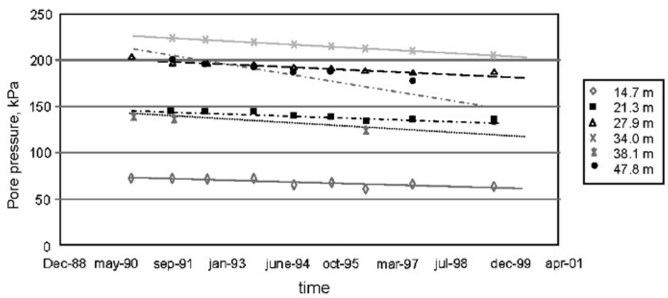

Fig. 3. Pore pressure decay rates at different depths and at different times.

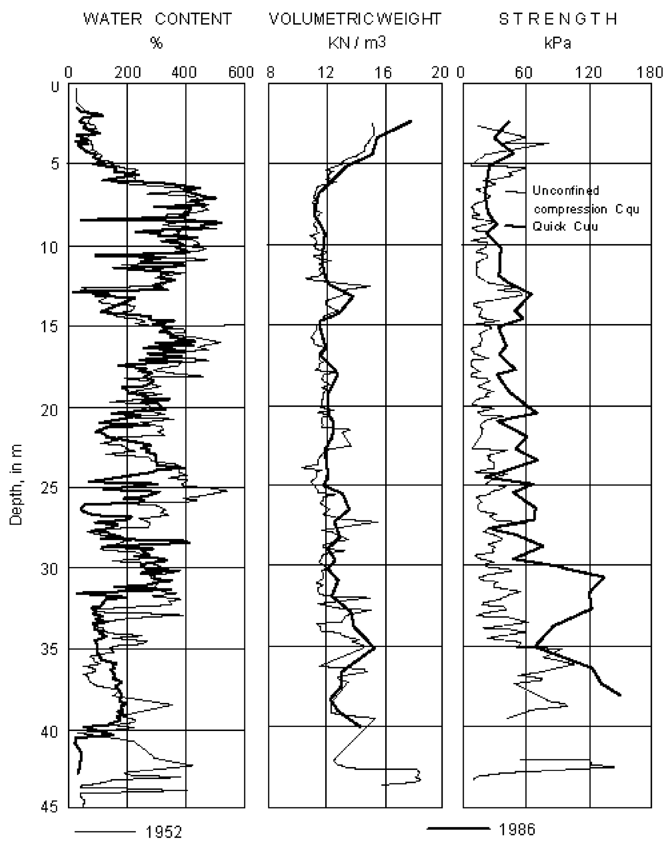

Fig. 4. Water content, volumetric weight and undrained strength.

have concentrated recurrently in the past. The specific place where the studies were made is a park where external overburdens have never been applied to its subsoil. Analysis of this figure shows that (a) thicknesses of the relevant clay strata have reduced as a consequence of regional subsidence; (b) water content reductions are especially significant below 15 m approximately which is consistent with the fact that pumping induced consolidation propagates upwards from the base of the clayey soils to the surface; (c) changes in soil density (volumetric weight) and in undrained strength confirm that soil strata densify and gain strength as the clay masses consolidate regionally.

Assuming that deformation of the clays is one-dimensional, the following equations can be used to calculate the changes in water content from the amount of compression in the clay strata [3]:

$$w_{\mathrm{f}} = w_{\mathrm{i}}\left[1 - \frac{\delta(t)}{H_{\mathrm{T}}}\left[\frac{1+e_{\mathrm{i}}}{e_{\mathrm{i}}}\right]\right], \tag{1}$$

where w_{i} and w_{f} are the initial and final water content values of a clay layer of initial thickness H_{T}; $\delta(t)$ is the vertical deformation suffered by this layer and e_{i} is its initial void ratio. Application of Eq. (1) can be difficult in practice since the value of e_{i} may at times be difficult to obtain. However, if full saturation of the clay is assumed,

$$w_{\mathrm{f}} = w_{\mathrm{i}}\left[1 - \frac{\delta(t)}{H_{\mathrm{T}}}\left(1+\frac{1}{w_{\mathrm{i}}G_{\mathrm{s}}}\right)\right], \tag{2}$$

where G_{s} is the specific gravity.

Changes in bulk unit weights will be given by

$$\gamma_{\mathrm{f}} = \frac{\gamma_{\mathrm{i}}}{1-\delta(t)/h_{\mathrm{i}}}. \tag{3}$$

2.3. Compressibility

The effects of regional subsidence on this property are examined through the results of one-dimensional oedometric tests performed on samples retrieved on different dates. In choosing the samples to perform these tests, it was necessary to identify precisely the same strata. The results of tests performed on soils retrieved from the same site as above are given in Fig. 5; since loading rate affects the shape of compressibility curves, care was taken to follow the same loading program on all the samples tested. As expected, void ratios decrease with time whilst the apparent preconsolidation pressures display an opposite trend. The

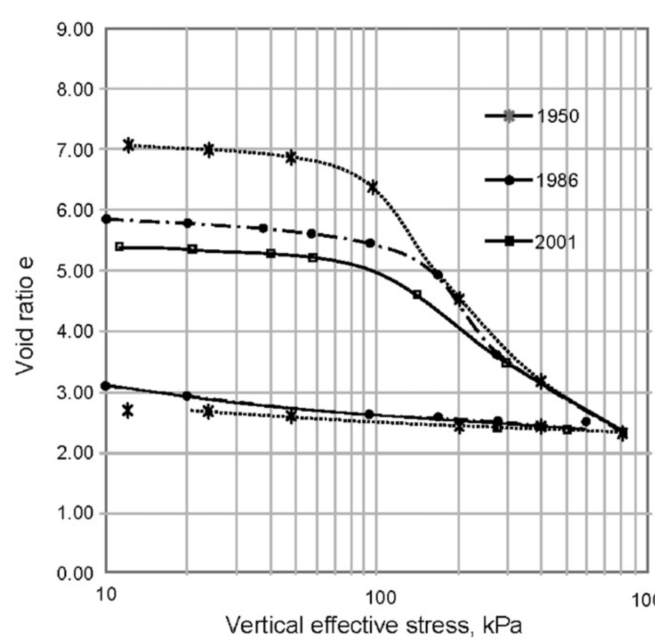

Fig. 5. Compressibility curves.

virgin consolidation line of the samples tested in 1986 and 2000 match the one obtained for the sample tested in 1952; thus, the general compressibility characteristics of the clay were not affected by the regional subsidence.

2.4. Shear strength

Given the geological conditions prevailing in the former lake bed and the recent effective stress increments produced by water pumping from the aquifer, the clays in Mexico City can be assumed to be normally consolidated. Consequently, shear strength can be written as

$$c_u(t) = \alpha_c \sigma'_v = \alpha_c[\sigma'_{v_0} + \Delta u(t)], \tag{4}$$

where $c_u(t)$ is the undrained shear strength, expressed as a function of time; α_c is a constant; σ'_v is the field vertical effective stress acting at time t; σ'_{v0} is a reference (initial) effective stress at time t_0 and $\Delta u(t)$ is the pore pressure decrement produced by water pumping during the interval $t - t_0$.

Other forms can also be used to express the effective-stress–time-dependency of shear strength, like the following [4]:

$$c_u(t) = \frac{M}{2}[p'_0 + \Delta u(t)] \exp\left(\frac{\Gamma - N}{\lambda}\right), \tag{5}$$

where $M = 6 \sin\phi'/(3 - \sin\phi')$; Γ and N are the ordinates in ep' space at a reference pressure corresponding to the critical state and virgin consolidation lines, respectively; λ is the isotropic compressibility; p'_0 is the initial mean effective stress and ϕ' the friction angle in terms of effective stress, The constants ϕ', Γ, λ and N are not affected by effective stress changes induced by regional consolidation.

2.5. CPT strength

Data from CPT borings performed in 1986 and 2001 at two sites within the former lake zone (SCT and CAO) show, in Figs. 6 and 7, the expected increase in penetration resistance. The change in the thickness of the main clay substrata is also evident.

Cone penetration resistance q_c is usually related to undrained shear strength by the way of empirical correlations of the form:

$$c_u(t) = \frac{q_c - p'(t)}{N_k} = \frac{q_c - [p'_0 + \Delta u(t)]}{N_k}, \tag{6}$$

where q_c is the cone penetration resistance; $p'(t)$ is the mean effective at time t and p'_0 its initial value; N_k is a correlation coefficient. In Mexico City the preferred form of that correlation is [5]:

$$c_u(t) = \frac{q_c(t)}{N_k} = \frac{q_{c0} + \Delta q_c}{N_k}, \tag{7}$$

where q_{c0} is the initial value of cone penetration resistance. Since q_c is directly proportional to shear strength and the ratio between shear strength and vertical effective strength

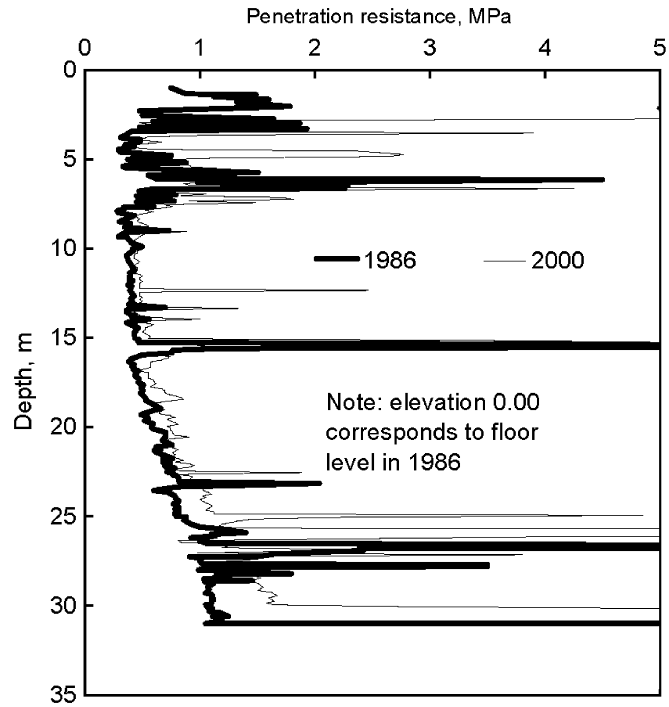

Fig. 6. CPT tests, SCT site, 1986 and 2000.

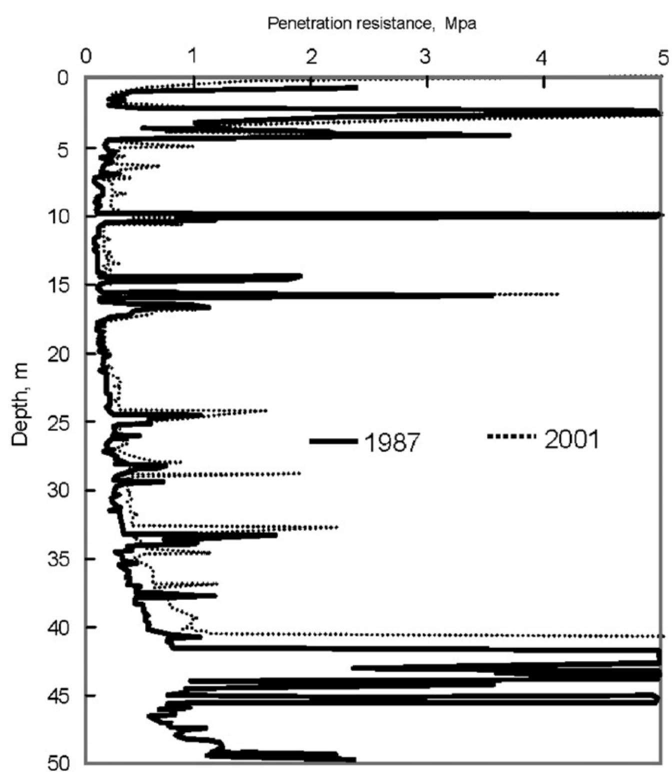

Fig. 7. CPT tests, CAO site, 1986 and 2000.

is constant for normally consolidated clays (Mexico City clay normally consolidated or, at the most, lightly overconsolidated), changes in point penetration resistance and compressibility due to effective stress increments can be accounted for by [5]

$$q_c = N_\sigma \sigma'_v(t) = N_\sigma(\sigma'_{v0} + \Delta u(t)), \tag{8}$$

where N_σ is a correlation coefficient equal to 5.5 and σ'_{v0} is the initial vertical effective stress.

2.6. Dynamic properties

Regional consolidation will also modify dynamic soil properties. In this respect we look at its effects on shear wave propagation velocities, shear moduli and damping ratios. Field evidence of changes on shear wave velocities is given in Figs. 8 and 9, from the results of suspension logging tests performed in 1986 and 2000 also at the SCT and CAO sites [6]. The expected stiffening of the clay strata over the 15 years that lapsed between the two dates is evident and can also be assessed from the results of resonant column and cyclic triaxial tests performed in those same years on samples retrieved from the same site (Fig. 10). The samples obtained in 2001 were taken from the same stratum as the 1986 samples. In both sets of experiments the samples were consolidated to the same range of isotropic consolidation pressures.

The dependency of shear wave velocity on effective stress increments can be stated explicitly from the following expression for the shear modulus at small strains, G_{max}, which was derived from the results of resonant column and cyclic triaxial tests performed on clay samples retrieved from several sites in the former lake bed, in Mexico City [7,8]:

$$G_{max} = \rho V_s^2 = 122 p_a \left(\frac{1}{PI - I_r}\right)^{(PI-I_r)} \left(\frac{p'_0}{p_a}\right)^{0.82}, \tag{9}$$

where r is mass density; V_s is shear wave velocity; p'_0 is the in situ mean effective stress; p_a is the atmospheric pressure; PI is the plasticity index; I_r is relative consistency. Hence,

$$V_s \approx 11\sqrt{\frac{p_a}{\rho}} \left(\frac{1}{PI - I_r}\right)^{((PI-I_r)/2)} \left(\frac{p'_0 + \Delta u(t)}{p_a}\right)^{0.41}. \tag{10}$$

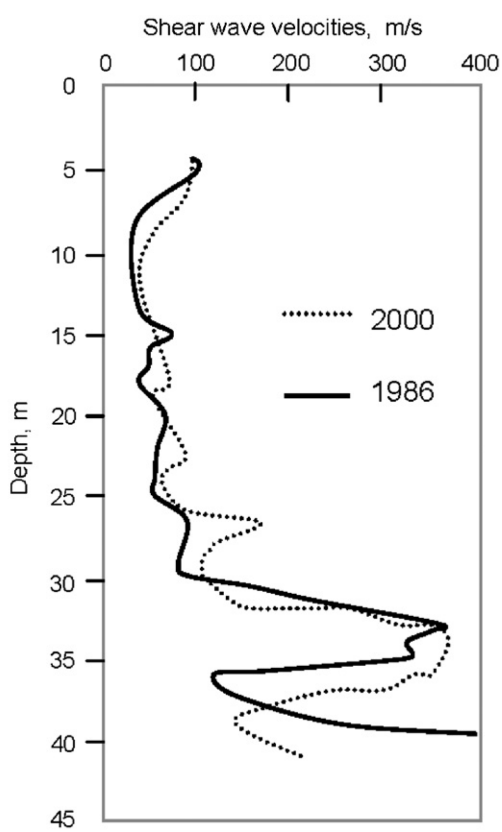

Fig. 8. SCT, changes in shear wave velocities, suspension logging tests performed in 1986 and 2000.

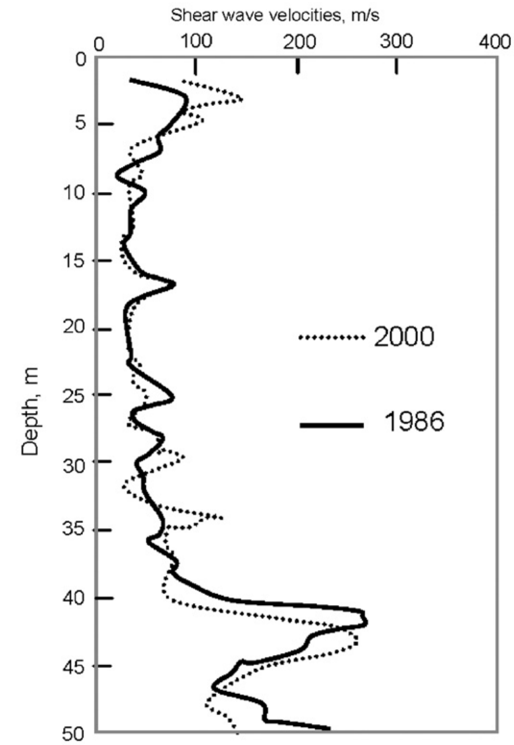

Fig. 9. CAO site changes in shear wave velocities, suspension logging tests performed in 1986 and 2000.

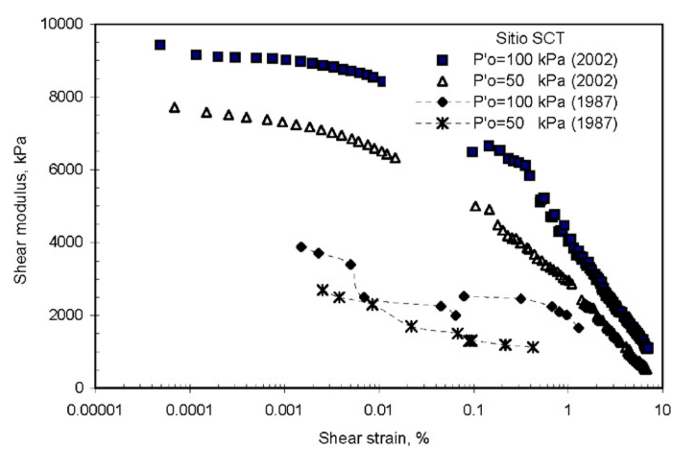

Fig. 10. Results of resonant column and cyclic triaxial, on samples retrieved from the same site.

Index properties, plasticity index and relative consistency, have been included in expressions 9 and 10, as noted before by other authors [9].

The complete shear modulus–strain relationship for the Mexico City clays can be formulated by means of hyperbolic functions of the type [10]:

$$G = G_{\max}[1 - H(\gamma)] = G_{\max}\left[1 - \frac{(\gamma/\gamma_r)^{2B}}{1 + (\gamma/\gamma_r)^{2B}}\right]^A, \tag{11}$$

where γ is the shear strain; A and B are experimentally determined parameters that also depend on soil plasticity whereas γ_r is a reference strain [7]. Damping ratios can also be expressed by means of the same hyperbolic function

$$\lambda = (\lambda_{\max} - \lambda_{\min})H(\gamma) + \lambda_{\min}, \tag{12}$$

where $\lambda_{\max}$ and $\lambda_{\min}$ are the maximum and minimum values of damping ratio, experimentally determined over a convenient range of shear strains.

Effective stress increments brought about by water pumping from the aquifers will also modify (shorten) the dominant periods of the soft clay deposits undergoing regional consolidation:

$$T_0(t) = \frac{4(h - \delta(t))}{\sqrt{G_{\text{avg}}/\rho_{\text{avg}}}} = \frac{4(h - \delta(t))}{V_{\text{savg}}}, \tag{13}$$

where the subindices refer to average values of shear modulus, mass density and shear wave propagation velocity. Average shear wave velocity is:

$$V_{\text{savg}}(t) = \frac{4(h - \delta(t))}{\sum V_{si}h_i(t)/\sum h_i(t)}. \tag{14}$$

As seen in expressions 13 and 14, the shortening of periods is due to the compression of the clay strata and to the increase of stiffness or shear wave velocity.

3. Seismic response

The effects of regional subsidence on the seismic response of Mexico City clay deposits are illustrated by studying two locations within the lake zone in Mexico City, the SCT and the CAO sites, where accelerographic stations have been in operation since the 1970s; CPT and shear wave velocity profiles obtained in 1987 for both these locations were given previously in Figs. 8 and 9.

In order to view how seismic response changes as water is pumped from the deep aquifers, it is first necessary to estimate the changes in the dynamic soil properties, which, as shown before, are related to increments in effective stress brought about during the regional consolidation process. These increments were estimated using a one-dimensional consolidation model in which the soil undergoing the consolidation process is assumed to be an elasto-viscoplastic material and has been described previously [11,12]. In applying the model, the following set of differential equations must be integrated:

$$c_{ve}\frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} - \frac{1}{m_{ve}}\,g(u, \varepsilon_z), \tag{15}$$

$$\frac{\partial \varepsilon_z}{\partial t} = -m_{ve}\frac{\partial u}{\partial t} + g(u, \varepsilon_z), \tag{16}$$

$$g(u, \varepsilon_z) = \frac{\psi/v_0}{t_0}\exp\left[-(\varepsilon_z - \varepsilon_{z0}^{vp})\frac{v_0}{\psi}\right]\left(\frac{\sigma'_z}{\sigma'_{z0}}\right)^{\lambda/\psi}, \tag{17}$$

where c_{ve} is a consolidation coefficient associated to elastic deformations, equal to $k/(m_{ve}\gamma_w)$; k is the soil's permeability and m_{ve} is the volumetric compressibility along the elastic portion of the one-dimensional stress–strain curve, equal to $\partial\varepsilon_z^e/\partial\sigma'_z = (\kappa/v_0)/(\sigma'_z)$; $\psi/v_0 = C_{\alpha\varepsilon}/2.3$, where $C_{\alpha\varepsilon}$ is the slope along the compressibility curve in log time versus strain; finally λ/v_0 is the slope of a reference one-dimensional stress–strain curve.

Eqs. (15)–(17) were integrated numerically with a finite difference algorithm that has been published elsewhere [13]. In applying Eqs. (15)–(17) to the case of Mexico City clay deposits, the subsoil was modelled considering the upper clay formation only, i.e. assuming that changes in the lower clay stratum do not affect significantly the overall seismic response which is a plausible assumption since the properties in the deeper more consolidated strata will not be noticeably modified in the future [14]. Initial conditions were specified extrapolating available piezometric readings obtained at nearby locations. Boundary conditions are time-dependent functions in which average pore pressure depletion rates were estimated from Figs. 2 and 3, i.e. assuming these are representative of conditions in the whole of the former lake zone. Relevant properties for modelling the consolidation process (compressibilities and permeabilities as well as thicknesses of each substratum) were updated after each time interval, with Eqs. (15)–(17).

The result, isochrone curves, like those shown in Figs. 11 and 12, were used to obtain effective stress changes which were then introduced into Eqs. (9)–(14) to modify dynamic soil properties. Stiffness–strain and damping–strain curves obtained at different dates (see, for example, Figs. 13 and 14) were then obtained for each relevant stratum. With these, seismic response was estimated using the one-dimensional wave propagation computer program, Shake [15].

Initial shear wave velocities were taken from the result of the 1986 soundings given in Figs. 8 and 9. Following previous researchers [16], the stratigraphy was simplified as shown in Fig. 15. The response spectra obtained were used as input motion accelerations measured at a rock outcrop which matched fairly well those obtained from accelerations measured at SCT and CAO during the Great Michoacán Earthquake of 1985, as seen in Figs. 16 (N–S component) and 17 (E–W component).

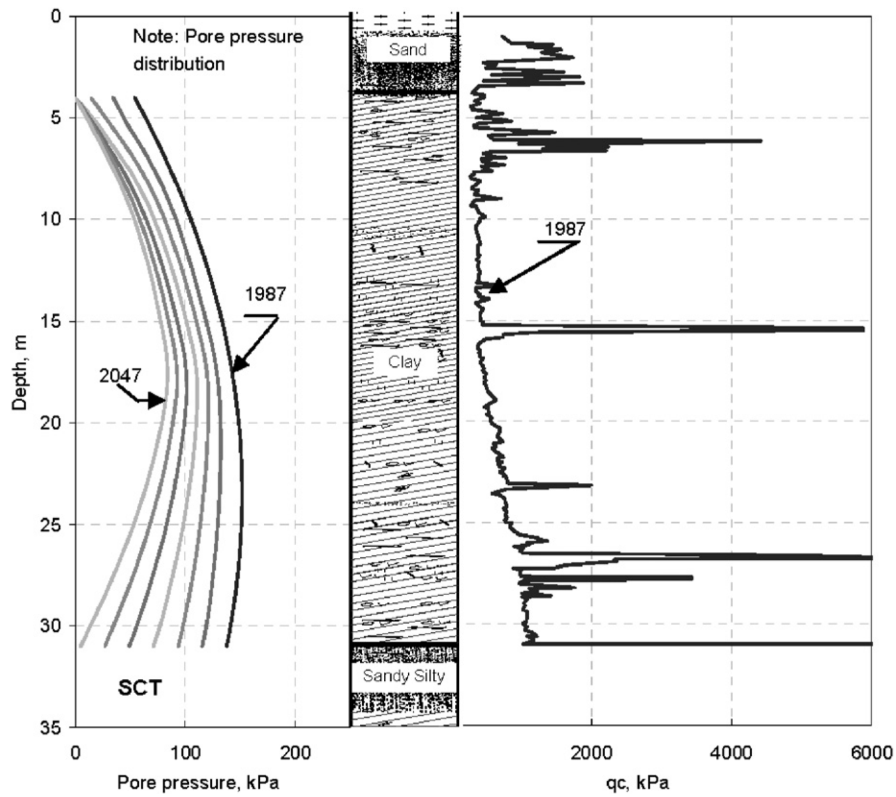

Fig. 11. Isochrone curves at the SCT site.

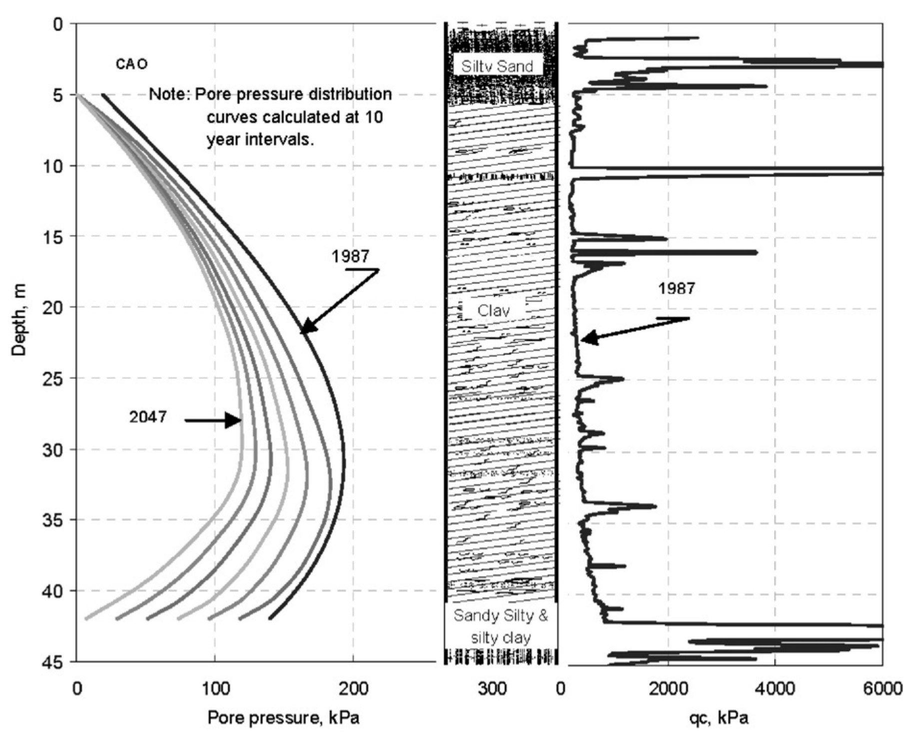

Fig. 12. Isochrone curves at the CAO site.

3.1. Analysis of seismic response

The sites chosen in these analyses, SCT and CAO, are both located in the former lake bed. Soft lacustrine clays are present in both sites but soil strata thicknesses as well as soil properties are notably different. Response spectra obtained from acceleration records measured at these two locations during the 19 September, 1985, earthquake

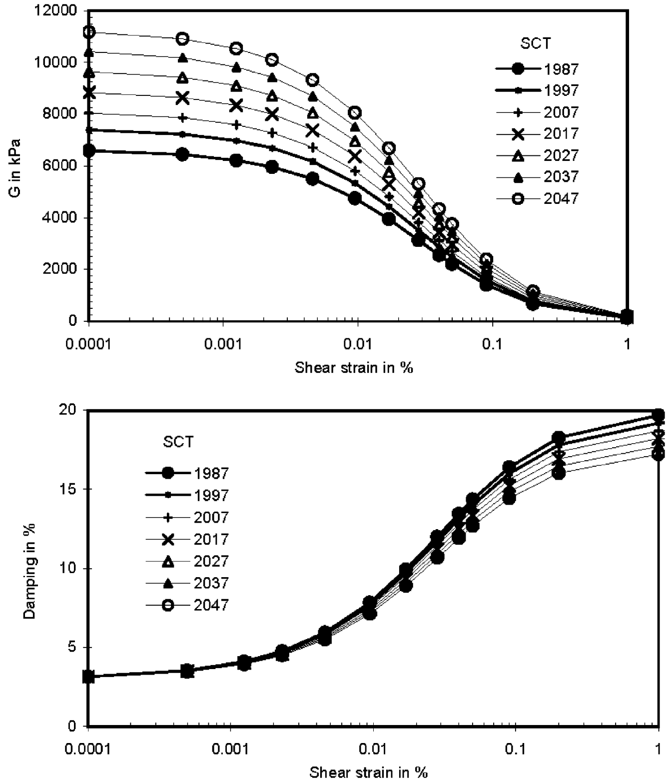

Fig. 13. Evolution of dynamic stiffness and damping in a clay sample retrieved from the SCT site.

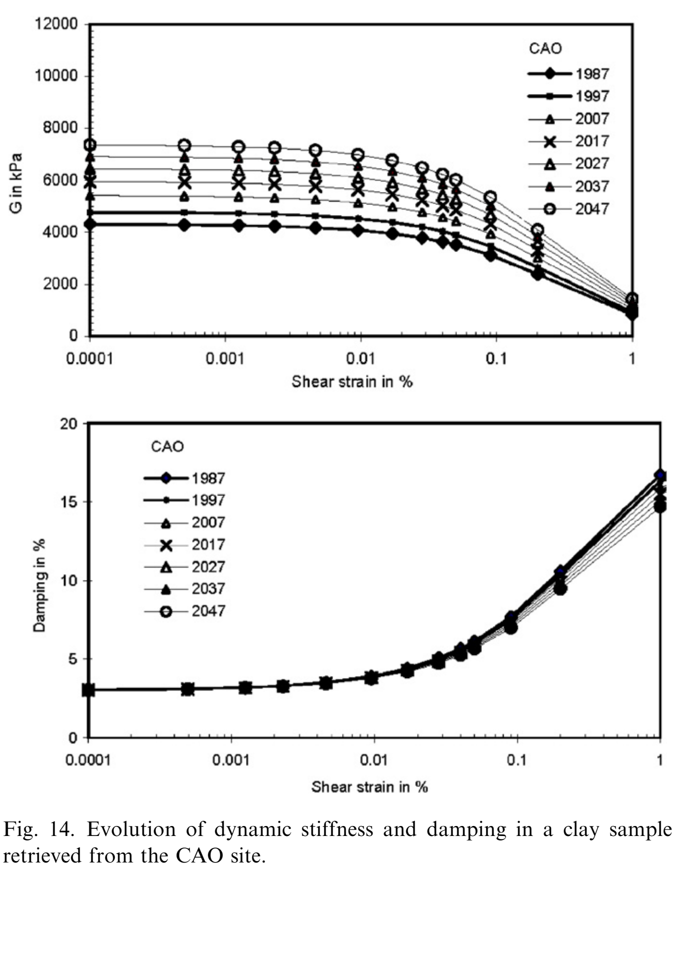

Fig. 14. Evolution of dynamic stiffness and damping in a clay sample retrieved from the CAO site.

(Ms = 8.5) show that soils at the SCT are stiffer and display a shorter dominant period than at the CAO site: about 2 s in the former and around 3.6 s in the latter; Figs. 18 and 19, which also displays a short period peak that has been associated to characteristics of the input motion, combined with the second mode site's response. The figure also includes response spectra obtained from motions calculated with a one-dimensional shear wave propagation seismic analysis program [15], using the simplified stratigraphical models shown in Fig. 15. The same input motion was used in these analyses, an acceleration record measured at a rock outcrop south of the city (CU site) as input motion during the 1985 event. As seen there, the calculated response spectra closely match the spectra obtained from the measured surface acceleration records.

Effective stress changes obtained with the consolidation model (Eqs. (15)–(17)) were used to modify soil properties and strata thicknesses of the simplified stratigraphical models at different times in the future. Modified thicknesses and soil properties were then used to estimate seismic response spectra having the outcrop acceleration record as input motion obtained in the 1985 earthquake which originated off the Mexican Pacific coast along a subduction zone, more than 400 km west of Mexico City. The energy of seismic motions that originate there typically concentrates around relatively low frequencies.

The effects of regional consolidation on the characteristics of future seismic motions differ at the two sites. In the SCT site, Fig. 18, spectral ordinates will increase until 2037 and then reduce. Note that period reductions will tend to occur at slower rates as consolidation of the soil strata advances in the future. Period shifts at the CAO site will be more pronounced and spectral ordinates in the first mode will increase considerably, for subduction events like the one recorded in 1985 (Fig. 19). Second period spectral ordinates will also increase noticeably.

Apart from subduction earthquakes, seismicity in Mexico City is also determined by deeper normal faulting events having their epicenters inland. One such earthquake took place on 15 June, 1999 (Ms = 6.5, Mw = 7.0; [17]), producing serious damage in the states of Veracruz, Oaxaca and Puebla. Energy of movements produced by these events tends to concentrate at higher frequencies than subduction earthquakes. As seen in Figs. 20 and 21, future seismic response to these events at SCT and CAO is influenced by the higher frequencies found in normal faulting events.

Response spectra for future inland normal faulting events at the SCT site, Fig. 20, display significant peaks around the 0.2–0.6 s period interval. Spectral ordinates in these peaks have magnitudes that tend to equalize the ordinates close to the site's time-shifting dominant period.

Seismic response at the CAO site is characterized by significant changes in the magnitude of spectral ordinates at the site's time-changing dominant period, as seen in Fig. 21. As the soils harden, spectral ordinates at the

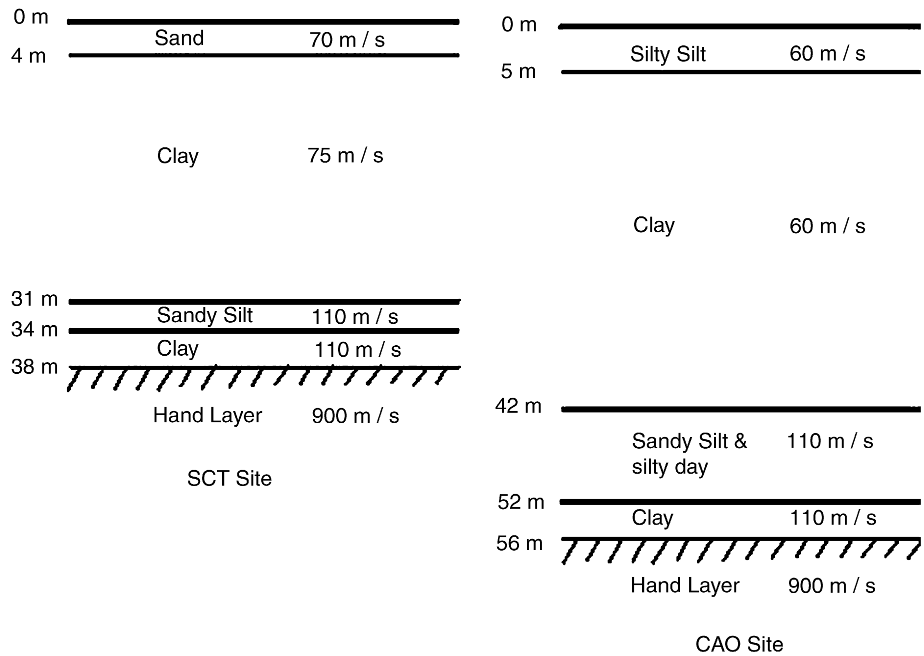

Fig. 15. Simplified soil profiles at the SCT and CAO sites.

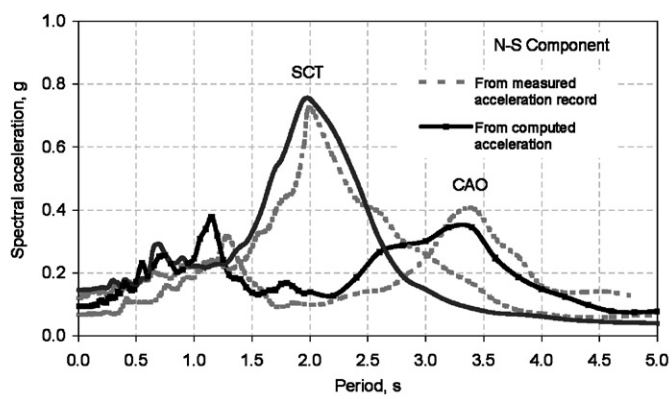

Fig. 16. Response spectra from measured and calculated accelerations at the SCT site for the Great Michoacán Earthquake of 19 September, 1985, N–S component.

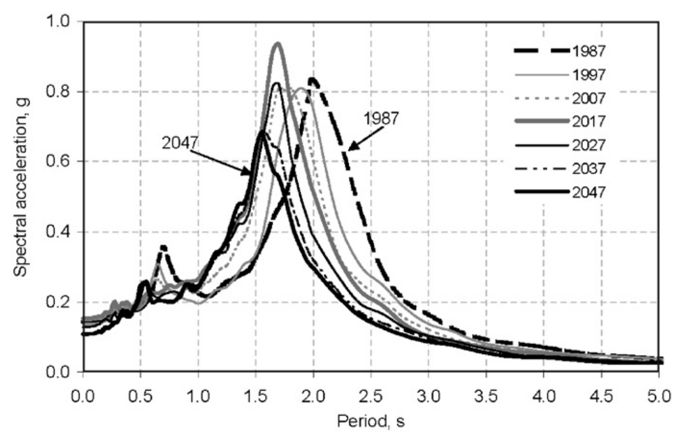

Fig. 18. Evolution of response spectra at SCT. The base of the soil deposit was excited with accelerations measured at a rock outcrop during the 19 September 1985 event.

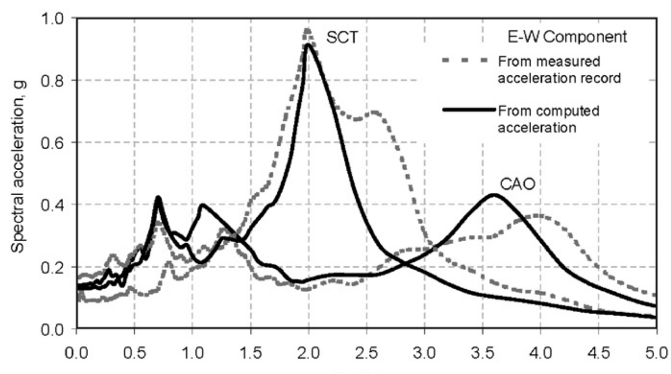

Fig. 17. Response spectra from measured and calculated accelerations at the CAO site for the Great Michoacán Earthquake of 19 September, 1985, N–S component.

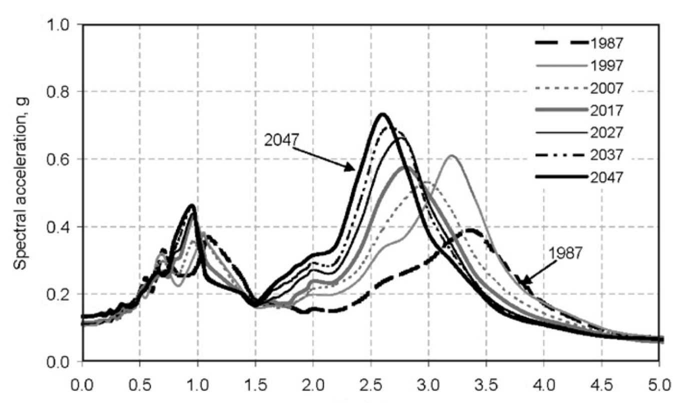

Fig. 19. Evolution of response spectra at CAO. The base of the soil deposit was excited with accelerations measured at a rock outcrop during the 19 September 1985 event.

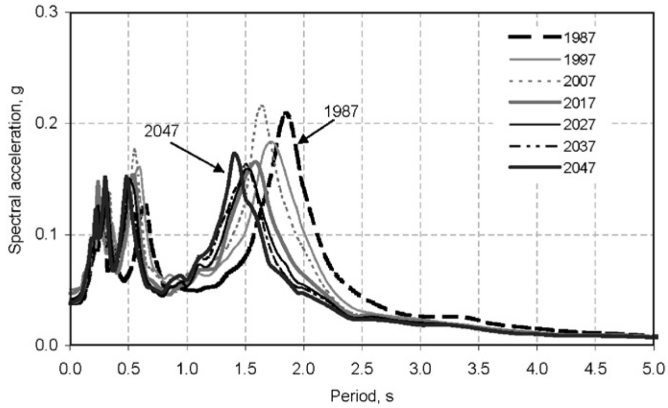

Fig. 20. Evolution of response spectra at SCT. The base of the soil deposit was excited with accelerations measured at a rock outcrop during the June 1999 event.

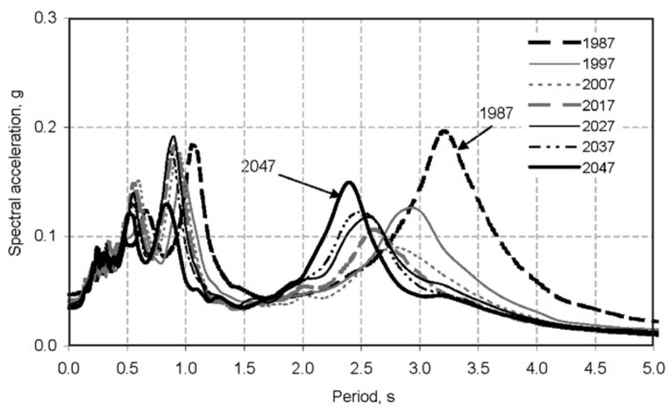

Fig. 21. Evolution of response spectra at CAO. The base of the soil deposit was excited with accelerations measured at a rock outcrop during the June 1999 event.

dominant period will first reduce (up to 2007) but will then increase again. In the shorter period range (less than 1 s), the overall effect of hardening will be to reduce spectral ordinates.

4. Conclusions

Static and dynamic soil properties in the soft lacustrine Mexico City clays will change in the future on account of regional subsidence brought about by water pumping from the deep aquifers that underlie the city. This paper presented new evidence of these changes, as well as simple expressions to estimate them in the future, as a function of future effective stress increments or of surface settlements. Given the present urban and demographical expansion trends, regional subsidence will be active in the city in the foreseeable future. Accordingly, the results presented in this paper are useful in gaining an insight into some of the problems that will affect the city due to this cause in the years or decades to come.

Expected effective stress increments induced by the exploitation of the aquifers can be estimated with a viscoplastic consolidation model which overcomes some of the limitations of Terzaghi's consolidation theory. The equations of this consolidation model were integrated with a finite difference program in which time-dependent boundary conditions were imposed, to specify pore pressure depletion rates from actual piezometric readings. Regarding dynamic soil properties, analyses and calculations shown here indicate that consolidation-induced effective stress increments mainly affect shear moduli or shear wave propagation velocities and have a minor, negligible, effect on soil damping.

The characteristics of future earthquake motions were examined studying the response of two sites at the former lake zone where thicknesses and stiffnesses of the clay strata are different. Effective stress changes were estimated with the viscoplastic consolidation model and future seismic motions with a one-dimensional wave propagation model. Input motions from two earthquakes having different source mechanisms were used in the seismic analyses: the Great Michoacán Earthquake of 19 September, 1985, a subduction earthquake rich in energy associated to long period components, and the Tehuacán Earthquake of 15 June, 1999, an inland normal faulting event, in which energy concentrates at shorter periods. Earthquake motions produced in these two sources represent extreme conditions of the types of earthquakes that affect Mexico City.

A practical consequence of the effects of regional subsidence on soil properties and seismic response in the city is that seismic zoning maps as well as their associated design spectra will have to be revised periodically in the future. As shown here, intensity of seismic movements as well as damage distribution will be affected by the general stiffening of the subsoil due to regional consolidation.

References

[1] Tamez E, Santoyo E, Cuevas A, Ovando SE. Diagnóstico y proyecto geotécnico. In: Zaldívar S, editor. Catedral Metropolitana: corrección geométrica, informe técnico México, Asociación de Amigos de la Catedral Metropolitana de México; 1995. p. 41–114 [chapter II].
[2] Tamez E, Ovando E, Santoyo E. Underexcavation of the Metropolitan Cathedral in Mexico City. In: Proceedings of the XIVth international conference on soil mechanics and foundation engineering. vol. 4, Hamburg; 1997. p. 2105–26.
[3] Mazari M. La isla de los perros. México: El Colegio Nacional; 1996.
[4] Romo MP, Ovando E. Effective shear strength from undrained tests. México: Serie Gris, Pub. No. E-59, Instituto de Ingeniería, UNAM; 1989.
[5] Santoyo E, Lin R, Ovando E. El cono en la exploración geotécnica. México: TGC Geotecnia; 1989.
[6] Jaime AP. Características Dinámicas de la arcilla del Valle de México. Tesis Doctoral, División de Estudios de Posgrado de Ingeniería, vol. I y II, UNAM. México, DF; 1987.
[7] Romo MP. Clay behaviour, ground response and soil-structure interaction studies in Mexico City. State of the Art Paper. In: Prakash S, editor. Proceedings of the third international conference on recent

advances in geotechnical engineering and soil dynamics, University of Missouri. Rolla, Saint Louis, Missouri; 1995.

[8] Romo MP, Ovando E. Modelling the dynamic behaviour of Mexican clays. In: Proceedings of the XII international conference on earthquake engineering. México, Acapulco; 1996, edición de CD.

[9] Dobry R, Vucetic M. Dynamic properties and seismic response of soft clay deposits. In: Mendoza MJ, editor. Simposio internacional de ingeniería geotécnica de suelos blandos, Sociedad Mexicana de Mecánica de Suelos, vol. 2, México, DF; 1997. p. 49–85.

[10] Gonzalez BM. Modelación de las Propiedades Dinámicas de Arcillas Marinas. Tesis de Maestría, Universidad Nacional Autónoma de México, UNAM. México, DF; 2005.

[11] Yin JH, Graham J. Equivalent times and one dimensional elastic viscoplastic modelling of time dependent stress–strain behaviour of clays. Can Geotech J 1994;31(1):42–52.

[12] Yin JH, Graham J. Elastic visco-plastic modelling of one dimensional consolidation. Geotechnique 1996;46(3):515–27.

[13] Ovando SE, Ossa LA. Modelo elastoviscoplástico para la consolidación de los suelos y su aplicación al hundimiento regional de la ciudad de México. In: Memorias, XXII Reunión Nacional de Mecánica de Suelos. México, Guadalajara, vol. 1; 2004. p. 291–9.

[14] Ovando SE, Romo MP, Contreras N, Giralt A. Some implications of the Future evolution of Central Mexico City's subsoil properties due to water pumping. Geofísica Internacional 2003;42(2):185–204.

[15] Schnabel PB, Lysmer J, Seed HB. SHAKE: a computer program for earthquaked response analysis of horizontally layered sites. In: Report UCB/EERC-72/12, University of California, Berkeley; 1972.

[16] Seed HB, Romo MP, Sun J, Jaime A, Lysmer J. Relationships between soil conditions and earthquake ground motions in Mexico City in the Earthquake of September 19, 1985. College of Engineering, University of California, Berkeley, California; 1987.

[17] Singh SK, Ordaz M, Pacheco J, Quaas R, Alcántara L, Alcocer S, et al. A preliminary report on the Tehuacán, México earthquake of June 15, 1999 ($M_w = 7.0$). Seismological Research Letters 1999;70(5): 489–503.