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Basin boundary seismic effects in Mexico City southern region

Effects sismiques de la limite du bassin dans la région sud de Mexico

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ABSTRACT: Rapid changes in geotechnical and geological ground conditions lead to major ground motion variability. This condition mostly occurs at the so called basin edges, in which there is an abrupt transition between soft highly compressible soils and stiffer materials. This problem becomes more relevant in those areas were ground subsidence changes drastically the dynamic response of high plasticity clays deposits, such as those found in Mexico City. This paper presents site response analyses at an abrupt transition area found in the southeast Mexico City region, along the edges of the Xochimilco-Chalco lakes, where large damage associated with wave propagation effects was observed in past earthquakes. Series of three dimensional finite difference models of the basin edge were developed with the software $FLAC^{3D}$ to evaluate ground motion variability, considering ground subsidence, topographic effects, as well as soil nonlinearities. From the results gathered in this research, it was clearly noticed the relevance of accounting for three-dimensional wave propagation fields, to properly assess site effects at basin-edge zones and to be able to implement proper risk mitigation measurements to the infrastructure located in the basin edges.

RÉSUMÉ : Les changements rapides des conditions géotechniques et géologiques du sol entraînent une variabilité majeure des mouvements du sol. Cette condition se produit principalement sur les bords dits de bassin, dans lesquels il y a une transition abrupte entre des sols mous hautement compressibles et des matériaux plus rigides. Ce problème devient plus pertinent dans ces zones où l'affaissement du sol modifie radicalement la réponse dynamique des dépôts d'argile à haute plasticité, tels que ceux trouvés à Mexico. Cet article présente des analyses de réponse de site dans une zone de transition abrupte située dans le sud-est de la région de Mexico, le long des bords des lacs Xochimilco-Chalco, où d'importants dommages associés aux effets de propagation des vagues ont été observés lors de tremblements de terre passés. Des séries de modèles à différences finies tridimensionnelles du bord du bassin ont été développées avec le logiciel FLAC3D pour évaluer la variabilité du mouvement du sol, en tenant compte de l'affaissement du sol, des effets topographiques, ainsi que des non-linéarités du sol. À partir des résultats rassemblés dans cette recherche, il a été clairement remarqué la pertinence de la prise en compte des champs de propagation d'ondes tridimensionnels, pour évaluer correctement les effets de site en bordure de bassin et pour être en mesure de mettre en œuvre des mesures d'atténuation des risques appropriées à l'infrastructure située dans le bords de bassin.

KEYWORDS: Seismic risk, ground motion variability, abrupt transition, numerical models.

1 INTRODUCTION

Ground motion variability in basin-like regions, such as Mexico City, has been historically correlated to site effects, in which soil layering and geological features play a key role in the wave propagation patterns. Often, these motions are further modified by topographical effects at the surrounding stiffer soils (e.g. Asimaki & Mohammadi 2018, Mayoral et al., 2019b). This variability is larger at abrupt basin boundaries, in which drastic changes from soft to stiff soils, or rocks, associated to specific geological formations, lead to three-dimensional modifications of the incoming wave field. In particular, these effects can significantly affect the amplitude, frequency content, and duration of strong ground motions associated with the large amplitude surface waves generated through seismic wave diffraction and energy focusing (Asimaki & Gazetas 2004a). Coupled basin and site effects due to alluvial soils and sediments on the seismic motions has been studied by several authors (Assimaki et al., 2005, Hasal & Iyisan 2014a), finding that the generated local surface waves and their subsequent trapping in the soft soil layers leads to the increased amplification with respect to the classical one-dimensional analysis often adopted in practical engineering applications. Nevertheless, the impact of the topographic, and geological features at basin edges in the seismic performance of a site located at abrupt transition between stiff soils and soft soil has not been fully addressed, accounting for potential changes in the dynamic soil properties and soil profile configuration due to regional subsidence, such as that observed in Mexico City. This paper presents site response analyses at an abrupt transition area found in the southeast Mexico City region, along the edges of the Xochimilco-Chalco lakes, where large damage associated with wave propagation effects was observed in past earthquakes. Three-dimensional finite difference models were developed with the software $FLAC^{3D}$ (Itasca, 2009). Due to the lack of information, pore pressure distribution was considered hydrostatic for initial conditions. Then, variations in dynamic properties, and layer thickness were taken into account based on the evolution of elastic predominant periods associated with regional subsidence, being the corresponding effective stresses the starting point for the dynamic analysis as described by Mayoral et al., 2017, & 2019b. Free field model response was calibrated for strong level of shaking (i.e. return periods 250 years) considering subduction events comparing the $FLAC^{3D}$ analyses results with equivalent linear analyses carried out with the program SHAKE (Schnabel et al., 1972). Three-dimensional effects, generated at the abrupt transition zone, strongly affects the actual ground motion amplification with respect to that obtained from one-dimensional analyses.

2 GEOTECHNICAL SETTINGS IN MEXICO CITY

Mexico City and its surroundings are located within an old basin that comprises the former Texcoco Lake and the Xochimilco-Chalco Lakes. As explained by Mayoral et al., 2019a, these lakes have largely disappeared due to both underground water extraction and land reclamation for urban development. Thus, while the peripheral part of the City is underlain by rock and hard soil deposits (layer of fractured lava overlying soft rock with a shear wave velocity of 450–700m/s), the central part of the City is located on soft lacustrine clay deposits of variable thickness

(Seed et al. 1988a). The former Texcoco Lake is located to the north of the City, and is separated by a ridge of hills across the northern edge of the Xochimilco-Chalco Lake. Both of the lake beds are now essentially filled with clay deposits, but the clays have different characteristics. The Xochimilco-Chalco Lake clays are stiffer and stronger than the Texcoco Lake clays. Commonly the soil profile in Lake Zone presents a desiccated crust of clay at the top extending down to a depth of 1.0 m, which is underlain by a soft clay layer approximately 30.0 m thick, with interbedded lenses of sandy silts and silty sands. Underlying the clay there is a 4.0 m thick layer, in average, of very dense sandy silt, which rests on top of a stiff clay layer, which goes up to a 60.0 m depth. Underneath this elevation, a competent layer of very dense sandy silt is found.

As presented in Figure 1, Mexico City has been divided into three main zones for geo-seismic zonation purposes according to the local Building Code (RCDF 2004): Zone I (Hills), Zone II (Transition), and Zone III (Lake). Zone III has further been subdivided into Zone IIIa, IIIb, IIIc and IIId to account for the increasing depth of the clay deposits when moving from the hill zones to the center of the old lakes. The important contrast variation in subsoil conditions leads to the elastic predominant soil period, Tsoil, distribution presented in Figure 1. These periods evolve constantly due to regional ground subsidence. This ground subsidence leads to the formation of cracks along the basin edges, in zones of abrupt transition as depicted in Figure 1.

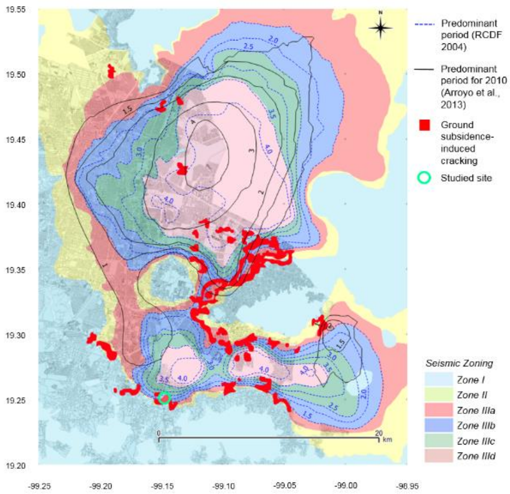


Figure 1. Mexico City Main Geotechnical Zones, predominant periods [in seconds], and ground subsidence-induced cracking.

Figure 2 presents the subsidence rate contours around Mexico City basin and surrounding areas (Auvinet et. al., 2017). Subsidence rates goes from about 2 cm/year at the basin boundaries, up to 43 cm/year in deeper clay zones. The evolution of elastic predominant periods associated with regional subsidence has been studied by several authors. In particular Figure 1 shows a comparison of the distribution determined by Arroyo et al., 2013, with that included in the former Mexico City building code (RCDF 2004).

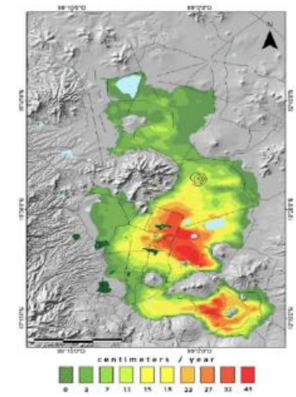


Figure 2. Map of the subsidence rate in Mexico City and surrounding areas (Auvinet et. al., 2017).

3 METHODOLOGY

The approach proposed by Mayoral et al., 2017 was used to study the effects of ground deformation, including settlements and layering distortion, in the expected seismic performance at the stiff soil-soft clay interface, as a mean to further explain the observed damage patterns (Mayoral et al., 2019c). Mayoral´s approach is comprised of eighth steps as follows: 1) Initial in-situ stress determination based on field data, 2) Evaluation of the consolidation evolution over the economic life of the structure, based also on medium to long term piezometers monitoring. Establishing pore water pressures evolution with time at the studied site is a requirement for obtaining the expected consolidation settlements due to regional subsidence. Due to the lack of reliable data regarding piezometric information, an iterative approach based on back analyses conducted using three-dimensional finite difference models was carried out. The pore pressure established for current conditions was varied until the ground settlement computed with the numerical model was in good agreement with that expected considering regional subsidence trends reported in the technical literature at the studied area (Auvinet et. al., 2017), 3) Determination of the volumetric modulus, mv, variation with the mean effective stresses, σm´, for the clayey formations found at the studied site, conducting one-dimensional consolidation tests, 4) Ground settlements calculation for each consolidation time considered, employing the analytical solution provided by Terzaghi´s theory for one dimensional consolidation, ΔH=mvpH, where mv is the volumetric modulus, H layer thickness, and ΔH the corresponding layer deformation, 5) Determination of small shear stiffness variation with mean effective consolidation stresses. Instead of using resonant column or bender element tests, an alternative method was followed. This alternative approach is based on the results of the three-dimensional models used in step 2, from which the deformed soil profile due to regional subsidence was established for each year considered. This procedure was deemed more representative of regional conditions prevailing in the area, 6) Site response analyses for each consolidation time considered, accounting for a three-dimensional earthquake environment, 7) Seismic-soil-structure interaction analyses for each consolidation time considered, and 8) Evaluation of post-earthquake settlements due to seismic-induced excess pore pressure, when dealing with sensitive or low plasticity clays. This evaluation will be required when soil stiffness degradation during cyclic loading leads to an important amount of pore pressure generation.

4 CASE STUDY

The studied site is located in the southern abrupt basin border of the Mexico City valley, close to the Chichinautzin range (Figure

1), this area exhibits a unique geotechnical and geological conditions, associated to the rapid change in the stratigraphic conditions, passing from very soft high plasticity clay to very stiff cemented silty sands and sandy silts, and heavy fractured to sound rocks. The studied site includes a hill with an irregular semicircular shape, located in the so-called zone I, and part of the former Xochimilco-Chalco lake (Figure 3), in the denominated zone III.

Figure 3. Aerial view of the studied site.

4.1 *Subsoil conditions*

For the subsoil conditions characterization, a total of 25 exploration borings were conducted. A combination of cone penetration test, CPT, standard penetration test, SPT, selective sampling recovery of undisturbed samples, and PS suspension logging test, along with a laboratory investigation were conducted to obtain the static and dynamic properties of the soils found at the site for the strains level of interest. The depths of the exploration borings ranged from 15 to 60 m. At those depths where the hardness of the ground exceeded the applicability of CPT technique, standard penetration tests, SPT, was used instead. The Shelby sampler was used to obtain undisturbed soil samples at the studied site. The suspension PS logging technique was used in exploration boring S-06 and S-19 to determine in situ values of shear wave velocity. Figures 4 and 5 presents two cross sections, along the hillside, and along the transition between zone I and zone III.

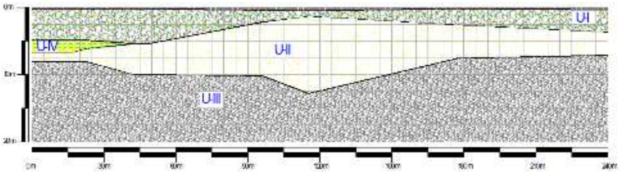


Figure 4. Stratigraphy along the hillside.

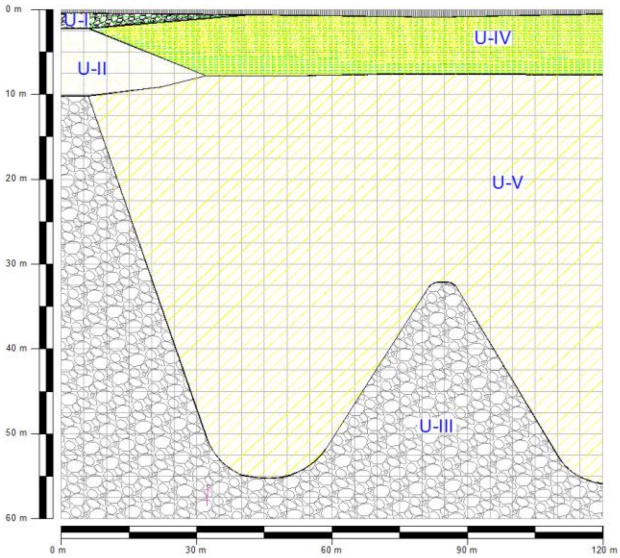


Figure 5. Stratigraphy along the transition between zone I and zone III.

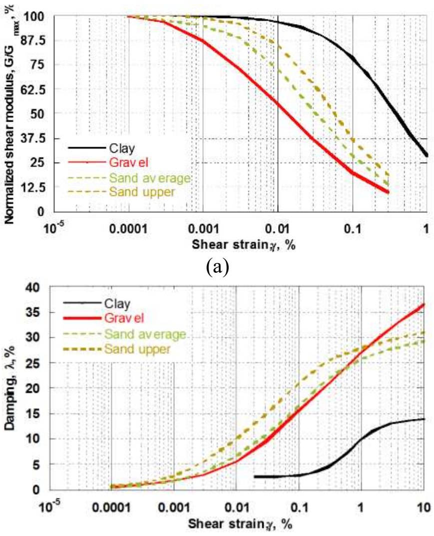
The main geotechnical units are identified as follows: 1) fill formed by gravel and sand in a matrix of brown clay and silt, 2) foothills comprised of gravel and rock fragments of angular shape, with clayey sand, 3) basaltic rock with varying fracture degree, interbedded with lenses of gravel and sand, 4) very dense to dense sand with some gravels, and 5) very soft high plasticity clay with interbedded lenses of sand, volcanic ash and silt. Table 1 summarizes the properties of main geotechnical units.

Table 1. Properties of main geotechnical units.

Unit	Unit weight, γ (kN/m^3)	Cohesion, c (kPa)	Friction angle, φ (°)	Young's modulus at 50% strain, E_{50} (kPa)
I	16.7-17.7	49.1-107.9	30-34	34883-53522
II	16.7-18.6	127.5-186.4	35-40	59542-78760
III	18.6-19.6	176.6-206.0	39-41	75461-84780
IV	17.7-18.6	-	32-38	40868-71966
V	12.8-15.7	22.6-42.2	4-19	159-427

4.2 *Normalized modulus degradation and damping curves*

Gonzalez & Romo (2011) proposed a simplified model to predict the normalized modulus degradation and damping curves for clays found in Mexico City, with the results obtained from the resonant column and triaxial tests. The model is able to match the shear modulus degradation and damping curves separately. Due to the practical difficulty in sampling the sand layers, the upper and lower bounds proposed by Seed & Idriss (1970) for normalized modulus degradation and damping curves, respectively, were deemed appropriated, considering that they had been used in 1-D wave propagation analysis (Romo et al. 1988; Seed et al 1988), which predictions were in good agreement with the measured response during the 1985 Michoacan earthquake. Figure 6 present the normalized modulus degradation and damping curves used in this research.



(a)

(b)

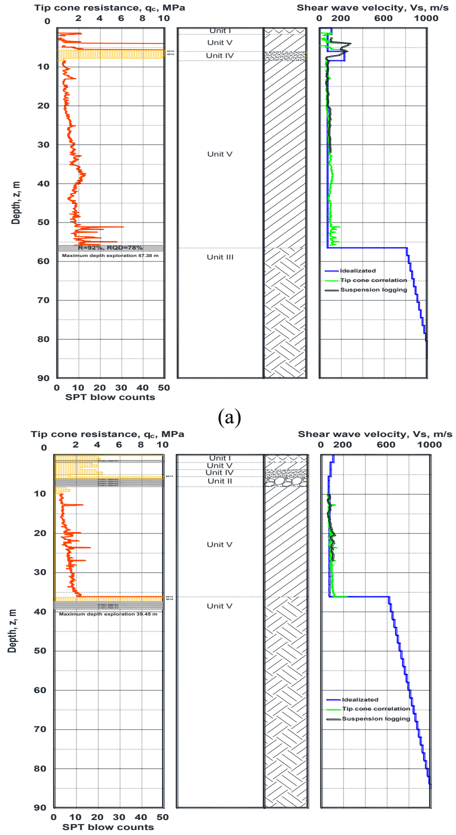
Figure 6. (a) Normalized modulus degradation and (b) damping curves.

4.3 *Shear wave velocity profiles*

Shear wave velocities were estimated with the expression proposed by Ovando & Romo (1990) (see Eq. 1) in terms of the tip penetration resistance, qc, measured with Cone Penetration Test., where Vs is the shear wave velocity, in m/s; qc is the tip cone penetration resistance in kN/m^2; γs is the unit weight of the soil in kN/m^3; N_{kh} and η are parameters that depend on the soil type, which were determined for the particular conditions of the site.

$$V_s = \eta \sqrt{\frac{q_c}{N_{kh}\,\gamma_s}} \quad (1)$$

For verification purposes, in-situ shear wave velocity distributions were measured at two sites SM-06 and SM-19, in the clay and abrupt transition zones respectively, using suspension login, SP, test. Figure 7 presents a comparison of a measured and estimated Vs profiles. As can be seen, estimations are in good agreement with measured Vs values.



(a)

(b)

Figure 7. Comparison of a measured and estimated Vs profiles for (a) SM-06 and (b) SM-19.

Table 2. Properties of main geotechnical units.

Date	Earthquake and site	Moment magnitude (Mw)	PGA (g)
19/09/1985	Michoacan (Cu, Mexico)	8.1	0.033

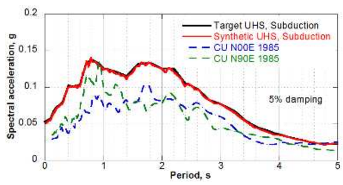


Figure 8. Uniform hazard spectra from Mexico City building code and synthetic ground motion response spectra.

5 SEISMIC ENVIRONMENT

Due to the lack of reliable ground recordings at a rock-site seismological station near the studied site, the seismic environment was established based on uniform hazard spectra, UHS, determined for a return period of 250 years, considering a subduction event, associated to the devastating 1985 Michoacan Earthquake. The UHS was developed for a rock outcrop site and corresponds approximately to the design spectra presented in the current version of the Mexico City building code (RCDF 2017) (Figure 8). To develop an acceleration time history which response spectrum reasonably matches the design response spectrum for the return period of analysis (i.e. T=250 years), the selected time history, usually called seed ground motion, was modified using the method proposed by Lilhanand & Tseng, (1988) as modified by Abrahamson (2000). This approach is based on a modification of an acceleration time history to make it compatible with a user specified target spectrum. The modification of the time history can be performed with a variety of different modification models. In doing so, the long period non-stationary phasing of the original time history is preserved. The 5% damped response spectra calculated for the modified time histories are compared with the target UHS in Figure 8. It can be seen that the response spectrum calculated from the modified time histories reasonably match the target spectrum. The characteristics of seed ground motion is described in Table 2.

6 NUMERICAL MODEL

A tridimensional finite difference model of the studied site was developed with the program FLAC^{3D} (Itasca 2009) to obtain the ground motion spatial variation due to site response, topographic effects, and basing effects (Figure 9). Figure 10 present section for analysis and control points in the tridimensional finite difference model. Although several constitutive models have been developed to account for nonlinearities in low plasticity clays and sands (Gajan, et. al., 2010; Carlton & Tokimatsu 2016), and medium to stiff clays (Borja & Amies 1994), there is a lack of enough experimental data to develop and calibrate a reliable constitutive model for high plasticity clays. Therefore, the stress-strain relationship of the soil was assumed elastoplastic, following Mohr Coulomb failure.

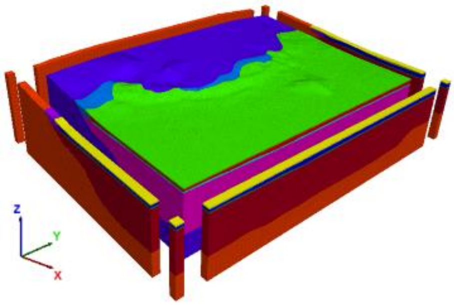


Figure 9. Tridimensional finite difference model.

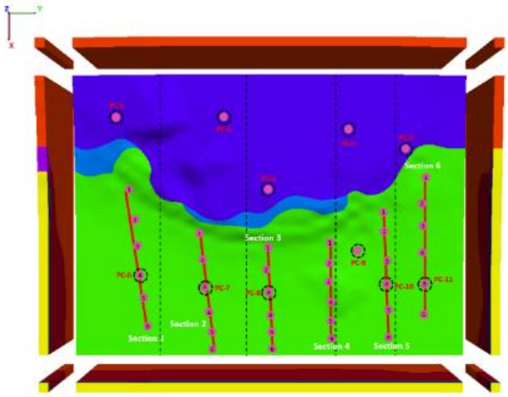


Figure 10. Sections of analysis and control points in the tridimensional finite difference model.

7 SITE RESPONSE ANALYSIS

Initially for completeness, the computer code SHAKE was used to conduct one dimensional equivalent linear site response analyses at the several points with in the studied area. A total of 11 one dimensional soil profiles, five of them located in firm soil (i.e. zone I), and six in lake zone (i.e. zone III), were used for comparison purposes with the results obtained from a three-dimensional non-linear finite difference numerical model. One dimensional finite differences models were also developed with FLAC^{3D}. These have a varying depth ranging from 90 to 95 m, and from 79 to 81 m for zone I and III, respectively. The free field boundaries implemented in FLAC^{3D} were used along the edges of the model. A flexible base was considered at the bottom of the model. Results gathered from frequency domain and time domain analyses, conducted with SHAKE and FLAC^{3D} respectively, assuming one-dimensional SH waves propagating vertically, are show in Figures 11 and 12. Good agreement can be shown in the computed response obtained in each analyzed case.

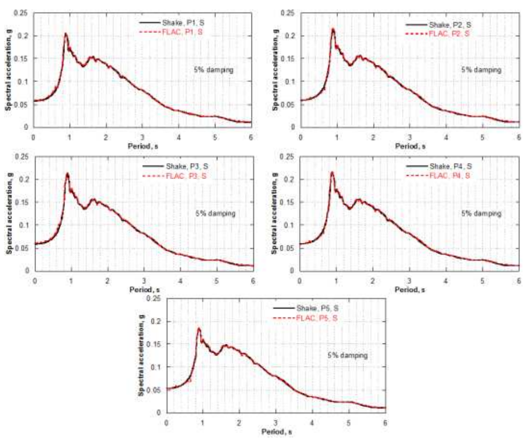


Figure 11. Response spectrum at surface for each soil profile in zone I.

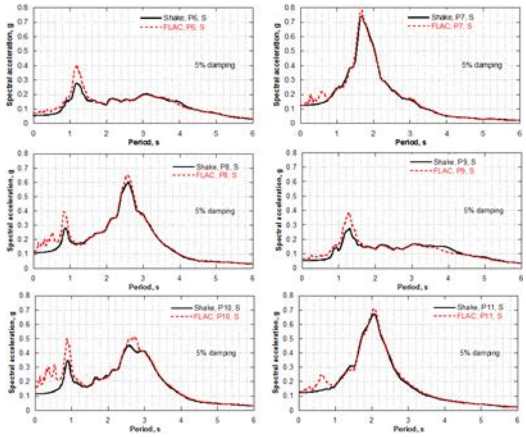


Figure 12. Response spectrum at surface for each soil profile in zone III.

8 RESULTS AND COMMENTS

Figures 13 and 14 show the surface response spectra for the subduction earthquake considered, it is observed that in all cases in the points present in zone I the response spectra maintain the shape of those obtained in free field, presenting slight amplifications. On the other hand, in the points located in the lake zone, an appreciable change is observed in the shape of the response spectra, as shown in Figure 14, but in some cases reaching the magnitude of the spectral ordinates, or surpassing them slightly, obtained in free field or as in the case of the spectra shown in Figure 13 where they are below. Ground subsidence at basin boundary interfaces lead to large relative displacements associated to the compressibility contrast observed between clays and the surrounding stiffer soils. To account for these effects in the computed seismic response presented herein, two scenarios were considered, corresponding to 5 and 30 years of consolidation. Figure 15 present the total settlements after 5 and 30 years respectively, and Figures 16 and 17 present the response spectra for control points located in Zone III.

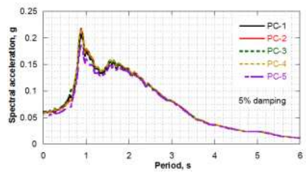


Figure 13. Response spectrum associated to subduction earthquake in control points at Zone I.

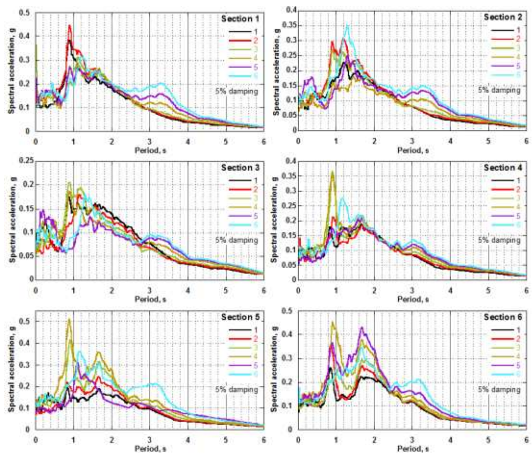
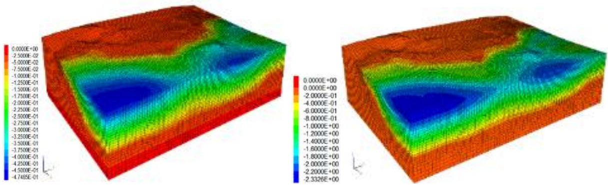


Figure 14. Response spectrum associated to subduction earthquake in Sections at Zone III.



(a) (b)

Figure 15. Total settlement after (a) 5 years and (b) 30 years (in meters)

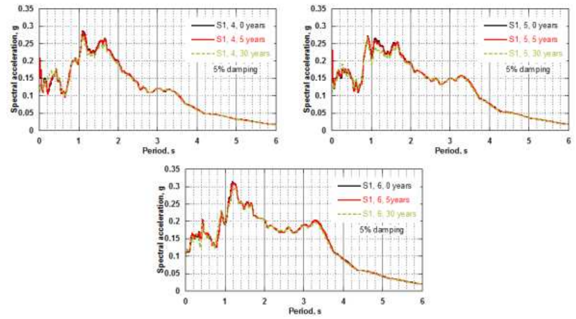


Figure 16. Seismic response associated to subduction earthquake, section 1 (zone III).

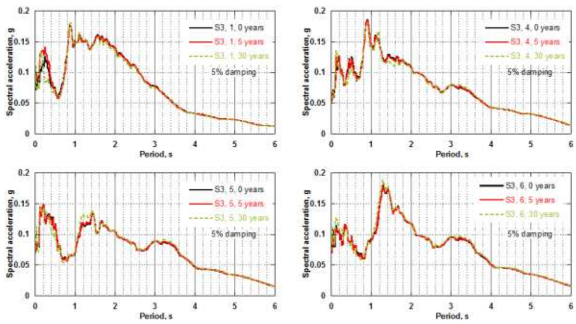


Figure 17. Seismic response associated to subduction earthquake, section 3 (zone III).

9 CONCLUSIONS

Seismic response in abrupt transition zones such as those found at basin edges of valleys is strongly affected by tridimensional effects associated to geologic features at the clay-stiff soil/rock interface. This paper revisits the impact that these effects had in the ground motion variability. A three-dimensional finite difference model was developed to simulate the southern basin edge of the Valley of Mexico. From the geotechnical stand point, these area was characterized by information gathered from 25 exploratory borings, selective sampling recovery, and in-situ testing, including two suspended logging tests. Three-dimensional effects were assessed through a comparison of one-dimensional and three-dimensional seismic response, established from numerical modelling. Strong ground motion variability was computed in both the surrounding basin stiff materials, and the high plasticity clay found at the former Xochimilco-Chalco lake. From the numerical study it was observed that in all cases in the points present in zone I the response spectra maintain the shape of those obtained in free field, presenting slight amplifications, on the other hand, in the points located in the lake zone an appreciable change is observed in the shape of the response spectra. Moreover, there is a complex interaction between incoming wave patterns, coming from the stiffer materials found at the bottom of the lake, and those associated with the waves coming from the stiff soil clay interface coming from the actual basin lateral boundary. This fact leads to changes in the spectral shape of the computed ground motions computed at the clay zone, been strongly affected by both the predominant site period, which is, in turn, associated with clay thickness, and the distance from the actual lateral basin border.

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