Soil Dynamics and Earthquake Engineering 103 (2017) 123–140

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Regional subsidence effects on seismic soil-structure interaction in soft clay

Juan M. Mayoral*, Ernesto Castañon, Jorge Albarran

Coordinacion de Geotecnia, Instituto de Ingeniería, Universidad Nacional Autonoma de Mexico, Mexico city, Mexico

ARTICLE INFO

Keywords:
Soil-structure interaction
Soft clay
Dynamic properties
Consolidation

ABSTRACT

Regional subsidence effects on dynamic soil properties and ground layering deformation are often ignored in practice, when dealing with seismic soil-structure interaction analyses. Nevertheless, these effects can substantially change the frequency content and spectral accelerations in both free field and in the soil-structure system. Pore pressure variations over the project economic life are due to both regional subsidence as well as dissipation of excess pore pressure caused by the structure weight. These variations lead to changes in effective stresses, which in turn, modify the dynamic properties such as shear wave velocity distribution and modulus degradation and damping curves, as well as soil layer thickness and shape. These changes can be substantial in highly compressible very soft clay, such as that found in Mexico City valley. This paper presents a numerical study on the seismic response of a conventional five-story building supported by a compensated box foundation built in soft clay, considering these effects. Three-dimensional finite difference models were developed with the software FLAC^{3D}. Initially, the evolution of effective stresses with pore pressure was established based on in-situ piezometer measurements of an instrumented site, and laboratory data. Then, changes in dynamic properties were taken into account based on the results gathered from series of resonant column tests conducted for several effective consolidation stresses, and a PS suspension logging test. The static behavior of the soil-structure system was assessed. For the cases studied herein, the complex interplay between soil nonlinearities, which lead to fundamental period elongation of the soil deposit, T_p, and the overall tendency of ground consolidation to shorten it, controls the variations in the spectral ordinates depending on how close T_p is of the predominant period of the excitation.

1. Introduction

Seismic performance evaluation of soil-structure systems built on very soft high plasticity clays is a complex problem, especially when expected changes in effective stresses during the economic life of the structure due to dissipation of excess pore pressure caused by the building gravity loads and regional subsidence are very large. These changes in effective stresses lead, in turn, to large settlements. This is particularly important in urban areas located in highly compressible clays, such as Mexico City, where the settlement rate of regional subsidence reaches about 10 cm/year in average, but can go as large as 35 cm/year in some areas. Thus, it is common to have ground settlements ranging from 40 to 90 cm, due to load consolidation, and around several meters due to regional subsidence [1]. These settlements produce changes in both soil profile configuration (i.e. layer thickness and geometry), as well as dynamic properties, such as shear wave velocity distribution with depth and modulus degradation and damping curves. These factors impact the seismic response of the soil-structure system. The effect of dynamic properties changes on the seismic response of sites located in soft clay, has been only marginally studied by other researches [2–5], finding that the variation of shear wave velocities and modulus degradation and damping curves with effective confining stresses can modify significantly the computed response. Nevertheless, the impact of these variations in the seismic performance of soil-structure systems has not been addressed, neither the effect of changes in the soil profile configuration after several meters of sinking. These effects however, can drastically modify both free field, near field and structural response over time. This paper presents a numerical study of the seismic response of a conventional five-story building supported by a partially compensated box foundation built in highly compressible soft clay, considering these effects. Three-dimensional finite difference models were developed with the software FLAC^{3D}. Initially, the evolution of effective stresses with the pore pressure was established based on in-situ piezometer measurements, and laboratory data. Then, variations in dynamic properties were taken into account based on a series of resonant column tests conducted for several mean effective consolidation stresses and a suspension logging test. The static behavior of the soil-structure system was assessed. The free field model response

---

[*] Corresponding author.
E-mail address: jmayoralv@iingen.unam.mx (J.M. Mayoral).

http://dx.doi.org/10.1016/j.soildyn.2017.09.014
Received 3 January 2017; Received in revised form 18 September 2017; Accepted 21 September 2017

was calibrated for moderate to strong level of shaking (i.e. return periods of 125 and 250 years, respectively) comparing the fully nonlinear analyses results with equivalent linear analyses carried out with the program SHAKE [6]. Finally, the seismic performance of the soil-structure system was studied to evaluate the impact of the changes on dynamic properties and layering configuration on the seismic response, considering an extreme subduction event associated to a 2475 years return period. Insight was gained regarding the complexity of the interplay of the effective stress history, and static and seismic soil-structure performance during an extreme earthquake.

2. Methodology

As it is well known, field evidence has shown that shear wave velocity increase overtime in highly compressible clays, such as those found in Mexico City, can lead to important changes in the seismic response of a given place during the life time of a particular structure [2–5]. Although ground subsidence effects on soil-structure interaction has been addressed for static loading conditions [7,8], to date, there is still a lack of information regarding how to account for this effect in seismic-soil-structure interaction analyses. This paper presents a numerical approach to address this problem to establish the effect of how the changes in effective confining stress can affect the seismic-soil-structure interaction. The proposed approach is comprised of eighth steps as follows: 1) Initial in-situ stress determination based on field data gathered from piezometers, 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, 3) Determination of the volumetric modulus, m_v, variation with the mean effective stresses, for the clayey formations found at the studied site, conducting one-dimensional consolidation tests, 4) Determination of small shear stiffness variation with mean effective consolidation stresses, using resonant column or bender element tests, and correction for field effects considering in-situ shear wave velocity measurements, 5) Ground settlements calculation for each consolidation time considered, employing the analytical solution provided by Terzaghi´s theory for one dimensional consolidation, $\Delta H = m_v pH$, where m_v is the volumetric modulus, H layer thickness, and ΔH the corresponding layer deformation, 6) Site response analyses for each consolidation time considered, 7) Seismic-soil-structure interaction analyses for each consolidation time considered. Depending on the level of shaking it could be necessary to account for soil nonlinearities, 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.

3. Case study

A conventional five-story building supported by a compensated box foundation located on the Texcoco Lake area (Fig. 1), was considered in the numerical study. Due to the particular characteristics of Mexico City clay having a high plasticity index, no significant reduction in shear modulus is observed even for shear strains as high as 0.1% [9–12]. Similarly, there is no significant increase in the damping ratio until angular distortions of the order of 0.3% are reached. Thus, the response of clayey soil deposits is nearly elastic even for shear strains as high as 0.3%, which leads to a high potential of amplification of the seismic waves. Indeed, amplification factors up to 5 (between peak ground acceleration, PGA, observed at soft soil with respect to those of rock outcrops) were observed during the 1985, Michoacan earthquake. During this event, the long distance that seismic waves needed to travel from the zone of energy release to the Mexico City area (around 390 km), filtered the high frequency waves, leading to have a long period ground motion (i.e. the energy is concentrated around 2–3 s). A double resonance effect was caused when the incoming seismic waves reach the city area, due to the fact that both the clayey soils and the most damaged buildings had a fundamental period ranging between 2 to 2.5 s, as well as the earthquake excitation.

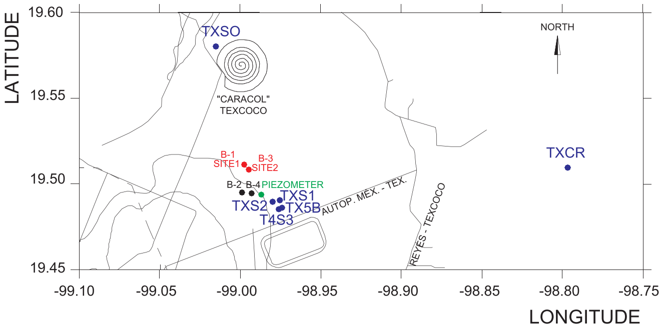

Fig. 1. Seismological stations, exploration borings and piezometer locations.

3.1. Soil stratigraphy

Soil profiles of Site 1 and Site 2 are presented in Fig. 2. Site 1 presents a desiccated crust of sandy silt at the top extending down to a depth of 1 m, which is underlain by a soft clay layer approximately 28 m thick, with interbedded lenses of volcanic ashes. Underlying this clay, there is a 1 m thick layer of very dense sandy clay and a 3 m thick silt layer. This layer rest on top of a stiff clay layer which goes down to 63 m of depth. Below this layer of clay, there is a second layer of very dense silty sand and sandy silt, often called the second hard layer. Site 2, presents the same layer of desiccated crust of sandy silt at the top, extending down to a depth of 1 m. This stratum is underlain by a soft clay layer approximately 28 m thick, interbedded by lenses of volcanic ashes. Beneath this formation a silt layer 3 m thick is found, followed by series of silty sands lenses down to a depth of 34 m. These layers rest on top of a stiff clay layer which goes down to 62 m, at which the second hard layer is located.

3.2. Piezometric measurements

A piezometer was installed at the instrumented site as depicted in Fig. 1. Initially, the evolution of pore pressure withdrawn with water extraction was established based on the available piezometer readings located at several depths (i.e. 9, 18, 31, 38 and 45 m) as shown in Fig. 3, which presents the evolution of normalized measured pore pressure, u, over the initial reading, u_o. Based on these data, empirically-derived equations were used to estimate the expected evolution of the pore pressure over time. Fig. 4 shows the corresponding computed pore pressure distribution with depth for each time of analysis (i.e. 5, 10, 30 and 60 years). It can be clearly noticed that the initial pore water pressure distribution is not hydrostatic.

3.3. Experimental data

For the subsoil conditions characterization, a total of four exploration borings (B-1, B-2, B-3 and B-4) were conducted (Fig. 1). A combination of cone penetration test, CPT, standard penetration test, SPT, and PS suspension logging, 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 CPT´s ranged from 50 to 70 m. At those depths where the hardness of the ground exceeded the applicability of this subsoil exploration technique, standard penetration tests, SPT, was used instead. In addition, a 65 m depth SPT was conducted for soil identification purposes, at the same locations. The Shelby sampler was used to obtain undisturbed soil