Seismic performance evaluation of a deep foundation system build in the lake zone area, in Mexico City

Évaluation séismique de la performance des systèmes de fondation profonde sous des conditions difficiles

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ABSTRACT

Seeking for developing both safe and economical designs, calibration of numerical models of soil-foundation-structure system is essential to improve the prediction of the seismic response of civil engineering structures during severe earthquakes. In difficult subsoil conditions, as those prevailing in Mexico City, the well-suited approach to calibrate these models is from data gathered from real-scaled instrumented structures. This paper presents the numerical modeling of one of the supports of a large vehicular bridge, part of a subway station, built 12 years ago in the so-called lake zone area, in Mexico City. This support has a mixed foundation system, consisting of a box foundation and friction piles, which was instrumented since its construction to monitor its response under static and dynamic loading. Ever since, several state variables that control the behavior of this type of foundation have been measured, including the evolution of contact pressures between the lower mat of the box foundation and the soil, the distribution over time acting on some pile heads, the pore pressure in the soil underneath the foundation, and the free field and soil-foundation-structure system seismic response. The seismic performance evaluation was conducted with finite element models of the system to estimate the bridge support response exhibited during the January 1st, 2004, Guerrero Coast earthquake (M_w=6.3). The computed response was compared with the measured response in the free field, box foundation, and structure, establishing the model prediction capabilities. Change in dynamic properties due the regional subsidence was accounted for in the analysis, and estimations of future performance were established.

RÉSUMÉ

Dans la recherche du développement des conceptions à la fois sûre et économique, la calibration des modèles numériques des systèmes sol-fondation-structure deviens essentiel pour améliorez la prédiction de la réponse séismique des structures d'ingénierie civil pendant des tremblements sévère. Dans des conditions difficiles de sol, comment ces qui prévalent à Mexico, l'approche bien adaptée pour calibrer ces modèles est la recollection des données des structures instrumentées en échelle réelle. Ce document présent le modelant numérique d'un des supports d'un grand pont véhiculé, qui est aussi une partie d'une station du Metro qui a été construis il y a 12 ans dans une région appelée « Zone du lac » à Mexico. Ce support à un système de fondations mixtes en intégrant une caisse de fondation et des piles de friction, qui ont été instrumentées depuis sa construction avec l'objectif de contrôler sa réponse sous des charges statiques et dynamiques. Depuis ça, on a mesuré beaucoup de variables d'état qui contrôlent le comportement de ce genre de fondation, on a aussi compris l'évolution de la pression du contact entre le plus bas tapis de la caisse de fondation et le sol, la distribution pendant le temps en action sous quelques têtes de pile, la pression de pore du sol sous la fondation, et la réponse sismique du système sol-fondation-structure et du champ libre. L'évaluation du rendement sismique a été conduit par les modèles d'éléments finît du système pour estimer la réplique du support du pont présent pendant le tremblement du 1er Janvier 2004 sur la côte de Guerrero (Mw=6.3). La réponse calculée a été comparée avec la réponse mesurée sous le champ libre, la caisse de fondation, et la structure, en établissant les capacités du model de prédiction. Un changement dans les propriétés dynamiques est dû à l'affaissement régional et a été observer dans l'analyse en tenant compte des estimations a propos du comportement futur qui ont été établis.

Keywords : Soil-structure interaction, instrumented bridge, seismic reponse

1 INTRODUCTION

Calibration of numerical models for seismic soil-structure interaction is essential to ensure both safe and economical designs, and to improve predictions of the structure response during major earthquakes. The required data to validate these models can be gathered through instrumentation of scaled soil-structure interaction systems or centrifuge testing (e.g., Gajan et al., 2004; Wang et al., 1998), and from actual instrumented structures (e.g., Mendoza et al., 2001). In this work, the dynamic performance of an instrumented bridge support, is presented. The Impulsora bridge, works as deck bridge in a surface subway station and it is located at the northeast of Mexico City (Figure 1). The instrumented support is located at the central portion of this bridge and it has a mixed foundation consisting of a pile friction-box. The main geotechnical variables that influence its seismic behavior have been recorded since its construction, 12 years ago, up to 2004. This paper focuses on seismic aspects only of one of the best documented cases: the January 1st, 2004, Guerrero Coast Earthquake.

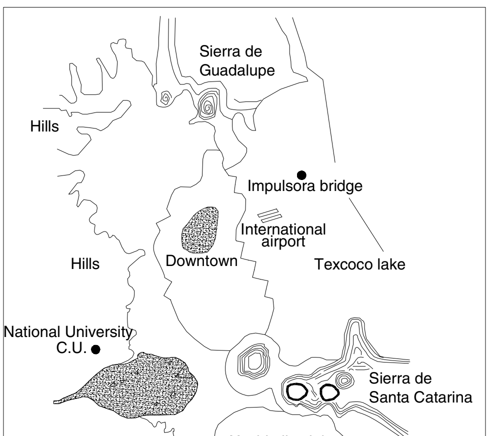

Figure 1. Seismic zonation of Mexico City

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2 INSTRUMENTATION

The bridge is comprised of support beams, which rest on top of the columns, and central beams that, in turn, lean on the previous ones. With this configuration, the effect that differential settlements between abutments may have over the bridge is minimized. The length of the bridge is 405 m, the central beams are 49 m length in the central span and 17 m at their maximum width, where there are two lanes of continuing traffic, two bays for passenger descend and two pedestrian entrances to the subway station beneath the bridge.

A plan view of the foundation is shown in Figure 2a. The box foundation has a rhomboidal shape and 77 reinforced concrete piles which have a square section of 0.5 by 0.5 m, and 30 m long. These piles work by friction, although loads measured at the pile heads indicate that the piles provided about 25% of the total foundation bearing capacity. The instruments are also presented in Figure 2a. The soil-structure system instrumentation is integrated by four accelerometers: one at 60 m of depth (A1), one at the surface (A-2) also in the free field, one at the box foundation center (A-3) and the last one in the upper support beam (A-4), 13 load cells, 6 piezometers and 8 pressure cells to measure soil-slab contact (Figure 2b).

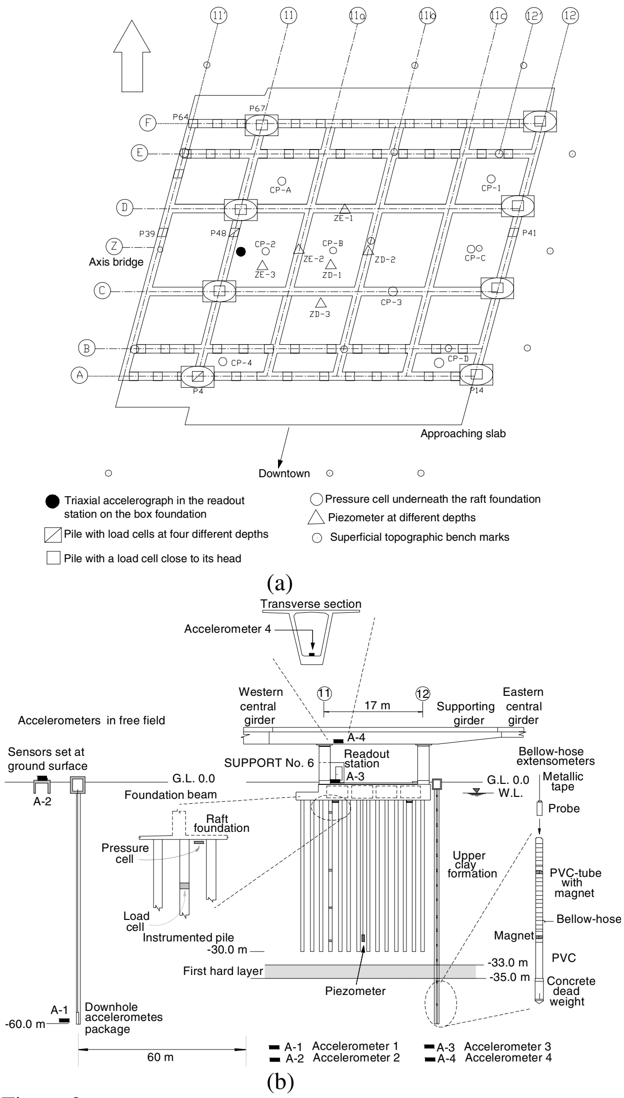

Figure 2. a) Plan view and b) lateral view of Impulsora Bridge

3 SUBSOIL CONDITIONS

The site is located in the so-called lake zone, which consists of very soft clay deposits interbedded by thin lenses of sand. To define the site stratigraphy and index properties, extensive field and laboratory tests were carried out, those results can be found in previous works (eg. Mendoza et al., 1998). Thus the soil profile at the studied site presents a desiccated crust of clay at the top extending up to a depth of 1.0 m approximately, which is underlain by a 1.0 m layer of fill that rest on top of a soft clay layer with organic matter about 30.5 m thick (Figure 3). The water content of these materials ranged from 208 to 331 %, and the plasticity index from 224 to 312%. The undrained shear strength, s_u, varied from 10 to 15 kPa. Underlying the clay there is a 2.5 m average thick layer of very dense sandy silt ($(N_1)_{60}$ larger than 65), which sits on top of a stiff clay (s_u between 21 to 26 kPa) interbeded by sand lenses. The water content of this layer goes from 253 to 280% and the plasticity index from 188 to 243 % approximately. Underneath this elevation a competent layer of very dense sandy silts ($(N_1)_{60}$ lager than 100) is found. The shear wave velocity profile was obtained in situ with the P-S loggin technique (Mendoza et al., 2001), which is idealized in Figure 3.

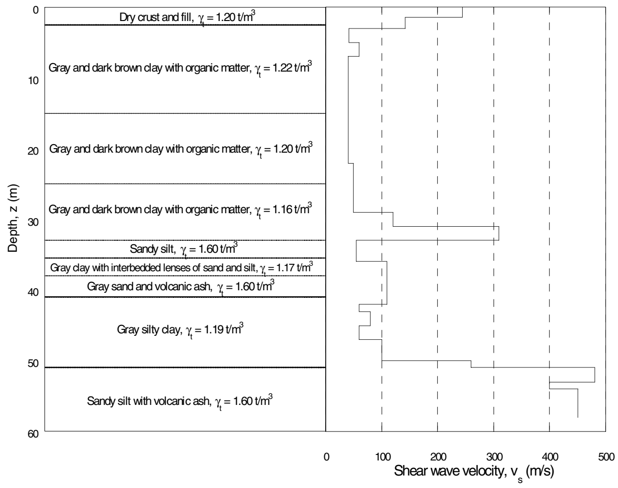

Figure 3. Stratigraphy and shear wave velocity profile

4 DYNAMIC PROPERTIES

Dynamic properties were computed using the previous data with the following equations (Romo, 1995):

$$G = G_{max}\left(1 - H(\gamma)\right) \text{ and } \lambda = \lambda_{max}\left(1 - \frac{G}{G_{max}}\right) \tag{1}$$

$$H(\gamma) = \left[\frac{(\gamma/\gamma_r)^{2B}}{1 + (\gamma/\gamma_r)^{2B}}\right]^{A'} \text{ and } A' = A + I_r \tag{2}$$

Where: G is the dynamic shear stiffness, G_{max} is the small strain shear stiffness, λ is the damping, $H(\gamma)$ is function of the shear strain, γ is the shear strain, λ_{max} is the maximum soil damping (i.e., near dynamic failure), considered as 14% for México City clays, A and B are soils parameters obtained as proposed by Romo (1995), which define the geometry of the curve G-γ and are a function of the plasticity index of the soil, γ_r is a fix reference value of the shear strain corresponding to 50% of modulus degradation, I_r is the relative consistency, which can be expressed as $I_r = \dfrac{\omega_L - \omega_n}{PI}$, and ω_L, ω_n and PI are the liquid limit, water content and plasticity index of the soil respectively. The computed shear modulus and damping curves are presented in Figure 4.

Due to the practical difficulty associated with sampling the sand layers, the average bounds proposed by Seed and Idriss (1970) for normalized modulus degradation and damping curves, were used for the analysis. Similar curves proposed by Seed and Idriss, have been successfully used in 1-D wave propagation analysis to predict the measured response during the 1985 Michoacán earthquake (e.g. Mayoral et al., 2008)

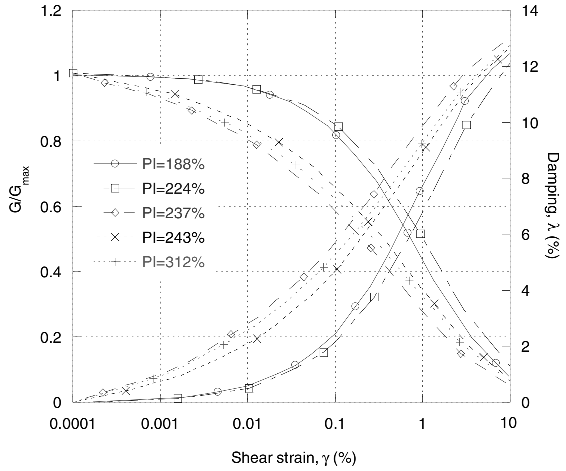

Figure 4. Shear modulus and damping curves used for Impulsora Bridge

5 SITE RESPONSE ANALYSIS

Using the computer program SHAKE (Schnabel et al., 1970), the estimated dynamic and soil stratigraphy, the site response analysis was conducted for the longitudinal and transverse directions. The acceleration measured at the 60 m depth point, was used as the input motion and the waves were propagated to the surface. The computed ground surface responses are shown in Figure 5 and 6 along with the measured response. As can be seen, the response computed is very approximate to the measured one, which validates the dynamic properties used for this analysis. The simulation captures the frequency content and the maximum spectral accelerations.

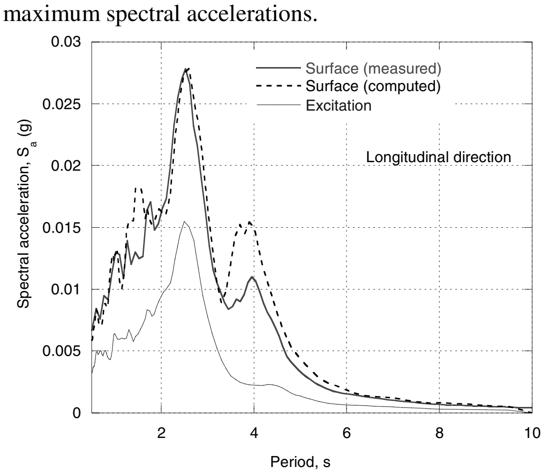

Figure 5. Response spectrum comparison for the longitudinal direction

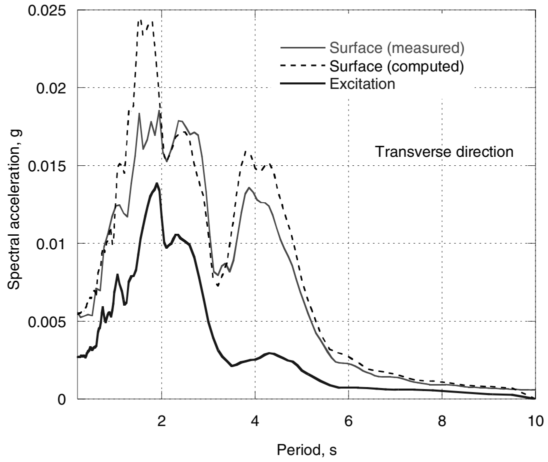

Figure 6. Response spectrum comparison for the transverse direction

6 SEISMIC- SOIL-STRUCTURE INTERACTION

The seismic-soil–structure interaction analysis was carried out with the computer program SASSI (Lysmer et al., 2000). The piles were modeled as beam elements and the box foundation with solid elements, the superstructure was idealized with a stick-lumped model, considering that the bridge superstructure behaves almost as a rigid body with the foundation. The equivalent lineal properties were computed using the program SHAKE.

Two models were developed for the analysis, one for the longitudinal direction and other for the transversal one. Figure 2a shows the axes chosen for modeling, where the accelerometers are located. Axes 11 and 12 were chosen for transversal direction and axis A for the longitudinal one.

Figure 7 presents the finite element model used for the longitudinal direction. A similar model was developed for the transverse direction.

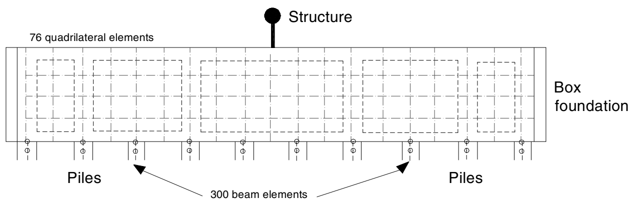

Figure 7. Box foundation nodes for transversal direction

Given the rigidity of the system, the acceleration time history of the central box node was considered representative of the whole foundation motion. Figure 8 shows a comparison between measured and predicted response in terms of response spectra for both, the longitudinal and transverse directions. As can be seen in both figures, the computed response captures the frequency content and the maximum spectral amplitudes. In Fig. 7a the computed spectrum reaches the maximum amplification that occurs at 2.6 s, which is the site predominant elastic period. In Fig. 7b it can be seen that the response at axes 11 and 12 is the same, which indicates that not important seismic torsional moment is acting on the support.

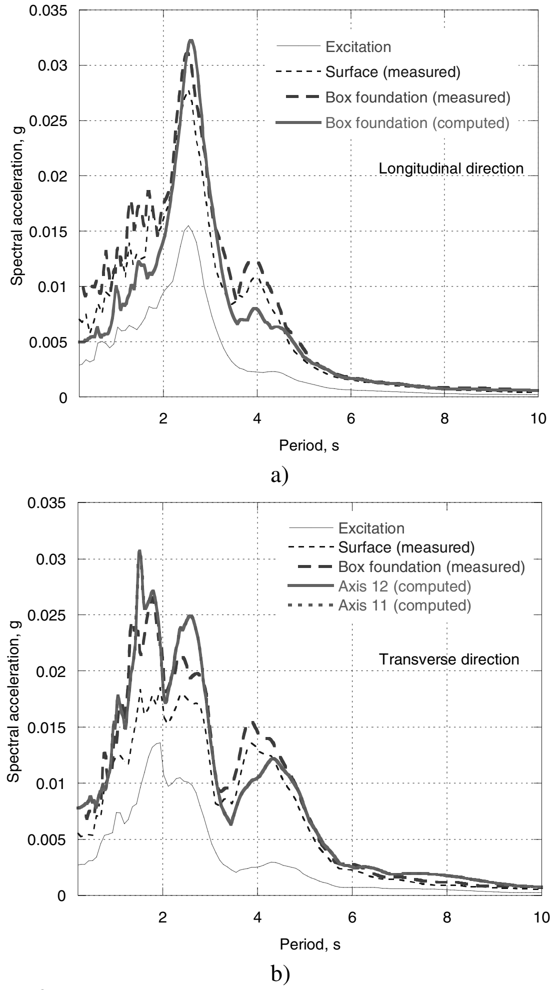

Figure 8. Response spectrums comparison for the a) longitudinal and b) transverse direction

7 LONG TERM PERFORMANCE OF THE FOUNDATION SYSTEM

Field evidence has demonstrated that soil consolidation due to regional settlements modifies not only the mechanical but also the dynamic properties (Ovando et al., 2006). This is particularly important for Mexico City clays that exhibit very large values of in-situ water content, which often varied from 200 up to 400%.

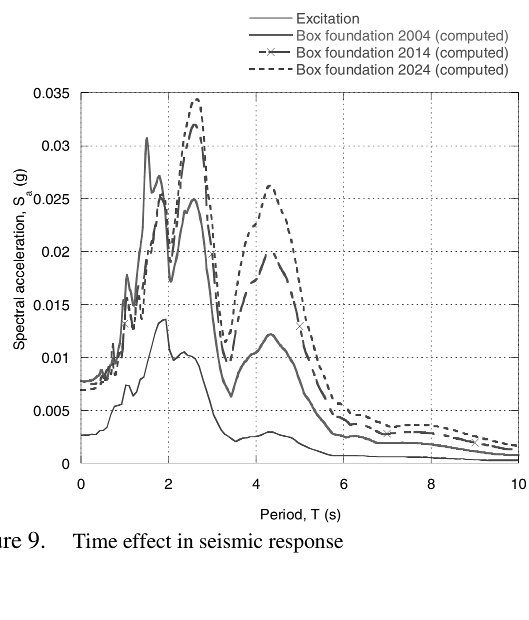

Figure 9. Time effect in seismic response

According to the results presented by Ovando et al. (2006) increments up to 10% and 15 % in the shear modulus can be reached over a period of 15 years. Thus, the dynamic properties presented in figure 5 were modified to estimate the soil-structure behavior in 10 and 20 years for the transverse direction and the seismic environment imposed by the January 1st, 2004, Guerrero Coast earthquake. The results obtained in terms of response spectra are depicted in Figure 9. As can be noticed, the maximum response has migrated to the right and higher spectral ordinates are reached for 2.5 and 4.5 seconds. The scenario after 20 years appears to be more critical than that one measured during the 2004 Guerrero earthquake. This should be taken into account during the design process.

8 CONCLUSIONS

This paper presents a seismic analysis of a central support, including the foundation system, of an urban bridge located in the very soft clay, prevailing in the Mexico City lake area, for the January 1st, 2004, Guerrero Coast Earthquake, 6.3 M_w, using the finite element technique. Numerical predictions obtained using finite element models compare fairly well with the measured response, specially in the frequency domain, for both horizontal ground motion components. Thus, numerical models as the one proposed in this paper can be used with confidence for designing this kind of deep foundation systems, allowing the simulation of important features such as changes in dynamic properties over time due to regional subsidence, which can significantly modify the response of the soil-structure system for long term analysis in lacustrine areas such as those found in Mexico City.

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