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Dynamic behavior of a foundation system based on piles with anomalies

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ABSTRACT: Cast *in situ* pile foundation systems have become one of the most commonly adopted solutions for the construction of increasingly high and robust structures such as buildings and viaducts in the western area of Mexico City. However, the presence of cold joints along the effective length of the piles, reductions or widening of the cross section of the piles, are anomalies that can occur during the construction process, which can modify the dynamic behavior before a large-scale seismic event. Therefore, this article reviews the behavior of a foundation system with a faulty pile using the finite difference method implemented in the program FLAC 3D V6.0.

1 INTRODUCTION

Urban expansion towards the Lomas area of Mexico City has prompted the development of high and robust structures that require foundation systems with deep elements to support and transfer loads adequately to a competent strata. For the construction of this type of projects in the western area of the city where firm and compact volcanic soils with high gravel content predominate, deep foundation systems with considerable cast *in situ* pile sections have become one of the most frequently employed solutions. However, to ensure satisfactory performance of these foundation systems and generate optimal service and structural conditions, strict quality control is essential during the execution of the elements cast *in situ*.

The pile integrity test (PIT, ASTM D-5882-07) is one of the nondestructive tests used for quality control of cast *in situ* piles. To perform the PIT, an impact is applied axially to the head of the pile, generating a wave that travels through the pile to the tip and then returns to the head of the pile (Gaviria et al. 2009). When an anomaly exists along the pile, changes in impedance occur, generating an early reflection of the wave, which is analyzed to predict the depth of the anomaly (Gaviria et al. 2009).

The most common anomalies that are generated during the construction process of foundation piles are cold joints and reduction or widening in the cross section, among others. These anomalies can modify the behavior of the soil-foundation-structure system, exposing undesired interaction effects under a large-scale seismic scenario.

Therefore, with the aim of contributing to the decision making and evaluating the effects upon the likelihood of this type of singularity occurring during the construction of an engineering project, this article reviews the dynamic behavior of a foundation system with a faulty pile using the finite difference method implemented in the program FLAC 3D V6.0.

2 PROBLEM STATEMENT

2.1 *Support description*

The foundation system of the support 4 of a viaduct located in the western area of Mexico City was modified in its geometry. The support originally consisted of a pile cap 11.0 m long, 8.0 m wide and 2.8 m high, supported by six cast *in situ* piles (1.5 m in diameter and 29.0 m in

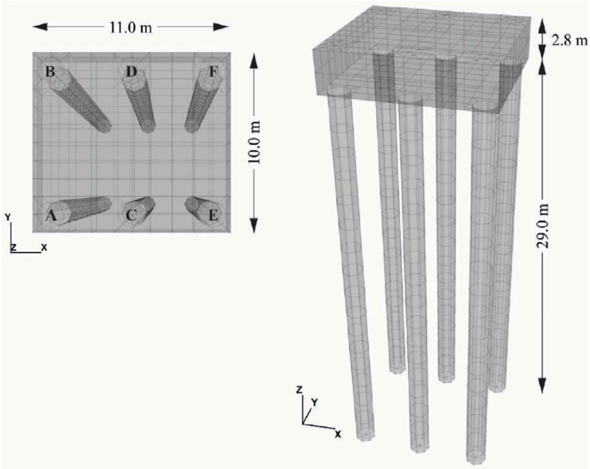

Figure 1. New foundation system for Support 4

Table 1. Geotechnical model for support 4

Stratum	Depth m	Description	γ kN/m³	Degradation curves
1	0.0 a 3.6	Clay filler	17.0	Vucetic & Dobry (1/91) IP=15
2	3.6 a 8.5	Fine sand with andesitic gravel	19.4	Seed & Idriss (1970)
3	8.5 a 14.0	Andesitic rock fractured in silt	23.5	Seed et al. (1986)
4	14.0 a 19.5	Andesite nodules in fine sand	23.2	Seed et al. (1986)
5	19.5 a 26.0	Andesite nodules in silty sand	23.2	Seed et al. (1986)
6	26.0 a 50.0	Gravel and andesite nodules	23.7	Seed et al. (1986)

effective length). However, three of these six foundation piles were poorly executed. For this reason, it was necessary to extend the base by adding 2 m in width and build three new piles to compensate the lost load capacity.

Once the new support foundation was completed, PITs were performed on the piles, and an anomaly identified as a cold joint was detected at a depth of 10 m in Pile D. An inspection of dynamic behavior of the structure was carried out using a three-dimensional numerical model with the program FLAC 3D V6.0, considering the new foundation system and disregarding the poorly constructed piles and without considering the presence of the anomaly in Pile D (Figure 1). Finally, the behavior of the foundation system was reviewed without considering the contribution of the pile with questionable integrity.

2.2 *Geotechnical model*

The geotechnical model was defined based on the information obtained from the exploration campaign conducted at the site where the studied support is located (Table 1).

3 SEISMIC ENVIRONMENT

3.1 *Characterization of the seismic environment*

The seismic environment of the site where the support to be reviewed is located was defined based on the design spectrum of the Lomas area (Zone I) according to the Mexican Building Code (RCDF 2004). With this spectrum and three seismic events registered by a seismological station located in the area of influence with Ms magnitude greater than 6.5, three histories of synthetic accelerations were generated in such a way that their response spectra were compatible with the design response spectrum defined for the study area.

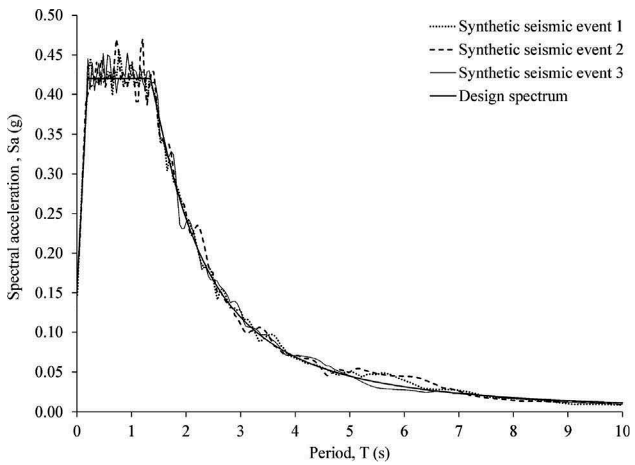

Figure 2. Response spectra in rock of the synthetic seismic events

Synthetic signals were obtained using the RSPMatch 99 program (Abrahamson 1992). This program implements the algorithm of Lilhanand & Tseng (1987, 1988) to modify a history of accelerations in the time domain and make it compatible with the specified reference spectrum. Figure 2 shows the response spectra obtained from the spectral adjustment of the records of synthetic seismic events.

3.2 *Site response analysis*

The SHAKE program was used to perform the one-dimensional site response analysis of the soil deposit where the support is based (Schnabel et al. 1972). To consider the nonlinearity of the soil, the stiffness degradation and damping curves that are showed in Table 1 were taken into account.

The dynamic characteristics of the geo-materials studied were obtained from the cross-hole tests performed in the deposit where the support 4 is located (Figure 3).

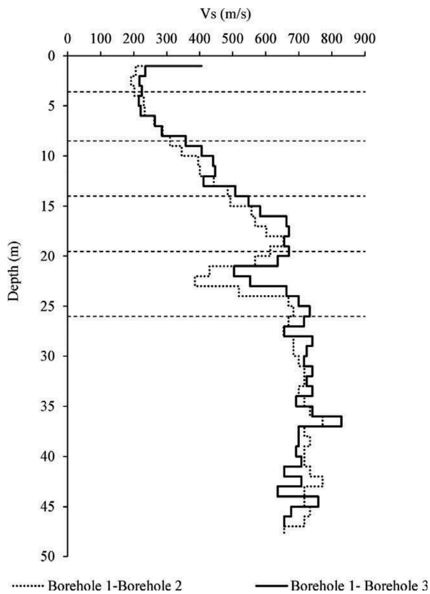

Figure 3. Stepped profiles of shear wave velocity

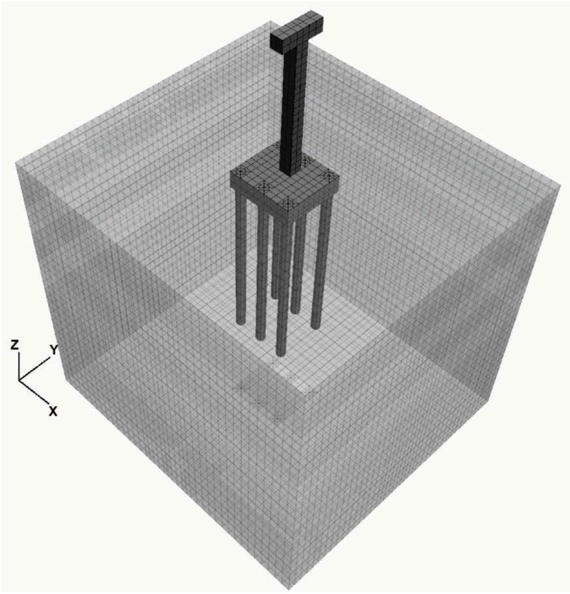

Figure 4. Finite difference mesh in FLAC 3D V.6.0 for dynamic analysis

Once it was verified that the response in the free field in the FLAC 3D model was consistent with the one obtained in the SHAKE program, a soil-structure interaction analysis was carried out, considering a combination of 0.30X+Y (30% of the seismic event intensity in X and 100% in Y) in each of the study cases.

4 RESULTS

To establish the magnitude of the soil-structure interaction and determine the influence of the support on the soil response, the response spectrum obtained on the surface of the ground (0.0 m), for the theoretical case, was compared to the one obtained on the free field (Figure 5). Figure 5 shows that no significant effects are expected as a result of the soil-structure interaction for the design conditions.

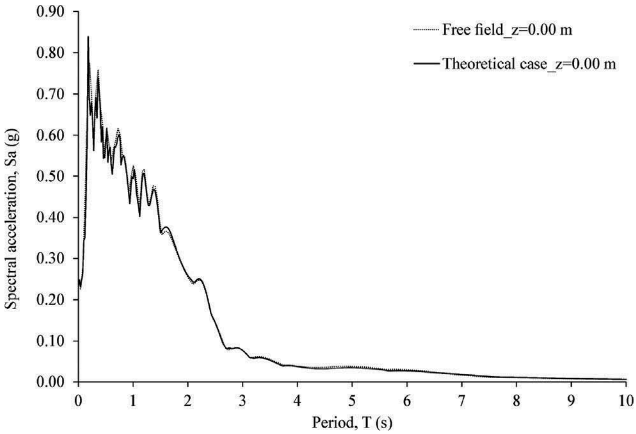

Figure 5. Comparison of the theoretical case and free field response spectra

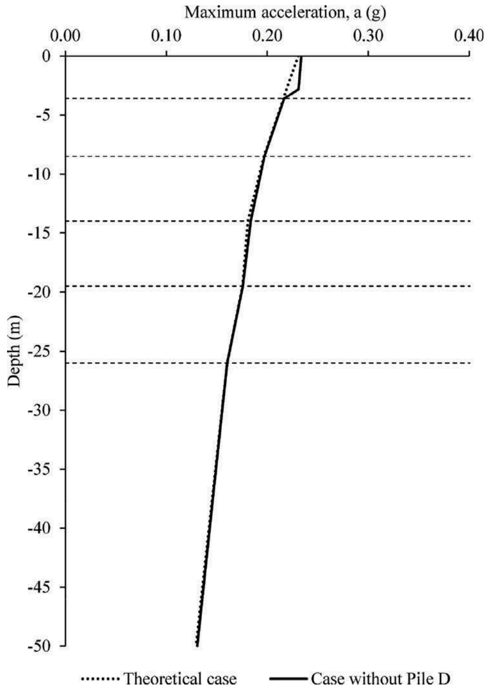

Figure 6. Comparison of maximum accelerations

Figures 6 and 7 show a comparison between maximum accelerations and the response spectra for each evaluation, respectively. In general, the theoretical case presents the same dynamic behavior of the one without considering the contribution of Pile D to the foundation system.

Figures 8–10 compare the vertical stress distributions generated in the piles of the support 4 at depths of 2.8 m, 3.6 m, 8.5 m, 14.0 m, 19.5 m, 26.0 m and 31.8 m due to the occurrence of the seismic event for the theoretical case and without considering the Pile D. These figures show, for the case analysis "without Pile D", an increase of stress

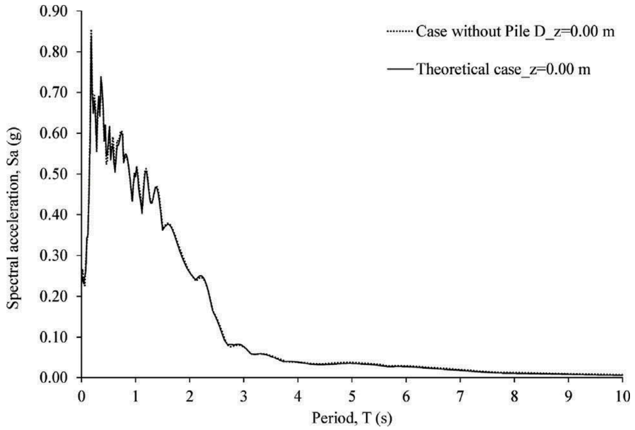

Figure 7. Comparison of the theoretical case response spectra without Pile D

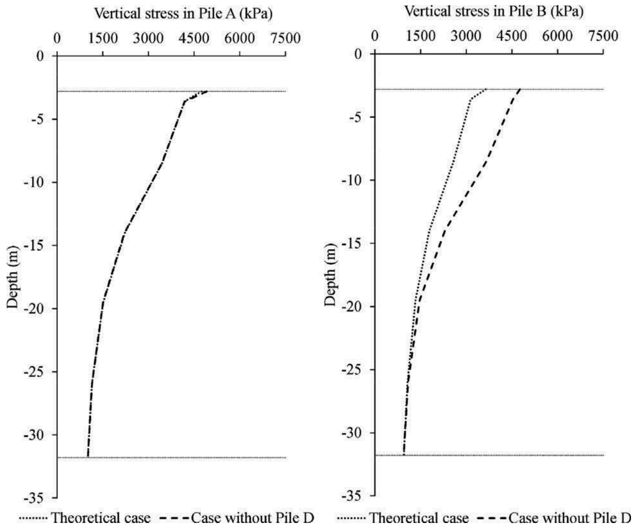

Figure 8. Vertical stress a) in Pile A, b) in Pile B

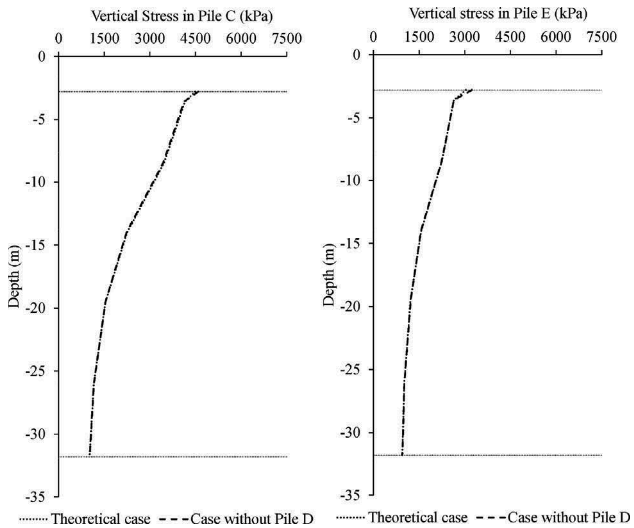

Figure 9. Vertical stress c) in Pile C, d) in Pile E

of 30% and 25% in piles B and F, respectively, relative to the theoretical stresses. In this sense, although no effects are observed in terms of soil-foundation-structure interaction, in the absence of Pile D, an evident redistribution of stresses in the remaining piles occurs.

Finally, to establish whether these increases in piles B and F exceeded the capacity of the structural elements of the foundation, the interaction diagrams presented in Figure 11 were obtained. In these figures is showed that the acting loads and momentums produced by the bidirectional effects of the combination of acting forces 0.30X+Y do not exceed the structural capacity of the piles.

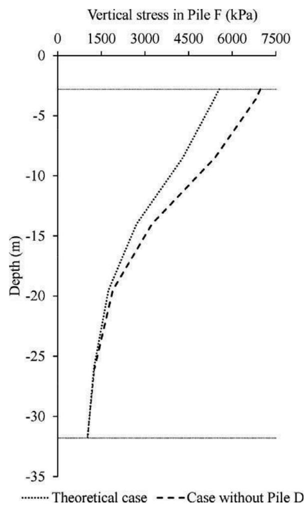

Figure 10. Vertical stress in Pile F

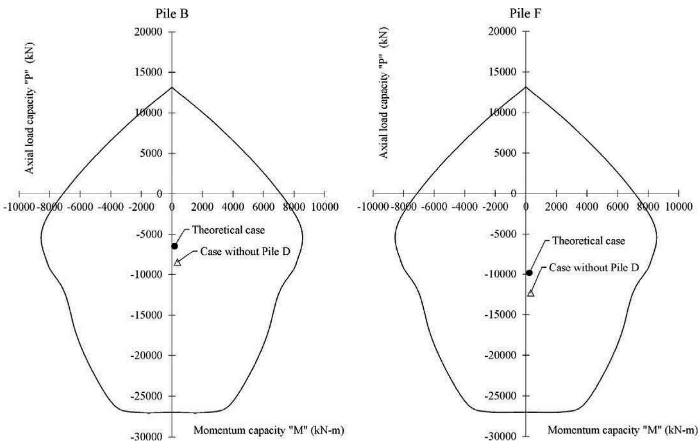

Figure 11. Diagram of interaction a) for Pile B, b) for Pile F

5 CONCLUSIONS

This article reviewed the dynamic behavior of a viaduct's support in the Lomas area of Mexico City, where integrity tests (PIT) were performed on cast *in situ* piles, detecting an anomaly at a depth of 10 m in one of the piles. In addition, this support was modified in its geometry during the execution of the foundation system, expanding its base by 2 m in width, to build three new piles to compensate the load capacity lost due to a poorly construction procedure in three of its six piles. The geotechnical model was constructed based on data from field and laboratory exploration. The seismic environment for the project was defined, determining a set of synthetic acceleration histories whose response spectra were adjusted to the design response spectrum of Zone I of Mexico City. To represent the accelerations adequately and the level of deformation induced by the seismic wave in the finite difference model, the response in the free field in this model was validated with the one obtained from the SHAKE analysis. When comparing the response spectra for the theoretical case with those obtained in the free field, it could be concluded that due to the properties of the soil deposit and the structural stiffness of the support, no significant soil-structure interaction effects were presented. When comparing the maximum accelerations and the response spectra considering the design characteristics and without considering the contribution to the foundation system of the pile with questionable integrity, it was observed that the presence of the cold joint did not affect the dynamic behavior of the structure under the seismic scenario. It is important to highlight that this work was carried out with the objective of reducing the uncertainty on the expected dynamic behavior in the presence of an anomaly in this foundation system;in addition, to contribute to the making decision upon the imminent probability of encountering this type of peculiarity during the construction of the viaduct. Although in this study case there were no significant changes in terms of the soil-foundation-structure interaction due to the presence of cold joints in the pile, an evident stress redistribution in the remaining piles occurs upon the absence of Pile D. Thus, our results cannot be generalized for other studies since these results depend on the conditions and properties of the soil deposit and the characteristics of the structural elements. Finally, it is recommended to review the structural dynamic behavior to ensure the integrity of the foundation system and the superstructure.

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