RECENT STUDIES ON SEISMIC SOIL-PILE-STRUCTURE-INTERACTION IN SOFT CLAY

Juan M. Mayoral\textsuperscript{1} and Miguel P. Romo\textsuperscript{2}

ABSTRACT

The evaluation of performance of deep foundation systems under seismic loading is one of the most complex problems in earthquake engineering, due to the varying degrees of nonlinear soil response observed during severe earthquakes. Strong shaking may lead to large excess pore pressures and strain-induced softening, increasing the amount of nonlinear behavior in the near, intermediate and free field domains. These effects overall become more significant for multi-directional shaking, which may reduce the soil stiffness and increase permanent deformations of the structure and/or soil even further. In particular, in the near field, lateral multi-directional movements of the pile can cause radial degradation of the soil stiffness, and can create radial gapping, which in turn, reduces the confinement of the pile, leading to an increase in bending moments on the structural members. Similarly, two-directional shaking may generate larger shear strains in the intermediate and free field. In practice, however, the seismic soil-pile-structure interaction problem is often oversimplified and the nonlinear effects are ignored. This paper revisits recent studies and developments directed to improve our understanding of these phenomena in soft clay, including analytical and experimental results. The predicting potential of non-conventional analysis techniques, including soft computing and nonlinear dynamics is discussed.

Keywords: Soil-pile-structure, seismic, multi-directional, interfaces, soft clay, soft computing, nonlinear dynamics

INTRODUCTION

With few exceptions, the analysis of seismic soil-pile-structure interaction problems is often oversimplified and the effects of two-directional shaking are ignored. Nevertheless, two-directional shaking may significantly increase the amount of non-linear behavior in the near, intermediate and free field domains. In addition, larger excess pore pressures and strain-induced softening may be generated due to two-directional loading, which can reduce the soil stiffness and increase permanent deformations of the structure and/or soil. Cyclic movements/displacements in one direction can soften the near field soil, and can significantly affect soil-pile interaction for subsequent movements in other directions. Usually, the response of the near field soil is represented with uni-directional p-y curves. However, two-directional lateral movements of the pile can cause radial degradation of the soil stiffness and create radial gapping, which is not captured by uni-directional p-y representations. The correct characterization of the radial stiffness degradation and gapping is crucial because this effect reduces the confinement of the pile, leading to an increase in the bending moment on the structural foundation member as well as a typically larger demand in the superstructure. The purpose of this paper is to review recent research efforts aimed at addressing these issues. In particular, in the near

\textsuperscript{1} Associated Professor, Institute of Engineering at UNAM, Mexico City, Mexico, jmayoralv@iingen.unam.mx

\textsuperscript{2} Professor, Institute of Engineering at UNAM, Mexico City, Mexico, mpr@pumas.iingen.unam.mx
field, this includes a two-directional pot testing device and an experimental methodology developed to characterize the multi-directional response of soil-pile interfaces, several series of cyclic multi-directional displacement control “pot” tests were performed, and a numerical model to described the observed behavior was proposed. The multi-directional “pot” testing device allows the study of soil-pile units to better characterize the multi-directional response of the near field during cyclic loading. The results obtained from these tests fill an important gap in experimental information regarding multi-directional p-y curves. In the far field a model proposed for multi-directional non-linear analysis of the free field soil response to seismic loading is commented. This model includes explicitly hysteretic behavior, plastic deformations, and pore pressure generation during cyclic loading.

NEAR FIELD RESPONSE

Recent observations during the Turkey (1999) and Taiwan (1999) earthquakes have showcased the multi-directional nature of strong shaking and the importance of directivity effects on ground motions. Following the research program that has been conducted at UC Berkeley for over a decade, to develop and calibrate numerical tools for assessing the seismic performance of structures supported on deep foundations in soft clay, Mayoral et al. (2002) designed, constructed and calibrated a new testing device to study the multi-directional response of clay-pile interfaces using the p-y spring concept. As a part of this research effort several multi-directional pot tests were conducted in a model soil. The model soil consisted of a mixture of 72% kaolinite, 24% bentonite, and 4% type C fly ash (by weight). This soil mixture was engineered to have similar mechanical properties to San Francisco Young Bay Mud with a scaling factor, $\lambda$, of 8 for 1-g shaking table experiments (Wartman, 1996). This soil was developed originally to be used in large-scale Seismic Soil-Pile-Superstructure Interaction (SSPSI) model tests, which were performed on the 6.1 m x 6.1 m U.C. Berkeley/PEER Center multi-directional shaking table to generate a suite of case histories to calibrate an advanced numerical code for SSPSI analysis (Meymand, 1998). Based on the experimental findings, a simple analytical discrete element model to simulate clay-pile interfaces subjected to bi-directional loading was developed and validated.

Multi-directional Pot Testing Sep Up

As described by Mayoral et al. (2005), the multi-directional pot testing device is an extension of the original pot test proposed by Matlock (1970). The main components are the instrumented model pile and a testing device capable of imposing a suite of prescribed soil/pile lateral relative displacements in two orthogonal directions.

Bi-directional pot testing device

Figs. 1a and 1b show schematically a cross section and a plan view of the new device illustrating some of the main components. The device is comprised of the following elements: loading unit, external and internal transducers, roller table, a loading frame and a data acquisition system. The loading unit has two pneumatic servo-valves and two orthogonally aligned loading pistons. The external transducers consist of two load cells and two DC-wire potentiometers. Wire potentiometers were preferred over LVDT’s because of the large displacements in each direction required during the test. The wire potentiometers are used both for data collection and for control of the closed-loop loading system. The wire pots are mounted on the loading frame with one of them connected to the roller table and the other one to the pile cap. The internal transducers are composed of orthogonal pairs of temperature compensated electrical resistance foil strain gauges placed at three elevations along the model pile. The equipment is completed with the model pile cap, model pile and soil container. A container with the model soil and the instrumented model pile is placed on the rolling table. The model pile can be loaded and/or displaced laterally independently in two orthogonal directions.

Model pile

The model-pile is a 51 mm diameter aluminum tube with 0.51 mm wall thickness and its mechanical properties are summarized in Table 1. The pipe pile has a rigid tip composed of a conical tip with a cylindrical termination that fits tightly into one end. The model pile was instrumented with orthogonal
pairs of temperature compensated electrical resistance foil strain gauges at three elevations 50, 126 and 202 mm.

Figure 1. Multi-directional Pot Testing Device (not to scale, After Mayoral et al., 2005)

Table 1. Summary of the Scale Pile Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Young Modulus, $E$, (kPa)</th>
<th>Diameter, $D$ (mm)</th>
<th>Wall Thickness, $t$ (mm)</th>
<th>Flexural Rigidity, $EI$ (N.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>140</td>
<td>51</td>
<td>0.3</td>
<td>2945</td>
</tr>
</tbody>
</table>
Multi-directional p-y Response

Multi-directional displacement controlled tests were conducted with the new device to model typical “free-field” ground displacement paths (also referred to as orbits) recorded in recent earthquakes, such as those depicted in Fig. 2. The x and y horizontal components of these paths are normalized by the Peak Ground Displacement, PGD, defined as the maximum displacement in one of the two components. These two examples cover a wide range of PGDs from approximately 3 to 90 cms for earthquakes with moment magnitudes ranging from 6.5 to 7.0. Although the orbits are very complex, the largest “loop” can be approximated by one (or a combination of several) simplified displacement paths, such as: a) linear, b) elliptical/circular, c) figure-8 and d) parabolic. In particular, a multi-directional p-y curve corresponding to a figure-8 pile displacement path is shown in Fig. 3. The typical flat portion in the central portion of the p-y curve is noticeable. The maximum normalized displacement amplitudes in the x and y directions for a given pile transit path are given by $A_x/D$ and $A_y/D$, respectively. $F_x$ and $F_y$ are the loading frequencies for a cyclic loading in the x and y directions, respectively. The lateral forces, $p_x$ and $p_y$, were normalized with respect the shear strength corrected for rate effects for the direction of maximum displacement, $s_u^*$, multiplied by the model pile diameter, D (i.e., $p/(s_u^*D)$). The displacements in the directions x and y are normalized by the pile diameter (i.e., $x/D$ and $y/D$). The resulting p-y response is dimensionless and it is only a function of the embedment ratio (L/D). The corresponding undrained shear strength and the residual shear strength were determined using a vane shear apparatus in three to four undisturbed portions of the model clay.

The data gathered from this experimental work fill the current lack of experimental data to formulate and calibrate p-y curves in multi-directional loading conditions. From this data, Mayoral et al. (2002 & 2005) concluded that the shapes of the p-y curves were strongly affected by the loading path and were a function of the evolution of the gap during the cyclic loading. This leads to a coupling between the passive and frictional components. This effect is more significant for circular and elliptical displacement transit paths. The number of cycles of loading required to achieve fully stabilized gapping behavior for multi-directional pot test was path dependent as well.

Modeling Soil-Pile Interfaces Subjected to Multi-directional Cyclic Loading

A discrete p-y spring element was introduced by Mayoral et al. (2006) to describe the nonlinear response of the near field for soft clays, including the progressive formation of gapping for multi-directional loading conditions. The nonlinear stiffness of the spring is controlled by a “plastic” and a “loading” surface that maps radially onto a boundary surface. The loading surface has two limiting stages, which define the first loading and loading conditions after the gap has been fully stabilized. In the first stage, the gap is not open and in the second stage, the gap is completely stabilized. The plastic...
surface keeps track of the displacement history of the pile. An interpolation function, which depends on the accumulation of plastic deformations, allows for a better representation of the gap evolution on the transition zone of the p-y curve, as can be seen in Fig. 4, which presents a comparison between model predictions and experimental data for a figure 8 pile transit path. Although radiation damping is not incorporated explicitly in the formulation, this nonlinear p-y spring can be used in series with a dashpot to model radiation damping (i.e., geometric damping) (e.g., Lok, 1999, Lok et al., 2000).

<table>
<thead>
<tr>
<th>Test Information</th>
<th>Soil Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test #</td>
<td>Path</td>
</tr>
<tr>
<td>f81312</td>
<td>Figure 8</td>
</tr>
</tbody>
</table>

Figure 3. Multi-Directional p-y Test: Figure 8 Displacement Path
In an attempt to model soil nonlinearities during multi-directional loading in the free field, Mayoral et al. (2006b), proposed a simplified plastic hysteretic model, which is based on an existing effective stress constitutive law developed to describe the cyclic behavior of lightly over consolidated clays in simple shear (Pestana et al., 2000), but modified to account for hysteretic behavior. The model was implemented in an 8-noded solid finite element to study the effects of two directional dynamic loading on the response of soil deposits, and validated throughout comparisons with other implementations and experimental results. Then, the predictions capabilities of the model are explored. Among the cases studied is included the analysis of a deposit of generic stiff soil that was previously studied by Rodriguez-Marek, (2000), using a total stress-based bounding surface plasticity model (Borja et al., 1999) for clays (c.f. Fig. 5).
Figure 5. Comparisons of the Predicted Response using a Total Stress Based Bounding Plasticity Model (BPM) and the Enhanced Hysteretic Model (EHM)
ALTERNATIVE METHODOLOGIES

Nonlinear effects in soft soils can also be studied through the application of non-conventional advanced mathematical tools, such as those based on soft computing and nonlinear dynamics. In particular, Romo (1999) showed that properly designed network architectures are capable of forecasting both earthquake ground movements and the seismic response of buildings in soft soils. He analyzed a seventeen story-concrete structure supported by a friction pile-box foundation. A scheme of the lateral façade is depicted in Fig. 6, where the strong motion instruments layout is indicated.

![Figure 6. Lateral façade of Plaza Córdoba building, Mexico City (After Romo, 1999)]](image)

The forecasting of unseen recorded acceleration time histories depicted in Fig. 7 is also highly accurate, although some peaks of the time series at floors 6 and 12 are slightly missed. In the prediction mode, the correlation was 0.989. The results point out toward the great potential of Artificial Neural Networks to increase the capabilities of computational tools to solve in practice the seismic-soil-structure interaction problem in soft clay. Similar techniques have been applied by Garcia et al. (2001) to study Mexico City ground motion response using neuronal networks (NNs). This research showed that knowledge-based procedures are capable of modeling accurately the seismic amplifications observed not only at predominantly clayed soils deposits existing in Mexico City (lake zone) but also at silty and sandy soils (transition zone). NNs were able to predict with a good degree of approximation ground surface responses to seismic events that come from different zones along the subduction source and intraslab source, as is the case of the Tehuacan seismic event (99/06/15). This result is particularly encouraging because it shows the flexibility and predicting capabilities of NNs. On the other hand, procedures based on empirical relative transfer functions failed to produce reliable results (Singh et al, 1999). Similarly, analytical tools do not seem to predict accurately ground responses for intermediate-depth seismic events. Other approaches, based on recurrence quantification analysis (RQA), have also shown potential for practical applications (Garcia et al. 2002). Proper interpretation of this powerful discriminatory tool in the NNs model of a dynamical system can yield definitive clues for the qualitative assessment of time series. With RQA one can graphically detect hidden patterns and structural changes in data or see similarities in patterns across the time series under study. In this sense, the addition of RQA parameters improves drastically the model forecasting capabilities.
CONCLUSIONS

Seismic performance evaluations of soil-pile-structure systems usually are oversimplified. Thus, multi-directional loading effects are seldom included in the dynamic response of the near field or the free field. These effects, however, may increase the amount of nonlinear behavior existing in the different parts of the system.

A new testing device to evaluate the multi-directional p-y response of soil-pile interfaces was developed. The results obtained for multi-directional pile transit paths show that the maximum normalized lateral forces and the initial tangent stiffnesses are independent of the loading path. However, the shape of the p-y curve is affected by the loading path, and is a function of the evolution of the gap and soil degradation during the cyclic loading. The number of cycles of loading required to achieve full stabilization of degradation (and gapping) for multi-directional pot tests was path-dependent as well. The data gathered showed that the multi-directional movement of the pile with respect to the near field has the following effects on the clay-pile interface response:

1. Loading induced anisotropy, which can significantly affect the behavior of the near field soil.
2. Generation of preferential deformation directions due to previous loading history that is controlled by the associated gap and softened soil zone.

The residual force after stabilization seems to be independent of the loading path. The reduction of the number of cycles needed to reach stabilization appears to be controlled by the accumulation of plastic deformations with progressive multi-directional loading.

A simplified discrete model formulated in the time domain was proposed to simulate the response observed during uni-directional and multi-directional loading of soil-pile segments. Overall, the formulation captures non-linear response associated with gapping and slippage of the pile during two-directional loading. The model was able to describe the evolution of the stiffness in the transition regime, accounting for the progressive formation of the gap around the pile.

Regarding the far field, a fully nonlinear constitutive model was implemented in an 8-noded solid finite element. The constitutive law is a derivative of a simple model to describe the response of clays in the simple shear mode of deformation which has been used to describe the response of lightly
overconsolidated clays in submarine environments (Pestana et al., 2000). Model capabilities to simulate the free field response to two-directional ground motion were evaluated in several case studies. Overall, bi-directional site response analysis using the enhanced hysteretic model predicted better the measured response than that obtained with an uncoupled uni-directional site response analysis. The plastic hysteretic model seems to provide a better representation of the cyclic soil response during transient and steady state conditions.

REFERENCES


