Response of a group of stiff piles to liquefaction induced lateral spreading: Numerical simulation of a shaking table experiment

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ABSTRACT

During recent years, extensive studies have been conducted around the world documenting liquefaction induced lateral spreading and its effects on deep foundations. This study is aimed to numerically model a shaking table experiment, to investigate the effect of lateral spreading on piles and also to assess the capability of an advanced critical state two-surface plasticity model in predicting soil and pile responses to lateral spreading. Changes in permeability of the soil layers during the shaking are also accounted for using the software's built-in programming language, FISH. Numerical results showed that the onset of liquefaction occurs after just a few cycles from the beginning of the shaking and the main share of ground lateral movement takes place during the first few seconds of dynamic excitement which is a common phenomenon in physical model testing of loose liquefiable layers. Response of stiff piles of a group to lateral spreading is investigated and different related aspects, including neighboring and shadow effects are discussed in detail. In general, comparison of the experimental data with the simulation results, showed decent accuracy of the numerical predictions of this study.

Keywords: Lateral Spreading; Numerical Model; Liquefaction; FLAC3D; Pile

1 INTRODUCTION

Liquefaction and the corresponding lateral ground movements can be devastating as it is reported in different earthquakes (McCulloch and Bonilla 1970, Youd and Hoose 1978, Ishihara and Koga 1981, Bardet and Kapuskar 1989 and Tokimatsu and Asaka 1995). During recent years rigorous experimental studies on liquefaction-induced lateral spreading and its effects on deep foundations have been conducted using the shaking table available at the Sharif University of Technology (Haeri et al. 2012, Kavand et al. 2012 , Haeri et al. 2013, Kavand et al. 2014, , Haeri et al. 2014,). Bouckovalas et al. (2016) studied effect of liquefaction on wave propagation in soil using the commercial code, FLAC (Itasca, 2000). They introduced thickness of liquefiable layer and period of input wave as two main controlling factors that determine whether the transferring wave would be damped or amplified on its way to ground surface. They also stated that a liquefied soil layer can effectively damp its input wave and act like a seismic isolation system if its thickness is larger than a specific ratio of input wave length (λl). Li and Motamed (2015) used the FEM based code, OPENSEES (Mazzoni et al. 2004), to study response of a pile group placed in liquefiable soil behind a free face. Using sensitivity analysis to assess the effect of maximum shear modulus and internal friction angle of soil on ground lateral displacement, Li and Motamed (2015) stated that increase in any of these two parameters would decrease ground lateral displacement. They also reported that changes in maximum shear modulus of soil has greater influence on ground displacements in vicinity of the quay wall and the effect of this parameter decreases with increase in distance from the quay wall. Ghasemi-Fare and Pak (2016) conducted a parametric study using PISA (formerly known as SAGE) software (Chan and Morgenstern, 1988) to study effects of different parameters , like ground slope, thickness of liquefiable layer, relative density of liquefiable layer, maximum input acceleration, frequency and number of dynamic loading cycles on ground displacements due to liquefaction-induced lateral spreading. They concluded that increase in input load frequency and relative density of soil would decrease ground displacements, whereas, increase in other aforementioned parameters would increase ground displacements.

In the present study, a shaking table experiment by Haeri et al. (2012) is simulated using the commercial code, FLAC3D (Itasca, 1997). This study is aimed to investigate the effect of lateral spreading on piles and also to assess the capability of the constitutive model proposed by Dafalias and Manzari (2004) in predicting soil and pile responses to lateral spreading. Permeability of the soil layers during the shaking is defined as a function of ru using the software's built-in programming language, FISH, based on the model proposed by Shahir et al. (2012). Comparison of the experimentally obtained data with the simulation results, showed decent accuracy of the numerical predictions which will be discussed in the following parts of the paper.

2 NUMERICAL MODEL

The setup of the experimental model which was studied by Haeri et al. (2012) is shown in Figure 1.

Model ground consists of a loose sand layer with relative density of 15% and thickness of 1 m (model scale) placed on a dense sand layer with relative density of 80% and maximum thickness of 0.25 m. Bottom non-liquefiable layer is used to provide a 4 degrees slope. Model piles are fixed at their bottoms using casings welded to the bottom of the container. Piles 1 and 2 were used to study shadow effect and piles 4, 5 and 6 were used to study neighboring effect while Pile 3 was used as a benchmark. Pile 7 with a half circle section was in contact with transparent Plexiglas of the rigid box. This pile was implemented to see the actual reaction of a pile to lateral spreading. In the present study, pile 7 was not modeled.

Numerical model was prepared in prototype size according to the similitude law proposed by Iai (1989) by applying a geometric scale factor of 8 to the dimensions of physical model shown in Figure 1. Stiff aluminum piles are used in the model, the properties of which are outlined in Table 1. Stiffness of normal and shear springs of the interface are determined using the following equation (Itasca 2017):

$$k_{s,n} = 10 \times \max\left[\frac{(K + \frac{4}{3}G)}{\Delta z_{\min}}\right] \qquad (1)$$

In the above equation, K and G are bulk and shear modulus of the soil, respectively, and Δz_min is minimum dimension of adjacent zone.

Number of structural elements used to build each pile in numerical modeling, is determined such that there is almost one structural node in each zone intersected with piles. Existence of more than one structural node in zones, doesn't increase accuracy of the numerical model whilst it increases required computational efforts. Piles are rigidly connected to Shell elements at their toes as shown in Figure 2. These Shell elements are rigidly connected to the bottom of the model.

Advanced critical state two-surface plasticity model proposed by Dafalias and Manzari (2004) was assigned to model ground. This constitutive model is a modified version of the model proposed by Manzari and Dafalias (1997) and is implemented into FLAC3D by Cheng et al. (2013). Model parameters are determined using the results of a series of triaxial experiments on Firoozkooh silica sand previously conducted by Farahmand et al. (2016) and are outlined in Table 2.

Permeability of the soil layers during the shaking is defined as a function of ru, using the software's built-in programming language, FISH, based on the model proposed by Shahir et al. (2012). Correlations proposed by Shahir et al. (2012) are as follows:

$$\frac{k_b}{k_i} = 1 + (\alpha - 1) \times ru^{\beta 1} \qquad r_u<1 \qquad (2)$$

$$\frac{k_l}{k_i} = \alpha \qquad r_u=1 \qquad (3)$$

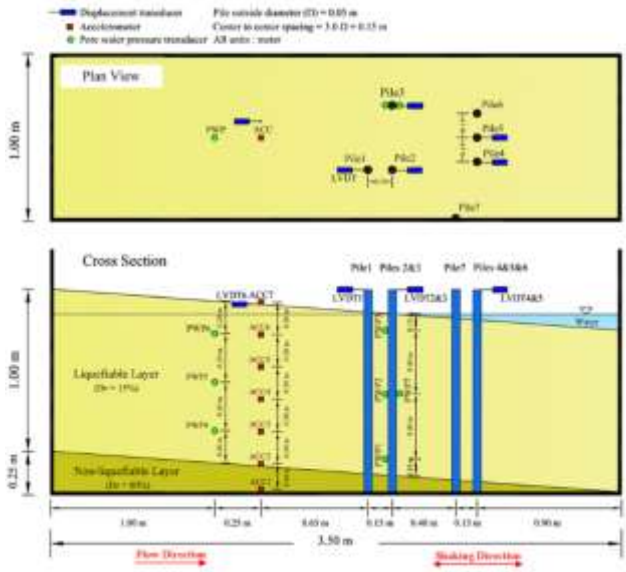

Fig. 1. Plan view and cross section of the physical model and the location of installed instruments, Haeri et al. (2012).

Table 1. Pile parameters in the numerical model (prototype scale)

Parameter	Value
Diameter (m)	0.4
Density (kg/m^3)	2700
Moment of inertia (m^4)	1.256×10^{-3}
Young Modulus (MPa)	122880
Interface spring stiffness (k_n, k_s)	Depends on adjacent zones (Eq. 1)
Interface cohesion (c_n,c_s)	0
Interface friction angle (φ_n, φ_s)	15

3 RESULTS

3.1 Acceleration time histories

Time histories of acceleration recorded on the base and surface of free field (Fig. 3), indicate decent conformity between experimental and numerical results. As can be seen in Figure 3, recorded accelerations on the base are in the form of a time history with frequency of 3 Hz and amplitude of 2m/s2 or 0.2g. On the ground surface, after first few cycles of shaking, amplitude of acceleration has considerably decreased, indicating damping of shear waves due to liquefaction.

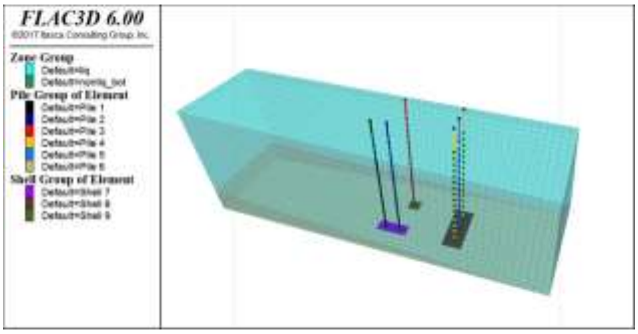

Fig. 2. Geometry of numerical model

Table 2. Dafalias and Manzari (2004) model parameters for firoozkooh silica sand

Elasticity	G_0 ν	85 0.1
Hardening	H_0 c_h n^b	2.6 0.8 1.4
Dilation	A_0 n^d	0.4 5
Critical State Line	M C e_{c0} λ_c ξ	1.4 0.714 0.925 0.0586 0.423
Yield Surface	m	0.01
Fabric Dilatancy	c_z Z_{max}	600 4

In above equations, α and β1 values are assumed to be 10 and 1 respectively.

3.2 Lateral displacements

Results from the displacement sensors of LVDT type along with the corresponding results of numerical modeling are compared and the time histories of each is outlined in Figure 4. Arrangement of the LVDT sensors in the model is shown in Figure 1. Time history of LVDT6 shows that major part of the ground displacement occur at early stages of shaking. It can also be seen that ground surface displacements of free field in numerical modeling is about 44% greater than that observed in the experiment by Haeri et al. (2012), however, the general trend of numerical diagram shows very good agreement with the experimental diagram.

Figure 4 also indicates that piles reached their maximum displacements toward the downslope at early stages of shaking and then bounced back as the soil lost its shear strength due to liquefaction.

It can be inferred from Figure 4 that piles started to bounce back before the ground surface (LVDT6) reaches to its maximum displacements. This caused ground heave and subsidence on the upslope and downslope of the piles, respectivel. Haeri et al. (2012) reported 5 cm of ground heave on the upslope of piles and 3 cm of ground subsidence on the downslope of piles. Results from numerical modeling showed 4 cm heave and about 2.5 cm subsidence on the upslope and downslope of the piles, respectively. The experiment showed about 8.4 cm subsidence in a distance of 70 cm from the upslope boundary of rigid soil container; this was observed to be about 9 cm in the numerical modeling. In Figure 4, It can be seen that the maximum displacement of pile 5 is smaller than that of pile 4 (Neighboring effect) and the maximum displacement of pile 2 is smaller than that of pile 1 (shadow effect); these can be seen in both numerical and experimental results.

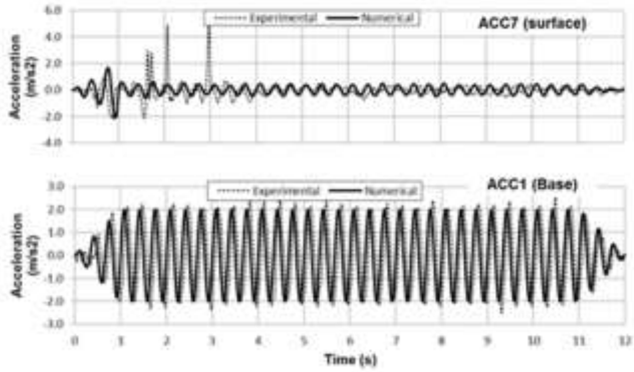

Fig. 3. Acceleration time histories of free field recorded on surface and base of the model.

4 CONCLUSION

In the present study, a shaking table experiment by Haeri et al. (2012) is simulated using the commercial code, FLAC3D (Itasca, 1997). This study is aimed to investigate the effect of lateral spreading on piles and also to assess the capability of constitutive model proposed by Dafalias and Manzari (2004) in predicting soil and pile responses to lateral spreading. Changes in permeability of the soil layers during the shaking until onset of liquefaction are also accounted for using the software's built-in programming language, FISH, based on the model proposed by Shahir et al. (2012). The following results can be concluded:

1. Accurate numerical modeling of dynamic response of saturated soils require the use of an advanced constitutive model and correct assumptions. The model proposed by Dafalias and Manzari (2004), which was implemented into FLAC3D by Cheng et al. (2013) is found to be a good choice for solving this kind of problem.

2. In loose saturated sand, major share of ground displacement occurs during early stages of shaking in physical modeling.

3. At early stages of shaking, piles started to bend toward downslope and after reaching to a maximum displacement, they bounced back as the shaking continued and the soil lost its shear strength due to liquefaction.

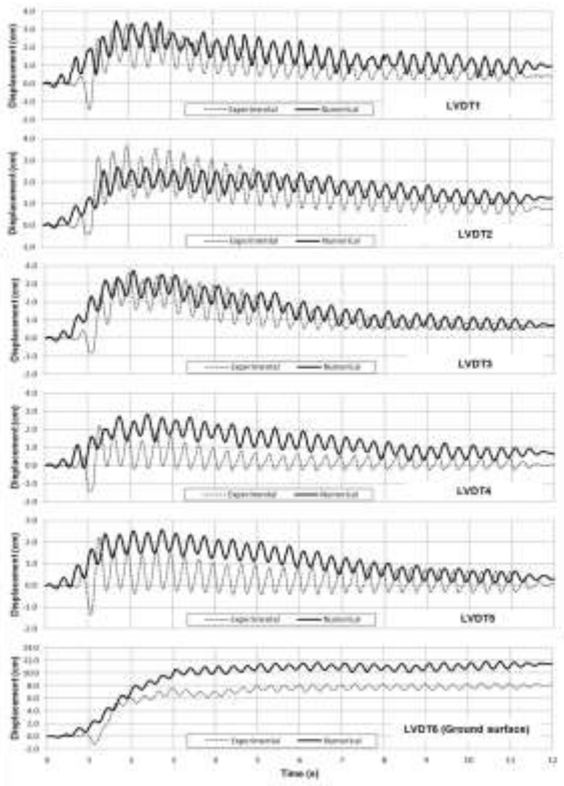

Fig. 4. Lateral displacements recorded at installation place of LVDTs in numerical and experimental models.

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