Sensitivity of pile seismic response analysis of gentle and steep liquefaction slopes

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ABSTRACT

The confidence of nonlinear FE analysis depends on the calibration and evaluation of the numerical method against physical data from either case histories or physical model tests. To explain the calibration of FE (Finite Element) models, the author used data report from the State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China, using MTS shaking table facility, China. The primary goal of this research is to get the right calibration for the experiment by determining the soil properties and liquefaction parameters. Numerically calibrated settings can be used to build an FE model by utilizing the OpenSeesPL computational platform to investigate the consequences for lateral spreading on pile foundations: ground surface slope (S), shaking direction and thickness of the liquefied layer. Other scientists have investigated elements and case studies involving lateral spreads which give direction as to as far down as possible these parameters might achieve. This paper will deal with the results of a progression of numerical case investigations to scrutinize the connection of interaction between adaptable piles and soil. Particular reference was made to the difference in the interaction affectability that is observed quickly to the pile at the different sides of the slope. The overall impact of degree of inclination (slope gradient) on the pile response was similar for all cases. In most cases, soil displacement increased with increasing degree of inclination.

Keywords: Gentle slope, seismic response, upslope, FE model, surface slope, liquefiable soil layer.

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INTRODUCTION

Vast regions of saturated sandy soils suffer from the loss of the strength of soil molecules and atoms as a consequence of shaking (Maula, 2016). The behavior can be noticed as laterally moving due to liquefaction, during the tremor. This liquefaction-induced lateral ground deformation and displacement reach more than 10 cm especially in flow slides cases and for gently sloping ground $\geq 9\%$, as knowing liquefaction-induced ground deformation are usually observed in gently sloping area due to losing of “shear strength of underlying saturated soils” (Cetin et al., 2006).

In this paper, an experiment on the behavior of the RC single pile in the medium-dense sand stratum with a clay crust is carried out as briefly described in previous research papers. Then, the FE results are provided and mentioned. Finally, a parametric examination is carried out to highlight the outcomes of some key parameters on the reaction of the pile within the steep sloping ground.

The effects of several factors influencing the magnitude of liquefaction-induced lateral spreading represented by the lateral displacement of sloping ground, which occur in soil slopes embankment that is saturated during an earthquake with or without low permeability sub-layer, are investigated through OpenSeesPL software. The observed behavior of typical sloping grounds to shock are controlled by mechanical and flow parameters, specifically lateral displacement, a variation of pore - pressures and bending moments close to the pile induced in them.

The primary challenge of this study is to research numerically the role of differences of sloping ground (degree of inclination) in such lateral spreading situations. Through significant calibration, finite element analysis models were developed wherein the response
moderately matched experimental data from shake-table testing.

SIMULATION OF THE SOIL-PILE SYSTEM

Review on dimensions of prototype and test protocol

Using test reported by Liang (2010), Maula (2013) and Liang et al. (2014), "shaking table experiments were conducted at the State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China, using MTS shaking table facility" (Maula et al., 2011).

The research employed a rigid soil container dimensioned into 3.8 m long, 2.0 m wide and 1.6 m high. The model foundation consists of 1.2 m thickness as SS with a 0.3 m depth as C. Water table level (GTL) was positioned at 0.3 m. The experimental was well instrumented to capture acceleration, pressure, strain, and displacements during the test program (Figure 1).

Through the properties list in Table 1, the liquefaction parameters can be calculated according to collect experimental data. The thickness of each layer of soil and the dimension of the pile is presented in Table 1.

The test application program subjected to a series of El Centro and sinusoidal earthquake events as representative ground motion input, listed in Table 2. The purpose of the usage of exclusive two different motion events was to ensure the correct and right calibration parameters. If that challenge was solved, it would be easier to utilize them in the investigation with the sloping ground.

Calibration platform software

The Open System for Engineering Simulation (OpenSees) is a product system for reproducing the seismic reaction of geotechnical frameworks (Maula et al., 2011).

OpenSees is a rising fabulous examination software in concentrating on soil-structure interaction, and has been decided for this study. "The upper and lower saturated clay layer have 20 nodes hexahedral element simulation; the central saturated sand can be considered by the pore pressure dissipation and redistribution associated with a three-dimensional pore pressure of soil - water fully coupled 20-8 node hexahedral element simulation. Saturated sand was treated as liquid-solid two-phase medium; using Biot equations of soil particles and water interaction. Based on the Biot theory of porous media and through the ground-water fully coupled physical processes of the unit. To ensure numerical stability, ensure the ground is almost no drainage, the water under the conditions of incompressible. Therefore, 20-8-node hexahedral element has essentially 20 parameters such as node hexahedral elements, 20 nodes that are solid, 8 nodes are liquid; specifically for the 8 corner nodes, each node has four freedoms degrees, one degree of freedom is the pore pressure degrees of freedom (p), another three said that the displacement of soil particles of the three degrees of freedom (u), only the soil particles on the other nodes of the three displacement degrees of freedom (Figures 2 and 3)." 3 × 3 Gauss-Legendre numerical integration method was used for solving solid phase correlation matrix, 2 × 2 Gauss-Legendre numerical integration method was used for solving water-related matrix (Elgamal et al., 2006). Reinforced concrete pile length is 2.52 m, 0.82 m long above the surface, diameter 0.1 m, density 2350 kg/m³, elastic modulus 8.24 × 10^3 MPa, and flexural rigidity 40.5 kN·m²” (Maula, 2011).

Soil and pile sensitivity response

The shaking table test was calibrated using the measured Acc.(g) and rₚ of the sand deposits, as well as the time pile histories in cases A and B shown in Figures 4, 5 and 6. As a rule, decent understanding is accomplished between the gain results in cases A and B.

OPENSEESPL NUMERICAL MODEL

The study was performed by using the 3D numerical model by OpenSeesPL, as shown in Figure 7. The soil and liquefaction parameters utilized are the same with the ones in the experimental calibration as mentioned earlier. The model consists of an inclined layer of loosely deposited sand of 1.9 m thick layer of loose liquefiable soil. Formation of liquefaction could happen if the right condition for it is provided. Therefore, the water table was at 0.3 m below underground level. The models were poured with reinforced concrete pile of 2.5 m length and 0.2 m diameter. The superstructure of a mass of 120 kg was set on the top of the pile head to imitate the effect of the bridge structure.

For the sake of comparison, two soil models with different ground sloping S will be investigated in this study, the response of these models to the earthquake are given in Table 3.

SIMULATION RESULTS

Influence of ground slope (S)

Level grounds are never zero degree (0°) of inclination accuracy. In fact, it is a gentle slope located in the area that seems flat. Therefore, it is hardly noticeable to the naked eye. An accurate survey of the land is necessary to determine the so-called “flat slopes.” Depending on the
Figure 1. Schematic diagram of whole test system and sensor arrangement (unit: mm) (source: Liang, 2010; Maula, 2013; Liang et al., 2014).

Table 1. Soil properties for shaking table test (level ground).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Medium-dense sand (S)</th>
<th>Clay (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>1900</td>
<td>1800</td>
</tr>
<tr>
<td>Reference shear modulus (kPa, $P_s = 80$ kPa)</td>
<td>$7.5 \times 10^4$</td>
<td>$6.0 \times 10^4$</td>
</tr>
<tr>
<td>Reference bulk modulus (kPa, $P_s = 80$kPa)</td>
<td>$2.0 \times 10^5$</td>
<td>$3.0 \times 10^5$</td>
</tr>
<tr>
<td>Friction angle (degrees)</td>
<td>35</td>
<td>12 (cohesion = 35)</td>
</tr>
<tr>
<td>Peak shear strain ($P_s$, 80 kPa)</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Reference mean effective pressure (kPa)</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Pressure dependence coefficient $n_p$</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Phase transformation angle (degrees)</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>Contraction parameter $c_1$</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Dilation parameter $d_1$</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Perfectly plastic strain parameter $y_1$</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Perfectly plastic strain parameter $y_2$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Permeability coefficient (m/s)</td>
<td>$9.0 \times 10^{-6}$</td>
<td>$1.0 \times 10^{-9}$</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.4</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Table 2. Testing shaking motion events.

<table>
<thead>
<tr>
<th>Event</th>
<th>Quake shaking</th>
<th>Base input, $A_{max}$ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event A</td>
<td>Sinusoidal shaking</td>
<td>0.10</td>
</tr>
<tr>
<td>Event B</td>
<td>El Centro shaking</td>
<td>0.10</td>
</tr>
</tbody>
</table>
importance of lateral spreading, engineering designer needs to determine not only the height of a gradient but the degree of the slope inclination as well.

The slope can be determined from the map or geological survey according to the slope angle. Seven types of slopes that concern the designer are as listed in Table 4.

To study the effects of ground slope, soil-pile model profile, shown in Figure 7a, was analyzed at slopes of 1 to 6% which represent gentle slopes, and at slopes of 7 to 15% as steep slopes. The results of these analyzes are shown in Figure 8, which indicate maximum lateral
Figure 5. Acc. time records of liquefied soil. a) Case A; b) Case B.

Figure 6. Time records of pile in case A and B. a) Case A; b) Case B.

Analyzes revealed that lateral pile displacements strongly depend on a ground surface slope. As expected, the level ground condition produced a little lateral movement. However, when $S$ is less than 6%, there is induced significant permanent change of about 0.17 mm. In contrast, deformation of steep slopes $S \geq 6\%$ shows minimal movement about 0.14 to 0.043 mm. This behavior disagreed with the results obtained by Maula (2013); these differences were due to model inclination options along longitudinal direction (ground surface tilt or whole inclined model).

**Influence of base motion direction**

FEM will be analyzed under two different ground slopes ($3\,\text{ and } 9^\circ$) to compare the behavior differences between...
gentle and steeply sloping ground, and the results from the free-field slope and near-pile soil behavior will be explained.

As can be seen from figures 9, 10 and 11, which show the generation of excess pore pressures measured 1.9 and 0.85 m depth in the near-field, full liquefaction gives 10 kPa of pore pressures during the earthquake for event A and about 12 kPa for event B for the two ground slope models. Due to the softness of the soil due to the quake, initial liquefaction occurs in approximately two cycles for the two slopes under event A; while in event B, liquefaction occurs in approximately one cycle due to influences of the earthquake in two directions. The soil behavior near the pile was explained using up and down slope action by taking results around ±5 mm from the surface collection body both up the slope and down the slope of the pile; results from these for the two ground slope models are given in Figures 9 to 11, showing lateral displacement recorded at the surface and 0.85 m depth.

As can be seen from the Figures, the lateral displacement measured at depth 0 and 0.85 m depth; for the event B, it can also be seen in the downslope side. A noticeable lateral movement observed neither upslope side for the two different slopes.

Upslope of the pile, "horizontal stresses are increased with soil flow, resulting in a drop in deviatoric stress, whereas down slope of the pile, horizontal stresses are relaxed, leading to an increase in deviatoric stress. Thus, more dilative behavior is seen downslope of the pile than

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**Figure 7.** Finite element model of pile-soil interaction.

**Table 3.** Mechanical and flow condition after (Karbasi et al., 2009).

<table>
<thead>
<tr>
<th>Mechanical</th>
<th>Flow</th>
<th>Event motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground slope (S)</td>
<td>Thickness of liquefiable layer</td>
<td>El Center 1940</td>
</tr>
<tr>
<td>Depth of barrier</td>
<td>Barrier layer thickness</td>
<td>El Center 1940</td>
</tr>
<tr>
<td>Relative density D&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Permeability of the liquefiable soil layer</td>
<td>El Centro 1940 (x-direction)</td>
</tr>
<tr>
<td>Motion characteristics</td>
<td>Shaking duration time and its direction</td>
<td>El Centro 1940 (x-y direction)</td>
</tr>
</tbody>
</table>

**Table 4.** Slope angle classification (http://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/cmp/slope.html).

<table>
<thead>
<tr>
<th>Code</th>
<th>Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Little or none</td>
<td>Little or no slope: 0 - 3% gradient</td>
</tr>
<tr>
<td>B</td>
<td>Gentle</td>
<td>Gentle slopes: 4 - 9% gradient</td>
</tr>
<tr>
<td>C</td>
<td>Moderate</td>
<td>Moderate slopes: 10 – 15% gradient</td>
</tr>
<tr>
<td>D</td>
<td>Steep</td>
<td>Steep slopes: 16 – 30% gradient</td>
</tr>
<tr>
<td>E</td>
<td>Extremely steep</td>
<td>Extremely steep slopes: 31 – 60% gradient</td>
</tr>
<tr>
<td>F</td>
<td>Excessively steep</td>
<td>Excessively steep slopes: &gt;60% gradient</td>
</tr>
<tr>
<td>n/a</td>
<td></td>
<td>Not applicable (water).</td>
</tr>
</tbody>
</table>
Figure 8. Ground surface slope (S) effect on lateral pile movement under El Centro 1940 motion.

Figure 9. Near-field excess pore pressure time-histories measured for one liquefied layer model with ground slope $S = 3$ and $9^\circ$.
Figure 10. Displacement time-histories measured for sand layer near pile, $S = 3^\circ$, event B.

Figure 11. Displacement time-histories measured for sand layer near pile, $S = 9^\circ$, event B.
upslope" (Haigh and Madabhushi, 2010). The influence of surface slope results that observed from this study agreed with Youd and Kiehl (1996) only on one part in this paper. The researchers explain that the direction of lateral spreading movement is determined by the surface slope (Rauch, 2007), and the most importantly, greater lateral displacements are intuitively expected in lateral spreads with steeper surface slopes, which can imparts greater static shear forces”. The conclusion from above concern with displacement relation with surface slope in this study agree event B only; it can observe from figures that movement increased when surface slope increase in event B.

Influence of liquefied thickness

The same finite element model is shown in Figure 7a analyzed with the same parameters, that is, ground surface slope of 3 and 9%, and base motion illustrated in Table 2. The benchmark study indicated an apparent dependency of pile lateral spread displacement on the liquefied layer thickness without varying groundwater table depth. The results of these analyzes are presented in Figure 12; the results of liquefied thickness influence can be explain with the following main points:

1. A steeper surface slope shows a greater displacement.
2. As the thickness of the liquefied soil deposit increase, higher pore water pressure might occur upward which caused a weak area below the non-liquefied deposit and its extending depends on liquefied thickness and presence.
3. Thicker liquefied deposit takes a longer period to be liquefied, as a result increasing the drainage path for excess pore water pressures and causing greater surface displacements.
4. Malty base motion direction can produce lateral movement twice that gained for one direction plate motion.

Influence of barrier layer

The effect of barrier (low permeability sub-layer) on seismic behavior of liquefiable infinite slopes was investigated. The parameter studied contains three parts: the first explores the influences of barrier presence on lateral spreading and sensitivity of pile response analysis, the second studied influence of variation of its thickness, while the third examined the effect of change barrier depth.

The study is performed by analyzing the numerical model using OpenSeesPL as shown in Figure 7b. The model consists of a horizontal low permeability sub-layer of 0.3 m thickness, overlaid by an inclined saturated liquefiable sand layer of 0.4 m thickness and underlain by a horizontal saturated liquefiable sand layer of 1.2 m thickness. The models were poured with reinforced concrete pile of 2.5 m length with a 0.2 m diameter. Superstructure in the tests was represented by an individual mass of 120 kg on the top of the pile head to characterize the inertial effect of the bridge structure. Soil physical parameters for the foundation are shown in Table 5. The model was subjected to El Center 1940 base motion. The analyses were conducted at 3 and 9% ground surface slope. The trend of pile lateral displacement increases with ground slope similarly to that seen in the profile without a barrier for S≥6%; however, a greater effect of inclination is observed for S≥6%. This corresponds to results shown in Figures 13 and 14, indicating that the rate of lateral pile displacement is higher on steeper slopes, and it increases linearly.

The analysis is conducted with the same finite element model of pile-soil interaction for gentle slopes of S = 3 and steep slopes of S = 9, with liquefiable soil with a thickness of DL = 1.9 m, subjected to El Centro 1940 base motion.

Influence of low permeability sub-layer depth (barrier)

As mention earlier, displacement at ground surface is equal to pile displacement. Time histories of surface lateral movements for various barrier depths are shown in Figures 15 and 16. The rate of displacement increases with boundary presence, especially for deeper barriers.

SUMMARY AND CONCLUSIONS

This study displayed the consequences of a parametric study on the impacts of contrast permeability ratio on seismic behavior of a typical liquefiable infinite slope with pile foundation. Reliable with the outcomes, the results of this work bring about the following conclusions:

1. There is a significant difference between results on grounds from severe earthquake impact; vertical pile inserted in sloping ground shows a lesser deformation with increasing inclination.
2. Vertical pile embedded in sloping ground (gentle or steep) presented less deformation compared with inclined pile inserted in sloping ground; therefore, further research is recommended to examine this phenomenon and develop the gained results as an improvement technique to reduce massive destruction of the building due to earthquake.
3. It is necessary to investigate the difference between the model inclination angle and ground surface inclination by making comparison with the software, which speculates for cases like Cyclic 1D.
Figure 12. Maximum lateral pile displacement vs. variation of liquefiable layer thicknesses under different base motion events. a) Event A; b) Event B.

Table 5. Physical properties of soil layer.

<table>
<thead>
<tr>
<th>Layer</th>
<th>$\gamma$ (kN/m$^3$)</th>
<th>$w$ (%)</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>$S_c$ (kN/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrier layer</td>
<td>17.0</td>
<td>27.3</td>
<td>1.73</td>
<td></td>
</tr>
<tr>
<td>Liquefy layer</td>
<td>56</td>
<td>35</td>
<td>9.3</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Figure 13. Increase of lateral pile displacement with ground surface slope ($S$) under El Centro 1940 motion (profile with barrier layer).
4. It is recommended to examine behaviors of soil-pile interaction by using Pisa software.
5. There is an inverse relationship between EPWP and embedded depth of soil profile; from the outcomes it is simply perceived that EPWP disseminates at deeper depth while it demonstrates higher values at shallower depth due to the less path of flow.
6. The relation between lateral displacement and permeability is positive.
7. The partially saturated layer can be considered for soil improvement against shaking, therefore, lowering water table is necessary.
Figure 16. Surface lateral displacement time histories vs. variation barrier depth.
REFERENCES


Karbasi S. (2009). Effects of void redistribution on liquefaction-induced ground deformations in earthquakes. A Thesis submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in the Faculty of Graduate Studies (Civil Engineering) at the University of Columbia.


