SHADOWING AND GROUP EFFECTS FOR PILES DURING EARTHQUAKE-INDUCED LATERAL SPREADING

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ABSTRACT :

A series of one-g shake-table experiments using a large rigid wall soil container was conducted to investigate countermeasures for piles in liquefying ground stratum. Special attention was given to lateral load on piles and pile group and shadowing effects under lateral spreading conditions. It was found that lateral spreading load on individual piles was a function of pile location in the pile group. Lateral load on an individual pile in the same row was only about 50% of that on a single pile due to the group effect. The shadowing effect reduced lateral load on the trailing pile by about 60%. These group and shadowing effects can be employed to design countermeasures for piles against liquefaction-induced lateral spreading. Additional protective piles may be installed in front of or at the sides of main pile foundations to reduce liquefaction-induced lateral loads.

KEYWORDS: Earthquake, Liquefaction, Lateral spreading, Pile foundation, Soil-structure interaction, Countermeasure, Shake-table

1. INTRODUCTION

Behavior of pile foundations under earthquake-induced lateral spreading conditions is currently the subject of major research in geotechnical earthquake engineering. Experimental investigations are being conducted employing centrifuge model tests, one-g shake-table simulations, and full-scale blast-induced lateral spreading tests.

On one hand, many of the experimental studies conducted have focused on pile foundations for the two important scenarios of a liquefying layer with or without an upper non-liquefiable stratum (e.g., Abdoun et al. 2003; Brandenberg et al. 2005, 2007; Ashford et al. 2006). Indeed, much observed pile damage has been attributed to these two important scenarios (e.g., Hamada and O’Rourke 1992; Tokimatsu and Aska 1998; Berrill et al. 2001). Analytical expressions and design procedures for estimating lateral spreading load have been developed on this basis (e.g., JRA 2002; Dobry et al. 2003; Cubrinovski and Ishihara 2004; Liyanapathirana and Poulos 2005a, b; Rollins et al. 2005; He et al. 2006, 2008).

On the other hand, there are relatively few studies on countermeasures for piles against lateral spreading (Imamura et al. 2004, Towhata et al. 2006). This paper presents a series of shake-table experiments to investigate mechanisms for reduction in pile lateral load during liquefaction-induced lateral spreading. Special attention in this investigation is given to shadowing and pile group effects under lateral spreading conditions and potential countermeasures for piles in a liquefying layer without an upper non-liquefiable stratum.

2. SHAKE-TABLE EXPERIMENTS

Three experiments were conducted on liquefiable sloping ground models (Model 180–1, 2, and 3) that included a single pile and multiple piles. In these experiments, strong shaking was imparted by a shake-table at the University of California, San Diego (U.S.) in collaboration with Waseda University, Japan (Meneses et al. 2002a, b). He (2005) presented detailed information and performed a comprehensive analysis of the experiments. Essential aspects of the experiments are briefly described below.

2.1 Experiment Model

Figure 1 shows the model configurations. In each model, the soil consisted of a single layer of saturated sand with a thickness of 1.8 m and a slope of about 6% (i.e., 3.4°). Silica sand from a San Diego quarry in California, USA was employed with the following grain size characteristics (He 2005): D_{50} = 0.32 mm, fines content F_c less t han 2%, and uniformity coefficient C_u = 1.5. The sand stratum was constructed by the sedimentation method (sand deposition in water). Relative density (D_r) was about 40% and saturated mass density was about 1940 kg/m^3. Each model was instrumented with accelerometers and pore pressure sensors within the soil (Figure 1).

Table 1 summarizes the characteristics of the three experiment models. A rigid wall soil container about 5 m long, 2.1 m high and 1.2 m wide (Meneses et al. 2002a, b) was employed in the study. Similar rigid wall soil containers of various sizes have been used in Japan to study liquefaction, lateral soil flow, and associated effects on pile foundations (e.g., Hamada 2000, Towhata et al. 2006).

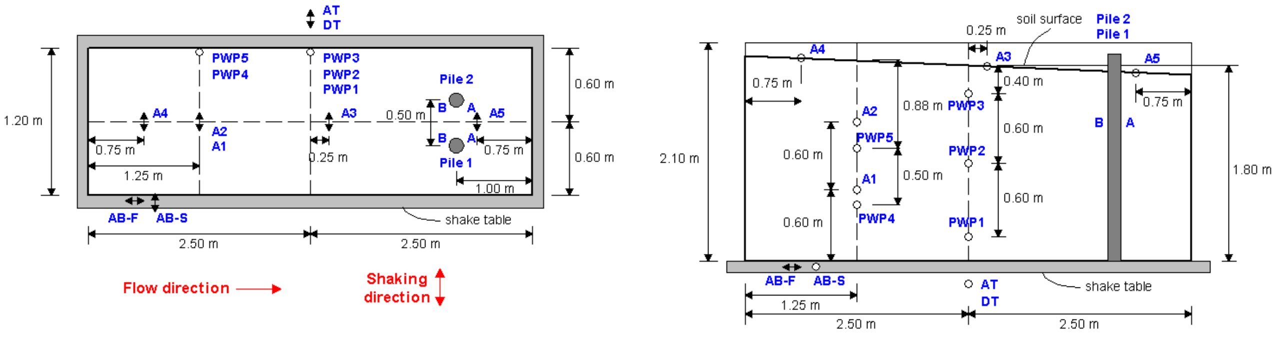
Table 1 Model configuration

Model No.	Saturated Ground		Instrumented Piles					
	Height (m)	Slope	Number of piles	Spacing	Outer Diameter “D” (m)	Wall Thickness (m)	Bending Stiffness EI (kN·m^2)	Base Fixity* K_r (kN·m/rad)
180–1	1.8	3.4° (6%)	2 aluminum piles perpendicular to the lateral spreading direction	5D	0.100	0.005	100	700
180–2	1.8		2 aluminum piles along the lateral spreading direction	5D	0.100	0.005	100	700
180–3	1.8		One single concrete pile	NA	0.152	Solid Cylinder	200	900

*Note: Pile base fixity condition is characterized by a rotational spring with constant stiffness.

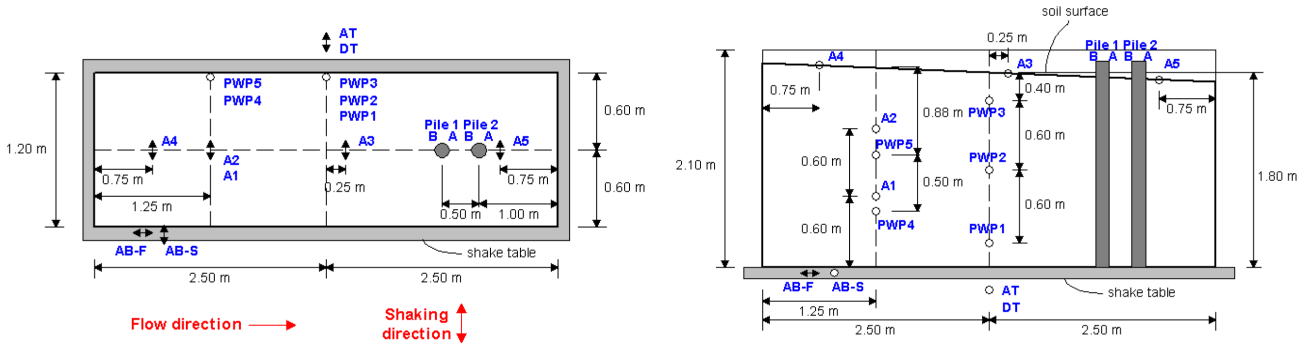
Models 180-1 and 180-2 included two separate aluminum pipe piles spaced at five pile diameters (5D) perpendicular to and along the lateral spreading direction, respectively. In Model 180-3, the response of a single pile consisting of a concrete cylinder with a larger diameter was investigated. Properties of the piles are summarized in Table 1. Note that a pile cap was not used and the individual piles in the pile groups (Models 1 and 2) were not connected. Such a setup was adopted in order to investigate pile group and shadowing effects and their potential as a countermeasure.

In all experiments, before construction of the soil stratum, the piles were connected to the base in an attempt to achieve a fixed-base condition, and static pushover tests were conducted on each pile to obtain the bending stiffness EI and the actual base fixity condition (Table 1). Each pile was densely instrumented with strain-gages to allow for the estimation of bending moments and deformation in the pile due to lateral spreading. A displacement transducer was also available at the pile head in Model 3.



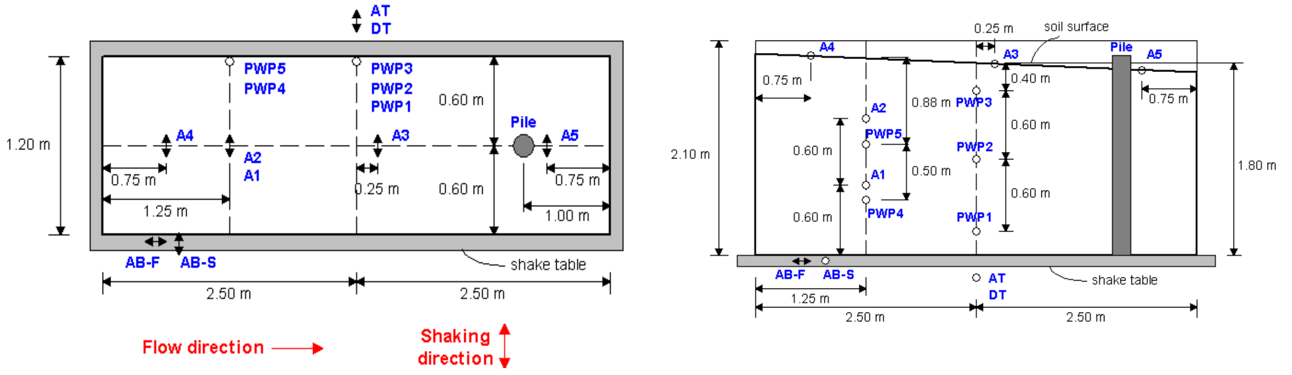
Plan View Elevation View

(a) Model 180-1



Plan View Elevation View

(b) Model 180-2



Plan View Elevation View

(c) Model 180-3

A5: accelerometer; PWP5: pore pressure sensor; AT: accelerometer on shake-table; DT: LVDT for Shake-Table

ABF and ABS: accelerometers for container in the lateral spreading and shaking directions, respectively

Figure 1 Model configuration (http://geotechnic.ucsd.edu/rigidbox/)

2.2 Dynamic Excitation

Shaking of the models was carried out perpendicular to the slope (i.e., the lateral spreading direction) to isolate inertial effects from lateral spreading effects. The input motion (Figure 2) was composed of a 12-second sinusoidal acceleration applied at the base of the models. The amplitude was about 0.4 g, with a one-second increase from zero to peak, and a one-second decrease from peak to zero at the end. The predominant frequency was approximately 3 Hz.

3. RESULTS AND DISCUSSIONS

Soil response (acceleration, displacement, and excess pore pressure) and pile response (pile head displacement and strains along the pile) were recorded during shaking (He 2005). This paper presents the recorded bending moments and back-calculated lateral soil pressure at the instant of peak pile moment.

For this purpose, pile bending moment was first calculated based on the measured strain using the traditional Euler-Bernoulli beam theory. The critical time step when maximum moment occurred was identified from the moment time histories. Below, attention is focused on lateral soil pressure at this critical time step.

3.1 Pile Bending Moment

Figures 3 shows representative moment time histories in the lateral spreading direction at representative cross sections of pile 1 in Model 180-1. The moment time histories show that the maximum response was reached quickly (at about 5 cycles of shaking) followed by a rapid decrease to nearly zero (at about 11 cycles of shaking). This rapid decrease signals that lateral load from the liquefied soil quickly diminished and the piles largely bounced back. This is due to the fact that as shear strain and pore pressure increased in the soil the liquefied soil lost its strength and stiffness substantially and started to flow around the piles. As shaking was applied perpendicular to lateral spreading, inertial effects were isolated from the lateral spreading effects. Therefore, these moments are mainly due to liquefaction-induced lateral spreading of the ground. As expected, moment increased with depth, reaching a maximum value near the base of the piles. Moments in all other piles depicted similar patterns. The maximum moment near the base of each pile is shown in Table 2.

3.2 Lateral Soil Pressure

For the purpose of investigating pile group and shadowing effects, this paper assumes a uniform soil pressure distribution as proposed by Abdoun et al. (2003). This uniform lateral pressure is back-calculated for each pile so as to provide a best match of the measured peak moment profile (Table 2). Figures 4-6 show the measured moments and the back-calculated soil pressure and moments for each pile.

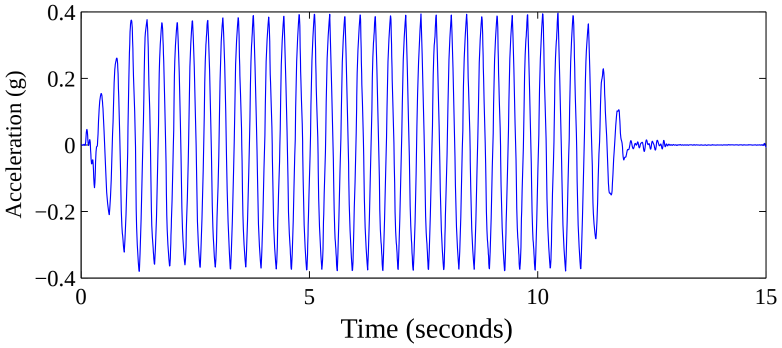


Figure 2 Imparted dynamic excitation

Table 2 Maximum response of test piles

Model No.	Pile	Pile Base Depth (m)	Moment (kN·m)	Equivalent Uniform Soil Pressure (kPa)	Pile Head Displacement (m)
180-1	Pile 1	1.53	0.63	5.5	--
	Pile 2	1.53	0.64	5.5	--
180-2	Pile 1	1.56	1.4	11.5	--
	Pile 2	1.53	0.53	4.5	--
180-3	Concrete	1.53	1.86	11.5	0.014

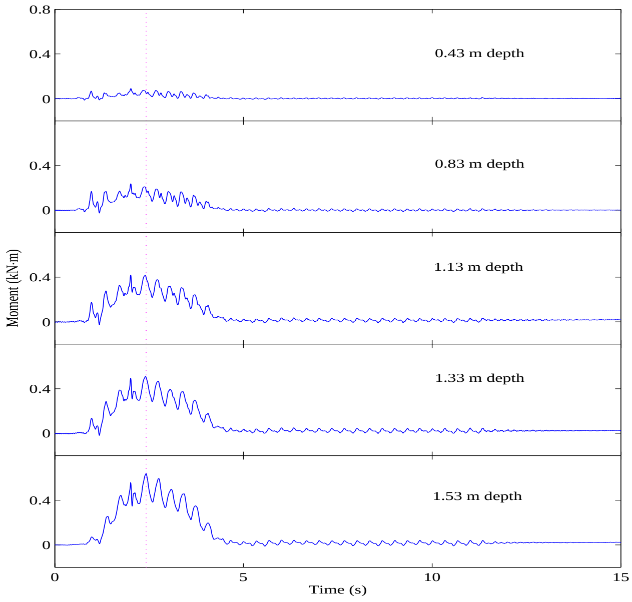


Figure 3 Bending moment in Pile 1 of Model 180-1

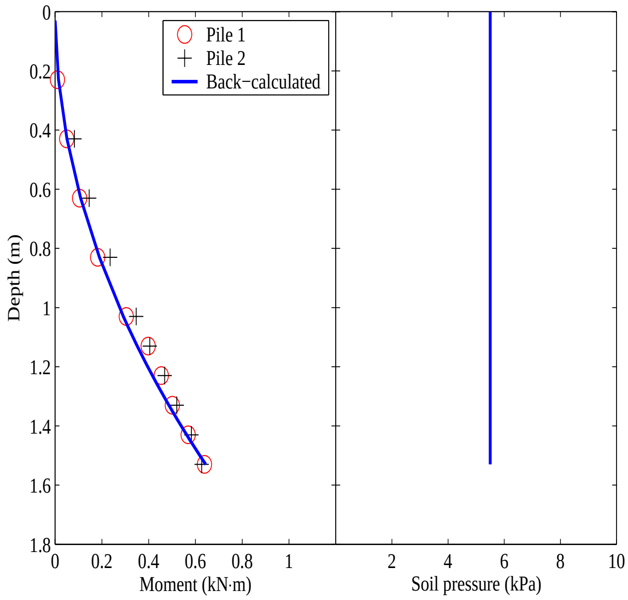


Figure 4 Maximum pile moment and equivalent uniform soil pressure in Model 180-1

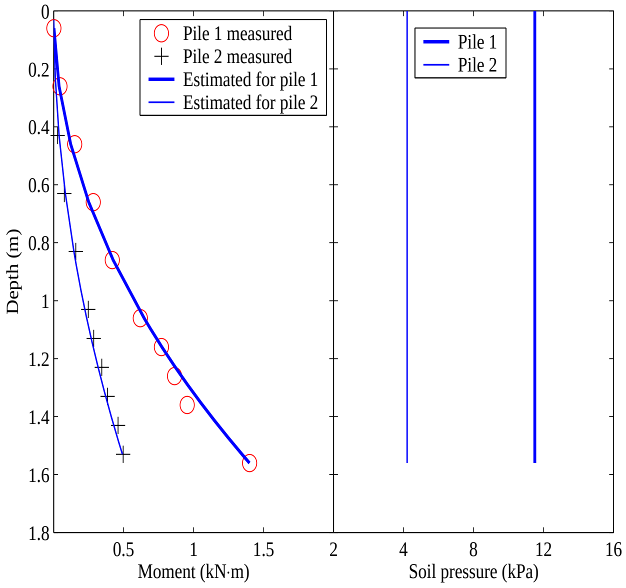


Figure 5 Maximum pile moment and equivalent uniform soil pressure in Model 180-2

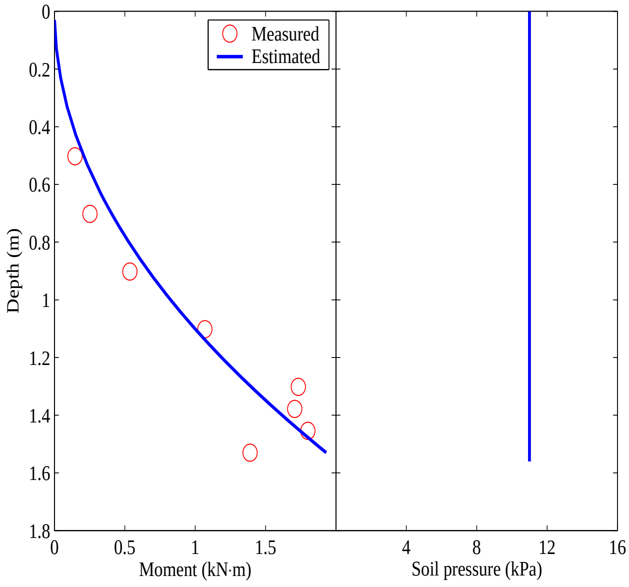


Figure 6 Maximum pile moment and equivalent uniform soil pressure in Model 180-3

3.3 Pile Group and Shadowing Effects

3.3.1 Group effect

As mentioned earlier (Figure 1), Model 180-1 included two piles spaced at five diameters perpendicular to the lateral spreading direction, and Model 180-2 included two piles one behind the other along the lateral spreading direction. The measured maximum moments in the two piles in Model 180-1 were 0.64 and 0.63 kN·m, near the base of the piles (Table 2), respectively. This is about 46% of the maximum moment in the front pile during Test 180-2 (1.4 kN·m). This observation is also supported by the moment and pressure profiles in the front pile of Model 180-2, which are nearly double of those in the piles of Model 180-1 (Figures 4 and 5).

The back-calculated soil pressure on the piles in Model 180-1 was about 5.5 kPa, compared to about 11.5 kPa on the front pile in Model 180-2 and the single pile in Model 180-3 (Table 2 and Figures 4 and 5). The pressure reduction of about 50% in Model 1 appears mainly due to the group effect of Model 180-1, as a result of overlapped shear zones in front of the piles.

3.3.2 Shadowing effect

Model 180-2 included two piles one behind the other along the lateral spreading direction (Figure 1). Measured maximum moment in the front pile was about 1.4 kN·m, with only 0.53 kN·m in the trailing pile about 40% of the moment in the front of pile (Table 2). Such a load reduction in the trailing pile was also observed in the moment profiles and corresponding soil pressures (Figures 5 and 6). This lateral load reduction indicates the presence of a pile shadowing effect as a result of the reduced shear zones.

Thus, the shadowing effect has apparently reduced lateral load on the trailing pile by about 60% in Model 180-2. As a consequence, the soil pressure on the trailing pile is only 4.5 kPa, compared to about 11.5 kPa on the front pile of Model 180-2 and the single pile of Model 180 (Table 2).

3.3.3 Discussions of pile group and shadowing effects

Similar group and shadowing effects at various levels were also observed by Towhata (et al. 2006) and Motamed et al. (2007). However, the effects are different from those of Rollins et al. (2005) obtained from lateral load tests on a pile group in a blast-induced liquefied ground experiment at Treasure Island in California, USA. Rollins et al. (2005) concluded that group interaction effects were relatively unimportant for pile groups in a fully liquefied sand stratum. The difference can probably be explained by:

1. The heads of the piles in this study were not connected, while in the Treasure Island experiment the pile heads were connected through a pile cap. Consequently, in this study lateral pressure on one pile was not transmitted to the other pile in contrast to the cases when pile heads are connected. Therefore, lateral soil pressure on each individual pile due to lateral spreading could be separately identified in this study, and
2. The downslope flow of soil in lateral spreading scenarios as in this study imposes a different pattern of pressure compared to the level ground scenario. As a result of overlapped or reduced shear zones, group and shadowing effects may be expected to reduce lateral soil pressure.

3.4 Countermeasures for Piles against Lateral Spreading

The observed group and shadowing effects are significant from the view of practice. Specifically, single piles in lateral spreading scenarios may sustain substantially more load compared to pile groups and closely spaced single piles. In this regard, the above described group and shadowing effects may be of value as a countermeasure for piles against lateral spreading as suggested earlier by Towhata (et al. 2006) and Motamed et al. (2007).

Along this logic, sacrificial protection piles may be installed in front or at the sides of pile foundations to help reduce lateral spreading loads on the main foundation. Such an approach may reduce damage to the pile foundations and the superstructure if lateral spreading occurs during an earthquake. Maintenance of these sacrificial front or side piles may be inexpensive, as the protective function may be fulfilled despite partial damage. Additional considerations that may also play a beneficial role include (He 2005):

1. The pile-pinning effect provided by the installed sacrificial piles, and
2. Mobilization of additional pile resistance by deploying a fixed-head pile configuration for added stiffness and rigidity (e.g., by placing a rigid pile cap on the installed piles). Further research is needed to explore such fixed-head pile scenarios.

4. CONCLUSIONS

A series of large scale one-g shake-table experiments of a saturated sand stratum was conducted to investigate a potential countermeasure for piles against liquefaction-induced lateral spreading. Lateral soil pressure was examined for a single pile and pile groups without a pile cap. The main conclusions of the study are summarized as follows:

1. Lateral spreading load on individual piles was found to be a function of pile location within a pile group. In the investigated case, piles in the same row at 5D spacing, lateral load was only about 50%. The shadowing effect reduced lateral load on the trailing pile by about 60%.
2. Group and shadowing effects can be a basis for designing countermeasures for piles against liquefaction induced lateral spreading. Protection sacrificial piles can be installed in front or at the sides of pile foundations to reduce lateral loads on the main pile foundation.
3. Studies are needed to further investigate and quantify the efficacy of this countermeasure mechanism.

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