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Effectiveness of a vertical micro-pile system for mitigating lateral spreading damage on pile groups: 1g shake table tests

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ABSTRACT: In this study, effectiveness of a micro-pile system as a lateral spreading countermeasure is evaluated using 1g shake table model tests on a 3×3 pile group. For this purpose, two physical models including a benchmark model without any mitigation measure and a model remediated with micro-piles were built and tested. Both models were densely instrumented with various sensors to monitor the behavior of the soil and the piles during lateral spreading. In general, the results of the shake table tests on these models showed that the micro-pile system deployed in current research did not considerably reduce the kinematic lateral force as well as the induced bending moments due to lateral spreading on the pile group. Moreover, the accelerations recorded on the pile cap of the model remediated with micro piles were amplified compared to the case where no mitigation measure is adopted.

1 INTRODUCTION

Due to the destructive nature of liquefaction and its related ground displacements, numerous studies have been carried out by several researchers to assess the effectiveness of existing mitigation methods or to develop new approaches during past years (Adalier et al. 1998, Ashford et al. 2000, Elgamal et al. 2002, Adalier et al. 2003, Adalier et al. 2004, Kutter et al. 2004, Gallager et al. 2007 and Takemora et al. 2009). For example, Kutter et al. (2004) and Balakrishnan & Kutter (1999) examined the effects of dense sand layers of varying density and thickness on the behavior of a bridge abutment. In recent years some studies have been carried out concerning the use of micro-piles as a mitigating measure. McManus et al. (2005) studied the effect of micro-piles as inclined reinforcements on the settlement of a loose sandy soil. Mitrani & Madabhushi (2005) conducted a series of centrifuge tests investigating inclined grout micro-piles as a method of liquefaction remediation for existing buildings. They concluded that micro-piles have some beneficial effects due to increasing shear strains in the soil in the vicinity of the building and hence causing dilation in these zones. However, use of micro-piles can increase accelerations at the ground surface since the shear stresses transfer through the dilative soil more easily. Wong (2004) used finite element analyses to investigate the seismic behavior of vertical and inclined micro-pile systems. Despite all these studies, current knowledge about the applicability of micro-piles for remediation of the effect of lateral spreading on the piles is limited. Therefore, the objective of the present study is to evaluate the effectiveness of a vertical micro-pile system as a countermeasure for the effect of lateral spreading on piles. For this purpose, two physical models were built and tested. Model A was constructed without any mitigation measures as a benchmark while model B included a micro-pile system as a mitigation measure. The most important findings from these experiments are outlined in the following sections.

2 PHYSICAL MODEL AND MATERIAL PROPERTIES

This study was conducted at the Earthquake Engineering Research Center at Sharif University of Technology (SUT). This research center houses the SUT shaking table which consists of a 4m×4m deck with 3DOFS which can carry payloads up to 300 kN. A rigid box with dimensions of 3.5 m length, 1.0 m width and 1.5 m height was employed in this study as the model container. It is worth mentioning that using a container with rigid walls in this study may impose slight errors on the experimental results; however, because of the mainly kinematic nature of the lateral spreading (Haeri et al. 2012), these errors are expected to be small. Discussion on the possible effects of the container type on the experimental results has been studied and reported in a companion paper by the first author (Haeri et al. 2019), and is out of the scope of this paper.

Two physical models were tested including model A without any mitigation measure and model B with micro-piles as a remediation scheme. Non-liquefiable layers were constructed using wet tamping technique while the liquefiable layer was placed in the container using water sedimentation technique (refer to Figures 1 and 2 for more details). The sand used for construction of the model ground was standard Firoozkuh silica sand (No. 161) with a uniform gradation that is commonly used for physical model testing in Iran. The properties of Firoozkuh silica sand is outlined in Table 1.

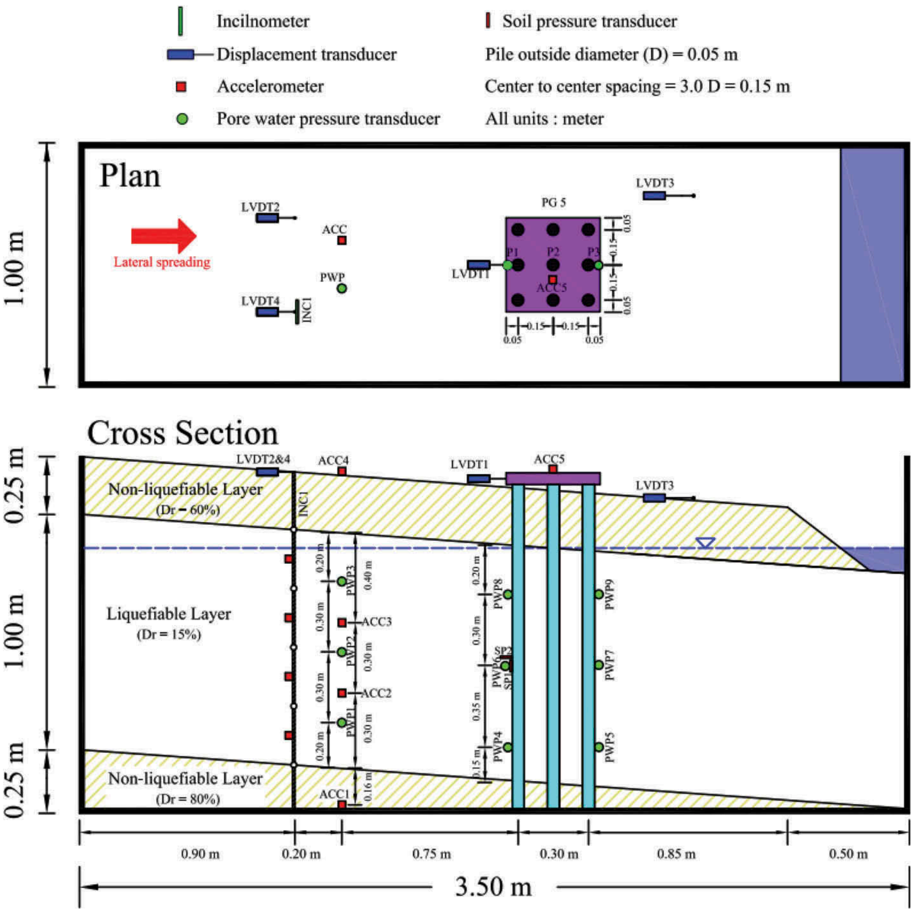

Figure 1. Plan view and cross section of model A and the instrumentation layout

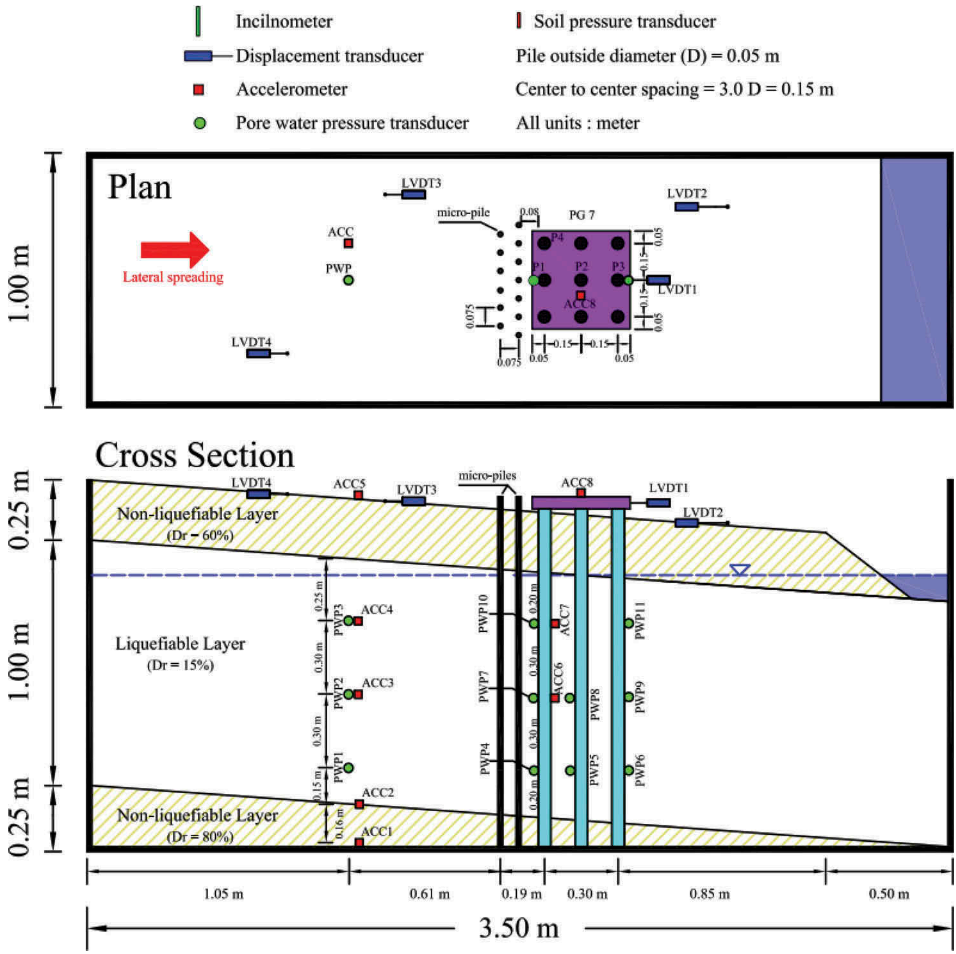

Figure 2. Plan view and cross section of model B and the instrumentation layout

Table 1. Properties of Firoozkuh silica sand (No. 161)

Specific gravity	Maximum void ratio (e_{max})	Minimum void ratio (e_{min})	Coefficient of uniformity (C_u)	Mean grain size (D_{50}) (mm)	D_{10} (mm)	D_{90} (mm)
2.698	0.87	0.608	1.49	0.24	0.18	0.39

In present study, the similitude law proposed by Iai et al. (2005) was utilized for scaling the physical model properties. Considering the dimensions of the rigid box, a geometric scale of $\lambda=8$ was used for this purpose.

Prototype pile foundations were designed based on JRA code (2002) to withstand the exerted lateral spreading forces. Geometrical and mechanical properties of the piles were then determined using the aforementioned similitude laws. All model piles were made of high density polyethylene (HDPE) pipes. Mechanical properties of the model piles are presented in Table 2. The prototype concrete micro-piles were 15 cm in diameter each of which reinforced with a φ28 steel bar. 28-day compressive strength of the concrete was assumed to be 210 kg/cm2. Polypropylene pipes were used as micro-piles in the model. Considering these assumptions and the aforementioned similitude laws, geometrical and mechanical properties of micro-piles in model scale were calculated which are presented in Table 3.

Table 2. Geometrical and mechanical characteristics of the model piles

Required parameters according to the similitude law			
Parameter	Scaling factor	Prototype	Model
$EI_{model\text{-}required}$(kN.m^2)	$\lambda^5=8^5$	11573	0.353
Outer diameter (cm)	$\lambda=8$	40	5.0
Adopted values for the physical model			
Outer diameter (cm)			5.0
Thickness (cm)			0.23
Inner diameter (cm)			4.54
I_{model} (cm^4)			9.83
E_{HDPE}(MPa)			760
EI_{model} (kN.m^2)			0.074

Table 3. Characteristics of the model micro-piles

Outer diameter (cm)	2.0
Thickness (cm)	0.42
Inner diameter (cm)	1.16
EI (kN.m^2)	0.0125

3 ACCELERATION IN THE FREE FIELD SOIL AND AT THE PILE CAP

The base shaking was applied in longitudinal direction of the rigid box, parallel to the model slope. The frequency of this sinusoidal shaking was 3.0 Hz and its amplitude was 0.3g. Recorded acceleration time histories for models A and B are shown in Figures 3 and 4, respectively. In these figures, the positive amplitude corresponds to downslope direction. The general trend of the recorded accelerations indicate that the free field soil in both models lost their shear strength within the initial few cycles of shaking while became liquefied. In both models, the acceleration

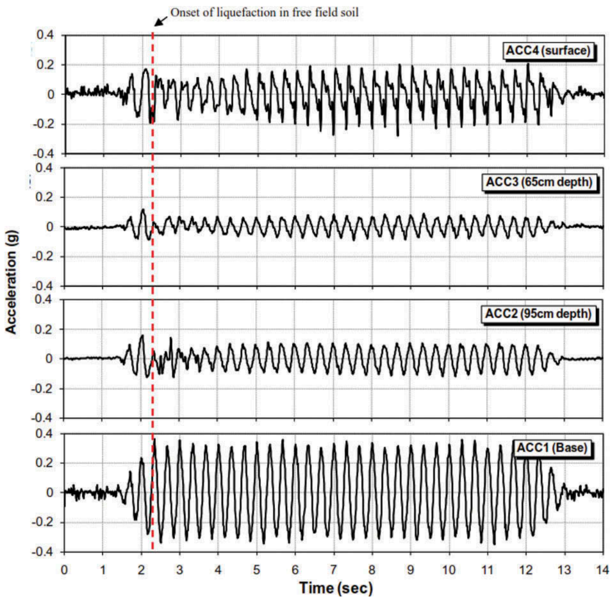

Figure 3. Time histories of acceleration in free field soil for model A

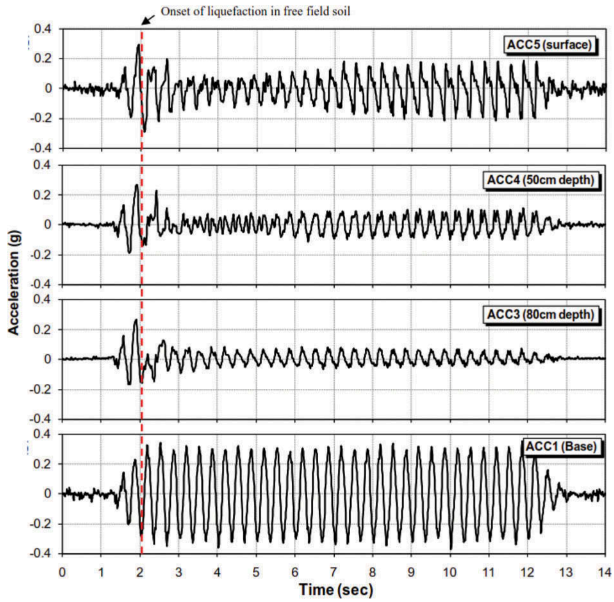

Figure 4. Time histories of acceleration in free field soil for model B

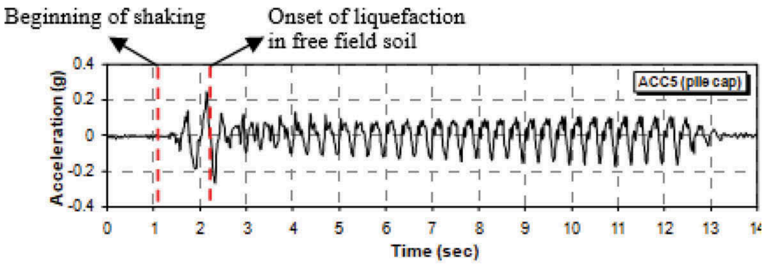

Figure 5. Time history of pile cap acceleration in model A

records at the ground surface show amplifications relative to those in deeper depths since the accelerometer was placed at the upper non-liquefiable layer. Moreover, the spikes observed in the acceleration record at the ground surface in negative amplitudes (toward the upslope direction) could be resulted from the strikes of the model piles to the upslope side of the upper non-liquefiable soil layer. As can be seen, there is no considerable difference between acceleration records in Figures 3 and 4, indicating that the adopted micro-pile system had no meaningful effects on the soil acceleration time histories in the free field.

Time histories of the pile cap acceleration for models A and B are outlined in Figures 5 and 6, respectively. Comparing these two figures, one can find that by adding the micro-pile system to the model, the maximum pile cap acceleration is increased from 0.25 g in model A to 0.38 g in model B. This is resulted from an increase in relative density of the soil around the micro-piles due to the installation process.

4 BENDING MOMENTS ALONG THE PILES

Figures 7 and 8 show profiles of observed bending moments along different piles of the pile group plotted at different times. As can be seen, the recorded moments at shallower depths

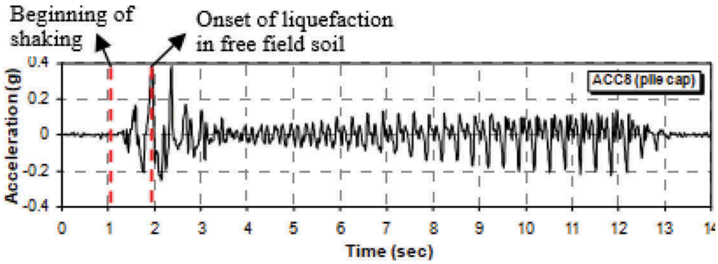

Figure 6. Time history of pile cap acceleration in model B

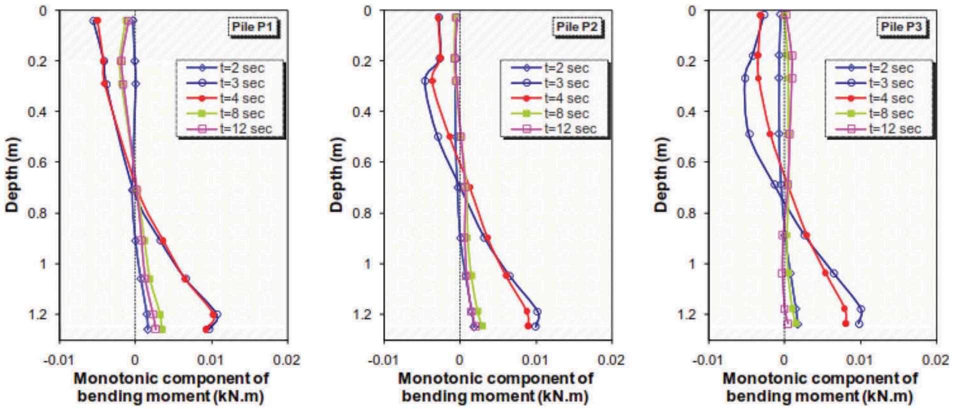

Figure 7. Profiles of bending moments along the piles in model A

have different sign with those measured at deeper depths. This is due to the fixity of pile ends at the bottom non-liquefiable soil layer as well as the partial fixity of pile heads at the cap. Besides, it can be seen that due to the loss of soil strength after liquefaction and the flexural stiffness of the piles, the recorded bending moments show a decreasing trend after reaching a maximum value. Comparing the moment profiles in Figures 7 and 8, no significant difference is observed, meaning that the adopted micro-pile system was not that much effective for reducing the induced bending moments in the piles due to lateral spreading.

5 CONCLUSION

In this study, two large scale shaking table model tests were performed to evaluate the effectiveness of vertical micro-piles inserted in a loose sandy layer as a lateral spreading countermeasure. The results showed that the adopted micro-pile system was not effective in mitigating the induced bending moments in piles. However, it was observed that using micro-piles increased the transferred accelerations to the pile cap (superstructure) that can be pointed out as a drawback. The experiments showed that the deployed micro-piles slightly restricted the displacement of the upper non-liquefiable layer and to some extent that of the upper half of the liquefiable layer. However, the lower half of the liquefiable layer was not affected. This observation confirms that the configuration used for micropile insertion to preserve pile groups from lateral spreading was not that successful. As a result one solution to possibly enhance the performance of micro-pile system can be deepening the micro-piles to penetrate into the lower nonliquefiable layer, using a rigid connection at the micro-piles head, enhancing

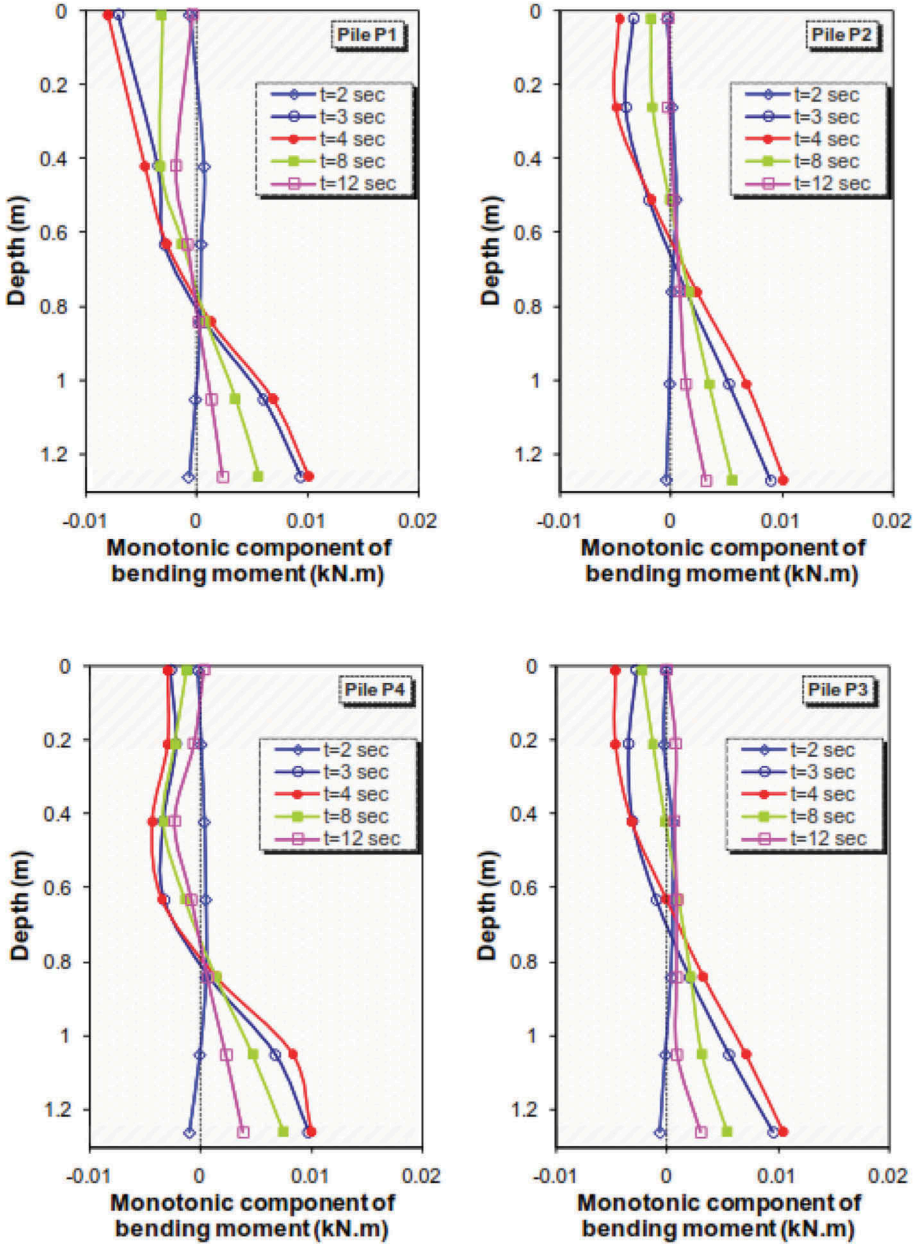

Figure 8. Profiles of bending moments along the piles in model B

the pattern and number of micro-piles and using much stiffer micro-piles. Detailed effectiveness of the named solutions needs further investigations in the future.

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