D105

Centrifuge and Numerical Modeling of Buckling Instability of Piles During Earthquake-induced Liquefaction

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1. Introduction

Earthquakes are low-probability but high-damage natural phenomena. Since earthquakes cannot be accurately predicted or prevented, it is important to understand the behavior of the foundations under such conditions, which can promote the design codes of safe earthquake-resistant structures for engineers. Pile foundation is the most popular form of deep foundation. Extensive damage to the pile foundation after an earthquake has been observed in many places related to liquefaction (Bhattacharya, 2003). This can lead to very serious and severe consequences and cause critical economic losses. Nevertheless, this failure mechanism is not specifically mentioned in most design codes.

Buckling failure of the pile foundations has been identified as one of the most destructive types in liquefiable grounds. The load transferred to the soil is partly by shaft resistance (friction) and normal stress generated at the base of the piles (end-bearing). When the pile length increases, the shaft friction of the pile will increase, which promotes the load capacity of the pile itself (Meyersohn, 1994). However, the buckling load will decrease rapidly when the pile length increases. During an earthquake, soils can get liquefied and the piles lose support from the surrounding grounds, which causes the formation of plastic hinges in the piles with structural failure and buckling collapse due to the lack of support from the soil (Knappett et al., 2009) (Bhattacharya, 2003).

This paper presents the results of centrifuge model tests of pile foundation subject to axial loading with seismic loading in the liquefiable ground. After that, the primary results of numerical simulation based on a 2-D plan strain model will be shown.

2. Physical Modeling

A uniform-density, 50 m long, 22 m deep was specified inside a laminar container for this prototype test. Dr 55% of Toyoura sand was used as liquefiable layers in all the tests. As for the piles, the model pile made of aluminum has an outer diameter of 8 mm and an inner diameter of 6 mm. The total active length of the pile is 250 mm, which means the effective length of the pile is 500 mm in the model scale, with a slenderness ratio of 100. The most popular buckling principle (e.g., Euler's buckling load, P_{cr}) is used in this study.

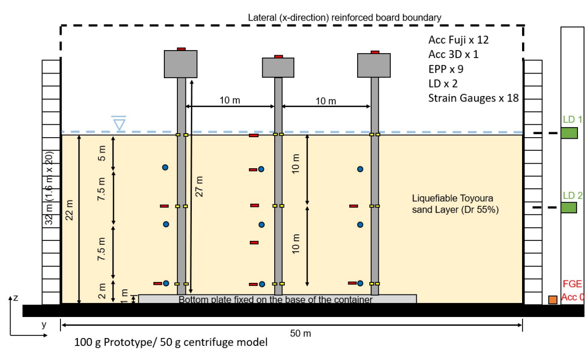

Figure 1. The setting of the standard centrifuge test model. (In prototype scale).

Table 1 shows the summary of the four tests emphasizing the axial load. Loads less than 1.0 Pcr did not fail during or after the earthquake, while the loads larger or equal to 1.0 Pcr failed during or after the shaking process. One thing needs to mentioned that these piles were under axial load and inertia load by the superstructures.

Table 1. Summary of pile response of each test.

Test No.	Pile No.	Type	Weight of Pile head	Failed or not
Test 2	Pile 1	Piles with soil	1.4 Pcr	Failed during spin-up
	Pile 2		1.2 Pcr	Failed after shaking
	Pile 3		0.8 Pcr	Did not failed
Test 3	Pile 1	Piles with soil	1.0 Pcr	Failed after shaking
	Pile 2		0.85 Pcr	Did not failed
	Pile 3		0.7 Pcr	Did not failed
Test 4	Pile 1	Piles with soil	1.0 Pcr	Failed after shaking
	Pile 2		0.85 Pcr	Did not failed
	Pile 3		0.7 Pcr	Did not failed
Test 5	Pile 1	Piles with water	1.0 Pcr	Failed during spin-up
	Pile 2		0.85 Pcr	Failed during spin-up
	Pile 3		0.7 Pcr	Failed during spin-up

Considering the test results, there were many factors which might have great effects on buckling stability of the piles, such as imperfection of the materials, discrepancy of the installation, loading direction and so on. It has been observed that during the centrifuge spin-up, there were some constant vibration on each pile along the shaking direction and centripetal direction.

3. Numerical Modeling

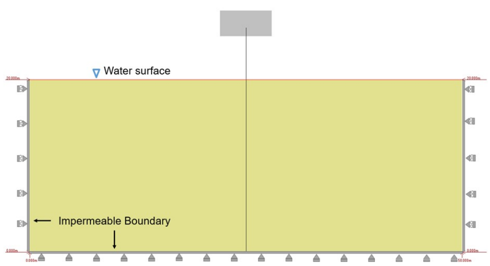

Figure 2. FEM Mesh and Boundary Conditions

The analysis was carried out under 2-D plane-strain conditions, aiming to simulate the single pile model in prototype scale. 1618 4-node quadrilateral elements (including the pore water elements), one 26-node beam element and 25 dual-node pile-soil spring elements were used in this study.

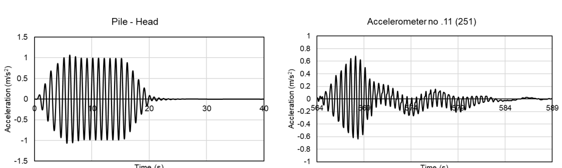

Figure 3. Response of the acceleration on the pile head (Test No 3 pile 2): (a) Simulated; (b) Experimental.

The acceleration, displacement and excess pore water pressure response are observed in the simulation program. The excess pore water pressure results show good agreement between the experiments and simulations, while the displacement and the acceleration response show some level of discrepancies.

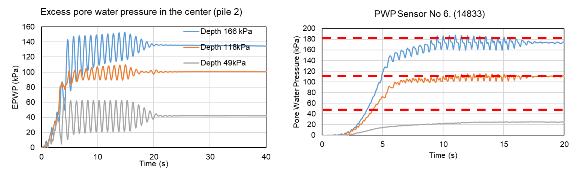

Figure 4. Response of the excess pore water pressure (Test No 3 pile 2): (a) Simulated; (b) Experimental.

6. Discussions and Conclusions

Several centrifuge tests were conducted to explore the mechanism of buckling instability of piles in liquefiable soils. The primary results of numerical simulation have been compared with the experiments Major conclusions are summarized as follows:

- End-bearing single piles passing through saturated, loose to medium dense sands, can buckle under the combination of axial load and horizontal inertial load during the earthquake-induced liquefaction.
- Even when the ground was highly liquefied in the centrifuge tests, the soil layers still offered considerable support to the piles in both experimental results.
- The deviation between the numerical simulation and experimental results shows the importance of the nonlinearity analyses based on large deformation theory.

Reference

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[3] Iai, S., Tobita, T., Nakahara, T. 2005. Generalised scaling relations for dynamic centrifuge tests. Géotechnique, 55(5), 355-362.