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*Physical Modelling in Geotechnics*


# Centrifuge modeling of buckling instability of piles during earthquake-induced liquefaction

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**ABSTRACT:** Earthquakes are low-probability but high-damage natural phenomena that cannot be accurately predicted or prevented in the real world. 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. This paper describes the results of a series of centrifuge tests as an investigation into the failure mechanism of piled foundations. Different axial loads were applied and different ground conditions were introduced in these tests. It has been observed that the end-bearing single piles resting on a rigid layer can buckle under the effect of axial load and horizontal inertial load during the earthquake-induced liquefaction. The failure type observed in the tests was similar to P-Δ effects in the liquefiable grounds. The slender pile foundations in the tests collapsed from 45 s to 70 s after the beginning of the shaking (duration of the shaking is 20 s). Besides, the soil layers offered considerable support to the piles even if the ground was fully liquefied during the dynamic loading. Without the soil, the pile model in this test could easily collapse before the model reached 50-g.

**Keywords:** centrifuge, liquefaction, buckling, pile foundation.

## 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. In the previous studies, centrifuge testing and numerical modeling were used to investigate the buckling failure phenomenon in liquefiable soils (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 briefly describing the specifications and the properties of Toyoura sand used for these tests, the primary results of the centrifuge tests will be shown.

## 2 TEST SPECIFICATIONS

Geotechnical centrifuge modeling is a powerful tool for investigating the response of soil and soil-structure interaction under static and dynamic conditions. The 24-g ton geotechnical centrifuge at the DPRI (Disaster Prevention Research Institute), Kyoto University, was used to conduct the tests. This beam centrifuge has a swinging platform with an effective radius of 2.50 meters.

The generalized scaling law (Iai et al., 2005) for centrifuge modeling was used in this test. For all the tests in this research, the partition ratio of the prototype/virtual model is 2, and the partition ratio of the virtual model/physical model is 50, which means the gravity level in the centrifuge test is 50 g and in prototype scale, 100 times.

The standard sand selected for this research was Toyoura sand, which can be defined as a naturally formed silica sand that leads to consistent results and stable outcomes during the laboratory tests. The particle distribution is within 106-300 µm. Dr 55% of Toyoura sand was used as liquefiable layers in all the tests.

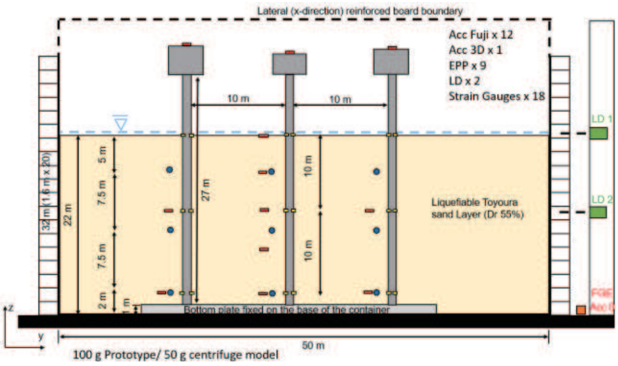


Fig. 1. The setting of the standard centrifuge test model. (In prototype scale).

A uniform-density, 50 m long, 22 m deep was specified inside a laminar container for this prototype test. Figure 1 shows the geometry, dimensions, and instrumentation of the target model. 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. Reinforcement parts were added to the connection point to prevent buckling from happening near the connection parts.

The most popular buckling principle (e.g., Euler's buckling load, $P_{cr}$) is used in this study for comparison and interpretation. $P_{cr}$ can be calculated using Eq. (1).

$$P_{cr} = \frac{\pi^2 EI}{L_{eff}^2} \tag{1}$$

where EI is the flexural rigidity of the column, and $L_{eff}$ is the effective length of the column.

Table 2 shows the details of each test. Test 1 is a preliminary test to calibrate the frequency of input motion and the generation of the excess pore water pressure. Tests 2 and 3 are designed to investigate the effect of axial loads on the response of the piles. Test 4 introduced a 2-degree slope on the platform to investigate the effect of slope on the response of pile buckling instability; the laminar box had a declination of 2-degree, and the piles were vertical to the gravitational direction. Test 5 aimed to calibrate the magnitude of the support force by surrounding soils in the centrifuge model.

Table 2. Summary of the test proposal.

| Test No. | Pile No. | Type | Weight of Pile head | Ground condition |
|---|---|---|---|---|
| Test 1 | | Only soil | | Horizontal |
| Test 2 | Pile 1 | Piles with soil | 1.4 Pcr | Horizontal |
| | Pile 2 | | 1.2 Pcr | |
| | Pile 3 | | 0.8 Pcr | |
| Test 3 | Pile 1 | Piles with soil | 1.0 Pcr | Horizontal |
| | Pile 2 | | 0.85 Pcr | |
| | Pile 3 | | 0.7 Pcr | |
| Test 4 | Pile 1 | Piles with soil | 1.0 Pcr | 2 degree slope |
| | Pile 2 | | 0.85 Pcr | |
| | Pile 3 | | 0.7 Pcr | |
| Test 5 | Pile 1 | Piles with water | 1.0 Pcr | Horizontal |
| | Pile 2 | | 0.85 Pcr | |
| | Pile 3 | | 0.7 Pcr | |

## 3 CENTRIFUGE TESTS

When the piles were fixed on the bottom plates, strain gauges were carefully installed with waterproof tapes. The specified technique for sand placement was air-pluviation in this test. The sand is prepared without tamping to obtain a low relative density (i.e., DR = 55%). After the air-pluviation step, the laminar box was placed in a vacuum chamber to achieve a fully saturated condition. After the saturation, the container was lifted out of the chamber gently. Pile heads of different masses were placed on the piles as gently as possible to prevent disturbing the saturated soil layers. When the preparation was finished, the laminar box was placed on the platform ready to be tested.

The testing procedure includes a spin-up (from 0 to 50 g) step and a high-frequency vibration step in the model scale. During the spin-up, the data from each sensor were recorded as important references. 2 Hz was chosen as the frequency of the input motion for all the tests in the prototype scale during the shaking, as shown in Figure 3.

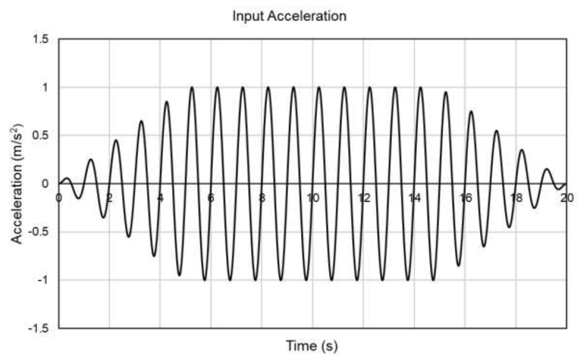


Fig. 3. 2 Hz standard input acceleration (Prototype scale) used in this study.

Table 3 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.

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Table 3. 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 |

The strain response of the target points on each failed pile at the failure point was shown in Figures 4-6. By elastic assumption, the bending moment at failure time was calculated. For the piles that failed during or after the shaking, strain level will be considered instead of bending moment.

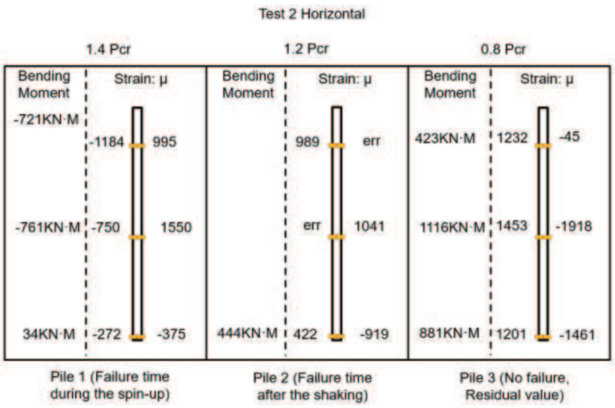


Fig. 4. Measured strain response of target points on piles at failure point with calculated bending moments in test 2.

Figure 4 shows the bending moment of Test 2. Pile 1 showed a concentrated bending moment distribution on the upper part, which indicated that before the bending moment had been well transmitted to the base part, the pile has collapsed because of the large axial load. Pile 3 showed the highest strain level near the middle part of the piles. The piles on both sides tended to move towards the edge. This showed the existence of the lateral force due to the radial effect of the centrifuge. Since there were some errors reported by strain gauges on pile 2, this pile was neglected during this discussion.

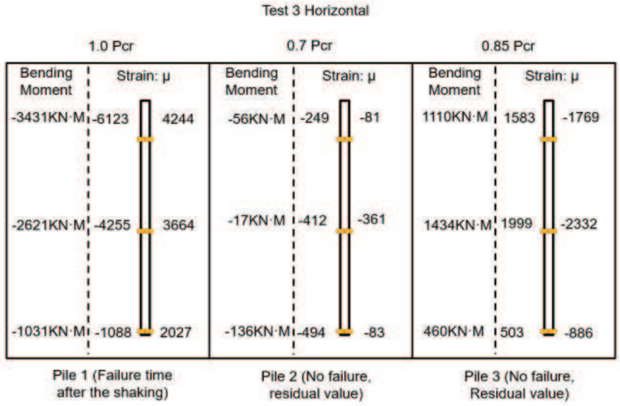


Fig. 5. Measured strain response of target points on piles at failure point with calculated bending moments in test 3.

Tests 2 and 3 shared the same test conditions except for the axial load on each pile. Comparing pile 1 with pile 3, a large axial load on the pile will lead to a large strain level distribution. However, if the axial load is too large for the pile to resist, the development of the strain level will not increase to an expected level, which is shown on pile 1 in test 2 and test 3.

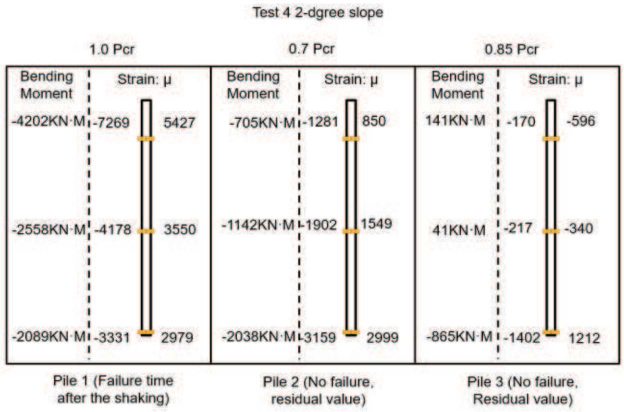


Fig. 6. Measured strain response of target points on piles at failure point with calculated bending moments in test 4.

Tests 4 and 3 shared the same axial load setting on each pile, but Test 4 adopted a 2-degree slope on the base of the container. One thing that needs to be mentioned is that the PGA of Test 4 is slightly larger than Test 3 . Pile 1 showed a larger strain level on the surface and bottom layers in slope condition, while pile 2 showed an increase in strain level at all points measured in this test. Pile 3 showed a reduction in the strain level due to the compensation from the lateral spreading load of the sloping ground on the lateral force due to the radial effect.

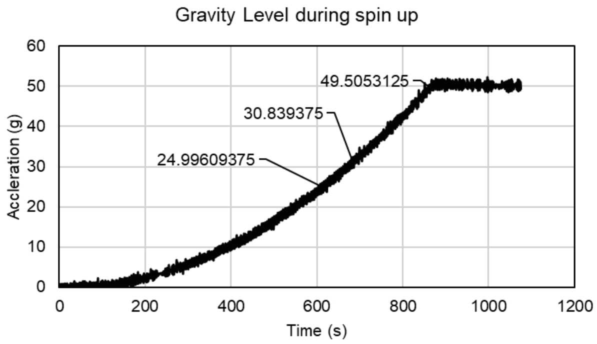


Fig. 7. Acceleration level of failure point of each pile during the spin-up - test No 5

In Test 5, all the piles collapsed during the spin-up step. It indicated that even though the soil was fully liquefied during the shaking process, the piles were kept stable with considerable support from the soil layer. By calculating the actual loads on piles 1-3 at the failure point with the gravitational level, 0.51 Pcr, 0.70 Pcr, and 0.53 Pcr were acquired. The left side and right side showed an obvious reduction in the resistance of the static axial load, mainly due to the lateral force caused by the radial effect. Without the support of the soils, the piles were vulnerable to the lateral load while under a large axial load.

## 4 CONCLUSIONS

Five centrifuge tests were conducted to explore the mechanism of buckling instability of piles in liquefiable soils. 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. Piles with axial loads greater than or equal to 1.0 Pcr collapsed during or before the shaking in the centrifuge tests.
- Lateral force due to the slope of the ground will increase the strain level. The alternating quantity will depend on the angle of the slope.
- 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. Good support conditions will greatly decrease the effects of imperfection on the foundation.
- From the centrifuge test results, the centripetal effect is confirmed in the tests. Lateral inertial force due to the earthquake, and friction between the platform and cantilever beam, combined with the imperfection of materials and installation, contribute to the buckling failure of the piles in this model.

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