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สำเนาบทความต้นฉบับ (Manuscript)

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Vol.10, No.3 EARTHQUAKE ENGINEERING AND ENGINEERING VIBRATION September, 2011

Earthq Eng & Eng Vib (2011) 10: 1- **DOI**:

Experimental investigation on seismic behavior of single piles in sandy soil

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Abstract: This paper describes a quasi-static test program featuring lateral cyclic loading on single piles in sandy soil. The tests were conducted on 18 aluminum model piles with different cross sections and lateral load eccentricity ratios, *e/d*, (*e* is the lateral load eccentricity and *d* is the diameter of pile) of 0, 4 and 8, embedded in sand with a relative density of 30% and 70%. The experimental results include lateral load-displacement hysteresis loops, skeleton curves and energy dissipation curves. Lateral capacity, ductility and energy dissipation capacity of single piles under seismic load were evaluated in detail. The lateral capacities and the energy dissipation capacity of piles in dense sand were much higher than in loose sand. When embedded in loose sand, the maximum lateral load and the maximum lateral displacement of piles increased as *e/d* increased. On the contrary, when embedded in dense sand, the maximum lateral load of piles decreased as *e/d* increased. Piles with a higher load eccentricity ratio experienced higher energy dissipation capacity than piles with *e/d* of 0 in both dense and loose sand. At a given level of displacement, piles with circular cross sections provided the best energy dissipation capacity in both loose and dense sand.

Keywords: seismic behavior; single pile; sandy soil; load eccentricity ratio; lateral resistance

1 Introduction

Pile foundations that support a variety of important structures are widely used for offshore platforms, docks, dolphin structures and bridges. Apart from the usual loads from superstructures, piles in sandy soil in coastal regions should also resist lateral loading such as wind, waves and earthquakes. These phenomena result in considerable degradation of the interactive performance of the pile-soil system, causing progressive reduction in pile capacity associated with increased pile-soil stiffness. This may ultimately lead to disastrous consequences. Thus, understanding the seismic behavior of pile foundations is very important for many essential structures. Severe damage to piles has been observed during some earthquakes. For example, earthquake damage to piles due to large imposed curvatures has been described by Gerwick (1982), Sheppard (1983) and Banerjee *et al.* (1987).

Because in situ tests of piles are costly and time consuming, some small-scale tests on piles have been undertaken in the past few decades. Park and Falconer (1983) report in the test results obtained from five prestressed concrete piles under axial compressive load and intense cycles of lateral loading which simulated severe seismic loading. Joen and Park (1990) tested six full-scale prestressed concrete piles subjected to simulated seismic loading in New Zealand. Narasimha and Mallikarjun (1995) tested the behavior of model piles subjected to lateral loads of different load ratios. Dou and Byrne (1996) investigated the pile response to free vibration and forced vibration simulating earthquake loading. The dynamic *P-Y* curves (soil resistance versus lateral pile deflection relationship) were found to be highly nonlinear and hysteretic at shallow depths under strong shaking. The *P-Y* curves for low-level shaking showed essentially linear elastic behavior. Test investigation to determine the ultimate resistance and displacement of piles under working loads was carried out by Verdure *et al.* (2003). Guo (2006) noted that the response of laterally loaded free-head piles was primarily dominated by the limiting force profiles (variation of the net limiting force per unit length with depth) and the maximum slip depth. In recent years, some research has focused on piles in cohesionless soil (Rahman *et al.*, 2003; Chik *et al.*, 2009). Basack and Purkayastha (2007) compared the experimental results with the theoretical results of single piles under lateral cyclic loads in marine clay. Kisshore *et al.* (2009) carried out tests of model piles of PVC and aluminum embedded in soft marine clay bed. The dynamic behavior of piles is another area of interest in recent years (Kitiyodom *et al.*, 2007;

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Supported by: Thailand Research Fund and Commission on Higher Education, Under Grant No. MRG5180268
Received April 14, 2011; **Accepted** June 29, 2011

Boominathan and Ayothiraman, 2007). Hussien *et al.* (2010) in Japan presented experimental and FE analysis of model piles excited by a shaking table.

All the reported research has shown that pile and soil characteristics, position of the lateral loads and embedment depth affect the carrying capacity of piles. However, most of this research focused on the effect of cyclic magnitude and the number of cycles of lateral loading. In this study, quasi-static tests of model aluminum piles were carried out to determine the effect of different pile sections, soil densities and the load eccentricity ratio, *e*/*d*, (*e* is the lateral load eccentricity and *d* is the diameter of pile) on the seismic behavior of single piles.

2 Test program

2.1 Sand used

Dry river sand was used as the foundation medium in the test tank. The properties of the sand were determined through testing as follows: the effective particle size, D_{50} = 0.24 mm; the uniformity coefficient, C_u = 2.56 and the elastic modulus of sand, E_s=20 MPa. For dense conditions (relative density of 70%), the placement density of the sand during testing was 17.6 kN/m^3 and the friction angle was Φ = 43°. For loose conditions (relative density of 30%), the placement density of the sand was 1600 kg/m^3 and the friction angle was Φ = 41°. The sand was saturated with some water to achieve a conformed moisture content of 30% similar to the sandy soil in the Samut Prakan region of Thailand.

2.2 Model piles

Eighteen model aluminum tube piles with different cross sections were used in this test (see in Fig. 1). All the model piles have the same length of 650 mm. The modulus of elasticity for aluminum, E_p, was recorded as 69 GPa. The pile friction angle, δ, was recorded as 37° for dense conditions (70%) and 35° for loose conditions (30%), respectively. The relevant parameters of the model piles are presented in Table 1. The piles were instrumented with three pairs of strain gauges at an interval of 240 mm (see Fig. 2). These gauges were used to find the lateral deflections and bending moment along depth.

2.3 Test set-up

The sand was then placed into a steel tank located inside a steel loading frame, 650 mm in diameter and 750 mm in height (see Fig. 3). The model pile was installed into the sand with a vertical jack to a desired embedded length. The lateral cyclic load was then applied by pneumatic cylinder attached to the loading frame. A load cell was used to measure the cyclic loading (see Fig. 4). The lateral displacements of the piles at the ground line (soil surface) were measured by a linear variable displacement transducer (LVDT).

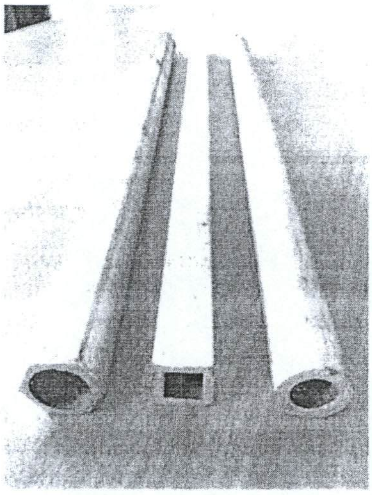

Fig. 1 Aluminum model piles with different section

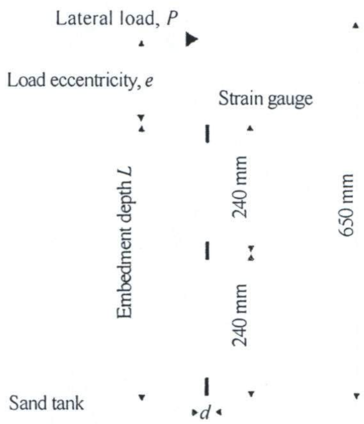

Fig. 2 Dimension of the model piles

Table 1 Parameters of the model piles

Pile No.	Cross section	Outside dimension (mm)	Inside dimension (mm)	Flexural rigidity, E_pI_p (10^6 N/mm^2)
1–6	Square	Length 14	Length 9	183
7–12	Circular	Diameter 16	Diameter 10	188
13–18	Hexagon	Circumradius 10	Inner diameter 13	181

2.4 Test procedure

The pile was free headed and subjected to cyclic lateral loading only. The lateral load was applied from a height of 6 mm (considering the size of cylinder), 60 mm and 120 mm above the sand surface, corresponding to a load eccentricity ratio, e/d, of 0, 4 and 8 (e is the lateral load eccentricity and d is the diameter of pile, shown in Fig. 2). The displacement controlled lateral loading consisted of two cycles of displacement with a ductility factor of increasing magnitude. The ductility factor was the ratio of the maximum displacement in each loading cycle to the displacement at yield. The displacement at yield was defined as 1.33 times the displacement measured in the first loading circle when 0.75 of the ideal flexural strength of this pile was reached (Park and Falconer, 1983). The ideal flexural strength of the pile was obtained from the static loading tests of each pile. The failure of the pile was achieved when a displacement ductility factor of 8 was reached or when the pile was pulled out from the sand.

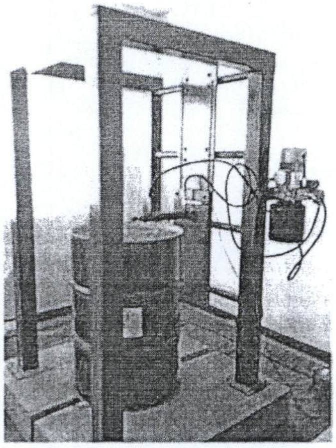

Fig. 3 Loading frame and tank

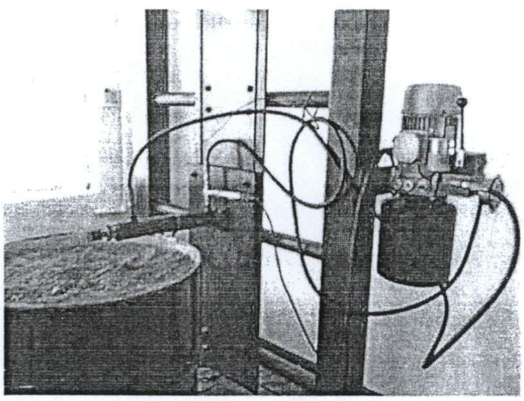

Fig. 4 Pneumatic cylinder

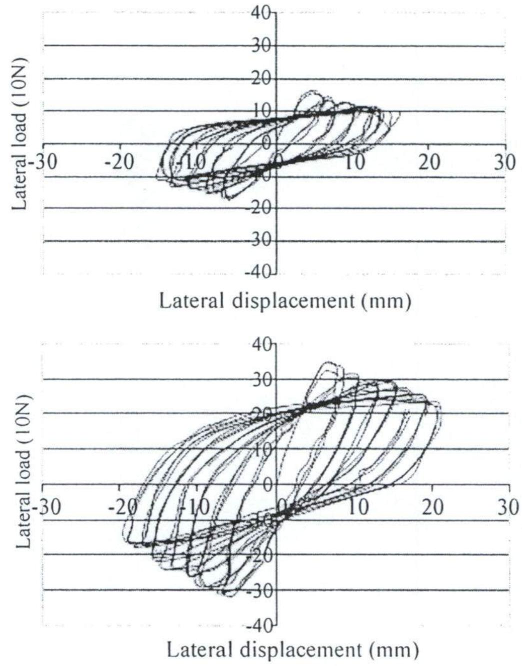

Fig. 5 Measured hysteresis loops for circular section piles in loose sand (top) and dense sand (bottom)

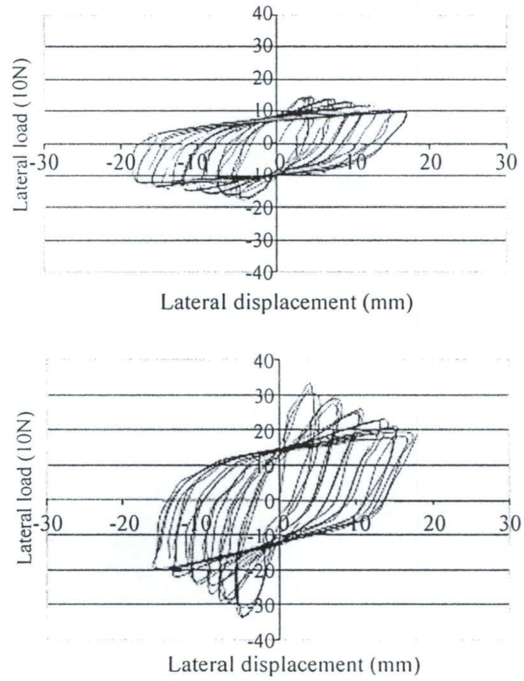

Fig. 6 Measured hysteresis loops for square section piles in loose sand (top) and dense sand (bottom)

3 Test results and discussion

3.1 Load vs. displacement hysteresis loops

Figures 5 to 7 show the measured lateral load versus lateral displacement hysteresis loops for piles with different cross sections embedded in loose and dense sand with load eccentricity ratio $e/d = 0$.

All the piles showed satisfied ductility performance, but the density of the sand was found to have a significant effect on the behavior of the piles. For a pile embedded in dense sand, the peak lateral strength was

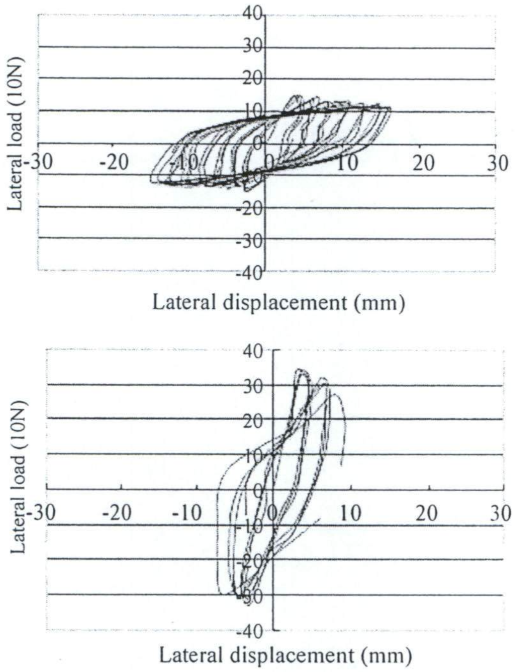

Fig. 7 Measured hysteresis loops for hexagon section piles in loose sand (top) and dense sand (bottom)

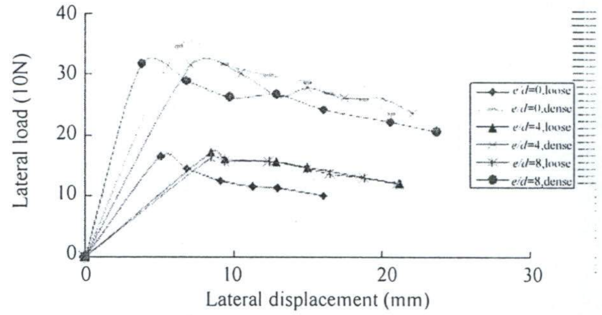

Fig. 8 Skeleton curves for circular section piles

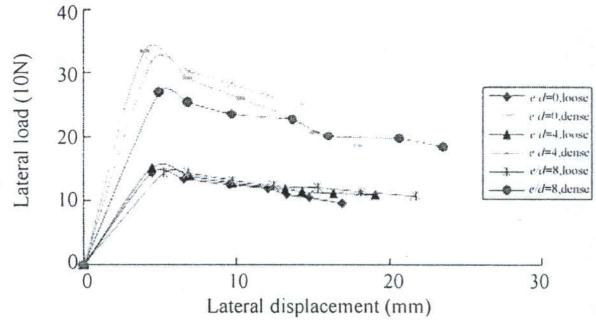

Fig. 9 Skeleton curves for square section piles

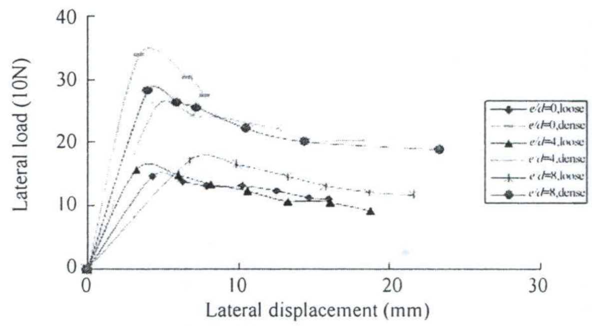

Fig. 10 Skeleton curves for hexagon section piles

about double that of a pile in loose sand. A large lateral strength reduction was induced for piles in dense sand, about 30% to 40% of its peak strength. However, for a pile in loose sand, the drop in lateral strength was more gradual. The main reason for the reduction of lateral strength was the decrease in the passive resistance of the soil bed when the gap around the piles formed.

3.2 Skeleton curves

The skeleton curves were envelopes developed from the lateral load versus displacement hysteresis curves by joining the peak value point of every cycle in the same loading direction. Figures 8 to 10 show the skeleton curves of all 18 model piles with different test variables.

It can be seen from the results that the load eccentricity ratio *e/d* has an obvious effect on the response of the piles. Although the piles have different cross sections, they exhibit coincident behaviors. When embedded in loose sand, the maximum lateral load in all the loading cycles and the maximum lateral displacement at a pile's failure increased as *e/d* increased, which indicated that piles with a higher load eccentricity ratio *e/d* had the better ductility when embedded in loose sand.

Contrarily, when embedded in dense sand, the maximum lateral load of piles decreased as *e/d* increased, while the maximum lateral displacement of the piles increased as *e/d* increased. The lateral resistance of piles with higher *e/d* showed a more gradual reduction with larger magnitudes of maximum lateral displacement, which means that piles with a higher load eccentricity ratio *e/d* embedded in dense sand also had better ductility.

3.3 Energy dissipation vs ductility factor curves

Because the imposed displacement in every circle was not the same for each pile, it is difficult to obtain a conclusion regarding the ductility and energy dissipation capacity of the model piles. Normalized parameters were used in this study to compare the hysteresis characteristics of these piles. The accumulated ductility factor was defined as a ductility factor for a given cycle plus the sum of the ductility factors in all the previous cycles. The energy dissipated by the piles in one displacement cycle was defined as the area enclosed by the overall hysteresis curve of each cycle. Therefore, the accumulated energy dissipation was calculated as the sum of the areas enclosed by all previous hysteresis loops. The relationship between the accumulated energy dissipation and the accumulated ductility factor for the 18 model piles are plotted in Figs. 11 to 14.

The comparison presented in Figures 11 to 13 shows

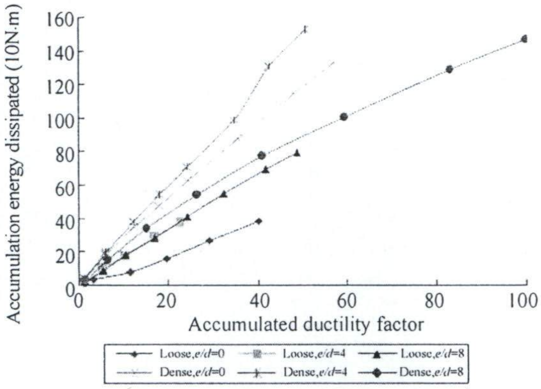

Fig. 11 Test results for circular section piles

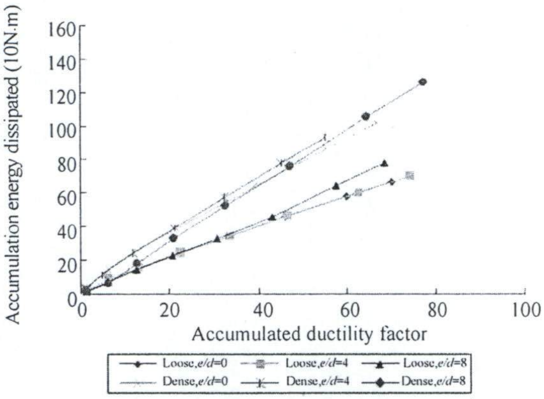

Fig. 12 Test results for square section piles

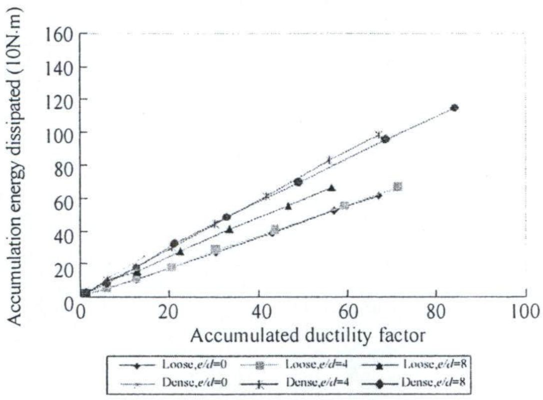

Fig. 13 Test results for hexagon section piles

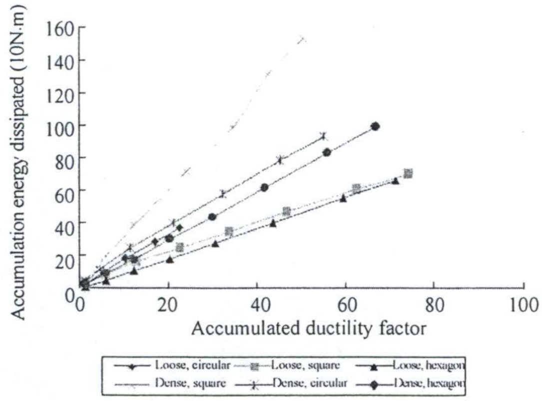

Fig. 14 Test results for model piles with *e/d*=4

that both the sand density and the load eccentricity ratio obviously contributed to controlling the energy dissipation capacity of the piles. At a given level of accumulated ductility factor, the energy dissipation experienced by the piles in dense sand were much higher than of the piles in loose sand. For all three cross sections, piles in dense sand with *e/d* = 4 experienced the highest energy dissipation capacity. Similarly, piles in loose sand with *e/d* = 8 experienced the highest energy dissipation capacity.

Figure 14 shows a comparison of piles of three different cross sections. At a given level of displacement, piles with circular cross sections showed significantly higher energy dissipation capacities in both loose and dense sand. This confirms the qualitative observations based on the shape of the hysteresis curves.

4 Conclusions

This project tested single piles in sandy soil subjected to lateral cyclic loading to investigate the influence of pile's cross section, the embedment depth and the different densities of sand on the seismic behavior of piles. The following conclusions are drawn from the present study:

(1) All the piles exhibited satisfactory ductility performance under seismic loads in sandy soil, but the density of the sand was found to have a significant effect on the behavior of the piles. The lateral capacities and the energy dissipation capacity of piles in dense sand were much higher than in loose sand, because of the increasing of shear resistance due to compaction in the dense sand.

(2) For the pile embedded in dense sand, larger lateral strength reduction was induced than for piles in loose sand.

(3) When embedded in loose sand, the maximum lateral load and the maximum lateral displacement of the piles increased as *e/d* increased. On the contrary, when embedded in dense sand, the maximum lateral load of the piles decreased as *e/d* increased, while the maximum lateral displacement of piles increased as *e/d* increased.

(4) Piles with a higher load eccentricity ratio, *e/d* of 4 or 8, experienced a higher energy dissipation capacity than piles with *e/d* of 0 in both dense and loose sand.

(5) At a given level of displacement, piles with circular cross sections provided the best energy dissipation capacity in both loose and dense sand.

Acknowledgement

The authors gratefully acknowledge the Thailand Research Fund and Commission on Higher Education, Under Grant No. MRG5180268.

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เอกสารแนบ 2

เอกสารตอบรับการตีพิมพ์ (Letter of acceptance)

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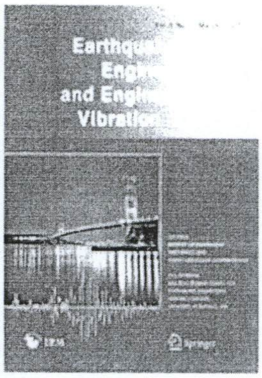

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