An experimental study on cyclic loading of piles in sand

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ABSTRACT

An experimental investigation into piles in sand subjected to lateral cyclic loading was conducted with instrumented model piles. Three typical tests including both static and cyclic loading are presented to study the effect of cyclic magnitude, and number of cycles of lateral loading. Comparison of the test results shows that the pile responses depend more on the magnitude of cyclic load than on the number of cycles.

1 INTRODUCTION

Pile foundations are extensively used in onshore and offshore structures. The piles supporting these structures are inevitably subjected to lateral static and cyclic loading generated by wave, current and wind etc. A variety of approaches have been developed to quantify the effects of cyclic load on piles (Broms 1964, Reese et al, 1974, Poulos, 1982). It has been shown that response of laterally loaded piles are normally dominated by the limiting force profiles (LFP) and its depth of mobilisation (slip, or gapping) along the pile (Guo 2006). In particular, under cyclic loading, the LFP and the depth of 'gapping' will change with the magnitude of cyclic load and number of cycles.

In situ static and cyclic loading tests have been conducted to investigate the behaviour of laterally loaded piles in the past few decades, but they were costly, time consuming, site specific and limited in number (Long & Vanneste, 1994). Small-scale tests and centrifuge tests on piles were also undertaken to determine their ultimate resistance and displacement under working loads (e.g. Kishida, et al 1985; Verdure et al, 2003). With the support of Australia Research Council, an experimental apparatus was developed at Griffith University. It has primarily been used for testing piles undergoing lateral soil movements. Recently, the apparatus has been modified to investigate the pile behaviour under cyclic loading.

In this paper, the modification of the existing testing apparatus for applying lateral cyclic loading is described. A few of typical test results are presented, deduced from the instrumented piles subjected to both static and cyclic lateral loading. The effects of cyclic magnitude, number of cycles on the maximum bending moment induced in piles and accumulated pile deformations are examined.

2 APPARATUS AND TEST PROCEDURES

Information regarding the apparatus has been reported previously by Guo & Ghee (2004). Thus only relevant parts and modification of the loading system for applying lateral cyclic loading are explained herein.

2.1 Storage box and lateral loading system

Figure 1(a) shows a photograph of the experiment apparatus. Figure 1(b) illustrates a schematic cross section of the storage box and loading system. The internal dimensions of the storage box are $1 \times 1 \times 0.8$ (height) m. The upper part of the box is made of a series of 25mm thick square laminar aluminium frames underlain by a 400mm high fixed timber box. A vertical jack is used to install piles into the storage box. The pile is subjected to lateral loading, which is applied via a weight and jack system. A flexible steel wire is attached to the pile. The wire is pulled horizontally through a pulley and loaded via a pan on which dead weights are applied. A hydraulic jack (No.8 in figure

1(b)) is placed underneath the loading pan. Pumping the hydraulic jack will uplift the weights (i.e unloading), while releasing the jack will load the pile. Great care was taken when releasing the jack to ensure the pile was gradually unloaded without impact. Thus, the inertia effect and rate effect are negligible.

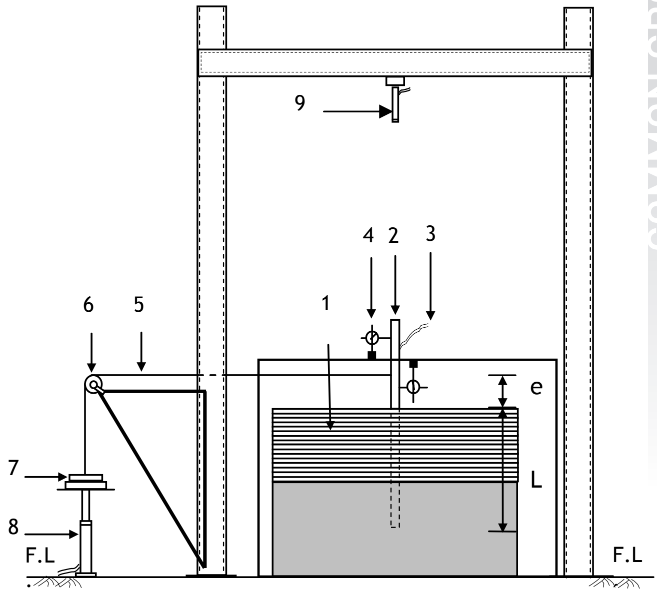

Figure 1(a): Photograph of the experiment set up Figure 1(b): Schematic diagram of the equipment
1.storage box; 2.model pile; 3.strain gauge wires; 4.LVDT; 5.steel wire; 6.pulley; 7.dead weights; 8.hydraulic jack; 9.vertical hydraulic jack

2.2 Model pile

Figure 2 shows a schematic diagram of the model pipe pile used in the tests. The aluminium pile has a length of 1200mm, outside diameter of 32mm and wall thickness of 1.5mm.The pile was instrumented with 10 pairs of strain gauges at an interval of 100mm. Prior to testing, the strain gauges were calibrated by using the procedure explained by Guo & Ghee (2004). In brief, the pile was transversely loaded with both ends clamped. Given various magnitudes of load, measured voltages were compared with calculated strains to give strain/voltage relationship, so that a calibration factor was obtained for each gauge, which in turn allows a measured strain to be converted to an actual strain. To protect from damage, the gauges were covered with 1mm epoxy and wrapped by tapes.

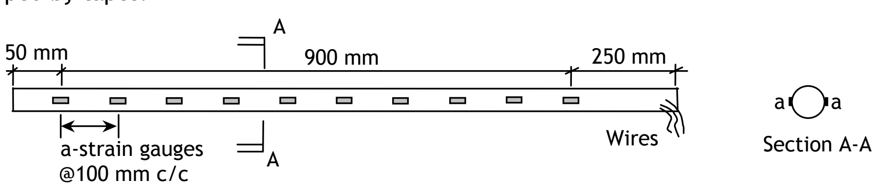

Figure 2: Instrumented model pile

2.3 Sand properties

In this study, oven dried medium grained quartz sand was used, with the properties noted below (Guo & Ghee, 2004): The effective particle size D_{10} of the sand is 0.11mm, with uniformity coefficient C_u of 2.92, and coefficient curvature C_c of 1.15. Sand was discharged into the storage box through of a rainer hanging over the box to achieve a reasonably uniform density with depth and from one test to another. A falling height of 600mm was chosen to produce a uniform density of 16.27kN/m^3. An angle of internal friction of 35° was determined from direct shear tests.

2.4 Test procedures

The storage box was firstly moved into the position beneath the sand rainer, which was suspended from an overhead crane in the laboratory. The storage box was secured, and sand then rained into the shear box from 600mm height. Secondly, the storage box was carefully moved to position under the vertical loading frame using a pallet truck. Thirdly, the pile was installed into the sand with the vertical jack to a desired embedded length. Fourth, the triangular steel frame (Figure 1) with the pulley was clamped on the vertical columns. The lateral loading devices were set up. Fifth, LVDTs were connected to the pile and strain gauges to a data acquisition system (which was controlled by a computer). By then, the pile was ready to be tested under static or cyclic loading. Upon finishing each test, the loading system and measuring devices were removed first, then the pile was withdrawn, and finally sand was emptied through an outlet at the base of the box.

2.5 Test details

Three typical tests on the model pile are presented using an embedded length of 500mm and eccentricity of 115mm, as shown in Table 1. The pile was restrained by soil only (free-headed), and was subjected to lateral loading only. TS1 was conducted under a gradually increased static loading until failure. TC1 and TC2 were tested under one-way cyclic loading. For instance, in Test TC1, lateral load was increased from a minimum value of P_{min}=0 to a maximum of P_{max}=215N and returned to P_{min}= 0 (no reversal of loading direction). This was repeated for 50 times (cycles). Afterwards, the pile was loaded monotonically until failure. The same loading procedure was used in Test TC2.

Table 1: Test details

Test	Loading type	Max lateral load P_{max}, N	Min lateral load P_{min} , N	Embedded length L,mm	Eccentricity e, mm
TS1	static	720		500	115
TC1	cyclic	215	0	500	115
TC2	cyclic	430	0	500	115

3 TEST RESULTS

A spreadsheet program operating in Microsoft Excel designed for pile undergoing lateral soil movement was modified and used to analyse the current test results, assuming free-headed condition and zero bending moment and shear force at the pile tip. The displacement profiles along the pile were derived from 2nd order numerical integration of the bending moment profiles. The profiles of shear force were deduced by single numerical differential of the bending moment profiles. The relationship between lateral load and pile displacement at ground, bending moment, shear force and displacement profiles were presented subsequently for each test.

3.1 Static loading test TS1

Test TS1 was conducted to determine the ultimate lateral loading capacity of the pile. Figure 3(a) shows the relationship between lateral load and pile displacement at the ground surface. The nonlinearity of the load displacement curve was apparent. The ultimate lateral load capacity was deduced as 740N, assuming a hyperbolic load-displacement relationship. Figure 3(b) shows the distribution of bending moment along the pile. The bending moment increased monotonically with the increase in lateral load (from 50N to 150 N, etc). For example, the maximum bending moment was deduced as 100.5N.m at lateral load of 700N, which occurred at a depth of 160mm below the ground. Figure 3(d) indicates the pile deflected mainly by rotating about a depth of 340mm.

3.2 Cyclic loading test TC1

For the TC1 cyclic loading test, Figure 4 presents the pile responses at the specified number of cycles. The strain gauges and LVDTs readings were recorded for each of the first five cycles, and every 5th cycles afterwards, which was the same for TC2 presented later on. The total pile displacement increased with increasing number of cycles. Slight increase in bending moment distribution along the pile was measured at larger number of cycles. The total pile displacements at ground level were 3.1mm and 4.9mm for the first and 50th cycles, respectively. Plastic soil deformation around the pile was noted (Figure 5). The separation between the pile and sand indicated a 'gap' occurred under the cyclic loading. It was noticed that with the number of cycles increasing, the failure zone enlarged and depth of the gap increased. The depth of the gapping was approximately 24mm after 50 cycles.

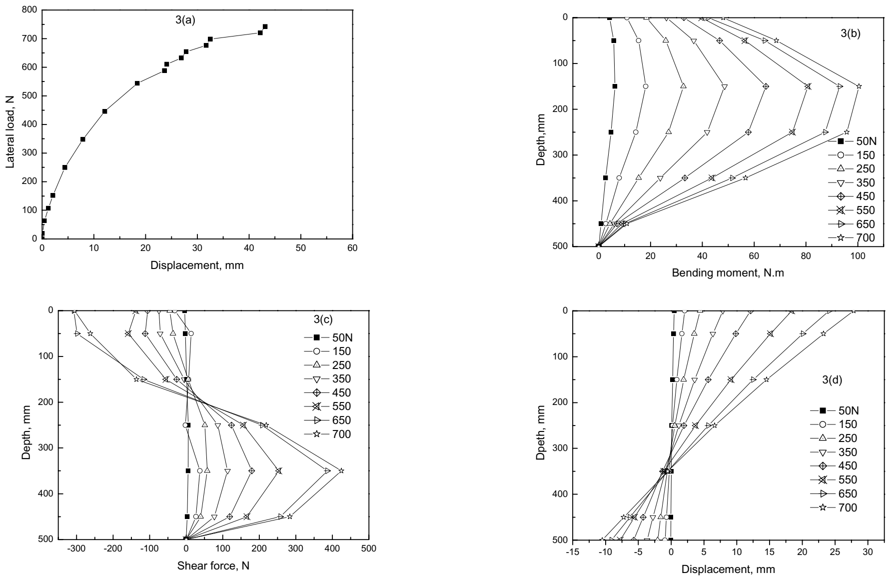

Figure 3: Response of pile during test TS1

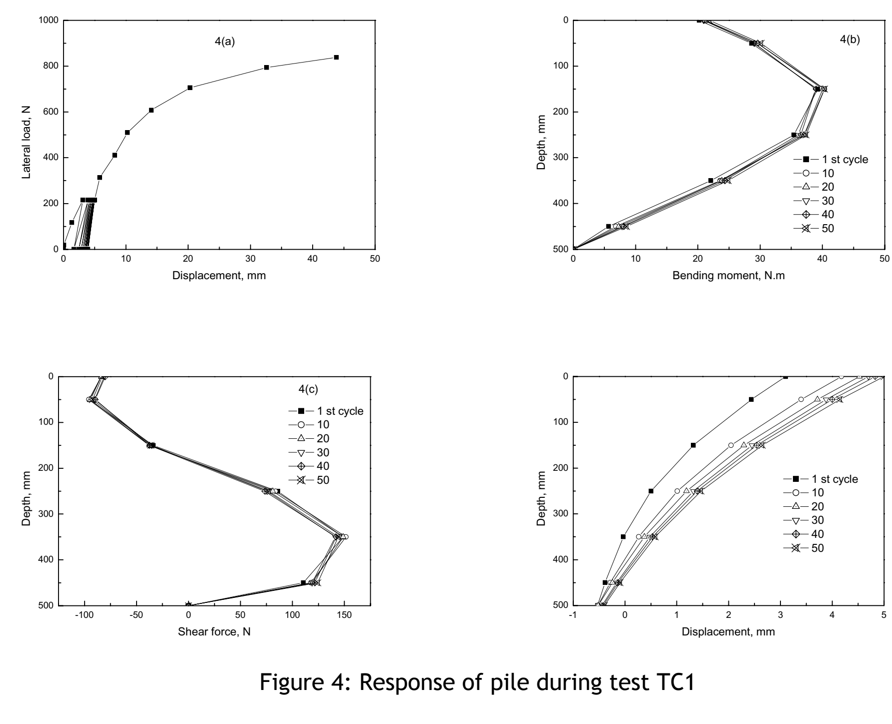

Figure 4: Response of pile during test TC1

3.3 Cyclic loading test TC2

Test TC2 was performed under identical condition to Test TC1, except that the magnitude of the lateral cyclic load was increased to 430N, which was about 60% of the ultimate lateral loading capacity of 740 N determined from TS1. This is to investigate the effect of the magnitude of cyclic load on the behaviour of the pile. Figure 6 shows the responses of the pile during the test. The relationship between the load and pile displacement is similar to that gained from Test TC1. However, the maximum bending moment at 50^{th} cycle was about 4% lower than that at the first cycle with a value of 81.5N.m. The zone of plastic soil deformation was also larger than that around TC1 with a depth of the gapping increased to 33.4mm after 50 cycles.

Figure 5: Soil displacement around the pile

Table 2: Summary of critical pile responses

Test	cycles	M_{max} N.m	V_{max} N	X_m mm	y_g mm	P_u N
TC1	1	40.1	144	160	3.1	810
	50	41.3	148	160	4.9	
TC2	1	81.5	324	220	8.1	820
	50	78.5	293	220	14.9	
TS1*	static	100.5	424	160	27.8	740

* Critical pile responses at P_{max}= 700N

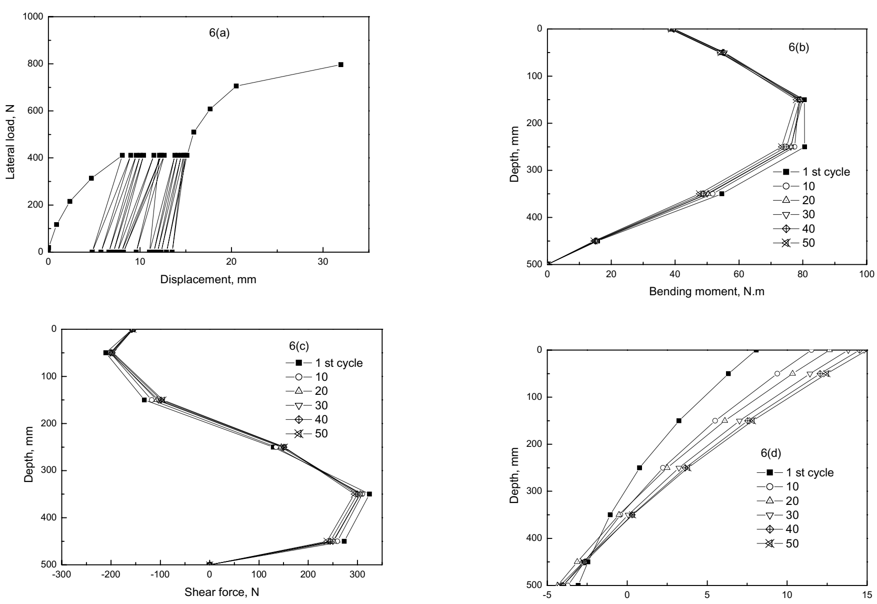

Figure 6: Response of pile during test TC2

4 DISCUSSION

Table 2 summarizes the critical responses of maximum bending moment M_{max}, shear force, V_{max}, depth of maximum bending moment X_m, and pile displacement at the ground y_g for the first and

50th cycle. Figure 7 shows the variation of M_{max} and y_g with the number of cycles. The effect of the first 10 cycles is more significant than the subsequent ones. For a specific cyclic loading condition, the total pile head displacements increase with increase in number of cycles, but at a decreased rate. From cycle 1 to 50, the y_g increases 60% and 85% in Tests TC1 and TC2, respectively. The increase in cycles, however, has a limited effect on the M_{max}. Figure 7 shows influence of number of cycles on the moment and deformation obtained from Tests TC1 and TC2. Apparently, the magnitude of the cyclic load has more profound impact than number of cycles. As the magnitude of cyclic load increases from 215N to 430N, the M_{max} is doubled, while the pile head displacement increases about 2.6 times for the first cycle, and is tripled for the 50^{th} cycle. The ultimate lateral loading capacity of TC1 and TC2 after 50 cycles is approximately 10% higher than that deduced from static loading test TS1, which shows slight densification of the sand under cyclic loading condition.

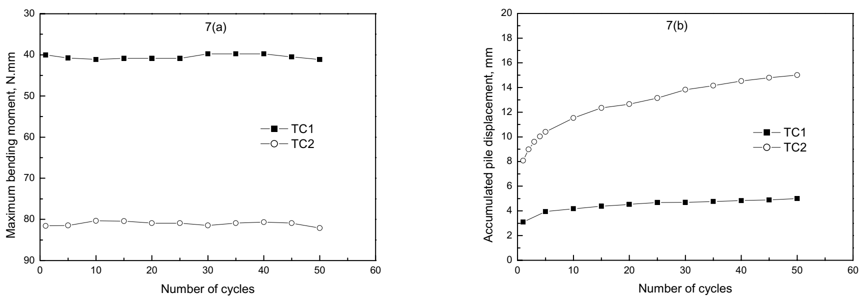

Figure 7: Critical pile response with number of cycles

5 CONCLUSIONS

Model tests have been conducted to investigate the responses of cyclic loaded lateral piles in sand. Three typical tests are presented, which show under cyclic loading (1) a slight increase (10%) in lateral load capacity of the pile compared to static loading; (2) 2~3 times increase in maximum bending moment by doubling the cyclic magnitude (from 215 to 430 N), even through the maximum magnitude of 430 N is about 50% the ultimate capacity of 820N; (3) 60~80% increase in the total pile displacement, but little change in the maximum bending moment with increase in number of cycles. More study is needed on the effect of magnitude of cyclic loading and its pattern.

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