

Group Effects of Piles Due to Lateral Soil Movement

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ABSTRACT: Laboratory model tests have been conducted to investigate the responses of piles subjected to lateral soil movement. The results of a single pile test and four tests on two piles arranged in a row perpendicular to the direction of soil movement are presented. The development of maximum bending moment, maximum shear force, and pile deflection with soil movement and the largest pile response profiles for the single pile and pile groups are compared. Group effect was evaluated using group factor which is defined in terms of the measured maximum bending moment. The major findings are (1) the pile head conditions (free or capped) are insignificant on piles subjected to lateral soil movement when arranged in a row, (2) the group factor decreases as the pile spacing reduces, (3) a linear relationship exists between the maximum bending moment and maximum shear force for both the pile groups and single pile.

Keywords: Piles, Group Effect, Lateral Soil Movement

1. INTRODUCTION

Structures built on piles are vulnerable to lateral forces caused by soil movements, which may be seen when they are used in slope stabilization, to support bridge abutments, and as foundations of tall buildings adjacent to tunneling and excavation or lateral spreading in liquefied sand during earthquake. Lateral loads generated by soil movements induce additional deflections and bending moments in piles or pile groups, which may undermine the structural integrity of the piles or groups and leads to serviceability or even failure of the piles. Although this characterization has been extensively studied through centrifuge modeling and 1g small scale model tests in [1]-[9], field tests in [10], [11] and theoretical and numerical analysis in [12]-[18], the pile soil interaction mechanism is still not clearly understood. For instance, the recent numerical studies in [12], [13] assumes a fixed depth of moving soil, in which the movement of soil is simultaneously mobilized along the pile. However, in a practical scenario, soil movement may be gradually mobilized to a deep layer [18]. The effect of progressive soil movement on the response of piles has not been completely investigated, particularly, when it is coupled with axial load.

With an experimental apparatus developed, extensive tests have been undertaken for piles and pile groups in sand to investigate the responses of piles under combined vertical load and lateral soil movement. Reference [5] presents simple solutions for piles in moving sand from the results of 14 typical 1g model pile tests. References [7], [8] further verified the solutions and findings by investigating the pile responses due to effective soil movement and impact of a uniform and triangular soil movement profile.

This paper investigates the group effects of piles due to lateral soil movement. Four tests on a group of two piles in a row with the pile head capped and a single pile of free head were conducted. Typical pile responses are presented. Group factors are used to quantify the group effect and

compared with previous experimental and numerical analysis results.

2. APPARATUS AND TEST PROCEDURES

For brevity, detailed information regarding the apparatus, test preparation, data acquisition and measurement system, and data process program are omitted. Only the relevant parts are briefly introduced herein.

2.1 Shear Box and Loading System

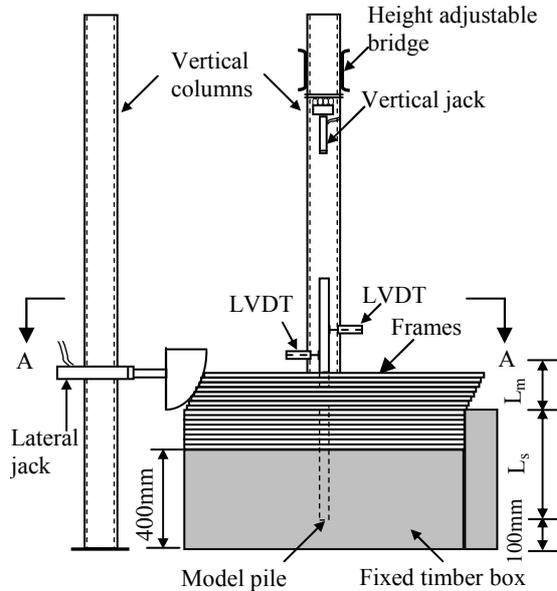
A schematic cross section of the shear box and the loading system is shown in Fig. 1. The internal dimensions of the shear box are 1 m by 1 m, and 0.8 m in height. The upper part of the shear box is made of a series of 25 mm thick square laminar steel frames. The frames, which are allowed to slide, contain the "moving layer of soil" of thickness L_m . The lower section of the shear box comprises a 400 mm high fixed timber box and the desired number of frames to achieve a "stable layer of soil" of thickness L_s (≥ 400 mm). A loading block is used to apply lateral force on the laminar frames, which is made into arc, rectangular, and triangular shape to impose varying soil movement profiles. In this paper, an arc loading block was used. The rate of movement of the upper shear box (thus the soil) is controlled by a hydraulic pump (lateral jack), and a flow control valve. A vertical jack is used to install the pile into the shear box.

2.2 Model Piles

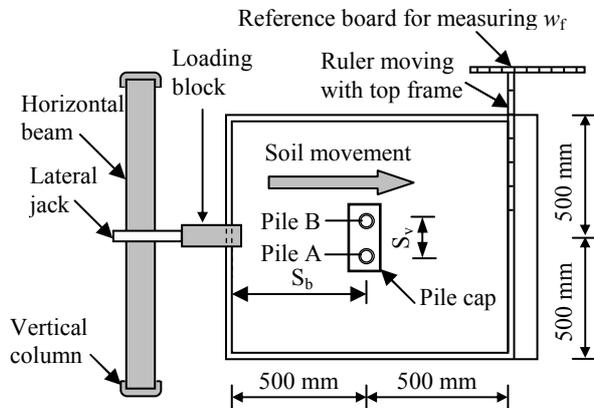
Fig. 2 shows a schematic diagram of the model pipe pile under testing. The aluminum pile has a length of 1200 mm, outer diameter of 32 mm and wall thickness of 1.5 mm. The pile was instrumented with 10 pairs of strain gauges at an interval of 100 mm. Prior to testing, the strain gauges were calibrated by exerting a transverse load in the middle of the pile clamped at both ends. Given various magnitudes of the load, measured strains were compared with those calculated for each gauge, so that a calibration factor was obtained, which in turn allows a measured strain to be converted to an actual strain. To protect from damage, the strain gauges were covered with 1mm epoxy and wrapped by tapes.

2.3 Sand Properties

The sand used in this study was oven dried medium grained quartz sand with a uniformity coefficient C_u of 2.92 and a coefficient of curvature of C_c of 1.15. The sand was discharged into the shear box through a rainer hanging over the box to achieve a reasonably uniform density within the shear box. The falling height of the sand was chosen as 600 mm, which gave a uniform relative density of about 89%, and a unit weight of 16.27 kN/m^3 . Angle of internal friction was evaluated as 38° from direct shear tests.



(a) Elevation view



(b) Initial plan view (A-A)

Figure 1. Schematic of shear box

2.4 Test Procedures

The model tests were conducted using an arc loading block as shown in Fig. 2. The instrumented pile was installed at a distance, S_b of 500 mm from the loading side (see Fig. 1(b)) to an embedded depth, L of 700 mm in the shear box. The predetermined final sliding depth, L_m and stable layer depth, L_s was maintained as 200 mm and 500 mm. After pile installation, a pile cap fabricated from solid aluminum was used to secure the piles in the pile cap. Weights were put on the pile cap to apply axial load. The strain gauges were connected to a data acquisition system and measurement system established. During testing, the frame

movement, w_f was measured from a reference board using a ruler moving with the top frame (see Fig. 1(b)) and up to 120 mm. Each test is denoted by a combination of letters and numbers, e.g. AS32-0 or AG32-3d-294, where ‘AS’ or ‘AG’ signifies Single pile or pile Group test using an Arc loading block; ‘32’ indicates 32 mm in diameter, ‘3d’ denotes the pile center to center spacing, $S_v=3d$, ‘0’ or ‘294’ represents an axial load of 294 N or 30 kg per pile.

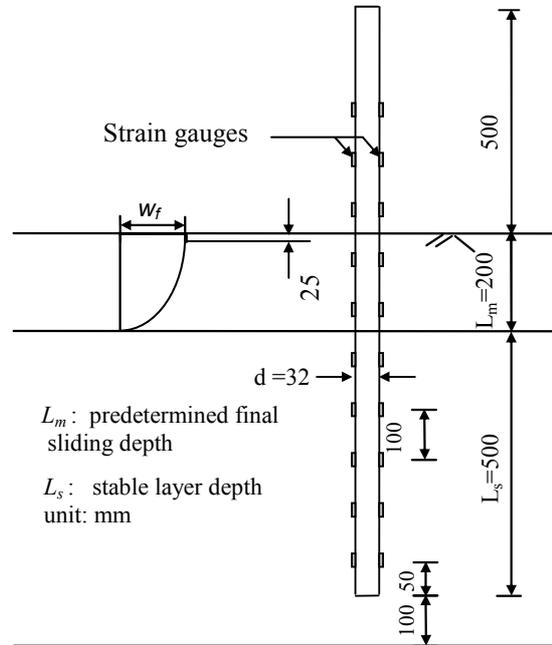


Figure 2. Schematic of a tested pile

3 TEST RESULTS

The pile deflection profiles were derived from double numerical integration of the bending moment profiles, using the measured pile deflection and rotation at ground surface as input boundary conditions. The shear force profiles were deduced by single numerical differentiation of the bending moment profiles. It is noted that both piles A and B (Fig. 1(b)) were instrumented with strain gauges. The pile responses obtained from the two piles are similar, therefore only the data collected from pile A were used. These profiles were plotted at every 10 mm frame movement, w_f for all the tests. Due to space limitation, only the profiles in tests AS32-0 and AG32-3d-0 were presented. The development of maximum bending moment, M_{max} , shear force, T_{max} and pile deflection at ground line, y_0 are plotted against the frame movement, w_f for all the tests. Table 1 summaries these values at $w_f=120$ mm.

3.1 Test AS32-0

Test AS32-0 was conducted without axial load. Similar to the tests using a triangular loading block described in [5], the arc loading block induces an increasing soil movement both horizontally and vertically with the progressive mobilization of the frames. Fig. 3 shows the pile response profiles for the frame movement, w_f up to 120 mm. The bending moment profile is of parabolic shape when $w_f \geq 90$ mm. The bending moment increases significantly at a frame movement $w_f \geq 80$ mm and has not reached the ultimate

value even at $w_f=120$ mm. The measured maximum bending moment occurs at about the same depth of 350 mm, which is about half of the pile's embedded length. At $w_f=120$ mm, two local largest shear forces of -137.2 N and 122.4 N was deduced from the bending moment profile. The pile rotated around the pile tip with a deflection of 4.2 mm at the ground level.

3.2 Test AG32-3d-0

Test AG32-3d-0 was conducted with the pile arranged in a row ($S_v=3d$) perpendicular to the direction of soil movement and pile head capped as shown in Fig. 1. Presented in Fig. 4 are the five response profiles. A very similar trend to those observed in the single pile test TS32-0 was noted. At $w_f=120$ mm, the maximum bending moment, M_{max} , is 23.5 kNmm, occurring at a depth of 350 mm. Again, two largest shear forces, T_{max} of -96.2 N and 88.8 N occur in the sliding and stable layers, respectively. The pile deflected by rotation, with a magnitude of about 3.6mm at the ground level.

3.3 Response of M_{max} , T_{max} and y_0 versus w_f

The development of the maximum bending moment, M_{max} shear force, T_{max} and pile deflection at ground level, y_0 for the five tests are plotted in Figs. 5(a), 5(b) and 5(c) against the frame movement, w_f . These figures demonstrate:

- The initial frame movement w_i of 40mm caused negligible or little M_{max} , T_{max} and y_0 for the pile group tests and single pile test using the arc loading block. At $w_f=40\sim 80$ mm, the three critical responses for the single pile are generally less than those of the piles in a group, but overall the pile responses are still very small. Afterwards, the single pile responses surpass those of the pile groups, showing greater rigidity of the pile groups with the pile head capped at larger soil movement.
- The development pattern of M_{max} , T_{max} and y_0 with w_f for the pile groups and single pile are similar, revealing that the pile cap and pile-soil-pile interaction have insignificant impact on the performance of the two piles in a row.
- Imposing the axial load of 588 N on the pile cap, i.e. 294 N per pile, and the pile spacing of 3d and 5d have little impact on the development pattern of M_{max} , T_{max} and y_0 with w_f .

3.4 Maximum Pile Response Profiles

The largest bending moment, shear force and pile deflection profiles with depth for the five tests at $w_f=120$ mm are plotted in Figs. 6(a), 6(b) and 6(c). These figures show that

- The bending moment profiles of the pile group tests and single pile test are similar amongst themselves and analogous to parabolic. The maximum bending moment occurs at a depth of 350mm below the ground surface, which is 0.5 times of the pile embedded length.
- The shear force profiles are also of similar shape. Two local largest shear forces of approximately equal magnitude but of opposite signs are deduced from the bending moment profiles.
- The bending moment and shear force profiles of the single pile encompass those of the pile group tests.
- Pile deflects mainly by rotation about the pile tip or a depth near the pile tip.

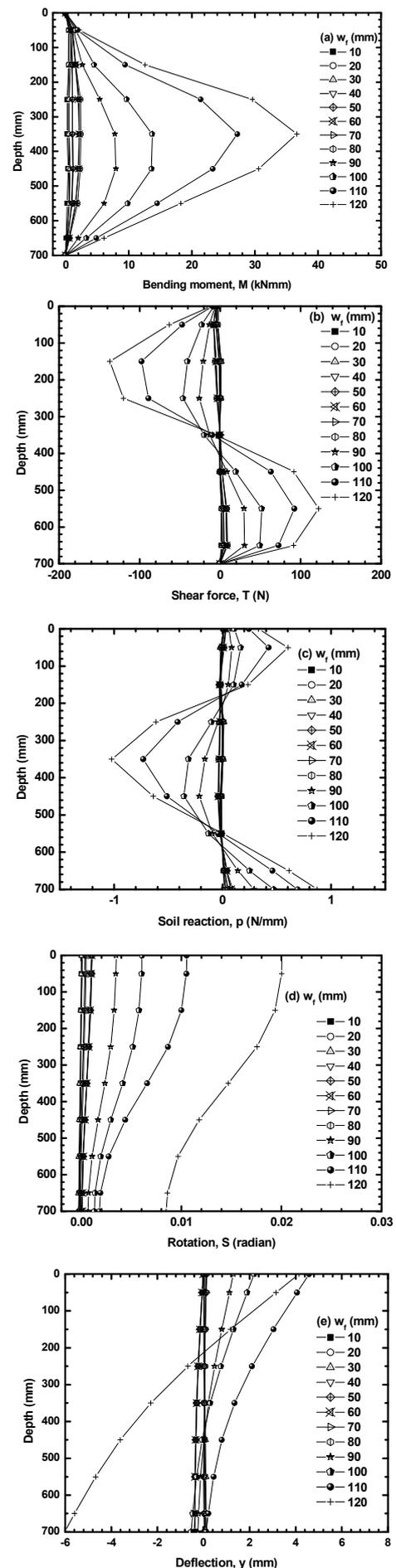


Figure 3. Response of pile during AS32-0

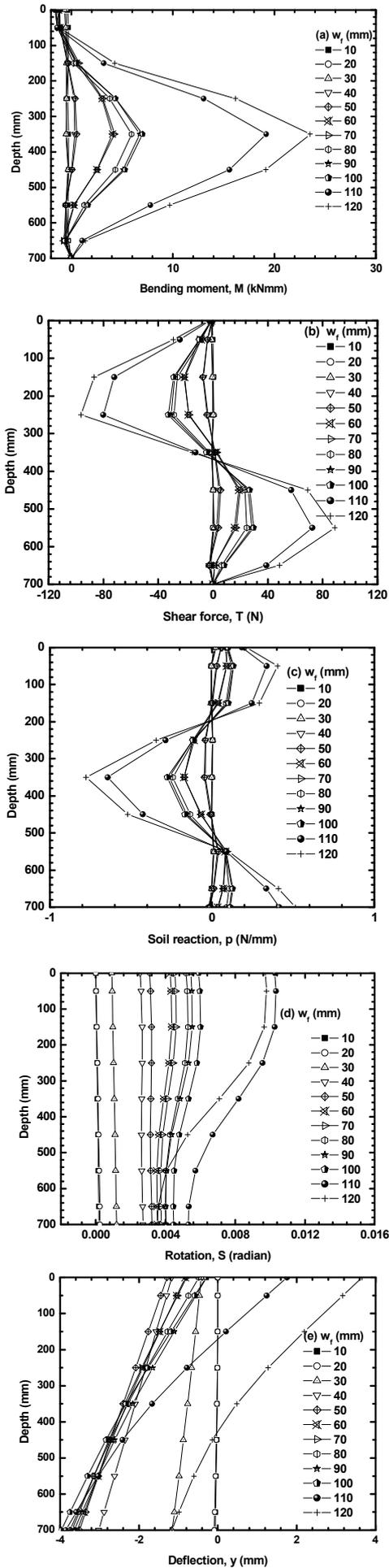


Figure 4. Response of pile during AG32-3d-0

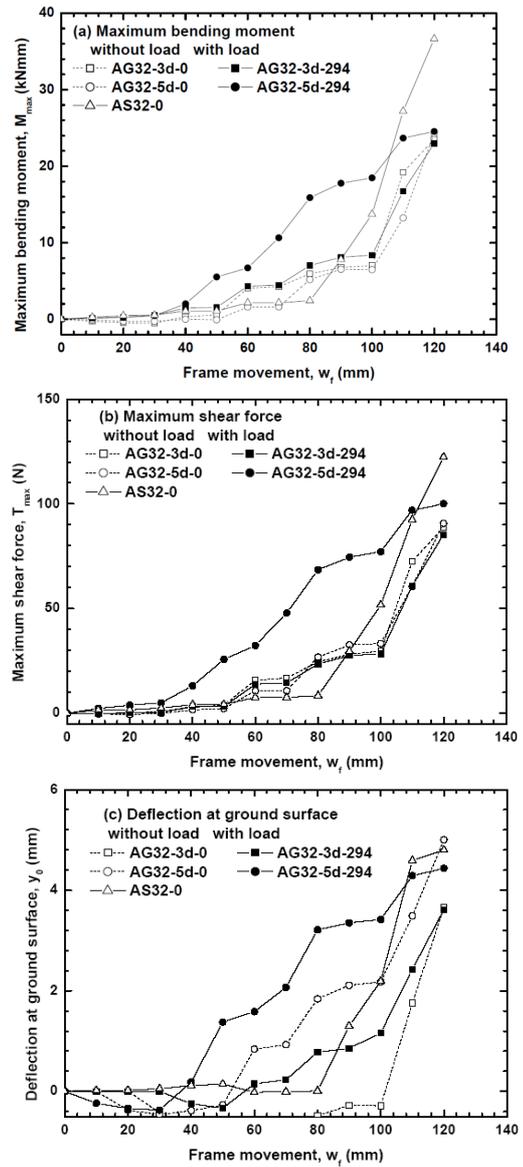
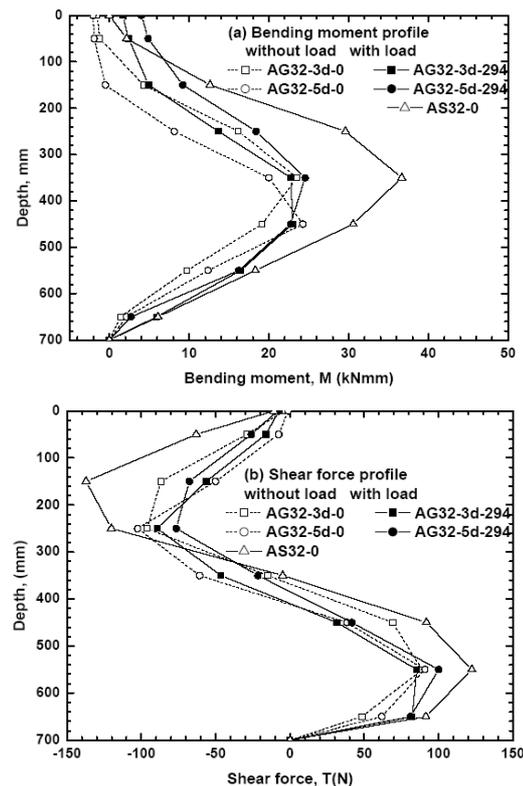


Figure 5. Evolution of maximum response of piles



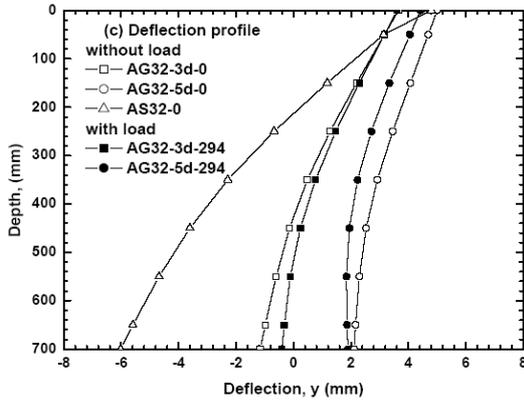


Figure 6. Maximum response profiles of piles

- The axial load of 588 N and pile spacing of 3d and 5d have little impact on bending moment and shear force profiles, except that very small bending moment of 1.67 kNm and 4.0 kNm was measured at the ground level in tests AG32-3d-294 and AG32-5d-294.

4 DISCUSSIONS

4.1 M_{max} versus T_{max}

The deduced T_{max} in Fig. 5(b) are plotted in Fig. 7 against the corresponding measured M_{max} in Fig. 5(a) for the five tests. A remarkably good linear relationship between T_{max} and M_{max} under any w_f , independent of the pile head restraint conditions and pile spacing, was shown in Fig. 7. Reference [5] presents equivalent elastic solutions for piles subjected to moving sand, giving

$$M_{max} = T_{max}L/m \quad (1)$$

where $L(=0.7m)$ is the embedded length of the pile and m is a non-dimensional constant. The value of m is estimated as 2.8 with a variation of $\pm 5\%$ for the best curve fitting between T_{max} and M_{max} for the 32mm diameter pile tests using a triangular loading block. The current test results corroborate this linear relationship as shown in Fig. 7. This equation may be used in the estimation of the lateral thrust (shear force), which is required in the design of reinforcing piles to increase slope stability [15].

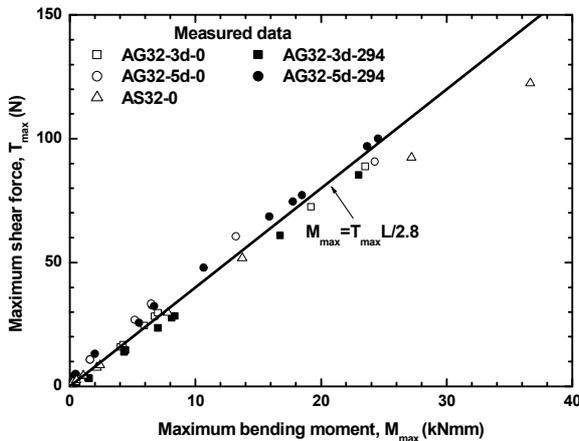


Figure 7. Maximum response profiles of piles

4.2 Group Effect

In order to assess the group effect and investigate the pile-soil interaction behavior of piles subjected to lateral

soil movement, the critical pile responses of a pile within a group, such as the maximum bending moment, pile head deflection and limiting soil pressure are compared with those of a single pile. Investigation on group effect on the behavior of piles subjected to lateral soil movement has been carried out both numerically and experimentally on piles with various pile head fixity conditions in sand and weathered soil in [2],[4],[16]. Reference [4] demonstrates that the group effect quantified in terms of measured maximum bending moment may be more reliable and consistent.

In this study, the group effect was evaluated by a group factor, F_m based on the measured M_{max} .

$$F_m = \frac{M_{gmax}}{M_{smax}} \quad (2)$$

in which M_{gmax} is the maximum bending moment for a pile in a group at a frame movement, M_{smax} is the maximum bending moment from the single pile at the same frame movement. Table 2 summarize the group factors, F_m at $w_f = 120$ mm and those obtained from the previous studies on capped-piles in sand.

Table 1 Summary of test results at $w_f=120$ mm

Test	M_{max} (kNm)	T_{max} (N)	y_0 (mm)
AS32-0	36.6	122.4	3.6
AS32-3d-0	23.5	88.8	5.0
AS32-5d-0	24.3	90.7	3.6
AS32-3d-294	22.9	85.3	4.4
AS32-5d-294	24.5	100.0	4.8

Table 2 Summary of group factor F_m

Spacing	2.5	3	5	7
Current (without load)		0.64	0.66	
Current (with load)		0.63	0.67	
Reference [16]	0.82		0.94	0.96
Reference [4]	0.72		0.78	0.84

The current test results indicate that for the capped-piles in a row, the group factor F_m for the group with a spacing of 3d is less than those of 5d. The axial load of 294 N per pile has virtually very limited impact on the group factors. The group factors are plot in Fig. 8 against the normalized pile spacing. It is found that the group factors are less than unit in the investigated pile spacing of $(2.5\sim 7)d$ and decrease as the pile spacing decreases. Nevertheless, the group factors from the current results are 17% and 30% less than those presented in [2] and [16] on average. This may be attributed to the pile positions in the shear box discussed below.

The experimental results from three series of nine tests on a 25mm and 32mm pile using a triangular and a rectangular loading block [5]-[7] show that the M_{max} decreases with increasing distance S_b between the pile location and the loading side where free soil movement is generated. The experimental investigation on two piles in a row subjected to soil movement induced by a triangular loading block in [6] further reveals that the group factor F_m decreases with increasing S_b for both free and capped pile head fixity conditions.

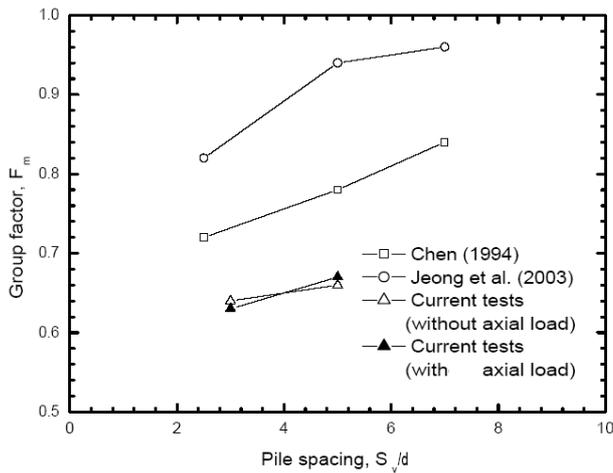


Figure 8. Variation of F_m with pile spacing S_v/d

5 CONCLUSIONS

Laboratory model tests were conducted to investigate the responses of piles due to lateral soil movement. The results of a single pile test and four group tests on two piles in a row with pile head capped were presented. These tests were carried out using an arc loading block, which induces progressive soil movement. The group effect was assessed by using group factors. The key findings from the studies are summarized as follows:

1. The bending moment, shear force and deflection profiles for a pile in the two piles in a row group tests are analogous to the shape of those in a single pile test, including the position of the maximum bending moment, but their magnitudes are generally smaller, showing group effect.
2. The development pattern of M_{max} , T_{max} and y_0 with w_f for the pile groups and single pile are similar, revealing that the pile cap and pile-soil-pile interaction have insignificant impact on the performance of the two piles in a row.
3. The axial load of 588 N on the pile cap, i.e. 294 N per pile, has little impact on the responses of the capped piles in a row.
4. A linearly relationship exists between the M_{max} and the T_{max} , which can be described by Eq. (1) with $m=2.8$.
5. The group factors, F_m are less than unit in the investigated pile spacing of (2.5~7)d and decrease as the pile spacing decreases.
6. The group factors, F_m from current experimental investigation are 17% and 30% less than those obtained in [2], [16].

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