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Model tests on free-standing passive pile groups in sand

Wei-Dong Guo
Griffith University, wdguo@uow.edu.au

E. H. Ghee
Griffith University

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Abstract

A number of tests have been conducted to investigate response of vertically loaded capped pile groups in sand undergoing uniform lateral soil movement. The development of shear force, bending moment and deflection along the piles was measured. Presented in this paper are 4 tests on 2-pile free-standing groups, with a view to establish solutions for predicting the pile response. It was concluded that (1) maximum bending moment Mmax is largely linearly related to the sliding force Tmax in stable and moving layers; (2) The combined impact of pile-cap fixity, soil movement profiles, and axial load may be quantified by a single moment (Mo); (3) Each pile in a group behaves as free-head in stable layer or semi-fixed head in sliding layer, with a floating base; and (4) The previous solutions for single piles were extended to simulate Mmax and Tmax for piles in groups.

Keywords

groups, standing, sand, passive, free, tests, model, pile

Disciplines

Engineering | Science and Technology Studies

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Model tests on free-standing passive pile groups in sand

Wei Dong Guo & E. H. Ghee
Griffith University, Gold Coast, Australia

ABSTRACT: A number of tests have been conducted to investigate response of vertically loaded capped pile groups in sand undergoing uniform lateral soil movement. The development of shear force, bending moment and deflection along the piles was measured. Presented in this paper are 4 tests on 2-pile free-standing groups, with a view to establish solutions for predicting the pile response. It was concluded that (1) maximum bending moment M_{max} is largely linearly related to the sliding force T_{max} in stable and moving layers; (2) The combined impact of pile-cap fixity, soil movement profiles, and axial load may be quantified by a single moment (M_o); (3) Each pile in a group behaves as free-head in stable layer or semi-fixed head in sliding layer, with a floating base; and (4) The previous solutions for single piles were extended to simulate M_{max} and T_{max} for piles in groups.

1 INTRODUCTION

Pile foundations designed to support offshore platforms, structures and services may be subjected to lateral soil movements and axial loads simultaneously. There are extensive studies on piles subjected to vertical loads, and some research on piles subjected to lateral soil movements. Limit equilibrium solutions were derived for piles in a two-layered cohesive soil (Viggiani 1981; Chmoulian 2004). They allow maximum bending moment M_{max} to be correlated to lateral thrust T_{max} by stipulating (i) A fixed sliding depth; and (ii) A uniform soil movement profile (without axial load on pile-head). The solutions are popularly used for passive piles.

Among others, elastic solutions (Fukuoka 1977; Cai and Ugai 2003) and elastic-plastic solutions (Guo 2009) were developed. The former compares well with measured pile response at the reported loading level. The latter (elastic-plastic) solutions capture well nonlinear response of passive piles at any soil movement. The impact of soil movement profiles on the response has been clarified recently via model pile tests, coupled with an axial load and in pre-failure state. For instance, Guo & Qin (2010) presents 14 typical test results under an inverse triangular loading block. They revealed a linear relationship between the bending moment M_{max} and the thrust T_{max}, from which they proposed simple expressions to capture the relationship with respect to impact of subgrade modulus, vertical load, 2 (translational or rotational) loading modes, and effective soil movement. The solutions are further verified against measured data from eight in-situ test piles and one centrifuge test pile by Guo (2009).

In this paper, typical test results are presented for instrumented model piles in 2-pile groups in sand, subjected to a uniform lateral soil movement and an axial load. They are analyzed to indicate the impact of the thickness of the movable soil layer, axial load, and pile-cap fixity. The linear relationship between the M_{max} and the thrust T_{max} was explored, which renders the solutions for single piles to be extended to piles in groups.

2 TEST DESCRIPTION

The group pile tests were conducted using a shear apparatus reported previously by Guo & Ghee (2004). Relevant information is introduced herein.

2.1 *Shear apparatus*

Figure 1 shows the schematic of the shear box. It has internal dimensions of 1 m by 1 m, and 0.8 m in height. The upper box for sliding depth (SD) L_1 is movable, which consists of a number of 25 mm thick square laminar aluminium frames. It allows a desired number of the frames to be moved together by a rectangular loading block (for this research to generate a uniform lateral soil movement) to a selected L_1 (< 400 mm). The lower section of the box is made of a fixed timber box 400 mm in height and a number of laminar aluminium frames, which allows a stable sand layer of thickness L_2 (≥ 400 mm). The rate of the frame movement w_f of the upper box is controlled by a hydraulic pump, and a flow control valve.

Figure 1 also shows that a vertical jack was used to drive the pile into the shear box. Axial load was applied using six weights (98 kN each) that were secured on the pile head by using a connector, at a height of 500 mm above the sand surface. The total load selected was less than 60% the ultimate capacity of the pile determined using the recorded jack-in pressure of 3.45 MPa.

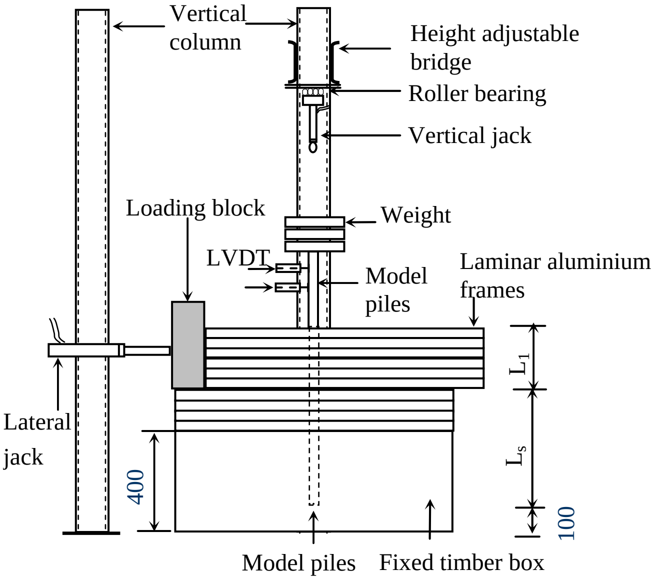

Figure 1. Schematic of the shear apparatus

2.2 *Sand, model pile & experimental procedure*

This study used an oven dried, medium grained quartz, Queensland sand. It was well graded with little to no fines. A sand rainer was used to control density of the sand in each shear test and from one test to another. The rainer was fabricated from plywood, having internal dimensions of 1 m by 1 m, and a height of 150 mm. Its base was fabricated from a piece of timber plate (18 mm in thickness) underlaid by a moveable plastic plate (6 mm in thickness). Both plates were perforated with 5 mm diameter holes in a 35 mm × 50 mm grid pattern.

Using a falling height of 600 mm in the raining process, the sand was controlled to have a dry density of 16.27kN/m^3, a relative density index of 0.89, and an internal frictional angle of 38^o (Guo and Ghee, 2004). The shear modulus at the middle depth of the shear box was ~220 kPa as determined from oedometer test with a shear stress level of 6~7 kPa.

The model piles used in the tests were made of aluminium tube, 1200 mm in length, 32 mm in outer diameter, and 1.5 mm in wall thickness. It has a bending stiffness (calculated) of 1.28 × 10^6 kNmm^2. Each pile was instrumented with ten pairs of strain gauges mounted along its shaft (see Figure 2).

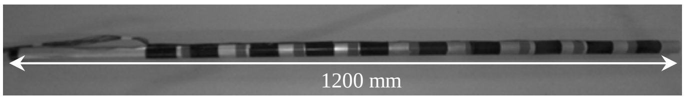

Figure 2. An instrumented model pile

2.3 *Loading conditions in the tests*

A number of tests have been conducted on the model piles subjected to a uniform lateral soil movement and axial load. Presented here are 4 tests on the piles with an embedment length L of 700 mm, as summarized in Figure 3. The piles were tested without any constraint but soil resistance. The soil movement was applied using the rectangular loading block at an increment of 10 mm until a total frame movement w_f of ~140 mm was reached. Strain gauge and LVDT readings and were used to obtain 'measured' bending moment profiles for typical values of frame movement w_f.

Test	L_1/L_s (mm)	Load (N)	Note
1	200/500	0	(1) Test 2 was actually conducted under a SD < 200 mm, owing to loading block; (2) $L_2 = L_s$+100 (mm)
2	200/500	588	
3	400/300	0	
4	400/300	588	

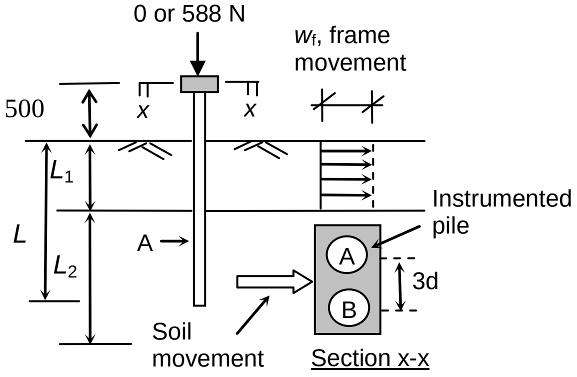

Figure 3. Tests on piles subjected to a uniform lateral soil movement together with different axial load (Group 1×2, 2 in row with L_1/L_s = 200 mm/500 mm, or L_1/L_s = 400mm/300mm)

The driving resistance per pile was monitored during the installation of the pile groups, in light of a mechanical pressure gauge attached to the hydraulic pump. Figure 4 shows the average force per pile (in a group). The force increases continuously with depth for the current tests of group 1×2 (s = 3*d*), indicating consistency of the model sand ground among the current tests. However, the force per pile is different from that observed in the group 2×2, reflecting group interaction (which is discussed elsewhere).

The forces exerted via the lateral hydraulic jacks on the shear box were recorded during advancement of the aluminum frames to the depth L_1(= SD). Figure 5 shows the lateral force per pile (i.e. total force over number of piles in a group) against frame movement, w_f, which demonstrates:

- A maximum lateral force was attained around a movement of 60 mm for all piles;
- A lateral force per pile of 1.8~2 kN was observed for all tests at SD = 200 mm, regardless of pile center-center spacing of 3*d*, 5*d*, or 10*d*, whereas
- A ~3 times higher load per pile of 4.3 kN and 6.0 kN was noted at SD= 400 mm for groups 2×1 and 2×2 (shown elsewhere), irrespective of axial load.

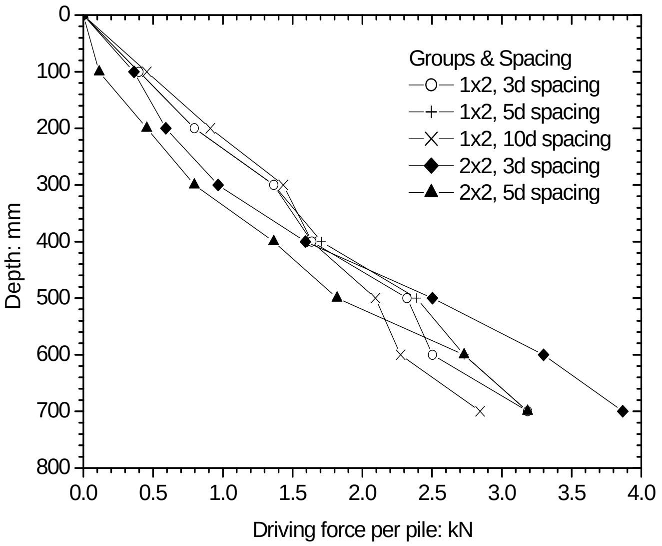

Figure 4. Jack-in force recorded during pile driving

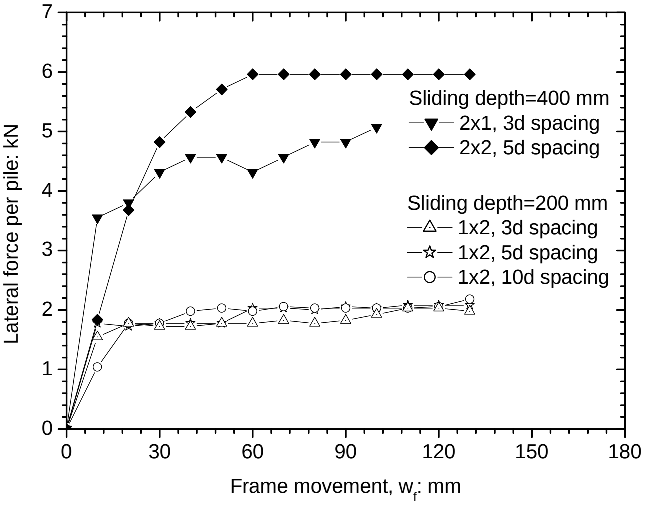

Figure 5. Total lateral force exerted to induce shear tests

3 TEST RESULTS

A spreadsheet program was written to analyze and process the data obtained from strain gauges and LVDTs. The inclination and deflection profiles along the pile were deduced, respectively from 1st and 2nd order numerical integration (trapezoidal rule) of the bending moment profiles. The profiles of shear force, and soil reaction were obtained by single and double numerical differentiation (finite difference method) of the bending moment profiles. The integration and differentiation methods were noted to offer consistent results. They were thus used to obtain bending moment, shear force, soil reaction, rotation and deflection for each test.

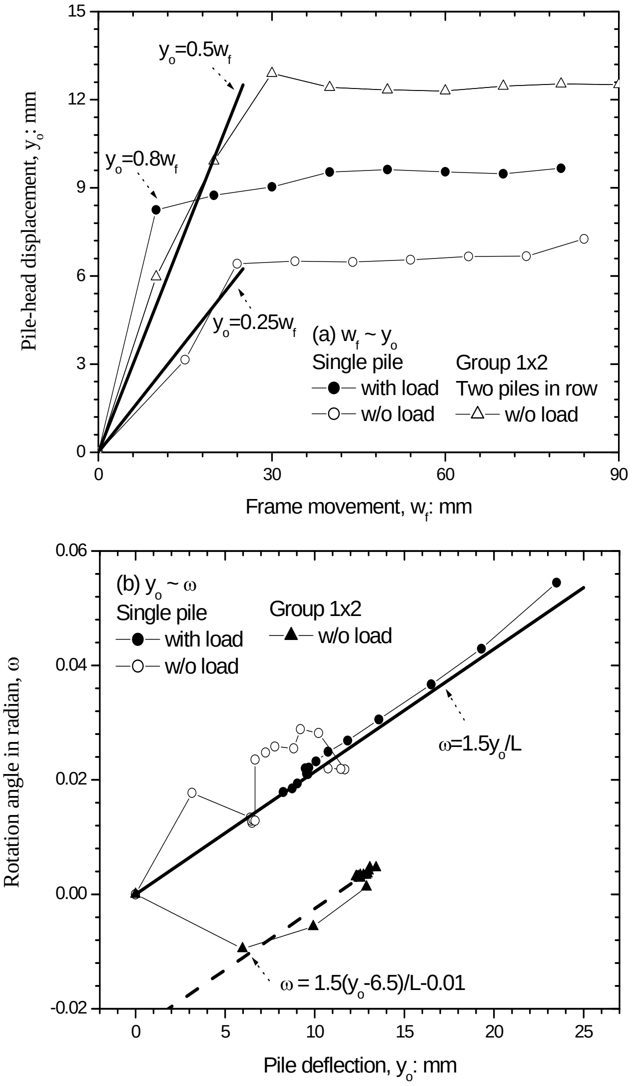

Figure 6. Development of pile-head deflection y_o, rotation ω (SD = 200 mm)

3.1 *Salient Features of Tested Pile Groups*

Figure 6 provides the pile-head deflection at sand surface y_o and rotation ω at various frame movements w_f along with those for a single pile. The rotation ω for the single pile and the 2 piles in row resembles a laterally loaded, free-head, floating base pile in a homogenous soil, as it is approximately governed by the theoretical relationship: $\omega = 1.5y_o/L$. An axial load of 294 N per pile renders the maximum y_o reduce by 34%.

Figure 7 provides the development of maximum bending moment $M_{\text{max}i}$ and maximum shear force $T_{\text{max}i}$ (i = 1 and 2 for sliding layer, and stable layer) induced in the capped 2 piles in a row (Group 1×2) as the frames advance. The 'unusual' low bending moment for 'with load' was caused by the bent of loading block, which resulted in a much smaller sliding depth than the intended 200 mm (The results for Test 2 were subsequently not presented herein). This problem was resolved subsequently.

As the SD increases to 400 mm (without an axial load), the response profiles of the instrumented pile

A were obtained and reported previously (Guo & Ghee 2006) for a set of frame movements, w_f of ~60 mm. A comparison with the previous results indicates, at a maximum w_f of 140 mm, (1) the 'ultimate' maximum bending moment in the stable layer, M_{max2} shifts upwards slightly from an initial depth of 550 mm (at w_f = 60 mm) to 500 mm; (2) The 'ultimate' bending moment and shear force shown in Fig. 8 are much strong than those at w_f = 60 mm. As with that for *SD* = 200 mm, the piles translate for w_f = ~40 mm, and rotate afterwards about the depth (0.64~0.743)*L*. Fig. 9(b) indicates the rotation basically resembles that of a free-head floating pile (Fig. 9(b)) explained previously. Nevertheless, Fig. 9(a) shows an increased deflection y_o of 0.81w$_f$ (without load, i.e. ~2.7 times the y_o for *SD* = 200 mm) or deflection y_o of 0.7w_f-7 (mm) (with the axial load).

The addition of the slightly eccentric load of 294 kN per pile reduces the pile deflections (see Fig. 9(a)), shifts the M_{max} in the stable layer slightly towards sand surface, and induces higher negative moment (~ twice that induced without axial load).

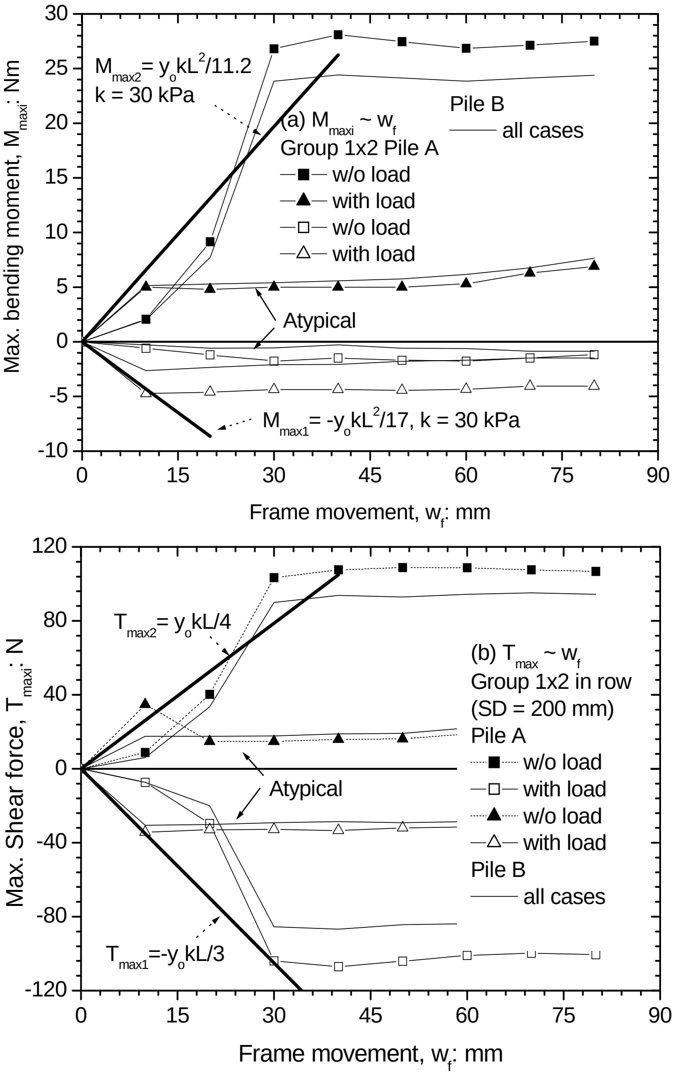

Figure 7. Development of M_{maxi} and T_{maxi} with frame movement w_f (Group 1×2 in row, SD = 200 mm)

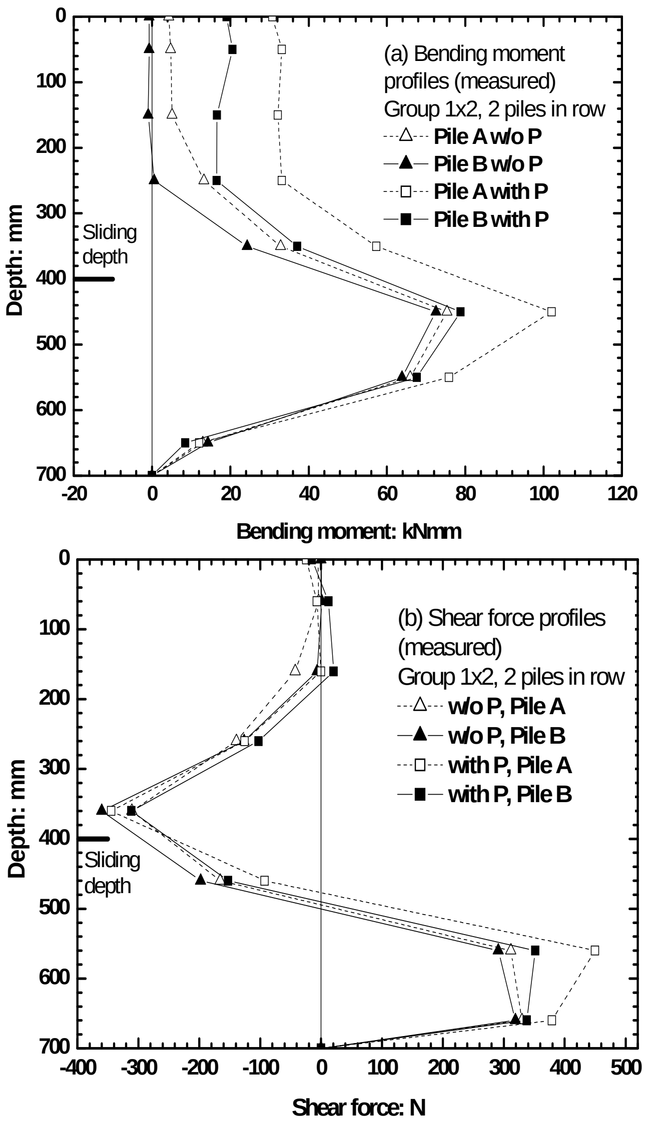

Figure 8. Response of Pile A (Group 1×2, SD = 400 mm) at ultimate state

4 DISCUSSION

The measured M_{maxi} and T_{maxi} are plotted together for each test in Figs. 10 and 11. They are evidently linearly related, which warrants

$$M_{\max 1} = \alpha_s T_{\max 1} L + M_{o1} \qquad \text{(Sliding layer)}$$

where $\alpha_s \approx -0.148$ (piles in a row) that captures the impact of cap fixity (see Table 1); and also

$$M_{\max 2} = T_{\max 2} L / 2.8 + M_{o2} \qquad \text{(Stable layer)}$$

An additional moment of M_{oi} emerges compared to single piles (Guo & Qin, 2010). It is the interceptor M_{maxi} at T_{maxi} = 0 for stable (i = 1) and sliding layer (i = 2), and originates from the impact of eccentric load, *P*-δ effect, sliding depth, cap bending rigidity, and soil movement profiles. The linear relationship between effective movement (= the difference between the measured w_f and the initial movement of 30~40 mm) and T_{maxi} was noted in Fig. 9(d), resembling a single pile and observing

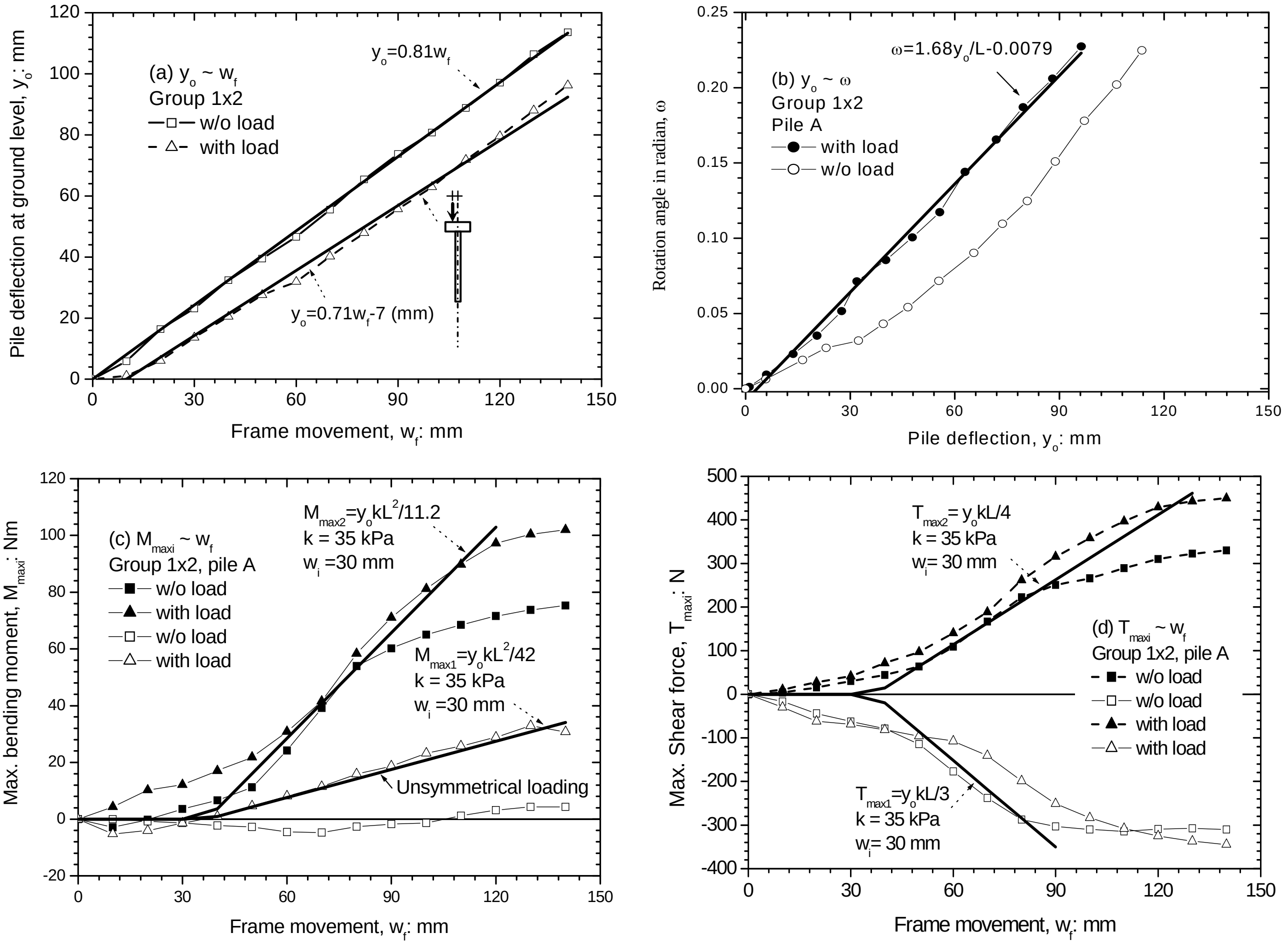

Figure 9. Development of M_{maxi} and T_{maxi} with frame movement w_f (Group 1×2, SD = 400mm)

$$T_{\max i} = y_o kL/3 \sim 4$$

where the denominator 3 is for sliding layer, highlighting 25% cap fixity; and 4 for stable layer featured by free-head condition; $k_{\text{group}} = (0.64\sim1)k_{\text{single}}$ with k_{group} and k_{single} being the k for piles in groups and in single isolated form, respectively.

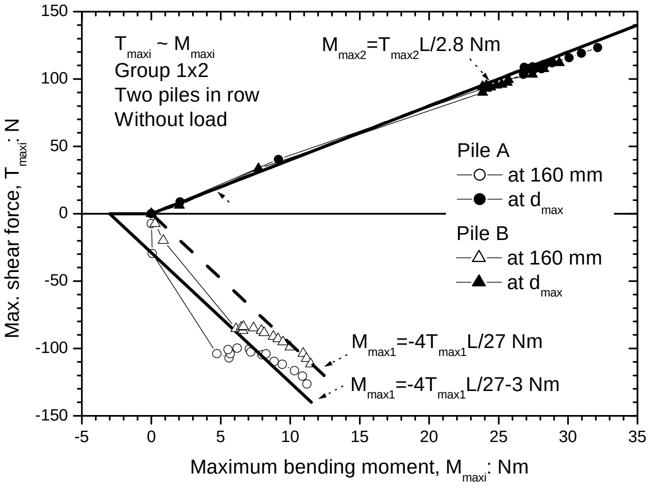

Figure 10. M_{maxi} versus T_{maxi} relationships (Group 1×2 in row)

In light of the newly proposed expressions, the M_{maxi} and T_{maxi} for typical piles were calculated for a set of w_f regarding tests on the groups 1×2. They are plotted in Figures 10, and 11 in which 160 mm = depth 160 mm; $d_{\max}$ = depth of the $M_{\max2}$, etc. The input values of M_{oi}, k and y_o are provided in Table 1.

5 CONCLUSIONS

Presented in this paper are 4 tests on capped 2 piles in a row. They were tested with and without vertical loading by imposing a uniform soil movement to the sliding depth of 0.29L or 0.57L. The results allow progressive development of shear force, bending moment and deflection along the capped piles to be ascertained. Simple solutions are proposed to capture the progressive response, which are compatible with those developed for a single passive pile. The model tests show that (1) The moment $M_{\max}$ is largely linearly related to thrust $T_{\max}$ in stable layer and moving layer; (2) The bending moment M_{oi} captures the combined impact of cap fixity and stiffness, soil movement, and sliding depth; (3) Pile-head deflection was linearly correlated with soil movement for the single and all capped piles, regardless of head fixity.

The solutions are characterized by the following (1) Maximum bending moment $M_{\max2}$-M_{o2} is generally equal to $T_{\max2}L/2.8$ given sliding shear force

Table 1 Prediction of model pile response (**1×2 in row**)

	Pile	Pile deflection y_o (mm)	k (kPa)	$\frac{T_{\max 2}L}{M_{\max 2}-M_{o2}}$	$\frac{T_{\max 1}L}{M_{\max 1}-M_{o1}}$	M_{oi} (Nm)	
				L_2 layer	L_1 layer	L_1 layer	L_2 layer
Test 1 [a] (SD = 200mm)	A	$0.5w_f$	30	2.8	-6.75	-3.0	0
	B			2.8	-6.75	0	0
Test 3 [a] (SD = 400mm)	A	$0.81w_f$	30	2.8	-17.0	0	0
	B			2.8	- (17~∞)	0	0
Test 4 [b] (SD = 400mm)	A	$0.71w_f$ -7	30	2.8	-6.75	-7	0
	B			2.8	-6.75	-14	0
Note	[a] : Without axial load; [b] With axial load; Test 3 was not presented, with actual SD < 200mm						

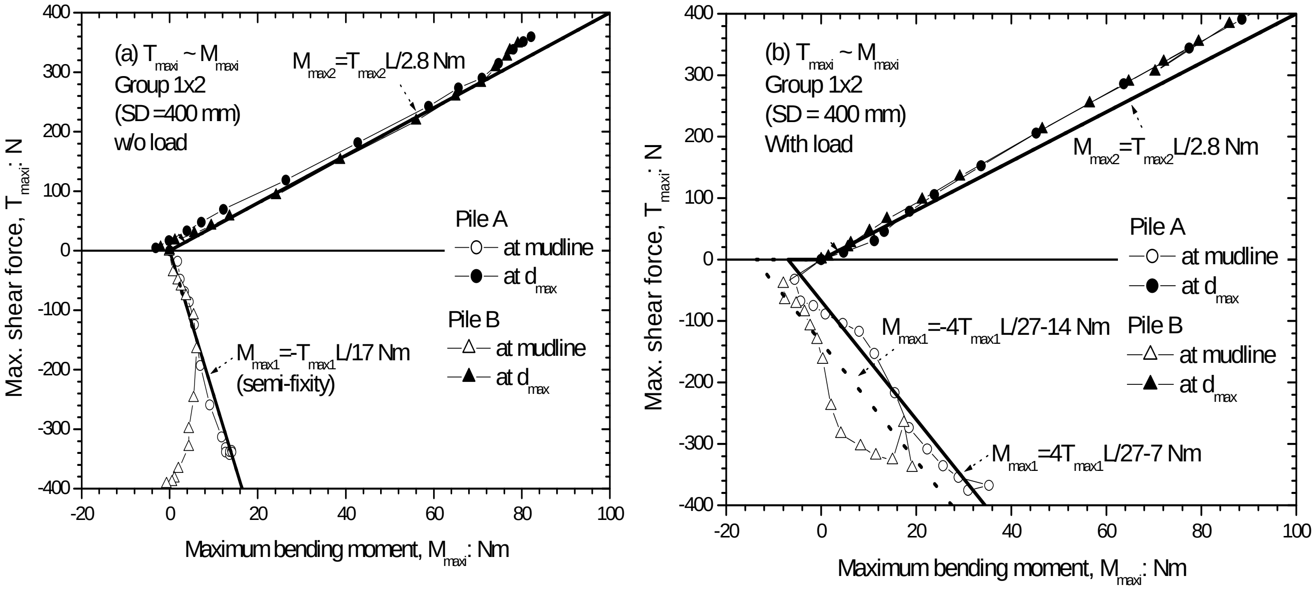

Figure 11 M_{maxi} versus T_{maxi} relationships (Group 1×2 in row, SD = 400 mm)

(thrust), or to $ky_oL^2/11.2$ for a known y_o (or soil movement w_f); and (2) The maximum bending moment M_{max2} may be employed to design passive piles, as it generally exceeds the M_{max1} induced in sliding layer (unlike laterally loaded capped piles).

The current test results are typical except where specified. The simple solutions actually offer satisfactory predictions for all model (single, group) pile tests conducted to date, which are currently in preparation for publications.

6 ACKNOWLEDGMENTS

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