FLAC^{3D} analysis on soil moving through piles

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Abstract: Piles may be utilized as deep foundations or employed to support offshore structures, which may be subjected to passive loading due to lateral soil movements. The safety of the piled foundations depends on the additional stresses induced. This issue has been investigated recently by conducting model tests on single piles and on pile groups with a new apparatus developed by the authors. Typical test results were analysed and reported previously. In this paper three-dimensional finite difference analyses are reported: (1) to predict the results of two model tests (with and without axial load); and (2) to investigate the effect of the moving and the stable depths of soil on the pile response. Typical results of the comparison between the FLAC^{3D} analysis and the model tests for single piles in sand are presented in terms of three profiles namely: bending moment; shear force; and pile deflection profiles. A unique linear relationship between the maximum shear force (thrust) and the maximum bending moment induced on the piles is obtained regardless of the ratios of the moving depth over the stable depth.

1 INTRODUCTION

Pile foundations designed to support offshore structures and services are often subjected to lateral soil movements and axial load simultaneously. There have been active studies on piles subjected to vertical load, and on piles subjected to lateral soil movement. However, little information is available for evaluating the response of vertically loaded piles due to soil movement. This response is important, in particular, for offshore foundations, API (2000) specifies that possibility of soil movement against foundations should be investigated and the forces caused by such movements, if anticipated should be considered in the design. Studies on piles due to liquefaction induced lateral soil movement have found that the influence of axial load can cause on the piles (1) additional bending moment; (2) additional compression stress; and (3) additional lateral displacement (Bhattacharya 2003). The first two findings are consistent with those observed from the model tests conducted by the author (Guo & Ghee 2004), however, lateral displacement of a free-head pile is found to have reduced rather than increased.

With the support of the Australian Research Council, a new apparatus was developed to simulate axial load and lateral soil movement on the pile. The details of the apparatus and typical test results were previously reported in Guo & Ghee (2004) and Guo et al. (2006).

In this paper three-dimensional finite difference (FLAC^{3D}) analyses were conducted: (1) to predict the response of two model piles (with and without axial load); and (2) to investigate the effect of the moving and the stable depths of soil on the pile response.

2 FLAC^{3D} ANALYSIS

FLAC^{3D} version 2.1 (Fast Lagrangian Analysis of Continua in 3 Dimensions) was used to perform the numerical analysis. One of the main features of the FLAC^{3D} is that it can operate in small or large strain mode. The large strain mode occurred when the grid point (mesh) coordinates are updated at each strain or movement increment, according to the computed displacement. This is particularly important to the present study involving large soil movements.

In order to model piles subjected to lateral soil movements, a lateral velocity (defined in FLAC^{3D} as a unit of movement per step or iteration, mm/step) is applied in the direction parallel to x-axis as shown in Figure 1c. Experience gained from calibrating the model pile indicates that a minimum of 150,000 steps is required for the unbalanced force to arrive at a small value, and also remain constant without significant changes. Therefore, the velocity was applied over two intervals: firstly by an velocity of 10^{-6} mm/step to bring the pile and soil into equilibrium at

30 millions steps which is equivalent to 30 mm of lateral soil movement; subsequently using a 10 times higher velocity in order to minimise the accumulation of truncation errors that arise when very small displacement increments are added to generate coordinate values in large strain mode.

2.1 *Geometry and Constitutive Model*

In order to capture the effect of soil arching, and soil flowing on response of passive piles, a three-dimensional model was deemed necessary. The symmetrical nature of the model test allows using only half of the actual pile-soil system to model overall pile response, as shown in Figure 1. The soil strata were modelled with eight-noded brick shape elements and the pile using six-noded cylindrical shape elements. Interface elements were placed between the soil and the pile

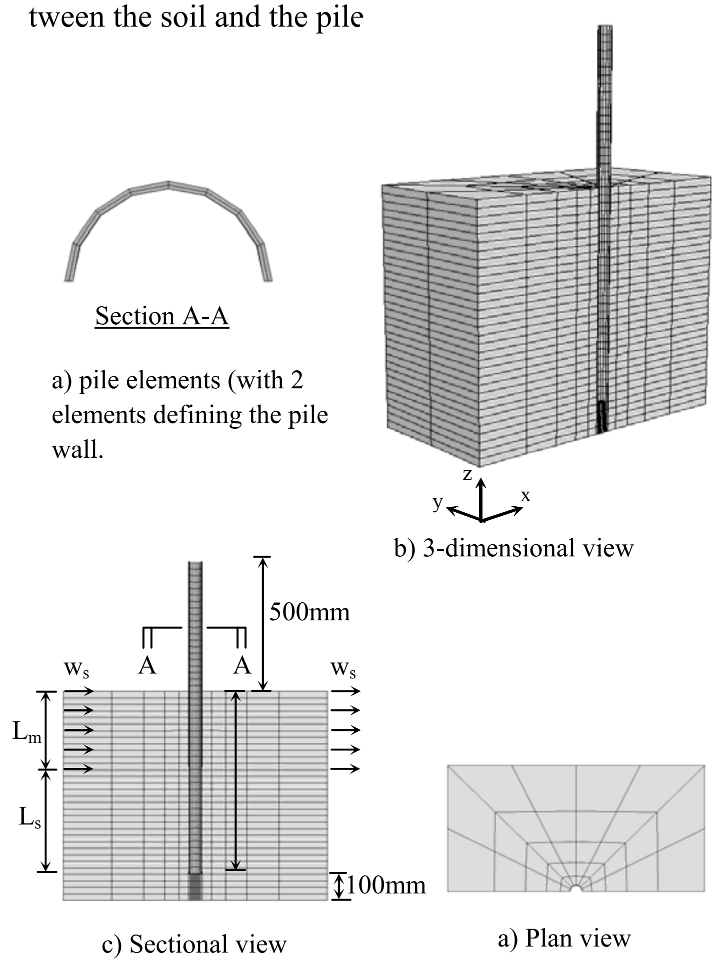

Figure 1 Mesh of soil and pile used in FLAC^{3D} analysis

For the standard model, with a single pile, the mesh comprised of 1856 elements with 2894 nodes or grid-points. With the current computer capacity (Intel® Core™ 2 Duo), the computation took approximately one day for a single analysis. It was found that should a higher number of elements been used, only a small increase in accuracy would be achieved, and would require longer computing time.

The bottom face of the mesh in Figure 1b was fixed in all three directions x, y and z. Both faces parallel to the yz-plane were fixed in the x direction and the other faces parallel to the xz-plane were fixed in the y direction. The surface of the mesh is not fixed in any direction.

The sand strata were modelled with an elasto-plastic Mohr-Coulomb model and using a non-associated flow rule. The Mohr-Coulomb criterion does affect the behavior in the moving soil layer at large sand movements.

Interface elements were attached to the outer perimeter of the pile shaft, hence separating the pile and the adjacent soil. These interface elements were defined by the Coulomb failure criterion with the following parameters: 1) friction angle of 28°; 2) normal stiffness and shear stiffness of 1.0×10^8 N/m^2/m; 3) zero cohesion and dilation; and 4) zero tensile strength. The interface elements (with limiting tensile stress set to zero) allowed the soil to slip and/or seperate from the pile. In most analyses, slip between the pile and the soil occurred due to the relative movements, most notably at the surface of the soil.

2.2 *Soil properties*

The sand properties used are taken directly from that reported in the model tests (Guo & Ghee 2004). In both the moving (L_m) and the stable (L_s) layers (see Fig. 1c), the sand was assigned the following:

- A friction angle of ϕ = 38° (peak angle obtained from the direct shear box test). This angle was set to remain constant in the Mohr-Coulomb model.
- A dilation angle estimated using the equation (after Chae et al. 2004): $\psi = \phi$-30°.
- A Young's modulus E_s of 572 kPa obtained from oedometer test data (assuming Poisson's ratio of 0.3) for a vertical stress of 6.5 kPa over the middle depth of the sand in the shear box.
- An initial stress calculated by specifying a density of 16.27 kN/m^3 and by a coefficient of earth pressure at rest, K_o (= 1 – sinϕ, see Jaky 1944) estimated using the friction angle.
- zero tensile strength.

2.3 *Pile model*

The maximum bending moment in the pile in this study was expected to be much less than the yield moment of the pile (M_{yield} = 1,340 Nm). Therefore, the pile was modelled as an isotropic elastic hollow pile that consisted of cylindrical elements (Fig. 1a).

The mesh of the FLAC^{3D} model (Fig. 1) has been setup to suit the dimensions of the experimental apparatus (Fig. 2), and for the two model tests detailed in Table 2. For comparison purposes, the results obtained from the $FLAC^{3D}$ analyses and the model tests will be presented together, in this paper.

Table 2. Details of $FLAC^{3D}$ analyses

Test	Axial load (N)	Pile diameter (mm)	Moving layer, L_m (mm)	Stable layer, L_s (mm)
1	0	50	400	300
2	284			

As a calibration, a $FLAC^{3D}$ analysis was first conducted on a cantilever pile, i.e. the pile was first fixed at one end into ground, and without soil around. The length of the pile was 1.2 m and the internal and the external diameters were 50 mm and 48 mm respectively. The aluminium pipe had Young's modulus of 7.0×10^{10} N/m^2 and Poisson's ratio of 0.3. Note these are the actual dimensions and properties of the pile used in model tests. A lateral load of 300 N was applied on the free end of the cantilever pile. The obtained deflection from $FLAC^{3D}$ shows a maximum 5 % difference from analytical results. Thereby, the $FLAC^{3D}$ analysis is sufficiently accurate.

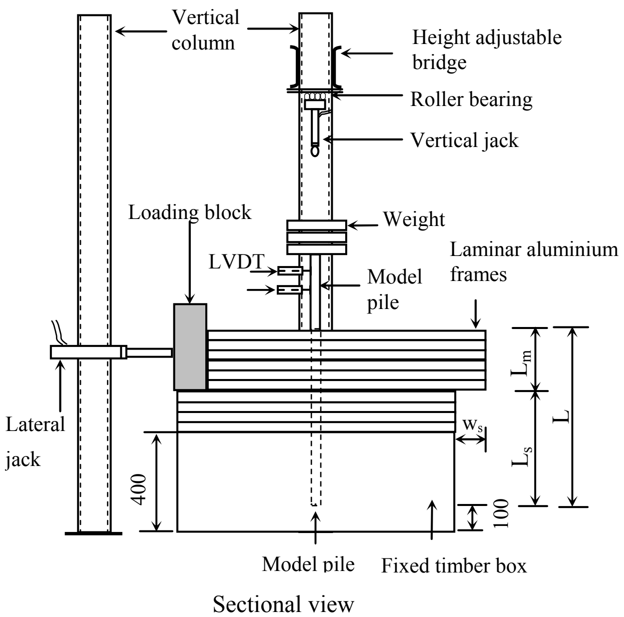

Figure 2 Physical model test setup

3 PREDICTION OF MODEL TESTS

In the first stage, this paper will simulate two model tests reported by Guo & Ghee (2004) and Guo et al. (2006). The shear apparatus used to conduct the model tests is shown in Figure 2. It is mainly made up of a shear box, a loading system, and a data acquisition system.

- The shear box is of 1 m (width) ×1 m (length) × 0.8 m (height). The upper section of the shear box consists of 25 mm deep 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 height fixed timber box and the desired number of laminar steel frames that are fixed, so that a "stable layer of soil" of thickness L_s ($\geq$ 400 mm) can be guaranteed. Changing the number of movable frames in the upper section, the thicknesses of the stable and moving layers are varied accordingly. Note that the L_m and L_s are defined at the loading location, and they do vary across the shear box. The actual sliding depth L_m around a test pile is unknown, but it would not affect the conclusions to be drawn.
- The loading system encompasses a loading block that is placed on the upper movable laminar frames, and some weights on top of the test pile. The loading block is made to different shapes in order to generate various soil movement profiles. A uniform loading block is shown in the figure that enforces a pre-specified sliding depth of L_m. A hydraulic jack is used to drive the loading block.
- The surcharge is exerted by the weights through the loading plates.

Response of the pile is monitored via strain gauges, and via the two linear variable displacement transducers (LVDTs) above the model ground. The test readings are recorded and processed via a data acquisition system and a computer.

3.1 *Test 1 at L_m/L_s = 400/300 and Q = 0N*

For Test 1, Figure 3 presents the pile responses when subjected to soil movement w_s, of 60 mm. For comparison purposes 'three' profiles namely the bending moment, shear force and pile deflection obtained from both the $FLAC^{3D}$ analysis and the test data are presented. A spreadsheet program was written to analyse the displacement data obtained at every 100 mm interval along the pile. The bending moment profile along the pile was first derived from the 2nd order numerical differentiation (finite difference method) of the pile deflection profile. Subsequently, the shear force profile was derived from the 1st order differentiation of the bending moment profile.

Figure 3a shows 104% difference in the maximum bending moment (located in the stable layer) between $FLAC^{3D}$ and test data, although the bending moment profiles show similar shape with double curvatures (negative and positive bending moments).

Generally the $FLAC^{3D}$ analysis underestimated the shear force and the pile deflection. The pile deflection at the soil surface is much less than measured value of 79.7 mm. The deflection profiles indicate that the pile deformed like a rigid pile with a rotation point at the depth in between 600 mm and 700 mm.

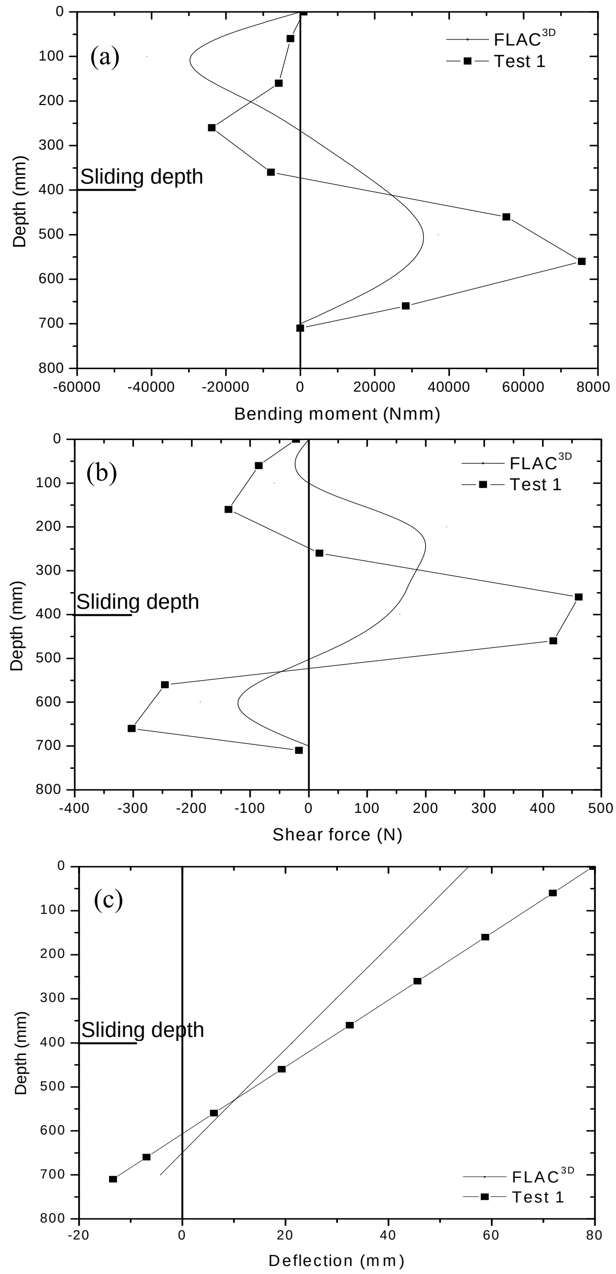

Figure 3 Response of 50 mm pile L_m/L_s = 400/300 (Q = 0N)

3.2 *Test 2 at L_m/L_s = 400/300 and Q = 284N*

Test 2 was performed under identical conditions to Test 1, but with an axial load of 284 N applied on top of the pile at 500 mm above the soil surface (Fig. 1c). Figure 4 presents the three profiles of the pile responses subjected to soil movement, w_s of 60 mm, which were obtained from both the FLAC^{3D} analysis and model test, respectively. A similar shape of bending moment profiles is noted again.

The maximum bending moment (M_{max}) obtained from FLAC^{3D} analysis is 49% higher as compared to that obtained from the model test. This similarity is also noted in the maximum shear force (S_{max}) and the deflection profiles (Figs. 4b, c). The deflection obtained from FLAC^{3D} analysis at the soil surface is 61.1 mm, compared to the model test of 59.5 mm, showing only 3 % difference. However, at the pile toe, the deflections from the model test and FLAC^{3D} analysis are 32.8 mm and -7.6 mm, respectively. The FLAC^{3D} analysis predicts the pile rotates as the soil movement increases, while, the model test shows that the pile first rotates and later translates. These differences are attributed to the way axial load is applied on the pile head (by placing weight in the model test and by applying a uniformly distributed vertical stress in FLAC^{3D}).

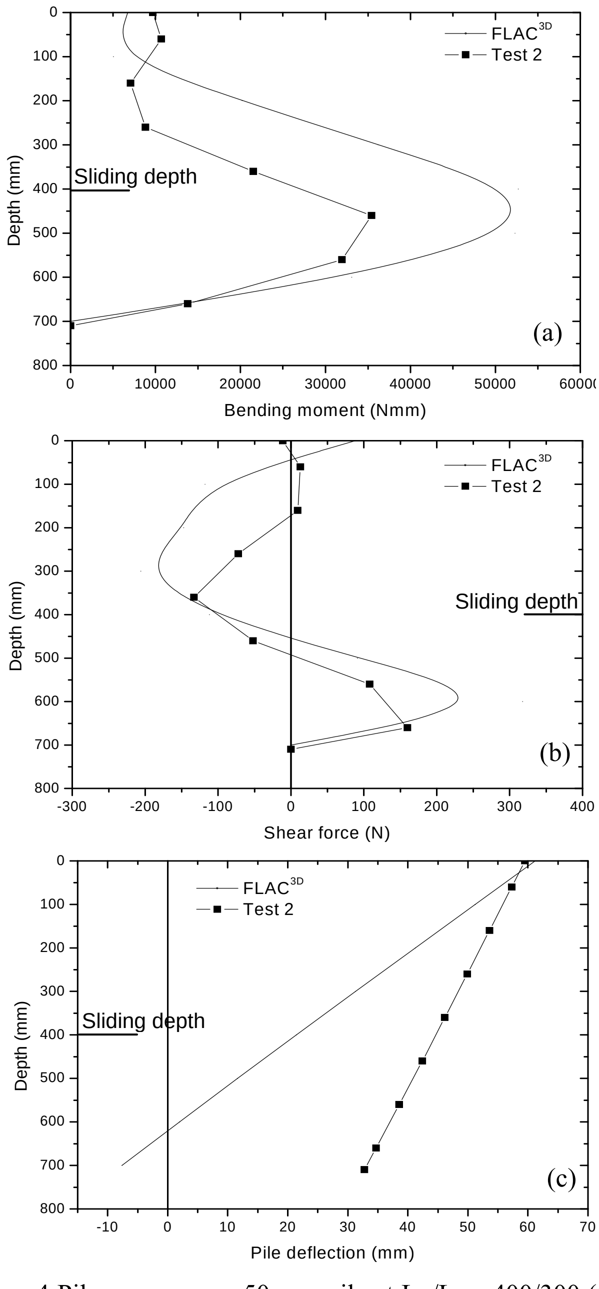

Figure 4 Pile response on 50 mm pile at L_m/L_s = 400/300 (Q = 284N)

3.3 *Summary of results and discussion*

Table 3 provides a summary of the maximum bending moment shear force and maximum pile deflection. Further comparison between the results from the FLAC^{3D} analysis and the model tests shows : (1) the 104 % difference in the bending moment on the pile without axial load; and (2) the 3% (lowest) difference in the maximum pile deflection with axial load; (3) the 96 ~ 99 % difference in shear forces.

Table 3. Summary of FLAC^{3D} and the model test results

Model 1			
Max. value	FLAC^{3D}	Model tests	Difference
M_{max} (Nmm)	37,094	75,672	104 %
S_{max} (N)	235.5	461.5	96 %
Pile def. (mm)	55.5	79.7	44 %
Model 2			
Max. value	FLAC^{3D}	Model tests	Difference
M_{max} (Nmm)	52,700	35,424	49 %
S_{max} (N)	317.9	159.7	99 %
Pile def. (mm)	61.1	59.5	3 %

FLAC^{3D} model over-predicted and underpredicted the magnitude of the pile response (M_{max}, S_{max}, Pile def.), respectively, for the tests with and without axial load. The differences are attributed to the following factors used in the FLAC^{3D} analysis:

- the selection of stiffness (E_s) and strength parameters (ϕ, ψ) of the sand
- the selection of Mohr-Coulomb model, which may be not able to the real soil behaviour;
- using an uniform distributed vertical stress on the pile elements (Fig. 1a), which is different from the way of placing weight blocks (axial load) on pile head in the model tests (Fig. 2).
- the difficulty in capturing the actual mechanics of the moving soil and the stress induced on the pile at large soil movements, when the soil starts to flow around the pile.

Parametric analysis has also been carried out to investigate the effect of soil properties on the agreement between the FLAC^{3D} analysis and the model test. This analysis is reported in Ghee (2009).

4 EFFECT OF L_m/L_s RATIO

The aforementioned two analyses for the model tests have L_m/L_s of 400/300. The L_m/L_s ratio has major impact on the pile response. This is investigated through six FLAC^{3D} models, and presented in form of bending moment and pile deflection profiles. These models have ratios of L_m/L_s ranging from 100/600 to 600/100. The 50 mm diameter pile is again studied here with no axial load on the pile-head. The numerical results at w_s = 60 mm are presented in Figures 5a, b for bending moment (smoothed with B-Spine method for better comparison) and pile deflection profiles, respectively.

It should be noted that the w_s = 60 mm is applied at the boundary of the shear box, and may not represent the actual soil movement as it reaches the pile. In fact, FLAC^{3D} analysis and model test indicate the actual soil movement at the pile location decreased to approximately half of the w_s applied at the boundary of the shear box. The shape of the bending moment profiles show either a single curvature at $L_m \leq 200$ mm, or a double curvature at L_m = 300~500 mm when the pile deflection exceeds the actual soil movement of ~ $w_s/2$.

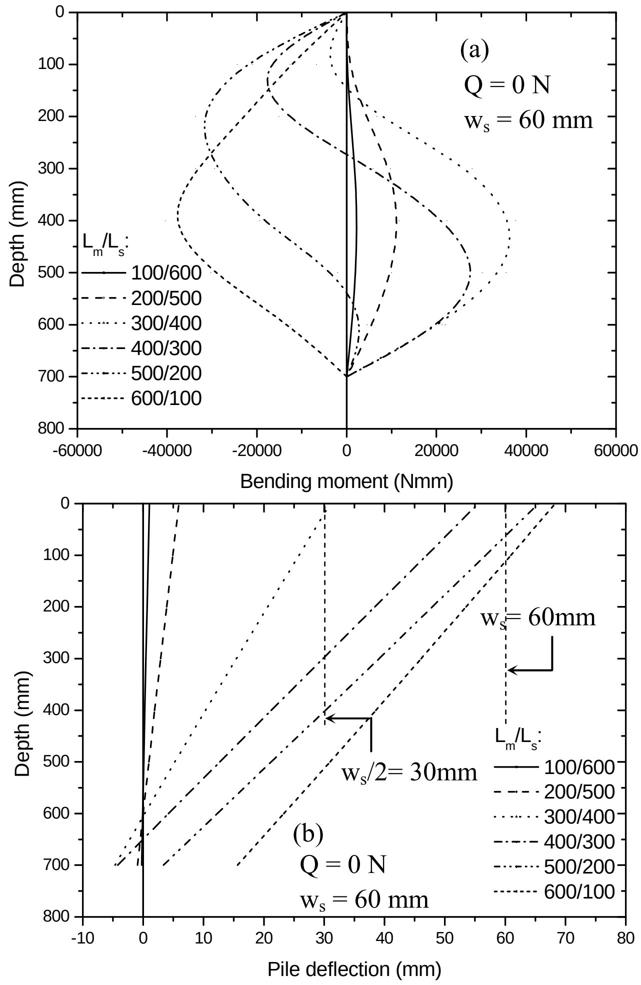

Figure 5 The pile response at different L_m/L_s ratios

At L_m = 600 mm, the bending moment profile shows a single curvature shape with the M_{-max} of -40,374 Nmm at the depth of 400 mm. The magnitude of this negative moment is approximately the same as M_{+max} obtained at L_m/L_s = 300/400. In summary, for a fixed pile length, by increasing the L_m/L_s (from 0.17 to 6.00), the M_{+max} and M_{-max} change, but did not exceed ± 40,374 Nmm, respectively. However, the pile may not be stable when L_m/L_s > 400/300, due to its excessive deflection (> 50 mm or 1 pile diameter).

The deflection profiles show rotation, or rotation-translation of the pile as the L_m/L_s increases. The deflection attains maximum at the surface, and increases with L_m/L_s ratio. Starting at L_m/L_s = 500/200, the pile also begins to translate through the stable layer (L_s), as the soil movement increases (the pile deflection exhibits an initial rotation, and then rotation-translation at a higher w_s).

Figure 6 shows the M_{max} against S_{max} for the FLAC^{3D} models having L_m/L_s of 100/600 to 600/100 (see Table 4). Each model shows a linear correlation between the M_{max} and S_{max} for any magnitude of soil movement, as is noted in model pile tests (Guo & Qin 2010).

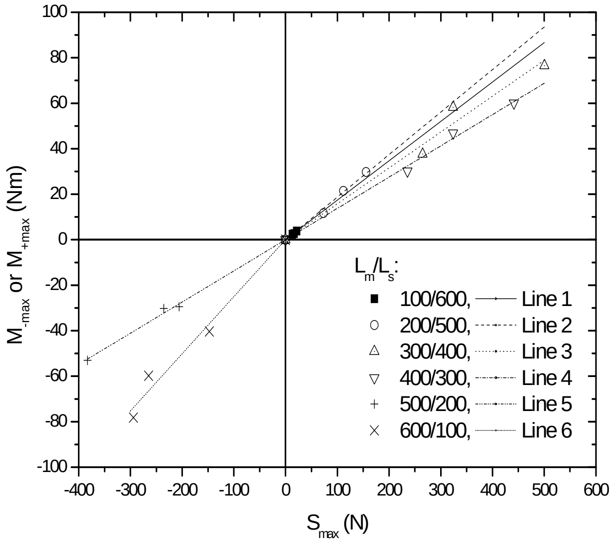

Figure 6. The relationship between M_{max} and S_{max} (w_s = 30 ~ 120 mm)

Table 4 Gradient α of M_{max} against S_{max} relationship

L_m/L_s	α	Line
100/600	0.17	1
200/500	0.19	2
300/400	0.16	3
400/300	0.14	4
500/200*	0.14	5
600/100*	0.25	6
*Note: *Both S_{max} and M_{max} are negative*		

The gradient of each line (model), α, is obtained and provided in Table 4. The following are noted:

- The α generally reduces with the increase in L_m/L_s until L_m/L_s = 400/300;
- The α of 0.14 (line 5) and 0.25 (line 6) are correct for the L_m/L_s of 500/200 and 600/100 respectively, as negative magnitude of both the M_{-max} and the S_{-max} are noted (see Figure 5(a) for the bending moment profile).
- The lines 1 to 4 rotate around the origin in an anticlockwise direction, as L_m/L_s increases. This reflects progressive change in the pile movement mode (discussed previously), as L_m/L_s increases.
- The ratio α (= M_{max}/S_{max}) is 0.14 ~ 0.25 from all the FLAC^{3D} models. This range of values are consistent with 0.13 ~ 0.28 obtained theoretically and experimentally by Guo and Qin (2010), regardless of magnitudes of soil movements.

5 CONCLUSIONS

FLAC^{3D} analysis was conducted regarding the model pile tests subjected to lateral soil movement. The predictions show some difficulty in modeling the magnitude and the profile of the measured pile response. However, the ratio α of maximum bending moment M_{max} over shear force S_{max} induced in each pile is well simulated. The FLAC^{3D} analysis shows that: 1) the bending moment and pile deflection profiles change with the increase in L_m/L_s ratios; 2) The ratio α is unique for each model in the stable and moving soil layers, independent of soil movement level; and (3) The ratio α for the investigated L_m/L_s ratios is 0.17 ~ 0.25.

6 ACKNOWLEDGEMENTS

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