The stability of piles adjacent to a slurry-supported trench

C.K. Choy & R.J. Mair
Cambridge University Engineering Department, Cambridge, UK

J.R. Standing
Imperial College London, London, UK

ABSTRACT: The use of diaphragm walls in many deep excavation projects has become increasingly popular during the past three decades. Diaphragm walls are frequently constructed close to existing structures, and yet the understanding of the interaction between diaphragm wall installation and adjacent structures is very limited. An investigation of the installation effects of diaphragm walls adjacent to piled foundations has been undertaken by means of a series of small-scale model tests in the geotechnical centrifuge at Cambridge University. The research focused on the stability of piles adjacent to a slurry-supported trench in dry dense fine sand. This paper presents a description of the centrifuge model and the observations from a parametric study of the influence of reduction in slurry level on the pile and soil responses. The results suggest that pile stability increases as the length of the trench decreases or when it is at a larger offset distance away from the trench.

1 INTRODUCTION

Diaphragm walling techniques have become more popular during the past three decades and have been adopted in many deep excavation projects. The wall construction is frequently carried out close to existing structures, however, the understanding of the interaction between diaphragm wall installation and adjacent structures is very limited. Therefore, a series of small-scale model tests in the geotechnical centrifuge at Cambridge University has been conducted to investigate the installation effects of diaphragm walls close to piled foundations.

The stability of piles close to a slurry-supported trench in dry dense fine sand was the focus of the research. A system was developed to simulate the construction sequence of a wall panel. During each centrifuge test at 75 g, an instrumented model pile was driven a short distance to its final depth in-flight and a constant load was maintained at the pile head to simulate an axially loaded driven pile. The induced changes in soil and pile deformations and load distributions on the pile were recorded.

This paper presents a description of the centrifuge model and the observations from a parametric study of the influence of reduction in slurry level on the pile and soil responses.

2 PARAMETRIC STUDY

For the first series of centrifuge tests, a model pile, segmental in nature, was tested at 75 g at three different locations, i.e. at $x = 3.5D$, $5.6D$ and $7.7D$ ($D =$ pile diameter) away from the edge of a 80 mm long model trench, to investigate the effect of relative pile-wall distance on the system responses.

At a later stage in the research, a new improved model pile, made from one continuous length of tubing, was used. To assess the improved capabilities of the model pile, one of the previous tests was repeated using a 80 mm long model trench with the new pile at $x/D = 3.5$. The new pile was also installed at the same x/D value away from a shorter trench (40 mm in length) to study the influence of trench length on the pile and soil responses. Figure 1 shows the geometry of trench and pile and gives a summary of the values changed in the centrifuge tests. Details of the design and operation of the equipment can be found in Choy *et al*. (2002) and Choy (2004).

3 CENTRIFUGE MODEL TESTS

3.1 *Sand*

Fine silica sand was used in the centrifuge tests, with grain size ranging from 90 μm to 150 μm and mean grain size of 140 μm. The critical state friction angle of the sand is 32° and its specific gravity is 2.65. Detailed physical properties of the sand were reported by Tan (1990). The dry sand density adopted in the tests was set to be 1555 kg/m^3 ($I_D = 77.3\%$) and the variation of the relative density I_D was within ±1%.

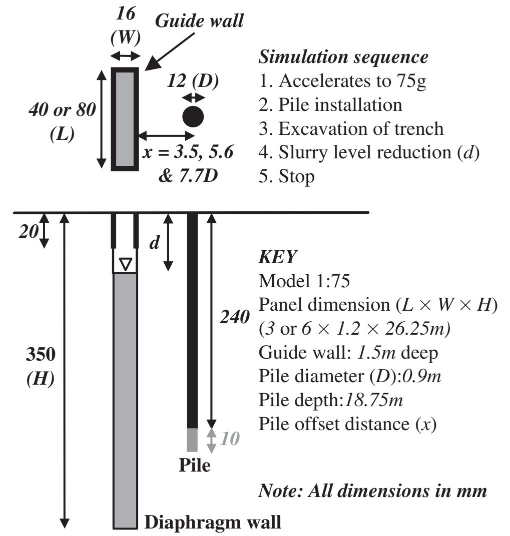

Figure 1. Geometry of test set-up and summary of the values changed in the centrifuge tests.

3.2 *Instrumented model piles*

During the first series of centrifuge tests, a segmental instrumented model pile (see Choy, *et al.*, 2002; Choy, 2004), equipped with five cylindrical load cells, was used to measure the axial load distribution along its length. However, due to the considerable amount of lateral soil movement during the reduction in slurry level inside the model trench, additional rotations at the joints could occur, causing erroneous load cell readings. In order to retain the flexural rigidity and solve the problem of joint rotation between each segment of the model pile, a new instrumented model pile was developed.

The new version model pile (see Figure 2) was made from a continuous Dural (an aluminium alloy) tube with the same external geometry as the old version model pile, and an outer diameter of 12 mm (0.9 m at prototype scale when testing at 75 g). The total machined length was 270 mm, but the pile was installed to a depth of 250 mm (18.75 m at prototype scale). All strain gauges for measuring axial and bending strains were fixed externally because of the tubes' small internal diameter (8.7 mm) and long total length (360 mm). A hard coating was applied to the external strain gauges to protect them from the harsh testing environment. All excess coating was sanded off using emery paper to restore the external circular geometry of the model pile. The surface of the new pile was rougher than the old version (measured using a Talysurf Stylus machine). Five pairs of axial strain gauges together with the tip load cell were used to monitor axial load distribution. Development of bending moment along the pile length was monitored by five pairs of bending strain gauges (see Figure 2).

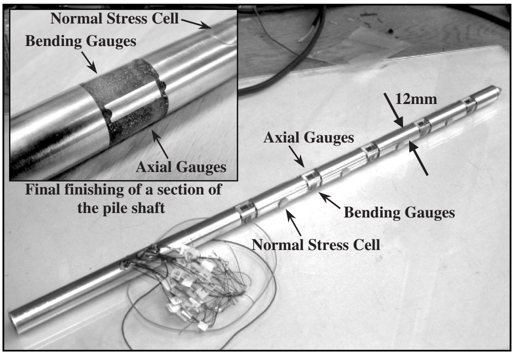

Figure 2. Measuring units of the new version instrumented model pile.

Normal stresses along the model pile were measured by four normal stress cells (see Figure 2). Since lateral soil movement was expected to be significant during testing, displacement of the stress cells in their slots in the pile would be excessive, resulting in unreliable measurements. Therefore, one side of the stress cell (the side facing the model trench) was fixed to the pile shaft so that the normal stress acting on the back of the pile could be measured.

The particle size effect on the piles was assumed to be insignificant since the ratio of pile diameter to mean sand grain size was about 85, which is much larger than the value of 20 recommended by Bolton *et al.* (1993).

All strain gauges were assembled in full Wheatstone bridges to produce a temperature compensated system. Details of the design, construction and calibration of the model piles can be found in Choy (2004).

3.3 *Model diaphragm wall panels*

The model trench was made of a 0.5 mm thick latex membrane, with its length (*L*), width (*W*) and height (*H*) of 40 or 80 mm, 16 mm and 350 mm respectively (see Figure 1). For a 1:75 scale model, the equivalent dimensions were 3 or 6 m long, 1.2 m wide and 26.25 m high. A thin Dural former was attached to the top 20 mm of the model trench to simulate a 1.5 m deep guide wall. Details of the plumbing system used for the simulation of construction sequence can be found in Choy *et al.* (2002) and Choy (2004). The simulation of the construction sequence of a diaphragm wall panel can be carried out by changing the density of the support fluid inside the model trench (e.g. Powrie & Kantartzi, 1996). This is discussed further in Section 3.5.

3.4 *Instrumentation*

LVDTs were fixed at various locations along a supporting beam to measure surface settlement around the model trench. Horizontal and vertical model pile head movements were measured by laser distance sensors. A pressure transducer was attached to the bottom of the model trench to record the fluid pressure. Axial load, bending moment and normal stress distributions along the pile were determined by using strain gauges. The total applied load to the pile head was monitored by a load cell.

3.5 *Test procedures*

Due to the practical difficulties in driving the model pile from the surface to its final depth of 250 mm, the model pile was installed to 10 mm above its final penetration depth prior to each centrifuge test. A brass weight, with a mass of 1.36 kg (about 1 kN at prototype scale), rested on the pile head throughout each test to simulate an axially loaded pile.

After the acceleration level had reached 75 g, the pressure supplied to a pneumatic actuator was increased to drive the model pile to its final depth in-flight so that a realistic stress distribution around the model pile could be achieved. Since the ratio of pile driven distance to pile diameter was about 83%, which is much higher than the recommended value by Randolph *et al*. (1994), the pile bearing capacity was assumed to be fully mobilised. On retracting the piston of the actuator, some unloading of the pile occurred, although the service load was still maintained constant from the brass weight.

Once the installation of the model pile had been completed, the simulation of slurry-supported excavation was carried out. This was achieved by allowing a sodium polytungstate solution, with a density of 1100 kg/m^3, to flow into the model trench to replace the water, which was used to provide lateral support to the sand during acceleration and pile installation.

After the model trench had been fully filled with the sodium polytungstate solution, the slurry level was gradually reduced by controlling a solenoid value connected to the bottom of the model trench. The centrifuge test was stopped either when the model pile underwent substantial movements, or the model trench had been emptied completely.

4 TEST RESULTS AND DISCUSSION

The effects of variation of slurry level inside the model trench on both the pile and soil responses are presented and discussed in the following sections.

4.1 *Base load*

Figure 3 shows the variation of normalised base load (Q_{bn}: a ratio of the current base load to the base load recorded at $d/H = 0$, i.e. before slurry level reduced) at different normalised distances from the edge of the

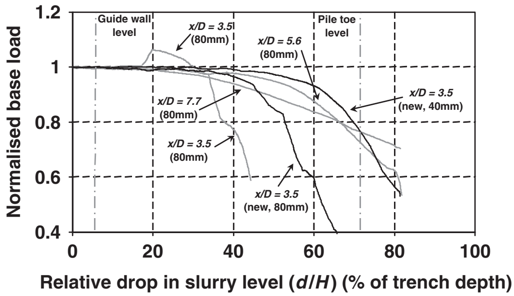

Figure 3. Variation in normalised base load (Q_{bn}) on piles installed at different normalised distances from the edge of the trench (x/D) with relative drop in slurry level (d/H).

trench (x/D), plotted against the relative drop in slurry level (d/H).

For the old version model pile closest to the trench ($x/D = 3.5$), an early increase in base load was observed, with a peak value recorded at $d/H = 20\%$. This was probably due to the settlement of the soil being larger than that of the pile, inducing negative skin friction along the shaft. The increase in this downward force was compensated by the increase in the base load. The load decreased again with further reduction in slurry level because of the drop in the soil stress level around the pile tip. A substantial reduction was observed when the relative drop in slurry level d/H was about 33% because the soil was no longer strong enough to support the pressure from the pile tip.

The responses of the old piles installed further away from the trench were different and the base loads kept reducing with falling slurry level. For the old pile installed at $x/D = 5.6$, the base load decreased at a slow and constant rate up to $d/H = 40\%$, followed by an increasing reduction rate. A sudden and sharp decrease in the base load was observed when the slurry level was dropped to 80% of the trench depth (i.e. just below the pile toe level). The base load of the old pile installed at the furthest distance ($x/D = 7.7$) dropped gradually with reducing slurry level and no sharp changes in the base load were observed.

Unlike the base load response of the old pile at $x/D = 3.5$ during the early stage of slurry level reduction, the base load of the new pile decreased with a small and constant rate. The base load then reduced at an increasing rate and a substantial change in the gradient was observed at $d/H = 53\%$. The stability of the new pile could be maintained at a higher d/H value because of its higher surface roughness, resulting in higher shaft capacity (see Choy, 2004). By reducing the length of the trench to 40 mm, the magnitude of base load reduction at the same d/H value was smaller, meaning the pile could maintain its stability with a larger drop in slurry level.

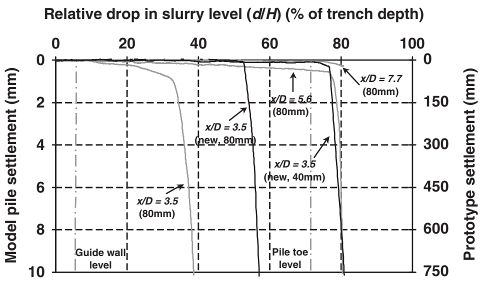

Figure 4. Variation of settlements at head of piles installed at different normalised distances from the edge of the trench (x/D) with relative drop in slurry level (d/H).

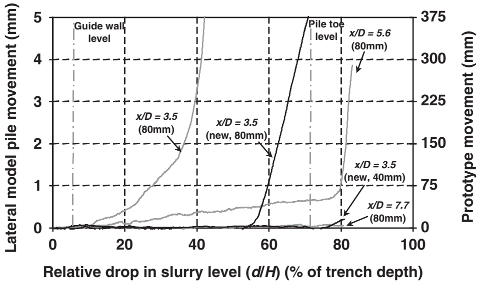

Figure 5. Variation of lateral movements at head of piles installed at different normalised distances from the edge of the trench (x/D) with relative drop in slurry level (d/H).

4.2 *Pile settlement*

The variation of settlements of the piles installed at different normalised distances from the edge of the trench (x/D), plotted against relative drop in slurry level (d/H) is shown in Figure 4.

For the old pile installed closest to a 80 mm long model trench ($x/D = 3.5$), a noticeable pile settlement began to develop once the slurry level had been dropped by 10% of the trench depth. The magnitude kept increasing at an almost constant rate. But the settlement started increasing at a higher rate beyond a slurry level reduction up to 32%, followed by a sudden substantial increase in settlement.

A similar trend was observed for the old pile installed at $x/D = 5.6$, although in this case a gradual settlement started after a 22% relative drop in slurry level. This continued until there was a sudden increase in the pile settlement, which occurred after the slurry level had dropped below the pile toe level. Settlement of the old pile installed at the greatest offset ($x/D = 7.7$) was only observed once the slurry level had dropped below the pile toe level, with the magnitude increasing gradually.

Unlike the (segmental) old pile response, the settlement of the new pile at $x/D = 3.5$ was insignificant for d/H values below 53%. However, a sudden and significant increase was observed with a further drop in the slurry level, with an increasing rate similar to the measurement from the old pile. Because of the additional reserve shaft friction load of the new pile, it could sustain a larger base load reduction (i.e. higher d/H value) without substantial pile penetration (settlement).

Settlement of the new pile close to a 40 mm long model trench ($x/D = 3.5$) was negligible when the slurry level was kept above the pile toe level. A further reduction in trench pressure resulted in a small steady increase in settlement. However, a sharp increase occurred once the d/H value dropped beyond 77%.

4.3 *Pile horizontal movement*

Figure 5 shows the variation of horizontal head movements of piles installed at various normalised distances from the edge of the trench (x/D), plotted against the relative drop in slurry level (d/H).

The old pile installed at $x/D = 3.5$ started moving and the magnitude increased exponentially once the slurry had been dropped below the base of the guide wall. The pile collapsed when d/H was just over 40%. Noticeable lateral movements of the old pile located at $x/D = 5.6$ occurred at a larger relative drop in slurry level, with magnitude increasing at a reduced and almost constant rate. An abrupt increase was observed at a d/H value of 80%. The magnitude of movement reduced significantly when the old pile was installed furthest away from the trench ($x/D = 7.7$). A very minor gradual increase was noticed when the slurry level dropped below the pile toe level.

The test with the pile installed at the closest offset to a 80 mm long model trench ($x/D = 3.5$) was repeated with the new pile. The pile head started moving towards the trench at a much higher d/H value of 54%, followed by a substantial increase in lateral movement. For the same d/H value, the head movement of the old pile was higher than the new pile, showing the influence of the segmental nature of the old pile. The flexibility at the joints of the old pile contributed additional lateral movements because greater rotations at the joints were required to enable the full transfer of moment between pile segments. Therefore, readings from the continuous model pile are considered to be more representative of prototype pile behaviour.

For the new pile installed next to a 40 mm long model trench ($x/D = 3.5$), head movement was found to be insignificant when the slurry level was kept above the pile toe level. A steady increase in lateral head movement occurred after the relative drop in slurry level increased beyond 77%. No sudden and substantial increase in movement was observed, suggesting that a pile is less susceptible to lateral movement with decreasing trench length.

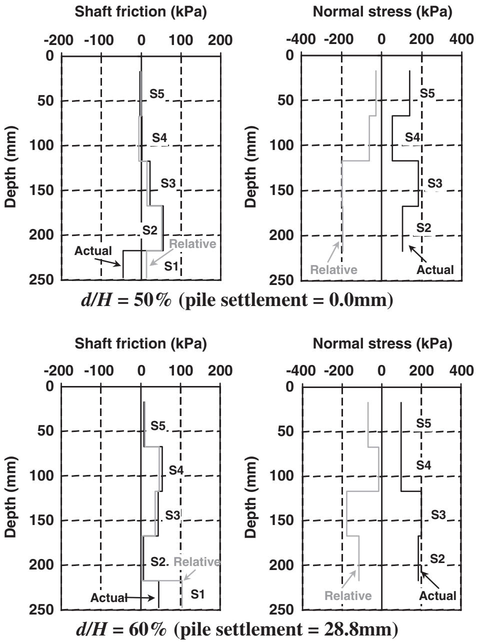

Figure 6. Shaft friction and normal stress distributions of a pile installed at $x/D = 3.5$ with different drops in slurry level (d/H) (80 mm trench).

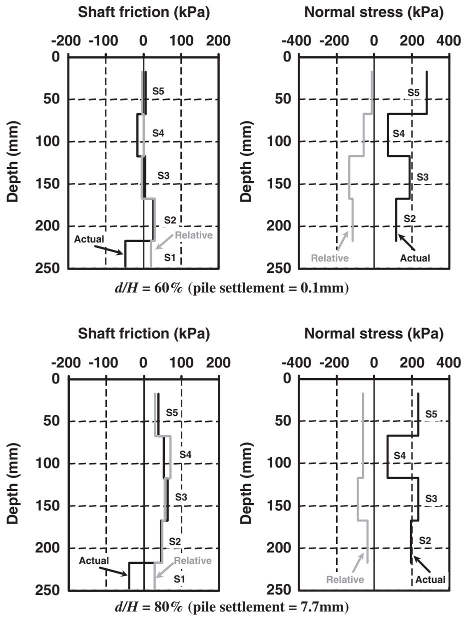

Figure 7. Shaft friction and normal stress distributions of a pile installed at $x/D = 3.5$ with different drops in slurry level (d/H) (40 mm trench).

4.4 *Load distributions*

The shaft friction and normal stress (acting on the back of the pile) distributions before and after the collapse of the new pile, close to both 40 and 80 mm long model trenches ($x/D = 3.5$) are summarised in Figures 6 and 7. The figures show the absolute measurements (labelled as "actual") at the stated d/H values, as well as the changes in magnitude with respect to the measurements at $d/H = 0$ (labelled as "relative"), which is the main focus of this section. The corresponding lengths of the pile (S1 to S5) are also shown in the figures.

4.4.1 *Shaft friction distributions*

Since the mobilisation of positive shaft friction only requires a small amount of relative pile-soil movement, a very small pile settlement was recorded before the pile collapse, with the base load reduction being compensated by the shaft friction being re-mobilised. For the long model trench (80 mm) scenario, a positive increase in the shaft friction was noticed near the lower section of the pile, with magnitude generally decreasing towards the surface before the failure (see Figure 6).

Once the shaft capacity had been fully mobilised, a further reduction in base load caused a significant increase in settlement since the pile had to penetrate much deeper to develop an increased shaft friction (from increasing normal stress) to achieve an equilibrium condition. Hence, an overall positive increase in the shaft friction occurred after the pile had settled substantially ($d/H = 60\%$) (see Figure 6), except for Section S2 for which the reading is thought to be erroneous. A similar trend in the development of shaft friction was also observed in the shorter model trench (40 mm) case (see Figure 7).

4.4.2 *Normal stress distributions*

During the reduction in slurry level, the soil stress between the trench and the pile decreased (Choy, 2004) and hence the radial stress acting on the front side of the pile was also expected to decrease. As evident from Figure 5, pile deflection towards the trench occurred, resulting in a reduction in soil pressure acting against the back of the pile, which was registered by the normal stress cells incorporated inside the model pile (see Figures 6 and 7). However, a recovery in the normal stress (acting on the back of the pile) was observed after the commencement of substantial pile settlement because the stress cells were now located at deeper depths.

4.5 *Soil deformation*

LVDTs were positioned along the centre-line of both sides of the trench so that the influence of the pile on the surface settlement response could be assessed. Figures 8 and 9 show the corresponding relative change (with respect to surface deformation measured

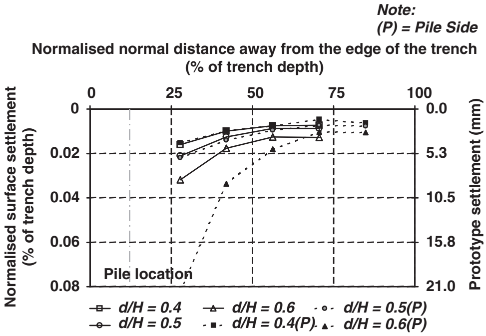

Figure 8. Normalised surface settlement (Δ/H) along the centre-line of the trench (80 mm) at different relative drop in slurry level (d/H) for case with $x/D = 3.5$.

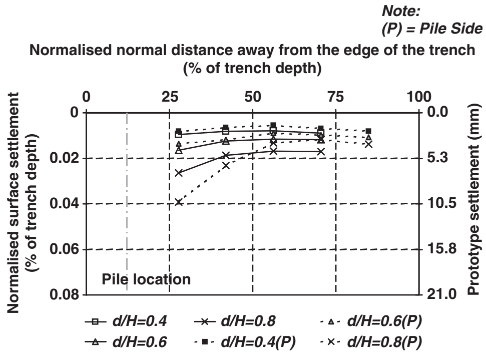

Figure 9. Normalised surface settlement (Δ/H) along the centre-line of the trench (40 mm) at different relative drop in slurry level (d/H) for case with $x/D = 3.5$.

at $d/H = 0$) in normalised surface settlement (Δ/H), i.e. the ratio of surface settlement to the trench depth, profiles perpendicular to the trenches (80 and 40 mm respectively) at selected relative drops in slurry level (d/H) for the case with $x/D = 3.5$. The surface settlement in the absence of the pile is represented by the continuous lines. The broken lines show the surface deformation on the side of the trench where the model pile was installed.

For the new pile installed nearest to a 80 mm long model trench ($x/D = 3.5$), the difference in settlements (either side of the trench) was minor before the commencement of significant pile movements (i.e. $d/H < 53\%$). The broken line (pile side) was shifted downwards relative to the continuous line (opposite side to pile) with a further reduction in slurry level. This implies the loaded pile had a destabilising effect on the soil mass, with the consequence that surface settlement behind the pile was increased.

The effect of the trench length on the soil settlement response was also observed. The amount of soil settlement for the same relative drop in slurry level (d/H) was smaller for the shorter trench (40 mm) because of the smaller pile movements.

5 CONCLUSIONS

The effects of variation of the slurry level during trench excavation on pile and soil responses have been investigated and the study has been presented in this paper. The main conclusions drawn from the centrifuge tests are as follows.

- Pile stability increases for the case when the length of the trench decreases or when it is at a larger offset distance away from the trench.
- Significant base load reduction is expected. Collapse of the pile occurs when the total amount of re-mobilised shaft load cannot compensate the loss in base load.
- The normal stress acting on the back of the pile reduces when the slurry level is being lowered. This reverses after significant pile movements have occurred (in practice the pile would have failed by this time).
- Horizontal pile movement is sensitive to the model pile design.
- The pile has a destabilising effect on the soil mass only after the pile has started moving significantly. This increases the magnitude of soil surface settlement behind the pile.
- The magnitude of soil settlement reduces with decreasing trench length.

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