The installation effects of a diaphragm wall on an adjacent piled foundation

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ABSTRACT: In recent years there have been an increasing number of urban developments involving deep excavations. These are frequently constructed using diaphragm walls to support the ground adjacent to existing structures. Research is being carried out at Cambridge University to study the effects of diaphragm wall installation on adjacent piled foundations using the geotechnical centrifuge to model the complex three-dimensional nature of the problem. The installation effects of a diaphragm wall on a nearby piled foundation in dry dense fine sand are being studied. This paper describes the centrifuge model and presents results from a parametric study where the model pile is installed at several positions relative to the diaphragm wall. The support fluid level inside the trench is varied to study its effect on the soil, trench and pile responses during excavation.

1 INTRODUCTION
In recent years there has been an increasing number of urban developments involving deep excavations. These are frequently constructed using diaphragm walls to support the ground adjacent to existing structures. Construction of this type of cast-in-situ permanent retaining structure results in soil deformations that could influence and possibly damage adjacent structures and there is particular uncertainty at present about the effects on piled foundations. Well-documented case histories are very scarce and so there is a need to investigate the influence of constructing diaphragm walls adjacent to piled foundations in order to analyse future cases realistically and to effect safe and economic designs.

Research is being carried out at Cambridge University to study the effects of diaphragm wall installation on adjacent piled foundations using the geotechnical centrifuge to model the complex three-dimensional nature of the problem. The installation effects of a diaphragm wall on a nearby piled foundation in dry dense fine sand are being studied. A plumbing system has been developed to simulate the construction sequence of a diaphragm wall panel. An instrumented model pile is driven a short distance to its final depth in-flight and a constant force is maintained at the pile head to simulate an axially loaded driven pile.

This paper describes the centrifuge model and presents results from a parametric study where the model pile is installed at several positions relative to the diaphragm wall. The support fluid inside the trench is varied to study the effect on the soil, trench and pile responses during excavation.

2 CENTRIFUGE MODEL TESTS

2.1 Sand
Fine silica sand has been chosen for the use in the centrifuge model. The soil grain size ranges from 90μm to 180μm, with \(d_{50}\) of 140μm. The physical properties of the sand reported by Tan (1990) are summarised in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d_{10})</td>
<td>95μm</td>
</tr>
<tr>
<td>(d_{50})</td>
<td>140μm</td>
</tr>
<tr>
<td>(d_{60})</td>
<td>150μm</td>
</tr>
<tr>
<td>(G_s)</td>
<td>2.65</td>
</tr>
<tr>
<td>(e_{min})</td>
<td>0.613</td>
</tr>
<tr>
<td>(e_{max})</td>
<td>1.014</td>
</tr>
<tr>
<td>(\phi')</td>
<td>32°</td>
</tr>
</tbody>
</table>

2.2 Model pile
The model pile used in the centrifuge tests is made from Dural (an aluminium alloy) tubing and it is machined to have an outer diameter of 12mm, which is equivalent to 900mm at prototype scale. The total machined length of the model pile is 270mm, however, the pile is only installed to a depth of 250mm
and this is equivalent to a depth of 18.75m for a 1:75 scale model.

The model pile is equipped with five cylindrical load cells each along its length as shown in Figure 1. Each load cell is internally instrumented with strain gauges, assembled in full Wheatstone bridges to produce a temperature compensated system. The strain gauges are arranged to measure axial strain.

The particle size effect on the model pile is assumed to be insignificant since the ratio of pile diameter to average particle grain size is about 85, which is much greater than the value of 20 recommended by Bolton et al. (1993).

![Detail 1](image)

Figure 1. Layout of a typical instrumented model pile

2.3 Model diaphragm wall panel

Based on the technique developed by Powrie & Kantartzki (1996), the whole construction sequence of a diaphragm wall panel can be simulated by changing the density of the support fluid inside the model trench. The model trench is made of a 0.5mm thick latex membrane, and its width (W), length (L) and height (H) are 16mm, 80mm and 350mm respectively. At an acceleration level of 75g, the equivalent panel dimensions are 1.2m wide, 6m long and 26.25m high. A thin Dural former is attached to the top 20mm of the model trench to simulate a 1.5m deep guide wall. Figure 2 shows the plumbing system used for the simulation of the construction sequence.

The top-up tank is filled with support fluid, which is used to model the bentonite slurry exerted on the model trench during excavation. Zinc chloride solution has been widely used as support fluid in centrifuge tests (e.g. Bolton & Powrie, 1987), however, safety is a concern because of its highly corrosive nature. Therefore, a chemical called sodium polytungstate has been selected to substitute zinc chloride, due to its less-corrosive nature and high solubility in water. The support fluid can be drained away either from the top or bottom of the model trench and all the unwanted solutions are collected and stored in Catch Tanks A and B (Fig. 2). A pressure transducer is installed to monitor the fluid pressure. Strain gages are installed inside the model pile to measure the axial strains at different locations along the pile. A load cell is also used to monitor the load exerting on the top of the pile.

2.4 Instrumentation

Surface settlements around the model trench are measured by LVDTS, which are fixed at various locations along a supporting beam. Laser distance sensors are used to measure horizontal and vertical pile movements throughout the test. A pressure transducer is connected to the model trench to monitor the fluid pressure. Strain gages are installed inside the model pile to measure the axial strains at different locations along the pile. A load cell is also used to monitor the load exerting on the top of the pile.

2.5 Test procedures and conditions

Pile installation and the variation of the bentonite slurry level are modelled in the centrifuge test. The procedures for a test in dry sand are described below.

2.5.1 Model preparation

The sand is poured into a strong-box made from Dural plate, with dimensions of 700mm long, 400mm wide and 470mm deep, from a predetermined drop height of 300mm by using a sand hopper and a flexible hose (Fig. 3). The dry sand density adopted in the tests is set to be at 1550kg/m³.
(\(I_D = 75\%\)) and this sand pouring method is found to be excellent since the variation of the relative density \(I_D\) is within \(\pm 1\%\).

Figure 3. Sand pouring

Figure 4. Installed model panel, model pile and brass weight at the end of model preparation

2.5.2 Pile installation
The installation effects of a driven pile should not be ignored since the bearing capacity of a pile installed at 1g is only 60% of one installed at 50g (Yet et al., 1994). Therefore, a realistic stress-strain distribution around a model pile can be achieved if the model pile is driven in-flight.

Prior to each centrifuge test, the model pile is installed to 10mm above its final depth, as there are practical difficulties in driving the model pile from the sand surface to its final depth of 250mm in-flight. The pile bearing capacity is assumed to be fully mobilised since the s/D ratio (ratio of pile driven distance to pile diameter) is about 83%, which is much higher than the value recommended by Randolph et al. (1994). A pneumatic actuator is used to drive the pile to its final penetration depth during the centrifuge test using the technique adopted by Jacobsz et al. (2001).

Since a constant load has to be applied at the pile head during the centrifuge test to simulate an axially loaded pile, a brass weight, with a mass of 1.38kg (about 1kN at prototype scale), is attached to the pile head and the total force exerting on the pile is measured by a load cell installed inside the weight. The required driving force supplied by the pneumatic actuator is equal to the load difference between the penetration resistance and the service load (brass weight).

Figure 4 shows the model diaphragm wall panel and the nearby installed model pile, with the brass weight attached at the top, at the end of model preparation.

2.5.3 Simulation of construction sequence
The whole construction sequence of a diaphragm wall panel can be simulated by changing the density of support fluid inside the model trench and this can be achieved by controlling the solenoid valves system (Fig. 2).

Before each centrifuge test, the model trench is filled with water to provide lateral support to the sand and all the valves are closed. Then, the centripetal acceleration is increased to 75g and the model pile is driven 10mm (0.83D) to its final depth \((H_p)\) of 250mm (18.75m at prototype scale) using the pneumatic actuator.

By opening Valve C, the sodium polytungstate solution with a density of 1100kg/m³ is allowed to flow into the model trench to simulate bentonite slurry excavation, the water is displaced upwards due to its lower density. Since the fluid level inside the trench has to be maintained at the ground surface, Valve B is now opened. The excess water flows through the drain pipe and is stored inside Catch Tank B.

Once the model trench has been completely filled with the sodium polytungstate solution, the slurry level is gradually reduced. This is achieved by controlling Valve A, which is connected to the bottom of the model trench and the unwanted chemical is stored inside Catch Tank A. The centrifuge test is stopped when the model trench has been emptied completely. Operation of the solenoid valves are summarised in Table 2.

Table 2. Operation of the solenoid valves

<table>
<thead>
<tr>
<th>Stage</th>
<th>Valves</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Close</td>
<td>Close Close Close</td>
</tr>
<tr>
<td>II</td>
<td>Close</td>
<td>Open Open</td>
</tr>
<tr>
<td>III</td>
<td>Open</td>
<td>Close Close</td>
</tr>
</tbody>
</table>

3 PARAMETRIC STUDY
Piles were tested at four different locations, i.e. 3.5D, 5.6D, 6.0D and 7.7D (\(D =\) pile diameter) away from the edge of the model trench. During each centrifuge test, the model pile was driven to its final
penetration depth of 250mm and the guide wall was installed to the depth of 20mm. Details of the first series of centrifuge tests are summarised in Table 3.

<table>
<thead>
<tr>
<th>Panel dimension ((L \times W \times H))</th>
<th>80 × 16 × 350mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guide wall depth ((H_g))</td>
<td>20mm</td>
</tr>
<tr>
<td>Pile diameter ((D))</td>
<td>12mm</td>
</tr>
<tr>
<td>In-flight pile driven distance ((s))</td>
<td>10mm</td>
</tr>
<tr>
<td>Pile penetration depth ((H_p))</td>
<td>250mm</td>
</tr>
<tr>
<td>Distance between the centre of the model pile and the edge of the trench ((x))</td>
<td>3.5D, 5.6D, 6.0D &amp; 7.7D</td>
</tr>
</tbody>
</table>

4 TEST RESULTS AND DISCUSSION

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

4.1 Pile movements

Laser distance sensors are used to measure the horizontal and vertical pile head movements with the target plates attached to the brass weight, which rests on the top of the model pile throughout the centrifuge test.

4.1.1 Pile settlement

Figure 5 shows the variation of settlements of the pile installed at different normalised distances away from the edge of the trench \((x/D)\) plotted against drop in fluid level \((d/H)\). For the pile installed at the nearest distance from the model trench, i.e. \(x = 3.5D\), significant pile settlement starts to develop once the slurry level has dropped below the base of the guide wall and the magnitude keeps increasing at an almost constant average rate. A similar trend is observed when the pile is installed at a larger offset distance \((x = 5.6D)\), however, it starts settling after a greater relative drop in slurry level and the magnitude is generally smaller. These two centrifuge tests were stopped when the drop in slurry level was about 40% of the trench depth to prevent any damage to the instrumented model pile by bending.

When the pile is installed slightly further away \((x = 6.0D)\) from the previous pile location, there is a significant change in the magnitude of pile settlement. The pile starts settling after a greater slurry level reduction, i.e. about 30% of the trench depth, and continues to settle at a rate similar to the previous two cases. A sudden increase in the pile settlement occurs when the slurry level drops beyond 78%. Settlement of the pile installed at the furthest offset \((x = 7.7D)\) is insignificant when the slurry level is above the pile toe level, i.e. \(d/H\) is smaller than 71%. Once the slurry level drops below the pile toe level, pile settlement commences.

4.1.2 Pile horizontal movement

The variation of horizontal movements of the pile installed at various normalised distances away from the edge of the trench \((x/D)\) plotted against relative drop in fluid level \((d/H)\) is shown in Figure 6. When the slurry drops below the base of the guide wall, piles installed at \(x = 3.5D\) and 5.6D start moving towards the trench at similar \(d/H\) valves and the increasing rates of lateral movements for both piles are very similar, although the magnitude is slightly smaller for the pile installed nearest to the trench. When the pile is located at \(x = 6.0D\), a significant horizontal pile movement is only noticed after a greater reduction in slurry level, i.e. \(d/H = 30\%\), and increases at a lesser rate compared with the previous two cases. The magnitude of horizontal movement drops significantly when the pile is installed further away from the trench. For the pile installed at \(x = 7.7D\), insignificant movement is observed when the reduction of slurry level is within 50% of the trench depth. A gradual increase is noticed as the slurry level keeps decreasing. Unlike the pile settlement
behaviour, no substantial changes in the pile lateral movement are observed when the slurry drops below the pile toe level.

4.2 End-bearing resistance

End-bearing resistance ($Q_b$) of the model pile is measured throughout each centrifuge test. Figure 7 shows the variation of normalised based load ($Q_{bn}$) ratio of end-bearing resistance currently experienced to end-bearing resistance recorded at $d/H = 0$ at different normalised distances away from the edge of the trench ($x/D$) plotted against relative drop in slurry level ($d/H$).

For the pile installed nearest to the trench ($x = 3.5D$), $Q_{bn}$ is just greater than 1 once the slurry drops below the base of the guide wall and falls back to 1 at $d/H = 27\%$ and keeps decreasing thereafter. A similar trend is noticed for the pile installed at $x = 5.6D$, but in this case, $Q_{bn}$ stays just greater than 1 until the relative drop in slurry level equals $40\%$.

There is a rapid decrease in end-bearing resistance of the pile installed at $x = 6.0D$ when the relative drop in slurry level is about $30\%$, it then stays constant up to $d/H = 40\%$. The reason for this sudden drop in end-bearing is not clear, but is probably related to the experimental boundary conditions. At values of $d/H$ greater than $40\%$ the end-bearing resistance steadily reduces. Base load of the pile installed at the furthest distance ($x = 7.7D$) also decreases gradually with fall in slurry level. Unlike pile settlement (Figure 5), there are no significant sudden changes in the end-bearing resistances of these two piles when the slurry drops below the pile toe level.

In summary, the base loads of the piles installed closer to the trench appear to increase slightly and before gradually decreasing with falling slurry level. The observed increase is almost negligible and might arise from the experimental boundary conditions. The piles installed further away from the trench only experience a steady reduction in end-bearing resistance.

4.3 Shaft friction distribution

Shaft friction distribution along the pile can be determined throughout each centrifuge test from the output of the axial load cells described in Section 2.2. Measurements from the piles installed at $x = 3.5D$ and $7.7D$ at a particular relative slurry level are presented here.

Figure 8 shows the shaft friction distribution recorded when the pile is installed at $x = 3.5D$ from the trench, with the relative drop in slurry level $d/H = 42\%$. The actual shaft friction measured during the test is labelled and relative refers to the change in shaft friction with respect to the shaft friction measured at $d/H = 0$. Positive values of shaft friction relate to shear stress acting upwards. An assumed potential failure surface of the soil mass behind the trench is also shown in Figure 8 to explain the observed shaft friction distribution.

At the location of Segment 1, the failure mechanism would imply that the soil behind the pile is moving diagonally towards the trench increasing both radial and downward forces on the pile. This is evident from the observed increase in shaft friction which could be caused by either the downward movement of the pile relative to the soil or an increase in radial (lateral) stress.

Below the level of Segment 1, changes in skin friction are complex, some zones having negative increments (possibly resulting from greater soil than pile movements in towards the trench), and one zone indicating a positive increment (possibly caused by the failure mechanism).

The shaft friction distribution recorded when the pile is installed at $x = 7.7D$, with the relative drop in fluid level of $53\%$ and the corresponding postulated mechanism are shown in Figure 9. In this case there is an increase in positive shaft friction along the entire length of the model pile. No negative changes in shaft friction were recorded possibly because the potential failure surface does not intersect with any pile segments. Although the soil mass near the trench moves towards the trench and causes stress relief in front of the pile, the mobilisation of shaft friction due to pile settlement compensates the loss in shaft friction caused by the reduction in the radial force acting on the pile. Additionally, the soil mass behind the pile also has a tendency to move towards the trench, but it is inhibited by the pile and therefore, the pile might experience an increase in radial stress.

Changes in the radial stresses acting on the pile shaft are being investigated in the next series of tests which are being performed with a pile capable of measuring radial stress as well as axial force along its length.
4.4 Soil deformation

The normalised surface settlement ($\Delta H$, where $\Delta$ = soil surface settlement) profiles along the centre-line of the trench at different relative drops in fluid levels ($d/H$) (Pile installed at $x = 3.5D$), are shown in Figure 10. The broken lines represent the soil surface settlement in the absence of the pile and the continuous lines relate to the surface deformation on the side of the trench where the model pile is installed. The broken line is always below the continuous line implying that the pile has a reinforcing effect on the soil mass with the consequence that the magnitude of surface settlement behind the pile is reduced. However, the large pile movements reported in Section 4.1 are likely to be a far more serious problem to the nearby piled foundations.

5 CONCLUSIONS

The effects of the variation of the slurry level during trench excavation on a single pile and ground responses have been presented and discussed in this paper. The main conclusions drawn from the centrifuge tests are as follows:

- The location of the pile relative to the trench is very important.
- Significant pile settlement and horizontal movement towards the trench are observed once the slurry level drops below the base of the guide wall.
- A sudden substantial increase in pile settlement is observed when the slurry level drops beyond the pile toe level.
- Significant pile end-bearing resistance reductions have been recorded.
- Pile has a reinforcing effect on the soil mass in reducing the magnitude of soil surface settlement.

REFERENCES