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Centrifuge modelling of the installation effects adjacent to an open-ended pile in a layered clay

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ABSTRACT The response of floating piles is often described using the neutral plane approach. This approach requires a reliable prediction of the soil settlements, which in turn are affected by the pile installation effects. This paper presents an approach to retrieve experimental data on immediate and long-term pile installation effects in the geotechnical centrifuge. An axisymmetric experimental test setup allows for measurement of full-field soil deformations, as well as pore pressures, during and after pile installation. These unique results indicate that pile installation effects, such as generation of excess pore pressure and change of the hydraulic conductivity in the soil due to remoulding, have an influence on the development on the neutral plane, and therefore affect the response of floating piles.

1 INTRODUCTION

Floating piles in soft soil deposits primarily mobilize their bearing capacity by means of shaft resistance. The upper part of the pile triggers a downward traction on the pile wall whilst the lower part mobilizes the shaft friction in the soil required for the pile bearing capacity. The transition between these two modes of shaft friction is often defined as the neutral plane. This plane, which is not at a constant level, assists in predictions of the (long-term) settlements of a pile in such a soil. Perhaps the extensive research published by Fellenius is most well-known (e.g. Fellenius, 1972, 1984, 2006). A remaining obstacle is the incorporation of the pile installation itself or, at least effects of the pile installation, in the analysis. This stage is often omitted from the analysis. Additionally to the numerical challenges the absence of spatially dense experimental data on the actual soil behaviour in these stages makes any advance in that direction cumbersome.

The current work aims to address this issue by presenting experimental data from a novel physical modelling test setup that allows favourable scaling of the consolidation process in the geotechnical centrifuge and in-flight pile installation whilst gathering immediate and long-term full-field deformation and pore pressure data in the soil.

Numerous research has been published on pile installation effects, in quantity and approach. The work ranges from clay to sand and from full scale (e.g. Bond & Jardine, 1991, Lehane & Jardine, 1994; Hunt et al., 2002), to laboratory tests at 1-g (e.g. White & Bolton, 2004; Ni et al., 2009) and geotechnical centrifuge tests at n-g (e.g. Cao et al., 2002; White & Lehane, 2004) tests.

This paper follows the interpretation of the stress and strain response according to the general framework first presented in Randolph (2003) and subsequently refined in Randolph & Gourvenec (2011). Three main phases during pile history show the known activated mechanisms of a displacement pile during and after pile installation. (a) During installation the pile is jacked or driven into the ground. The soil is displaced outwards by the pile resulting into remoulding and distortion of the soil with potential formation of residual shear planes (Bond & Jardine, 1991). The soil displacement leads to an increase in the mean total stress. Due to the rapid installation speed this process is regarded undrained. By definition there is no volume change in undrained loading, therefore the increase in mean total stress is accommodated by an increase in excess pore pressures. Additionally, the excess pore pressures increase or decrease due to contraction or dilation of the clay when sheared. (b) During equalisation these excess pore pressures will dissipate over time as the pore pressure gradient induces radial flow from the pile towards the far-field (e.g. Leung et al., 1991; Lehane & Jardine, 1994; Alves et al., 2009). As a result the mean effective stress changes and consolidation takes place around the pile. This results into a decrease of the mean total stress since the soil contracts away from the pile. However, the change in void ratio will generally lead to an increase in soil strength (unstructured clays). This dissipation of pore pressures is related to the registered pile setup, an increase in pile bearing capacity in time, in fine grained materials (Skov & Denver 1988). (c) Pile loading is the last stage and in which the pile head load is transferred from the pile to the soil. The large soil deformations and stress changes during installation in phase (a) govern the processes in the subsequent two stages.

2 EXPERIMENTAL SETUP

Two major influences on the pore pressures and consequentially the soil-structure interface friction are identified; equalisation (consolidation) triggered by the pile installation and consolidation due to the application of an additional surcharge load on the soil surface next to the pile. Ideally, both the pore pressures and deformations in the soil should be measured during pile installation and follow-up consolidation to investigate the influence of these phenomena. A common method to retrieve full-field soil deformations in physical model testing is to record a series of images of the soil movements behind a transparent window. The images are further processed before extracting the displacements using a Particle Image Velocimetry (PIV) algorithm. Altogether this is a non-intrusive method (White et al. 2003). Displacement fields are retrieved by cross-correlating the movement of the intensity peak in a small part of two sequential images. Images are taken with a camera of the clay through a Plexiglas wall. The stress information is retrieved on a separate instrumented wall adjacent to the transparent window in order not to obscure the field of view on the transparent window. The instrumentation consists of 40 pore pressure transducers. The deformations and stresses can be superimposed when, axisymmetric conditions and manageable wall effects are assumed. Combined this results into tracking the full field deformations and pore pressures of the soil in time. The strongbox used in the experiment has transparent windows made out of Plexiglas on the front and the back of the box and two aluminium side walls, of which one has been instrumented, with inner dimensions (L x W x H) 180 X 155 X 150 mm3.

The tests are carried out in the geotechnical centrifuge at Delft University of Technology, which is a small beam centrifuge with a radius of 1.22 m (Allersma, 1994) and is recently re-equipped with modern data acquisition and camera facilities for contemporary centrifuge testing.

2.1 Sample

Laboratory kaolin clay was used. The clay powder is mixed with de-aired water into slurry with a high water content of several times the liquid limit. The standard material has insufficient natural contrast because kaolin has a uniform white colour. Therefore, additional contrast material should be added on the clay surface behind the transparent window of the strongbox. (Ottolini & Dijkstra 2014).

2.2 Pile

The test setup requires a corner pile configuration in which one wall is used for optical observations and one wall is instrumented with additional sensors. Hence, a brass pipe with an inner and outer diameter of respectively 20 mm and 20.5 mm is milled into two separate quarter pipe sections. These pipe sections form the inner and outer shell of the pile, in between this sandwich there is plastic layer that extends and additional 4 mm on both sides. This plastic layer ensures a watertight seal between the pile and the wall. Grease is applied on the plastic layer to reduce friction and improve the sealing.

The pile is only a quarter segment of a circle, hence the stress increase developed in the soil plug forces the pile from the wall. In order to keep the pile aligned against the wall it moves through a template, positioned at the top edge of the strongbox. A schematic representation of the mechanism and the pile is shown in Figure 1, in which the top view is shown (a) with the pile in the corner, the template (b) and (d) and a cross-section of the model pile (c).

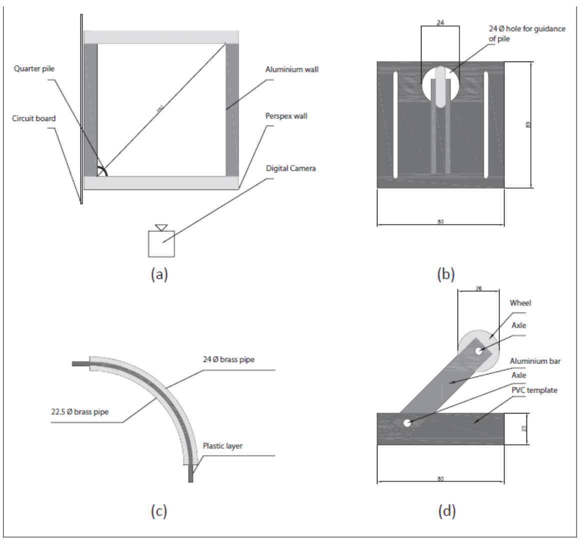

Figure 1. Pile and mechanical template; (a) top view of the strongbox, (b) top view of template, (c) top view pile, (d) side view template

2.3 Instrumented wall

The pore pressure transducers are spaced 30 mm horizontally and 16 mm vertically, in 8 rows of 5 devices in one of the aluminium walls of the strongbox. A total of 40 pore pressure meters are mounted.This setup allows for measurements of pore pressures close to the pile as well as in the farfield.

Contact between the water in the soil and the transducer is through a small channel in the aluminium wall with a 3 mm diameter at the transducer side and a 5 mm diameter at the soil side. A sintered glass porous disc, of 5 mm diameter, prevents the soil from entering the channel. The channel and the porous disc are de-aired with silicone oil under a vacuum close to -90 kPa to ensure a fast response.

3 TEST

The experiment models a single floating pile in a two layer system with a soft clay layer on top of a stiffer clay layer in an area where pile installation is accommodated by a fill on top of the soft clay layer. The surcharge from the fill results in down drag on the floating piles. Such a situation is not uncommon in soft soil areas in shallow waters.

The test procedure exists out of five stages, the first two are aimed to create a normally consolidated soft soil layer on top of a stiffer overconsolidated layer while the last three stages model the pile installation, equalisation and pile loading. In-between phases (1) & (2) and (2) & (3) the centrifuge has been stopped for test alterations. The detailed steps are; (1) preparation of over-consolidated layer at 160g , (2) preparation of top layer at 80g, (3) surcharge loading (equivalent to 30 kPa at 80g) and pile installation, (4) consolidation and (5) loading at 80g. Before phase (1) the Perspex wall is treated with the contrast material and lubricant. The kaolin slurry is poured in the strongbox and the layer is consolidated for 8 hours at 160g. The different acceleration levels between phase (1) and (2), 160g instead of 80g, ensures that the lower layer will become over-consolidated in subsequent stages as well as that the consolidation in this stage will be faster. Before phase (2) the expelled water on top of the bottom layer is removed and the Perspex wall is treated again. An additional layer with kaolin slurry is gently poured in the strongbox and is normally consolidated at 80g for 24 hours. At the end of phase (1) and (2) the top layer is 41 mm and the bottom layer 58 mm thick which corresponds to 3.28 m and 4.64 m thickness for the top and bottom layer respectively at 80g. The top layer has an undrained shear strength profile of 0 to 2.5 kPa from top to bottom, whereas the bottom layer is stiffer with a typical profile from 2.5 till 15 kPa. These values are calculated from reference experiments and validated with laboratory vane shear tests.

Before phase (3) a geotextile is placed on the top layer for proper stress distribution of the surcharge consisting out of sand and lead shot. The pile is installed by self-weight to ensure load controlled conditions and a free moving pile in phase (4) for tracking of the development of the neutral plane. Initially, the pile is fixed on friction between the pile and the wall with the pile tip on the clay surface. No sand but an equivalent weight is placed inside the pile to ensure no sand plug will develop. At 30g the pile starts moving and is installed. During phase (4) consolidation of both soil layers takes place and there is a development of the neutral plane. After 3.5 years of consolidation phase (5) is initiated by jacking the pile further in the soil with the actuator. These steps follow the general framework given in the introduction of; installation, equalisation, consolidation and loading.

4 RESULTS

4.1 Pile installation

The displacement contours derived from the image sequence and the PIV analysis in the soil immediately after pile installation are shown in Figure 2. Each line represents the displacement of the soil during pile installation. A zero displacement contour, the gray line, is also shown.
During pile installation the soil is radially displaced away from the pile tip. Displacement varies from 4.5D to 2D in the top and bottom layer respectively. The direction of the radial displacement is slightly reversed, in the direction of the pile, when the pile tip penetrates further. Finally, the soil is pushed upwards due to displacement of the soil in deeper layers. Around 0.5D underneath the pile tip the soil is also displaced in the direction of the pile movement in both the top and bottom layer. Furthermore, during installation vertical displacement of a very thin layer next to the pile shaft is observed. The pile displacement stops when the pile tip penetrated 0.35D in the bottom layer.

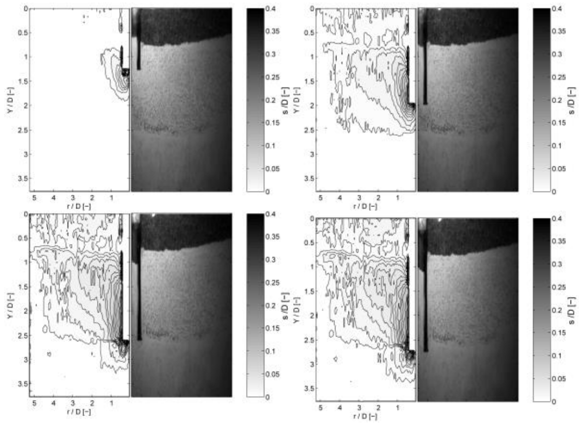

Figure 2. Contour plots of the total displacements in the soil at 4 penetration depths (1.25, 2.0, 2.6 & 2.75 y / D [-]) during and immediate after installation

As shown in Figure 3 a small excess pore pressure is generated near the pile tip after installation has finished. The pore pressures are shown from 0.94 x/D away from the pile until the far field. The pore pressures dissipate quickly close to the pile and dissipate towards the far field.

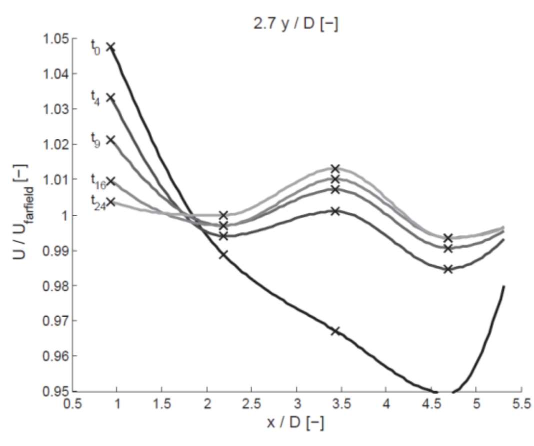

Figure 3. Dissipation of pore pressures near pile base after installation (subscript of t denotes prototype time in days) at 2.7 y / D

4.2 Consolidation and evolution of the neutral plane

In the second test phase both layers consolidate due to the weight of the surcharge load. This results in downdrag on the pile. The somewhat irregular downward movement of the pile partly results from stick-slip friction between the pile and the wall and partly due to cycles of generation and dissipation of excess pore pressures in the soil. The pile movement is triggered due to additional downdrag from the soil. Displacement of the soil around the pile is larger than in the far field when the pile is displaced downward and smaller when the pile is standing still i.e. the soil hangs on the pile. Development of the neutral plane, defined as the point on the pile-soil interface where no relative displacements occur is calculated from the PIV data. Extraction of this plane depends on the type of displacement formulation. The plane derived from the average incremental displacements over 0.5D around the pile at several distances radially away from the pile. It should be noted that calculation of the neutral plane is indistinct since the location where the soil transfers its shear friction to the pile is not trivial and depended on many factors. Multiple possible locations for the neutral plane are shown in Figure 4. For all cases the neutral plane is initially located at the top of the pile during pile installation. During consolidation it moves up and down the shaft of the pile until it reaches a stable position at the top of the pile. This indicates that the consolidation around the pile is larger than in the far field therefore the pile settles faster than the soil and full positive shaft friction is mobilized. Neutral planes derived from the average incremental displacement closer to the pile tend to stay closer to the pile tip since the soil is influenced by the pile and is displaced when the pile moves. But the general evolution trend is the same for the all locations. Movement of the neutral plane is in line with observations of Fellenius (2006) that a small relative settlement of the pile or soil can mobilize full positive or negative skin friction.

Consolidation around the pile is faster than in the far field. Pore pressures measured 0.9D away from the pile decrease significantly faster. Increase of the water level inside of the pile during testing indicates that excesses pore pressures around the pile tip dissipate through the open end of the pile resulting in faster drainage. Additionally, the permeability of the soil is altered after pile installation due to shearing and remoulding. Resulting in faster consolidation around the pile tip and therefore large displacements.

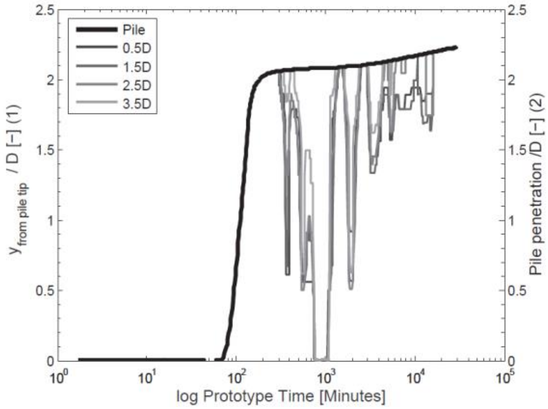

Figure 4. Development of neutral plane through time relatively to the pile base and the pile base displacement calculated from average incremental displacements of a 0.5D wide slice located at several distances in-between 0.5D – 3.5D

5 DISCUSSION

Although after installation the development of the neutral plane at the top of the pile after equalisation there is a need for incorporation of the pile installation effects to properly predict the initial location after equalisation. Also, the neutral plane interpretation is ambiguous. Both during installation and reloading excess pore pressures are registered, which is in line with the framework of Randolph & Gourvenec (2011). A change in effective stress results in a different pile / soil behaviour. Remoulding of the soil and possible mobilisation of a pile plug results in different drainage behaviour, therefore long-term effects, after pile installation. Both the change in permeability due to remoulding and deformation of the soil and the difference in drainage distance for soil near the pile tip should be taken into account for accurate modelling of the long-term pile response.

Due to test limitations creep is not incorporated in the current test data, however, some natural clays have significantly large creep rates. Presently, it is unknown to which extent the pile installation and loading will influence these creep rates.

6 CONCLUSIONS

Application of the method on pile installation, equalisation and loading supports the conceptual framework described in literature. The current data shows that also in the prediction of long-term pile response the effects from initial installation of piles should not be neglected. In the modelled two-layered system the pile tip is the dominant part of the pile for both the displacement and increase in pore pressures.

During consolidation alternating pile displacements are observed. When the pile displacement is larger than the soil displacement there is an increase in excess pore pressures. Vertical displacements due to consolidation are larger near the pile than in far field due to effects on the permeability resulting from the pile installation and the drainage behaviour of the pile.

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