Stress Changes due to Shape Effects in the Construction Process of Pile Walls

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ABSTRACT

The shaft friction of displacement piles in sand depends on the change in the horizontal stresses on the pile shaft during installation. Recent research has revealed that the sectional shape of a pile has a strong influence on the horizontal stresses, leading to great difference of the pile shaft friction. Based on these findings, an optimization idea has been proposed, referred to as the "switched-on mechanism". The main emphasis in this paper is given to understanding the changes in horizontal stresses measured during "switching-on" from open-section (installation individually) to closed (load testing for whole pile walls) in cross section. In order to model the construction and load test process for pile walls, a dual installation system was installed into the beam centrifuge. This paper discusses the stress changes through the whole construction process and the efficiency of the switched-on mechanism, and highlights how physical modelling has allowed this highly complex problem to be quantified.

Key words: *Stress change, shape effects, Pile walls, Centrifuge modeling*

1. Introduction

The shaft friction of displacement piles in sand de-pends on, amongst other things, the change in the horizontal stresses during installation. Although there have been few studies examining the effects of pile cross sectional shape, the authors has investigated the effects – i.e. shape effects– using centrifuge modeling and proposed a theoretical estimation based on vertical arching theory so far (Taenaka *et al*. 2008; Taenaka *et al*. 2010). Recent research has revealed that the sectional shape of a pile has a strong influence on the horizontal stresses, leading to great differences in the pile shaft friction.

Based on these findings, an optimization study based on this effect will be presented in this paper. An optimization idea has been proposed by White (2002), as "switched-on mechanism". A continuous wall of H-piles (**Fig. 1**) is able to generate high vertical arching due to close cross section, resulting in high load capacity, even if each H-shaped pile is driven individually. **Fig. 2** shows a

Fig. 1 Continuous H-pile wall (White *et al*., 2007)

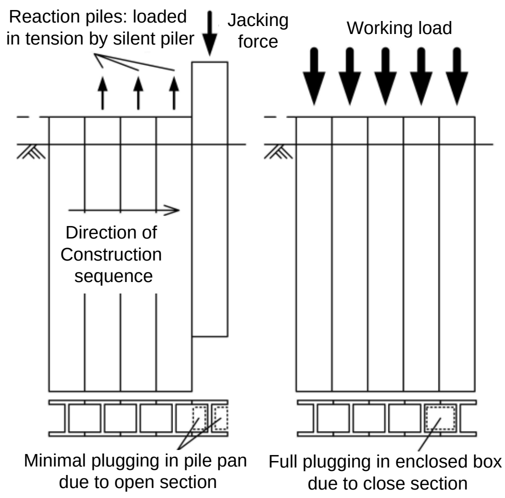

Fig. 2 Continuous H-pile wall and the construction sequence (White *et al*., 2003 & White *et al*., 2007)

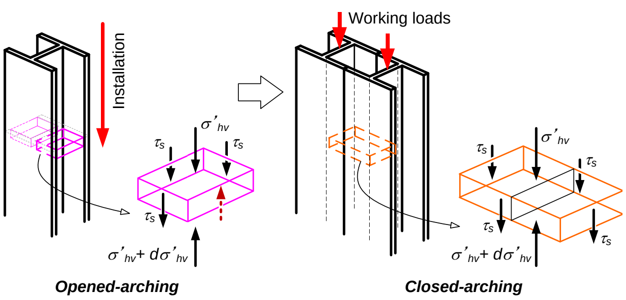

Fig. 3 Vertical force equilibrium during installation and in under working loads

schematic drawing during installation and under working loads. The first installed H-shaped pile, where the cross sectional shape is open as shown in the upper figure, mobilizes a weak arching effect, leading to a gentle increase in local shaft friction from "open arching", perhaps without plugging. After the second pile is installed, the cross section becomes closed between adjacent pairs of piles, resulting in the strong arching effect when both piles are loaded simultaneously. This strong arching effect perhaps leads to full plugging between close-section of two H-shaped piles and exhibits much higher end-bearing capacity under working loads, shown in the bottom figure, in comparison to the installation resistance. This concept means that the axial capacity of a pile can be varied if the effective cross section of the pile is changed from under construction to under working loads, and is therefore a quite fascinating idea for optimizing pile foundation systems in which a pile should be driven easily but should mobilize high axial capacity.

In order to model the construction and load test process for pile walls as **Fig. 2**, a dual installation system was installed into the beam centrifuge. The centrifuge testing program compared the behavior of two different-shaped piles, which were prepared in respect to the optimization of the cross sectional geometry of a pile. The main emphasis is given to the changes in horizontal stresses measured during "switch" in cross section. The measured stress changes were due to the shape effect of a single pile, the effect from the switch of the cross section as well as interaction effects. This paper discusses the stress changes through the whole construction process and the efficiency of the switched-on mechanism, and highlights how physical modeling has allowed this highly complex problem to be quantified.

2. Background

2.1. Shape effect

O'Neill (2001) showed that the stress transfer mechanism under compressive loading can lead to a measurable increase in the vertical stress around a pile, while the inverse occurs under tensile loading. In the sand in the vicinity of a circular pile, the cumulative downward vertical stresses (caused by the shaft resistance) can be dissipated rapidly, with support provided by the far field soil. Therefore the local stresses may not rise significantly. However, the phenomenon is likely to depend on the cross-sectional shape. The opposite extreme of stress transfer is the inside of the tubular pile. In this case the cumulative vertical stresses develop rapidly, often leading to soil plugging inside the pile.

To investigate the shape effect, Taenaka *et al*. (2008) proposed the estimation method based on the vertical force equilibrium as shown in **Fig. 3** according to the simplified arching theory proposed by Janssen (1985), giving a shape factor to describe difference in the cross sectional shape of a pile. Following the proposed theory, for example, an H-shaped pile developed much greater stress level within the concave area than an X-shaped pile, which has been observed in the centrifuge modeling by Taenaka *et al*. (2010), as shown in **Fig. 4**.

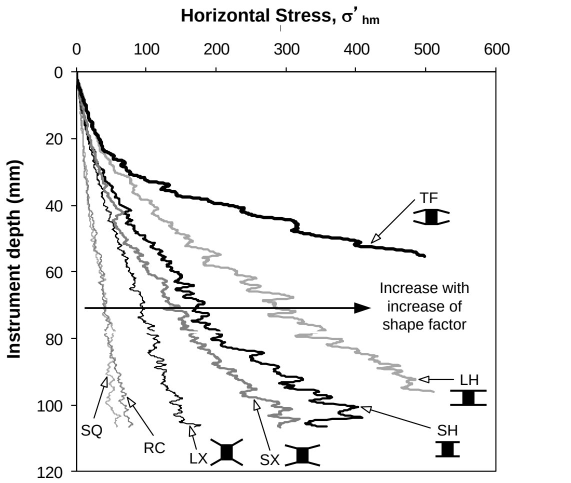

Fig. 4 Profiles of horizontal stresses measured near the pile tip during installation (after Taenaka *et al*., 2010)

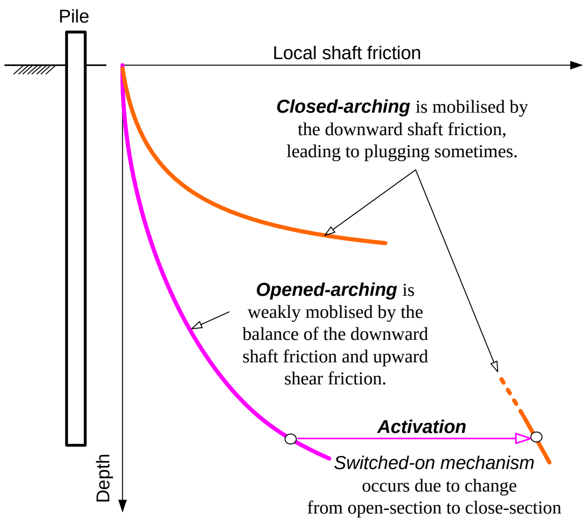

Fig. 5 Comparison of the shaft friction distribution on a single H-pile and H-pile walls and vertical force equilibrium at each stage

2.2. Switched-on mechanism

An individual H-pile is installed immediately adjacent to the previous. **Fig. 5** shows a schematic drawing for shaft friction distribution during installation and under working loads. The installed single pile, where the cross sectional shape is open as shown in the left **Fig. 3**, mobilize the weak arching effect, leading to a gentle increase in local shaft friction, perhaps with no plugging. A completed wall of H-piles consists of square box sections (close section) between adjacent two piles, resulting in strong arching effect. This strong arching effect perhaps leads to full plugging and exhibits much higher end-bearing capacity under working loads. Indeed, it is reported that the capacity of each pile within the walls is, around 50%, greater than single pile from the field tests (White *et al*. 2003). These results confirm that enhanced axial capacity can be activated after the installation of an H-pile wall due to switched-on in the cross sectional geometries.

This switched-on mechanism could be explained by the theory of the shape effect. Furthermore, this concept means that the axial resistance in a pile could be variable if the cross section of the pile be changed from construction to service stages. However, there have been few investigations in detail for the mechanism. The centrifuge modeling, which would be the first trial, is described in this paper.

3. Test Methodology

3.1. Dual pile installation systems

The University of Western Australia geotechnical beam-centrifuge was used in this investigation at 20 g acceleration. Sand samples in strong box (internal dimensions of W390 x B650 x H300 mm) were prepared by air pluviation, resulting in medium sand layer (Silica sand: G_s = 2.65; D_{50} = 0.20 mm; Dr ~ 0.55). To modeling "switch", two actuators was mounted in parallel across the width of the strong box as shown in **Fig. 6**. The model piles were placed adjacently between two actuator-bases by the arm parts mediated for shifting the positions, although a model pile usually grasped by the actuator directly. The three pressure sensors on each instrumented pile were set face-to-face to measure change in horizontal stresses. The instrumented pile with pressure sensors was designed in the same way as previous similar studies (e.g., Lehane & White, 2005). In addition, a settlement bar was used to quantify settlement of the adjacent soil relative to the model piles during testing via laser transducer above the top of the settlement bar.

During the switched-"on" mechanism, the first pile fixed to the actuator-1 was normally installed at 0.2 mm/sec to specified depth and then halted at this depth (**Fig. 7**). Subsequently, the second pile fixed to the actuator-2 was installed to the same depth without the

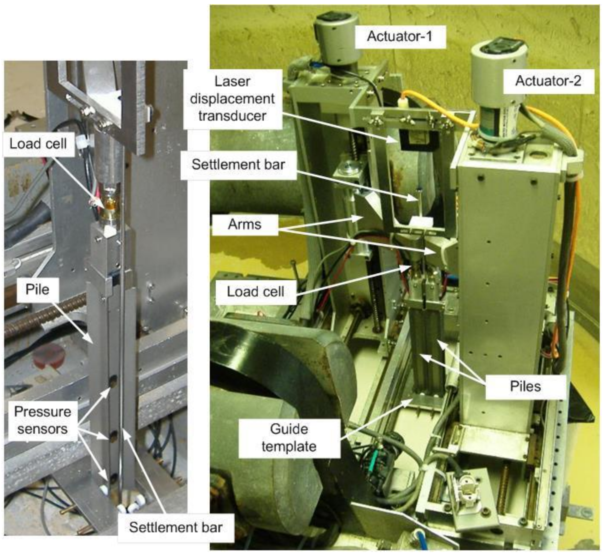

Fig. 6 Setting of dual pile installation systems for the switched-on tests

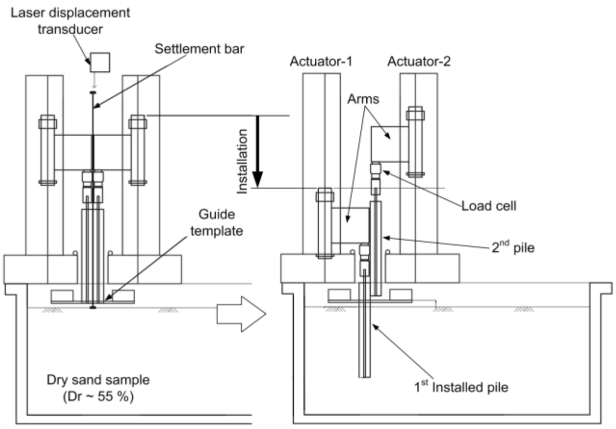

Fig. 7 Test sequence in the switched-on tests

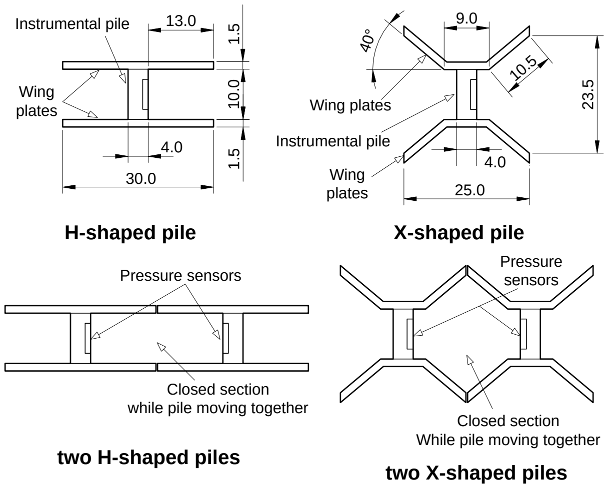

Fig. 8 Cross sectional shapes of model piles

first pile moving. Then the load test was performed at 0.02 mm/sec together. On the other hand, the switched-"off" mechanism is the reverse process, where the cross section changes from close to open. This process can be modeled in the dual pile installation systems, by which the two piles were installed together first, and then one pile was halted while another pile was kept moving.

3.2. Model piles

Two plate piles with 4 mm in thickness (t) and 10 mm in width (B) were used as instrument piles, which have miniature total pressure cells embedded on the pile shaft surfaces. These piles made it possible to change the cross sectional geometries by attached extra pieces to the side wall, for example, to model an H-shaped pile, both thin plates were bolted to both sides of the plate pile (**Fig. 8**).

The pressure sensors were placed at 10 mm (h/B = 1), 60 mm (h/B = 6) and 120 mm (h/B = 12) behind the pile tip on the 1st pile and at 10 mm (h/B = 1), 30 mm (h/B = 3) and 60 mm (h/B = 6) behind the pile tip on the 2nd pile to measure changes in the horizontal stresses within the concave area. For the pile wall tests, the face where the pressure sensors were mounted facing to each other as shown in **Fig. 8**.

In addition, X-shaped piles were prepared for modeling the switched-on mechanism only. It is because X-shaped piles can prevent increase in the horizontal stresses during a single pile installation, which has been observed by Taenaka *et al*. (2010). It is therefore expected that X-shaped piles could be effective to gain more activate change during the switched-on mechanism (i.e., lower installation resistance and then higher bearing capacity).

4. Comparison of open- vs close-section piles

Before investigation of the switched-on mechanism, the installation tests for a double H-shaped pile (DP) are compared to those for a single H-shaped pile (SP). The wide plates connected two instrument piles, forming one rigid double H-shaped pile. Settlement of ground adjacent to the pile or in the enclosed area during installation was measured as shown in **Fig. 9**. Settlement started to occur at 25 mm in pile installation and the measurement settlement in the double H-shaped pile was greater than in

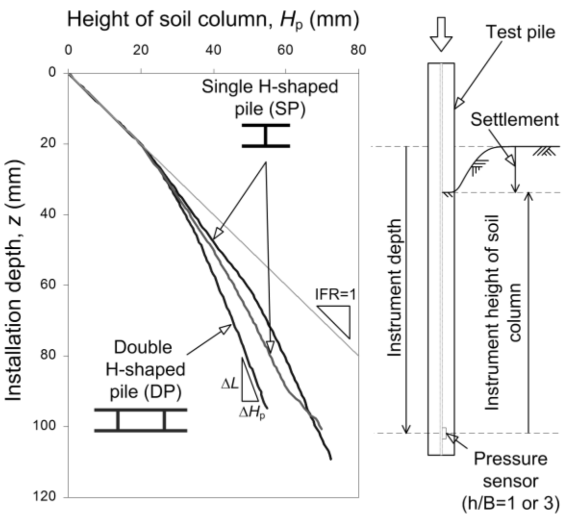

Fig. 9 Soil plug progression within the internal and concave area in double H-shaped pile and single H-shaped pile respectively

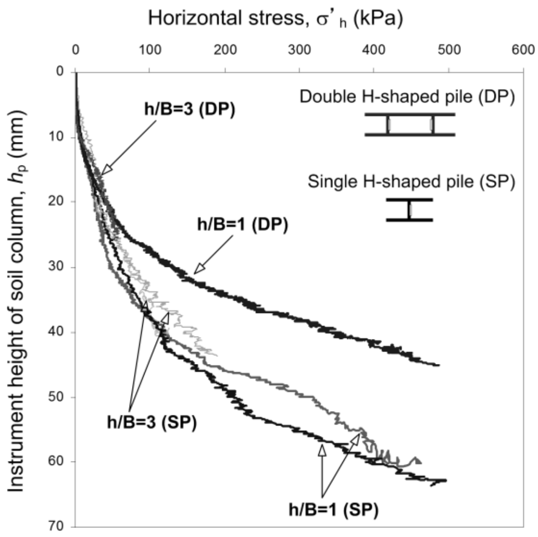

Fig. 10 Comparison of horizontal stresses with the height of soil column between open- vs close-section

single H-shaped pile due to downward drag force caused by the vertical arching effect.

Fig. 10 shows variation of horizontal stresses for average value at h/B = 1 and measurements at h/B = 3 for open- and close-section piles. In this figure, the instrument height was expressed in vertical axis, using the measurements of settlement. The pro-files of horizontal stress change were very similar to the schematic drawing of local shaft friction in **Fig. 5**. It is very clear that the close section in the double H-shaped pile developed higher horizontal stresses due to strong arching effect, while the horizontal stresses were governed by weak arching effect in open section of the single H-shaped pile.

5. Switched-on testing

5.1. Measured dataset

The switched-on testing of H-shaped piles and X-shaped piles are discussed in this section, in which the cross section of piles was initially open during installation and then turned to close form after completing installation. **Fig. 11** shows changes in the horizontal stress against the testing time in H-shaped piles. The horizontal stresses at h/B = 1 on both 1st and 2nd pile increased while the pile itself was installed. In particular, a drop in the horizontal stress at h/B = 1 of the 1st installed pile was initially measured in a while after 2nd pile installation. Afterward, a rapid increase was measured as the pile tip of 2nd pile approached the instrumented level. The detailed mechanism behind a stress change will be discussed later. Measurements were plotted in the same way for X-shaped piles in **Fig. 12**. The general features observed were very similar to H-shaped piles.

The maximum stress measurements were different between two tests. For the H-shaped piles in **Fig. 11**, the maximum horizontal stress during installation process was recorded in the pressure sensor on the 2nd installing pile (i.e. on the moving pile), where the maximum horizontal stress was developed due to amplification by shape effects from H-shape. On the other hand, for X-shaped piles, the maximum horizontal stress was measured in the pressure sensor on the 1st pile (i.e. stopped pile) during the subsequent pile coming as shown in **Fig. 12**. This maximum stress in X-shaped piles was caused probably by interaction effect by the adjacent pile installation rather than by the stress amplification due to shape effects.

5.2. Switched-on mechanism

Regarding the switched on mechanism, the stress change from installation to load testing needs attention. Ignoring the jump in stress measured on the 1st installed pile, the horizontal stresses in the load testing with close-section was over the values during pile installation

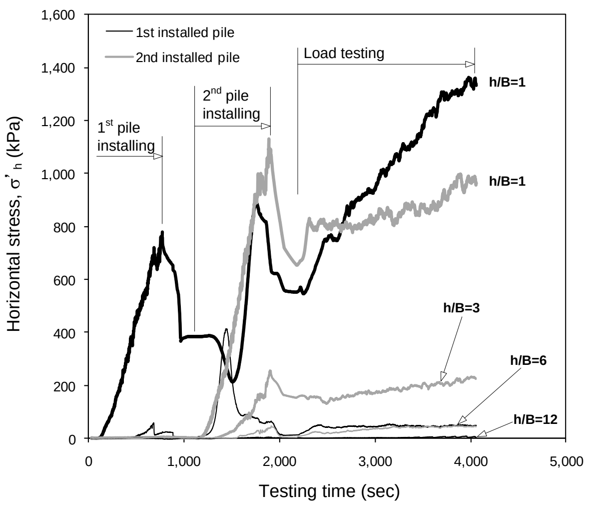

Fig. 11 Changes in horizontal stresses during two H-pile installations and in the load testing

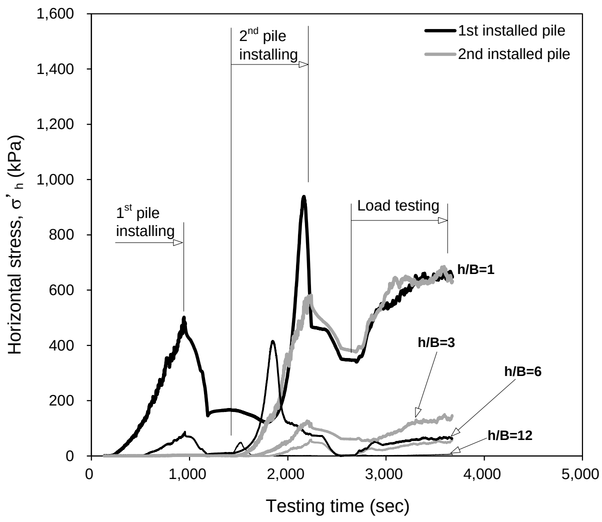

Fig. 12 Changes in horizontal stresses during two X-pile installations and in the load testing

in X-shaped piles as shown in **Fig. 13**. In this view point, this figure focused on the load testing stage. It is clear that the normalized horizontal stresses under the load testing in X-shaped piles went up rapidly and well over the maximum value measured during each pile installation, due probably to a switch of the cross section from open to close. This result successfully demonstrated the activation of the switched-on mechanism.

However, no big difference was observed between installation (open-section) and load testing (close-section). It is expected that even in the single H-pile may develop similar stress level to the double H-shaped piles, implying that the single pile could reach the limit value in stress level form a soil plug.

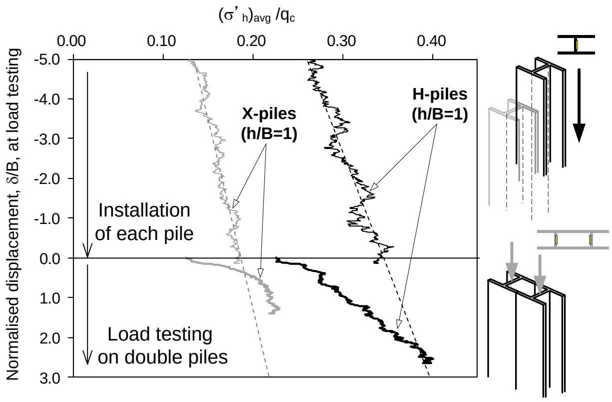

Fig. 13 Average values in horizontal stresses at h/B =1 normalized by the cone tip resistance during installation and in the load tests for H-shaped piles and X-shaped piles

5.3. Interaction effect

The changes in horizontal stresses at h/B = 1 and 6 on the existing pile (i.e. 1st installed pile) were plotted against distance to the tip of the 2nd pile during installation in **Fig. 14**. The horizontal stresses recorded 0.29 and 0.18 at h/B = 1 in the H-shaped pile and the X-shaped pile respectively during the 1st installation. In the subsequent releasing process of the head load to zero before the 2nd pile installation, the horizontal stresses dropped and kept the residual value initially for the 2nd pile installation because the pile tip was too far away from the pressure sensors.

The stress drops were observed at h/B =1 both the H-shaped pile and the X-shaped pile, in which the drop in the X-shaped was small. This is not specific to the investigation in this paper. Chow (1996) investigated pile interaction by recording radial stress changes on an existing pile during adjacent pile installation, although the piles were just rod-shape. Careful examination of Chow's data reveals that there were small stress drop observed before increase of horizontal stresses as shown in **Fig. 15**. On the other hand, stress field investigations around an installation pile have not reported such a stress drop (e.g. Leung *et al*., 1996; Gavin & Lehane, 2003), so that the stress drop was probably specific trend to the pile interaction. This interaction effect could link to a difficulty of centrifuge modeling for the switched

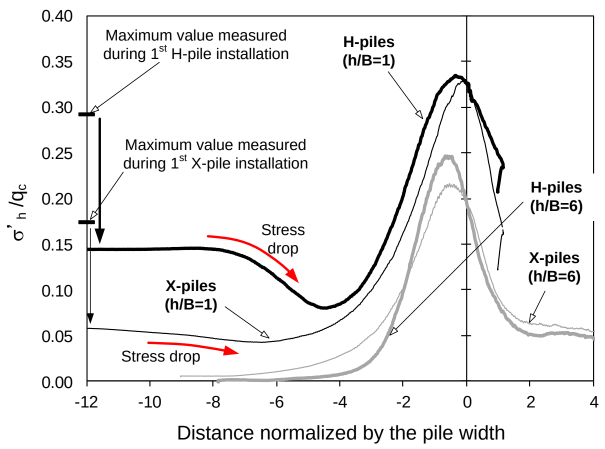

Fig. 14 Changes in normalized horizontal stresses on an existing during an adjacent pile installation

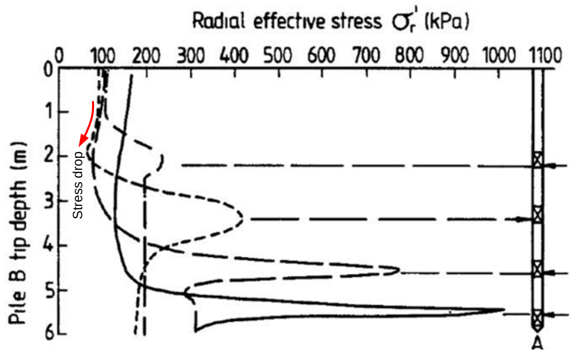

Fig. 15 Changes in normalized horizontal stresses on an existing during an adjacent pile installation (after Chow, 1997)

mechanism, which will be summarized in the next section.

After the stress drop, the measurements in horizontal stresses trended upwards to reach the peak stresses a little bit before the pile tip reached the instrument level. Similar trends were also reported by Leung *et al*. (1996) and Gavin & Lehane (2003). The peak stresses at h/B = 1 were similar between the two cross sectional shapes, although the amplification stresses measured on installation piles were quite different between H- and X-shaped piles. It suggested that the maximum horizontal stresses were not due stress amplification by shape effect, rather determined by cavity expansion stress from the tip of an adjacent pile during installation.

5.4. Modeling challenges in the switched-on condition

The interaction effect of the adjacent pile on the existing pile during installation is too great to ignore. A

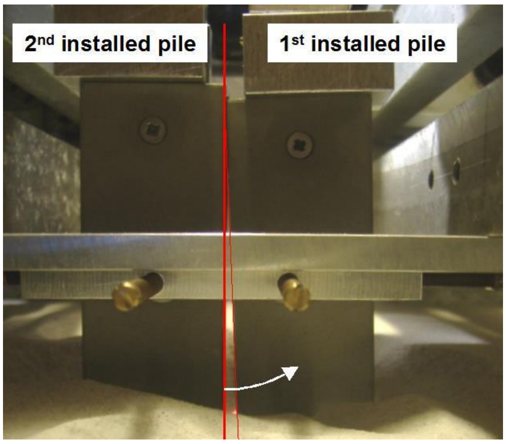

Fig. 16 Relative position for two H-piles after load testing

dramatic rise in horizontal (radial) stress on the adjacent pile occurred when the installed pile tip was passing. Indeed, it was observed that the magnitudes of rise in horizontal stresses due to interaction effect were sometimes higher than the stress amplification due to shape effects as shown in **Fig. 12**. Accordingly, the stress field around the existing pile was expected to be imbalanced with a large difference between the stress level occurring between the side facing on installation pile and the opposite side. **Fig. 16** shows a photo taken after completing the switched-on testing. A gap between two piles was observed because the first pile was subject to high horizontal pressure due to interaction effect, which was sufficient to overcome the rotational stiffness of the pile head connection and induce bending in the pile, leading to lateral movement.

As known widely, centrifuge modeling is a powerful tool to replicate in-situ stress level in terms of soil behavior depending on stress level and stress history. From this view point, the switched-on testing has been well performed and the stress level enhanced by the shape effect could be reproduced as similar to the stress level in the prototype scale. However, the very high lateral loads were unexpected and the stiffness of the pile head arrangement in the centrifuge model was not adequate to maintain verticality of both piles at ground level. Also, the stiffness of the model structures did not replicate the stiffness at prototype scale due to the scaling of the small model piles. In reality, the point of fixity is also lower down, close to the ground level, at the piling machine.

In addition, pile wall systems in practical use has interlocks to connect adjacent pile each other (see **Fig. 1**), which should be utilized to keep the cross section even if an existing pile is subject to high pressure from the moving pile, at least preventing it from a lateral movement due to interaction effect. However, it is quite challenging to replicate the interlocks in a reduced scaling model piles in centrifuge modeling.

6. Conclusion

The paper focuses on the horizontal stress change due to effect from difference of the cross sectional geometry of piles in sand –i.e. shape effects–, especially in construction process of a continuous H-shaped pile walls. The continuous H-shaped pile walls allow the cross section to be changed from open-shape during installation to close-shape under the working loads (switched-on mechanism). In order to replicate this process, the dual pile installation systems have been developed on the centrifuge, leading to the following findings obtained:

[1] It was successfully observed that close-section piles mobilized more rapidly and higher horizontal stresses during installation than the open-section piles, due to shape effects.

[2] Switched-on mechanism has been modeled successfully in terms of the horizontal stress changes in X-shaped piles, but not so well in H-shaped piles.

[3] Interaction effect on an existing pile from adjacent pile installation is so significant, sometimes resulting in high lateral enough to move the existing pile laterally in particular for a continuous pile wall.

[4] A difficulty for centrifuge modeling has been discussed. Centrifuge can model in situ stress level in soils but it is quite difficult to replicate the equivalent stiffness and strength of pile members as well as structural details such as interlocks. From this viewpoint, larger scale test even in 1g and/or field tests with well-planned data measurements need to be performed for verification for the switch-on mechanism.

7. Acknowledgements

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References

Chow, F. C. 1996. Investigations into the behaviour of dis-placement piles for offshore foundations. PhD thesis, University of London (imperial college), UK.

Gavin, K. G. &b Lehane B. M. 2003. The shaft capacity of pipe piles in sand. Canadian Geotechnical Journal, Vol. 40, 36-45.

Janssen, H.A. 1895. Versuche uber getreidedruck in silozellen. Zeitschrift, Verein Deutscher Ingenieure 39, 1045–1049 (partial translation in Proc. Inst. Civ. Engrs, 1986, 553).

Leung, C.F., Lee, F.H. & Yet, N.S. 1996. The role of particle breakage in pile creep in sand. Canadian Geotechnical Journal, Vol. 33, No.6, 888-898.

O'Neill, M.W. 2001. Side resistance in piles and drilled shafts. ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 127, No. 1, 3-16.

Taenaka, S., White, D.J., Randolph, M.F., Nakayama, H. & Nishiumi, K. 2008. A study of the effect of cross-sectional shape on the performance of sheet piles. 2nd Int. Conf. on Fndns (ICOF), IHC BRE Press, Dundee, UK, 319-330

Taenaka, S., White, D.J. & Randolph, M.F. 2010. The effect of pile shape on the horizontal shaft stress during installation in sand. Proceeding of the 7th Int. Conf. on Physical Modelling in Geotechnics. Zurich, Switzerland: 835-840.

White, D.J. 2002. An investigation into the behaviour of pressed-in piles. PhD thesis, University of Cambridge, UK.

White, D.J., Bolton, M.D. & Wako, C. 2003. A novel urban foundation system using pressed-in H-piles. Proc. XIIIth Eur. Conf. Soil Mech. & Geotech Engineering, Prague 2, 425-432.

Lehane, B.M. & White, D. J. 2005. Lateral stress changes and shaft friction for model displacement piles in sand. Canadian Geotechnical Journal, Vol. 42, No.4, 1039-1052.

White, D. J. & Deeks, A. D. 2007. Recent research into the behaviour of jacked foundation piles. Advances in Deep Foundations, Yokosuka, Japan, 3-26.