Proceedings of the Second International Conference on Press-in Engineering 2021, Kochi, Japan – Matsumoto et al (eds)

Stress changes in adjacent soils of tapered piles during installation into sand

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ABSTRACT: Tapered piles with increasing pile diameter from the pile tip to the top can develop high vertical bearing capacity, especially a high shaft friction owing to tapering and wedging effects. Many researchers have reported these merits over conventional straight piles based on small model tests and furthermore the mechanism has been explained using a cylindrical cavity expansion theory. However, few researchers have examined the installation effect of tapered piles. There must be a certain installation effect even in a tapered pile, and its effect could be affected by its pile geometry. Therefore, this study investigates the radial and vertical pressure in adjacent soils between a straight pile and a tapered pile during installation into sand at 1g. The test results suggest that the profiles of pressure changes around the piles are quite different, leading to differences in the radial stress distribution between tapered and straight piles.

1 INTRODUCTION

Tapered piles with increasing pile diameter from the pile tip to the top can develop highly vertical bearing capacity, especially in high shaft friction owing to tapering wedge effect. Many studies have reported these merits over conventional straight piles. Experimental studies have demonstrated that the shaft friction under compression loading is higher than that of the straight piles through a comparison between different tapered angles, both 1g chamber tests and centrifuge tests (e.g. Wei & El Naggar, 1998; El Naggar & Sakr, 2000). Theoretical solutions under compression loads have also been provided based mainly on the cavity expansion theory by several researchers (e.g. Tominaga & Chen, 2006 and Manandhara et al., 2013). Other useful studies have already been carried out under different loading conditions for lateral loading (e.g. Sakr et al., 2005) and for uplift loading (e.g. El Naggar & Wei, 2000). In situ field testing was introduced for compression loading (e.g. Tominaga et. al., 2007a; Sato, et al., 2010) and lateral loading (Tominaga, et al., 2007b). These studies focused mainly on the behavior under the load-carrying stage. The mechanism behind the high performance of the tapered piles can be explained in a manner similar to that of non-displacement piles.

However, there are few studies discussing the installation effect for tapered piles. A few recent investigations were performed to model the pile installation process. Manandhar & Yasufuku (2013) measured the lateral soil pressure changes during pile installation at different distances from the pile center. They also have discussed the stress distribution where the stress was higher near the pile and reduced significantly from the center of the pile. Their results demonstrated that, when a tapered pile is installed into sand, radial displacement occurs in the adjacent soil owing to the increasing pile diameter along the pile shaft, leading to radial stress changes around the piles. These radial stress changes cannot be neglected when evaluating the performance of the tapered piles. There must be a certain installation effect even in a tapered pile, and its effect could be affected by the pile geometry of the tapered piles.

This paper discusses the installation effect of the tapered pile through the investigation of radial and vertical pressure changes in adjacent soils between a straight pile and a tapered pile during installation into sand. For this purposes, small model pile tests on medium dense dry sand ground at 1g were conducted for comparison between tapered and straight piles. Furthermore, the radial and vertical pressures were measured around the piles at different depth.

2 TEST METHODOLOGY

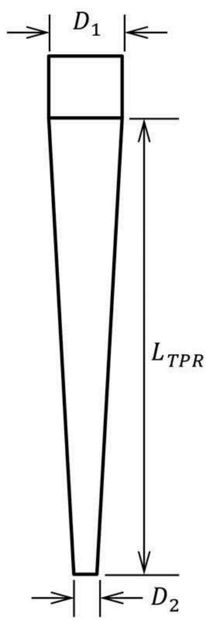
2.1 *Model piles*

Two types of piles were prepared for this study. One pile was a straight pile (STR) with a diameter

DOI: 10.1201/9781003215226-22

Table 1. Model piles of straight (STR) and taper (TPR).

	STR	TPR
Dia. at top D_1 (mm)	34.0	49.5
Dia. at tip D_2 (mm)	34.0	18.0
End bearing area (cm^2)	9.1	2.5
ΔD (mm) (= $D_1 - D_2$)	0	31.5
Taper length L_{TPR} (mm)	620	620
Taper ratio $\Delta D/L_{TPR}$ (%)	0.0	5.08
Pile Volume (cm^3)	2252	2380



of 34 mm. The other pile was a tapered pile (TPR) with an increasing pile diameter from the pile tip to the top. The maximum and minimum diameters of the tapered pile were determined to be similar volume to those of the straight pile at the final installation depth. This means that the soil volume moved by the pile installation was also similar between both piles, although their pile shapes were different. The detailed dimensions of both piles are summarized in Table 1.

2.2 *Test conditions*

The pile installation tests were carried out in a cylindrical steel tank of 700 mm in height and 520 mm in inner diameter at 1g with no surcharge pressure, as shown in Figure 1. Figure 2 shows the experimental apparatus and the tapered model pile. The ratio of the pile diameter to the diameter of the soil tank has been studies, and then Bolton et al. (1999) and Lee & Salgado (2000) has suggested less than 1/10 and 1/12 respectively. The ratio of the average diameter in the model piles (= 34 mm) to the soil tank (=520) was approximately 1/15 in this study, which satisfied their suggested range.

The soil, dry silica sand (D_{50}~0.20 mm), was prepared by the free-fall method with vibration to satisfy the pre-defined relative density condition of D_r~50 %. The soil strength at each depth was not clear in this study where the investigation hereby focused mainly on the comparison between two piles.

Then, such a test pile was installed monotonically from the soil surface at 10 mm/min until the pile tip reached around 620 mm in depth. The load and displacement at the pile head were measured during pile installation.

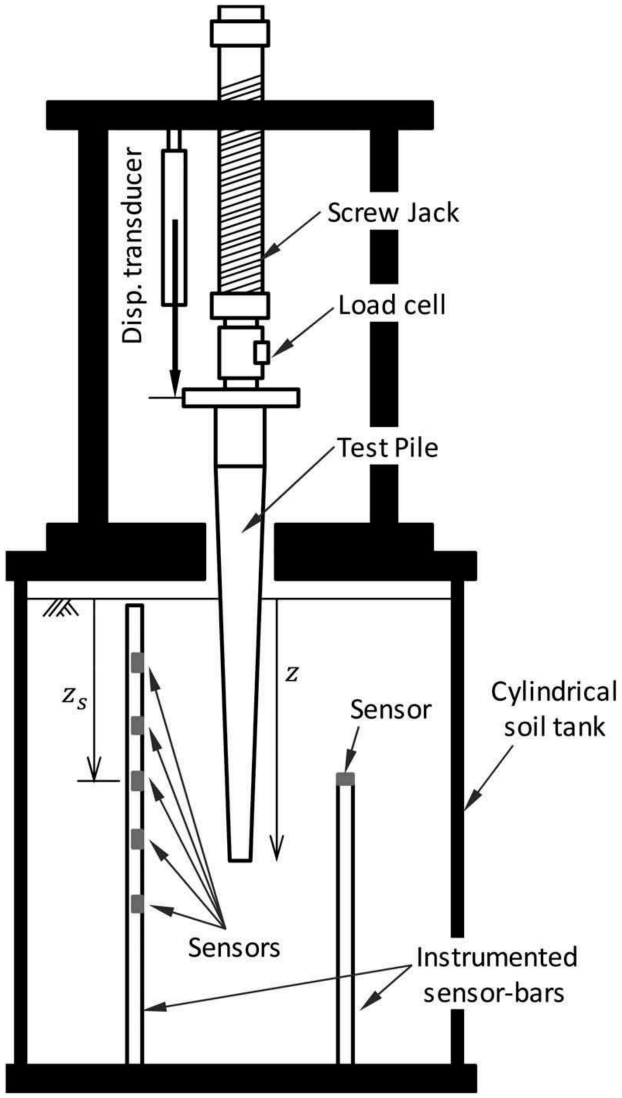


Figure 1. Experimental apparatus (soil tank, jack system and pressure sensors on instrumented bars).

2.3 *Data gathering*

As introduced in the beginning, a particular emphasis is given to the stress changes in the tapered pile during installation compared with the straight pile. Experimental studies utilizing several types of pressure sensors have been reported in many researches (e.g., Klotz & Coop, 2001; White & Lehane, 2004; Lehane & White, 2005; Jardine et al., 2009; Taenaka et al., 2010), where pressure sensors were mounted on the model pile itself to measure the radial pressure directly acting on the pile shaft. Another method was conducted using pressure sensors placed in the soil. Using this method several studies measured pressure changes or stress distributions in the soil around model piles (e.g., Leung et al., 1996; Gavin & Lehane, 2003; Manandhar & Yasufuku, 2013).

In order to investigate pressure changes, several miniature pressure sensors (Tokyo Sokki; PDA-200KPA; 7.6mm in diameter and 2.0 mm in thickness) were used in this study. Five pressure sensors were placed on the shaft of the instrumented sensor

Figure 2. Photographs of the experimental apparatus (left) and the tapered model pile under testing (right).

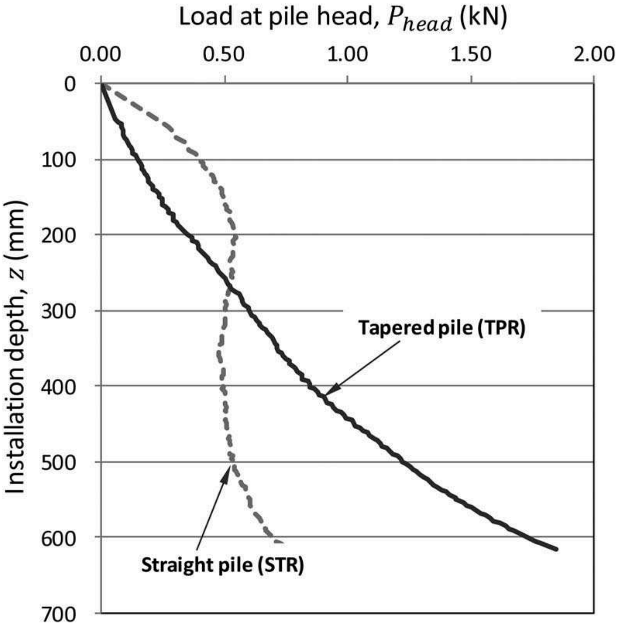


Figure 3. Load displacement curves during pile installation for straight pile (STR) and tapered pile (TPR).

bar (square stainless bar with 10 mm in width) fixed at the bottom of the steel soil tank (the left bar in Figure 1), which could influence on the resistance of pile installation. Therefore, while the installation resistance was reference data in this study, main emphasis was given to changes in soil pressure during pile installation. The sensors were located at 130, 230, 330, 430 and 530 mm from the soil surface to measure lateral pressure changes in the radius direction 48 mm from the pile center (i.e., pressure sensors in soils) during pile installation. Unfortunately, the sensors at 230 mm did not work well, and these data were removed from this study. Another pressure sensor for vertical pressure changes was embedded on the top of the instrumented sensor bar (the right bar in Figure 1) at 330 mm from the soil surface. Utilizing each sensor, the pressure changes were measured during the installation of straight and tapered piles in medium-dense dry sand.

3 TEST RESULTS

3.1 *Load displacement curves*

Different load-displacement curves were obtained between two kinds of piles, straight pile (STR) and tapered pile (TPR) during installation, as shown in Figure 3. The load on the straight pile increased first and then remained steady with installation depth.

During installation at shallow depth, the load on the tapered pile was lower than that on the straight pile owing to its small pile tip area. On the other hand, the tapered pile developed at larger load at the pile as the installation depth increased. It is easy to guess that the tapered shaft increased the shaft resistance according to the tapered angle, even when the end bearing resistance was still lower. Many researchers have already discussed this higher shaft resistance of tapered piles and also explained the mechanism based mainly on the cavity expansion theory.

3.2 *Radial pressure changes*

This study is focusing on the changes measured on the pressure sensor in the soils. These pressure sensors were set to zero before pile installation, which means that the initial soil pressure was not included.

Figure 4 shows the radial pressure changes with pile installation depth as the straight pile tip was approached. It is clear that each peak pressure was recorded slightly before the pile tip reached each pressure sensor level. Then the pressure level rapidly dropped as the pile tip passed. Similar observations were reported in the 1g chamber test, centrifuge test, and in-situ field test by Gavin & Lehane (2003), Leung et al. (1996) and Chow (1996) respectively.

On the other hand, Figure 5 presents the radial pressure changes in the tapered pile installed into sand. The peak pressure was recorded at a level very close to the sensor level (i.e. almost at the same time), and the magnitudes of the pressure level were quite lower than those in the straight piles. This lower pressure level could be caused by the small end-bearing area.

3.3 *Comparison of pressure changes*

The radial pressures during installation were compared between the straight pile and the tapered pile on the sensor at 330 mm in depth in Figure 6. The radial pressure in the straight pile increased as the

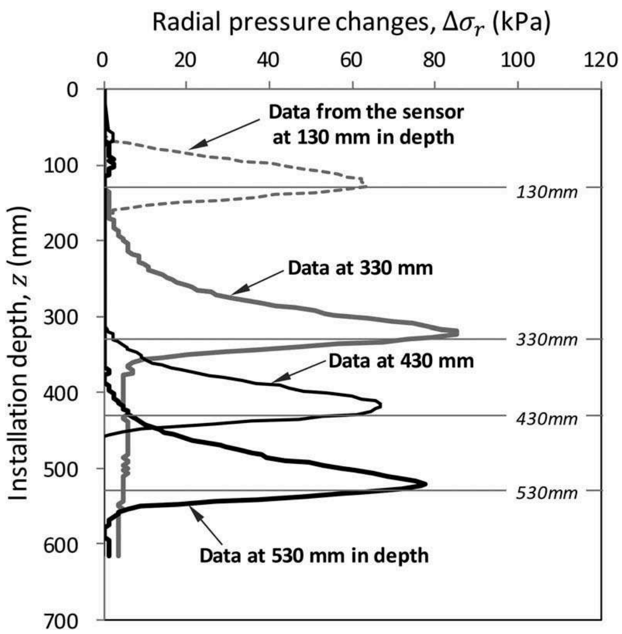


Figure 4. Radial pressure changes during pile installation of straight pile (STR) on four sensors at 48 mm from pile center.

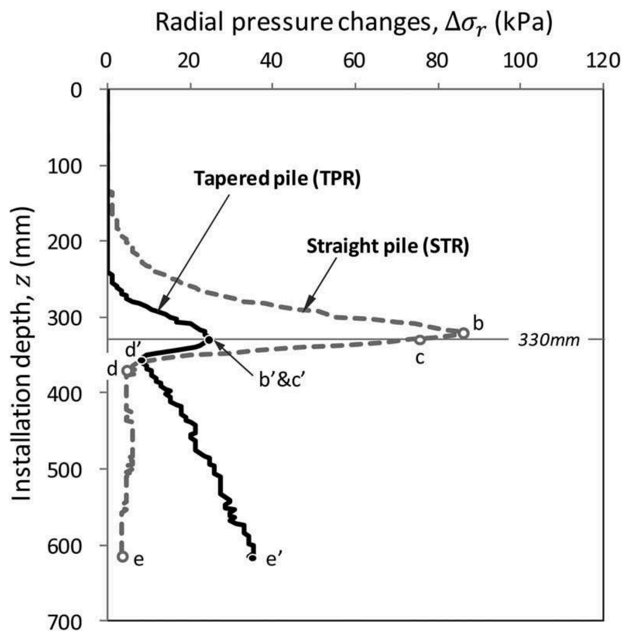


Figure 6. Comparison of radial pressure changes between straight pile (STR) and tapered pile (TPR) during installation.

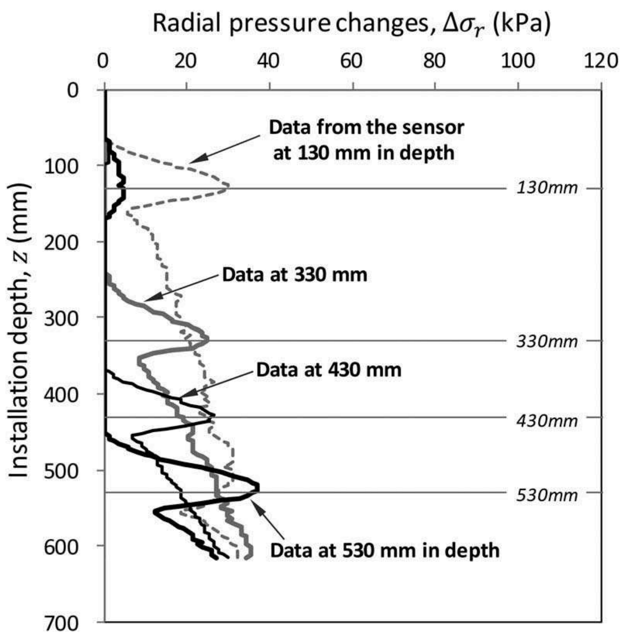


Figure 5. Radial pressure changes during pile installation of tapered pile (TPR) on four sensors at 48 mm from pile center.

pile was installed, and then increased rapidly to the peak at point [b] slightly before the pile tip reached the sensor level. Afterward, the pile tip passed through point [c] as the pressure dropped sharply. The radial pressure was almost bottomed out at point [d] a little bit above the pile tip. Finally, the soil pressure tended to decrease slightly as the pile was installed deeper. The pile installation test was completed at point [e].

The profile of the radial pressure changes in the tapered pile was different from that of the straight pile. The peak pressure of the tapered pile recorded almost at the same time when the pile tip reached the sensor level (points [b'] & [c']). The magnitude of the peak pressure was much smaller than that of the straight pile, which is approximately 30% of the straight pile. Another feature of this profile was that the radial pressure tended to increase after the pressure drop passed through the sensor level (i.e., from point [d'] to [e']). These increasing radial pressures could be developed by the tapered shaft angle of the tapered piles.

The vertical pressure changes were recorded at the same sensor level (i.e., 330mm in depth). These measurements were plotted for the straight and tapered piles in Figure 7. The vertical pressure in the straight pile increased earlier than the radial pressure (compared to Figure 6). The peak of the vertical pressure at point [a] was also earlier before the pile tip approached. Then, the vertical pressure dropped rapidly to point [d], similar to the radial pressure, but the vertical pressure increased again as the pile was installed at point [e]. This increase could be caused by the drag force owing to the load transfer from the interface of the pile to sand during pile installation. The load transfer and drag force were pointed out by De Nicola (1996) and O'Neill (2001). On the other hand, the vertical pressure changes in the tapered pile were quite different from those in the straight pile. The peak pressure was not very high at point [a']. The profile of the pressure changes meandered, but increased approximately at a constant rate throughout the entire process.

3.4 *Stress path in pile installation*

Figure 8 shows the stress path from the vertical and radial pressure changes in the vertical and horizontal

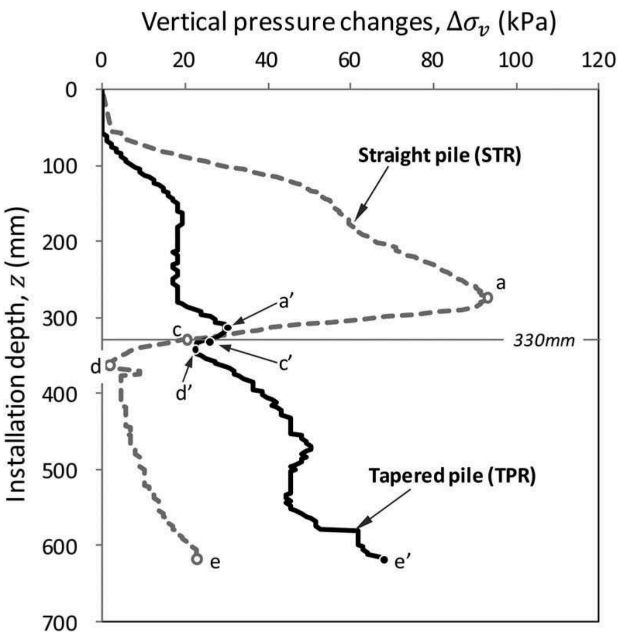


Figure 7. Comparison of vertical pressure changes between straight pile (STR) and tapered pile (TPR) during installation.

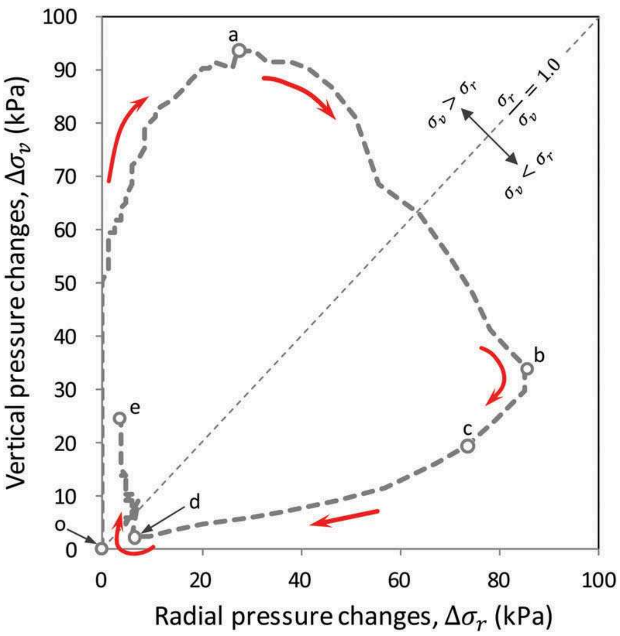


Figure 8. Stress path on pressure sensors at 330 mm in depth during installation of straight pile (STR).

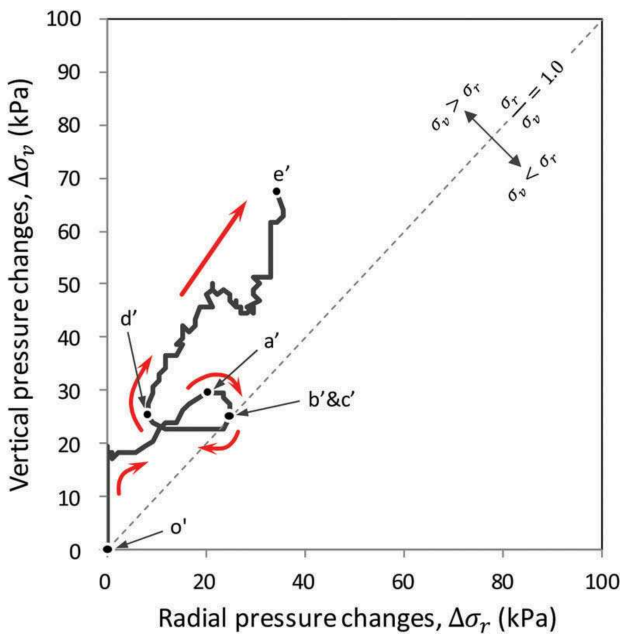


Figure 9. Stress path on pressure sensors at 330 mm in depth during installation of tapered pile (TPR).

directions, respectively, measured in the sensor at 330 mm during the straight pile installation for the entire process. The subscripts from [a] to [e] in the data plots are the same as in Figures 6 and 7.

In the first stage, the vertical and radial pressures increased to point [a], but more rapidly in the vertical pressure than in the radial one. Then, the radial pressure kept increasing with a decrease in the vertical pressure, reaching point [b] at which the radial pressure was at the peak. Point [c] indicates that the pile tip was at the same level as the sensor in both radial and vertical pressures decreasing between points [b] to [d]. After passing through point [d], the vertical pressure increased again from point [d] to point [e], while the radial pressure still slightly decreased. The profile of this stress pass demonstrated dramatic changes in the pile installation, but the final position [e] was not so far from the initial point [o] despite of such a large loop of the stress path.

Similarly, the stress paths for the vertical and radial pressure changes in the tapered pile are shown in Figure 9. This profile of the stress path was clearly different from that in the straight pile. In the tapered pile, the vertical pressure reached point [a'] and then dropped to the point [b'] and [c'] while the radial pressure increased. Subsequently, a decrease was observed in the radial pressure from point [c'] to [d']. This loop of the stress path was quite small compared to the loop in the straight pile installation. Unlike the straight pile, both radial and vertical pressures increased in the tapered pile from point [d']. As a result, both pressures at the final point [e'] were pretty higher than the initial point [o']. In particular, the pressure level in the tapered pile at the final installation [f'] ($\Delta\sigma_v = 67.3$ kPa, $\sigma_r = 34.3$ kPa) was much higher than the one in the straight pile ($\Delta\sigma_v = 24.0$ kPa, $\Delta\sigma_r = 3.5$ kPa).

4 STRESS FIELD AROUND PILES

4.1 *Radial pressure distribution*

The radial pressure distribution with sensors depth are shown in Figure 10, focusing on the final installation stage when the pile tip was penetrating the

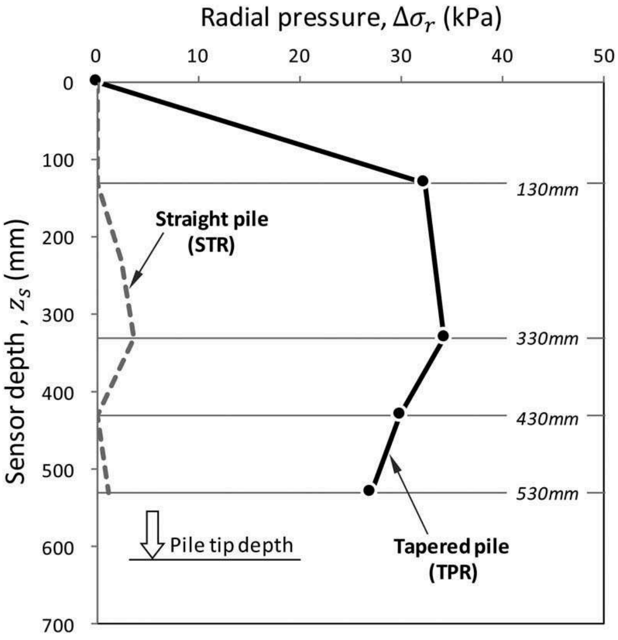


Figure 10. Comparison of radial pressure distribution with sensor depth at final installation stage between straight and tapered piles.

depth of 615mm. The pressure level was relatively small, as confirmed in Figure 8 in the straight pile.

On the other hand, the radial pressure level was highly developed along the pile shaft in the tapered pile. There was a tendency of reduction in the radial pressure under 330 mm in the sensor depth. This tendency likely depends on the ratio of the radial expansion owing to the tapered diameter. Therefore, the value of the radial pressure likely to be governed by the cylindrical expansion caused by the diameter change during pile installation at least below this depth.

4.2 *Stress field around tapered piles*

Based on the observation of the pressure changes in the pile penetration tests, the stress distribution around the pile is shown in Figure 11. The profile of the stress distribution in the straight pile is drawn according to White et al. (2005).

Regarding the straight pile, the high radial stress below the pile tip is created by the cavity expansion, and a drop in the stress behind the pile tip occurs, followed by a decrease of the stress, but only slightly in this test observation.

The stress distribution in the tapered pile installed into sand is quite different from that in the straight pile. The radial stress around the pile tip level is smaller in the tapered pile than in the straight pile, because the expanded cavity below the pile tip is governed by the small pile area in the tapered pile. More importantly, the stress distribution along the pile shaft increases from the pile tip to top owing to the increasing diameter of the tapered pile. This stress level is much greater than that of the straight pile, leading to the conclusion that the tapered piles could be strongly affected by the installation effect owing to the pile geometry.

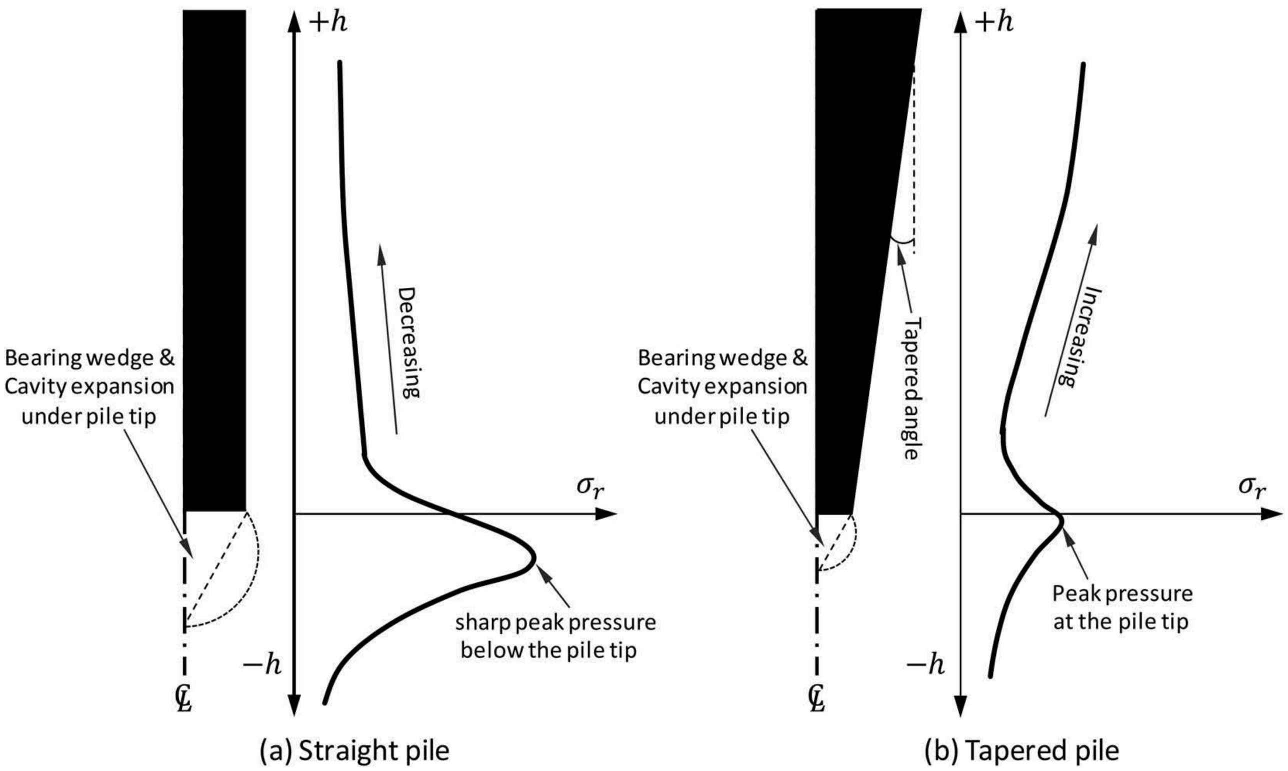


Figure 11. Schematic profiles of radial stress distribution in adjacent sand around installed pile; (a) Straight pile, (b) Tapered pile.

5 CONCLUSION

This study investigates the installation effect of tapered piles in sand in comparison to straight piles. The experimental results of this study indicate:

1. The peak pressure developed in the tapered pile around the similar level of the pile tip, although this peak pressure was not as great owing to cavity expansion below the pile tip as that of the straight pile.
2. The radial pressure increased behind the pile tip of the tapered pile as the pile was installed deeper owing to pile diameter expansion, while a slight decrease was observed in the straight pile.
3. The stress paths of the radial and vertical pressures were completely different between the tapered pile and the straight pile. The stress path in the straight pile drew a large loop, while the loop was small and the stress level tended to increase through the pile installation process in the tapered pile.
4. The stress field around the tapered pile was proposed conceptually based on the interpretation of the experimental results, suggesting that the installation effect could be much greater in a tapered pile than in a conventional straight pile.

Due to the page limitation, the data were reported for one geometry of the tapered pile with about five in the taper ratio in this study. Therefore, there is not enough data to discuss the phenomenon in detail, and it remains questionable whether this trend depends on the taper-ratio. Further discussion should be conducted to better understand the installation effect on tapered piles.

ACKNOWLEDGMENTS

This work was supported by Hironobu Matsumiya, formerly a researcher at Nippon Steel Corp. Without his contribution, the findings would not have been achieved in this paper. We would like to express our gratitude to him.

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