Effect of pile embedment length on horizontal and vertical displacement of a pile under repeated lateral loading

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ABSTRACT

Marine structures with pile foundations are subjected to repeated horizontal loads in numerous directions and at various load levels. It is well known that the horizontal behavior of piles subjected to load perpendicular to the pile axis is affected by the pile embedment lengths. In this research, not only horizontal displacement but vertical displacement of a pile were focused under the repeated horizontal loading. In the research, repeated horizontal loads were subjected to a single pile in dry sandy model ground. The pile head deflection at the maximum load was getting increased when a pile was repeatedly loaded in single direction. On the other hand, it was getting decreased when a pile was repeatedly loaded in double directions. The rate of change of the pile head displacement per number of repeated loading cycles was almost changed according to pile embedment length when embedment length of a pile was in short pile category. A pile was easily uplifted under repeated horizontal loading when the embedment length of a pile was in short pile category. Especially, when a pile was loaded double directions repeatedly, a pile was uplifted even if the embedment length of a pile was in long pile category.

Key words: *Repeated loading, Single Pile Structures, dry model ground*

1. Introduction

Marine structures with pile foundations are subjected to repeated horizontal loads in numerous directions and at various load levels under the effects of waves, winds, or earthquake. Consequently, piles supporting these structures experience repeated horizontal loading. Existing design methods for pile foundations, however, primarily focus on maximum load conditions. There are uncertainties regarding the deformation of piles under repeated loading. One example of a structure that considers repetitive horizontal loading is the single-pile structure (SPS) (Kiuchi et al., 1988, Kiuchi et al., 1990, Kikuchi et al., 1992, Kikuchi et al., 1993). SPS utilizes the inherent tendency of piles to flex horizontally, allowing them to share in absorbing the berthing energy. They are designed with the assumption that the piles will undergo significant deformation. Toward establishing these design methods, investigations have been conducted into the behavior of single piles under repeated horizontal loading and the behavior of single piles during significant deformations, where the ground undergoes plasticization (Kiuchi et al., 1988, Kiuchi et al., 1990). Furthermore, it is noted that the behavior of piles varies depending on whether repeated loading acts as virgin loading or at the elastic range loading level (Kikuchi et al., 1992, Kikuchi et al., 1993). In the design of harbor structures other than SPS, the influence of repeated loading is scarcely considered. Furthermore, there is currently insufficient research into the behavior of piles when subjected to repeated horizontal loading. Furthermore, even the piles used in marine structures are possibly constructed by press-in technology. The problems discussed in this research are common for every pile constructed in any construction methods.

In the studies mentioned above, investigations were conducted under the condition of sufficiently long embedded piles. Considering practical applications, the current trend in offshore structures towards larger diameter piles. In such a condition, the flexural rigidity of piles is increase and the embedment length of a pile securing long enough pile is increase. Consequently, it is believed that there may be cases where the embedment length of piles cannot be long enough to long embedded piles. The criterion for determining whether the pile is sufficiently long embedded is based on embedment ratio, E_r proposed by Kubo et al (1966). E_r is defined as the ratio of the actual embedment depth of the pile, L by the depth of the first zero bending moment of the pile in the case of a long pile, l_{m1}. It is well known that the horizontal behavior of piles subjected to load perpendicular to the pile axis is affected by E_r when E_r is less than 1.5.

Therefore, in this study, the embedment ratio E_r was focused and effect of E_r to the horizontal and vertical displacements of the piles were investigated by the repeated horizontal loading experiments on single piles.

2. Experimental Overview

2.1. Experimental Setup

In this study, the embedment depth and the repeated horizontal loading procedures on single piles were changed. An overview of the short pile experiment is illustrated in **Fig. 1** as an example. The model ground was prepared using the air pluviate method in a rectangular soil box (width 400 mm × length 1200 mm × height 700 mm) filled with silica sand #5 (ρ_s=2.65 Mg/m^3, e_{max}=0.821, e_{min} =0.526) to achieve a relative density of 80%. The thickness of the ground was set at 500 mm for the experiments with piles embedded 150, 215, 280, 500 mm and was set at 600 mm for the experiments with piles embedded 600 mm.

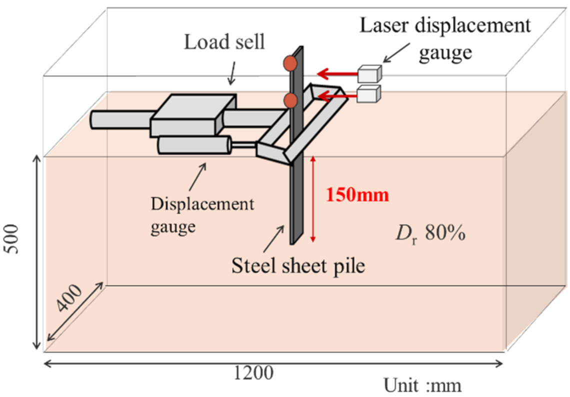


Fig. 1 Overview of Experiment in the case of 150 mm embedment case.

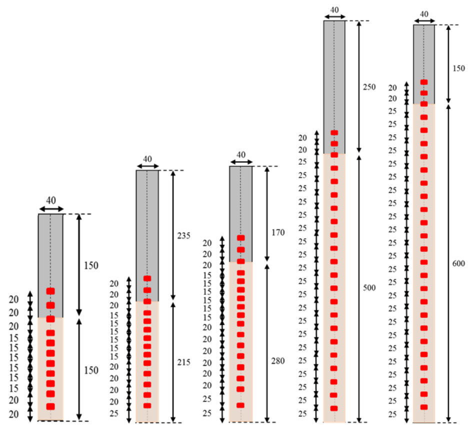


Fig. 2 The attachment status of strain gauges on model piles (Embedded length L=150, 215, 280, 500, 600 mm)

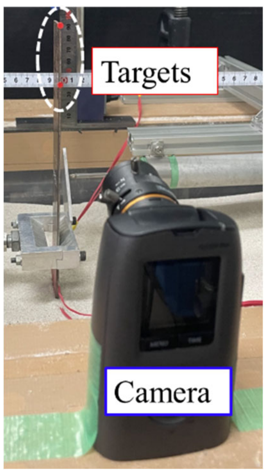


Fig.3 Two red circles were attached at the tip of the pile and their movements were recorded by camera

The piles used were steel plate pile with 40 mm width, 2.3 mm thickness (EI = 0.00831 kNm^2). Strain gauges were affixed to both sides of the piles at intervals of 15 mm to 25 mm to measure bending strains (**Fig. 2**).

For the investigation of the vertical displacement of the piles, as shown in **Fig. 3**, two red circular seals were affixed to the tip of the pile. The movement of these red seals were recorded using a video camera from the side every 2 seconds, and subsequent analysis was conducted.

The loading height was set at +50 mm from the ground surface in all cases, and horizontal load was applied at a constant displacement rate which was low enough to perform a static condition. Maximum loads of repeated horizontal loading were set from 25 N to 70 N, and the applied load was measured using a load cell.

2.2. Experimental Conditions

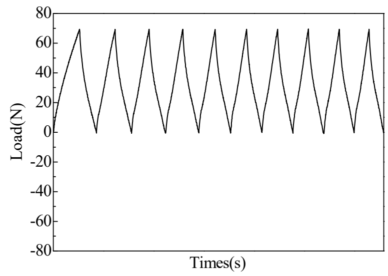
Experimental conditions were shown in **Table 1** and **Table 2**. Images of the load history for the repeated loading were in **Fig. 4**. In this study, there are two experimental series. In the first series, experiments were conducted mostly focusing on the horizontal deflection change. In the second series, experiments were conducted focusing on both the horizontal and vertical displacements of a pile. Discussing the behavior of the piles due to differences in loading methods, two types of loading methods were implemented: single direction loading and double direction loading. Furthermore, the number of loading cycles was set to 10 for the first series 20 for the second series of experiments. Embedment ratio E_r, which is defined as L / l_{m1} (where L is the embedment depth and l_{m1} is the depth of the first zero bending moment of the pile in the case of an infinitively long pile), is used for the index of the relative embedment length of a pile. According to Kubo (1966), relative embedment length was categorized in four categories. When $E_r \geq 1.5$, piles are classified as long piles, while when $E_r < 1.5$, piles are classified as short piles. Short piles are classified three subcategories such as $E_r < 0.6$, $E_r < 1.0$, and $E_r < 1.5$. Based on the above, experiments were conducted by varying Er between 0.7 and 2.5, as shown in **Tables 1** and **2**.

Table 1. Experimental conditions in the first series

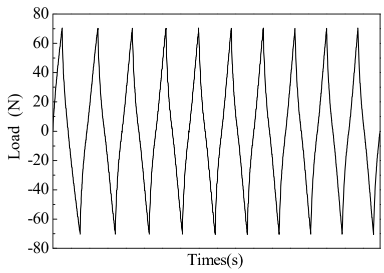
Case	Loading method	Maximum load (N)	Embedment length L (mm)	E_r
1	Single	40	150	0.725
2	Double	±25		0.781
3	Single	55	215	0.991
4	Double	±55		
5	Single	60	280	1.27
6	Double	±60		
7	Single	70	500	2.22
8	Double	±70	600	2.52

Table 2. Experimental conditions in the second series

Case	Loading method	Maximum load (N)	Embedment length L (mm)	E_r
9	Single	30	150	0.758
10	Double	±30		
11	Single	30	215	1.09
12	Double	±30		
13	Single	60		0.977
14	Double	±60		
15	Single	30	500	2.53
16	Double	±30		
17	Single	60		2.27
18	Double	±60		



a) Single direction loading experiment



b) Double direction loading experiment

Fig. 4 Images of time history of the repeated loading

3. Experimental results

3.1. Horizontal displacement

Fig. 5 shows the relationship between load and displacement at the loading point from Case 1 to Case 8. In this figure, plotted data are only the loading stage of the first loading cycle. The results of the single direction repeated loading tests (Cases 1,3,5,7) are shown with solid lines, while the results of the double direction repeated loading tests (Cases 2,4,6,8) are shown with dashed lines. Colors of the results are changed according to embedment length. The results shown by the solid and dashed lines generally agree at the same embedment length, indicating that the initial loading behavior in each case is consistent. This suggests that the coefficient of subgrade reaction in each case was the same.

As shown in Table 1, embedment ratio E_r of each case is different according to embedment length. It is noted that cases with shorter embedment length exhibit larger displacements at the loading points at the same load. In particular, in the cases that E_r was around 0.7, the displacement increased rapidly when the load was over around 30 N. Additionally, there were no significant differences observed in the load-displacement relationship up to the maximum load during the first loading cycle for cases with Er ≥ 1.0. From Kubo (1966), it is stated that under monotonic loading with $E_r \geq 1.0$, although the embedment length may be insufficient, the behavior is almost the same as that of long piles.

Fig. 6 shows the load-displacement at the loading point relationship of Cases from 1 to 8. From these

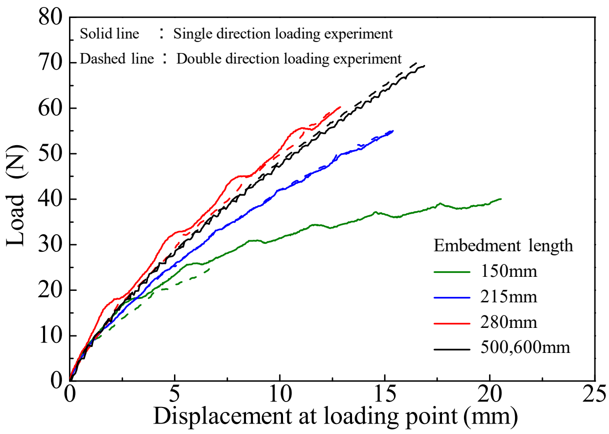


Fig. 5 Relationship between load and displacement at loading point of Cases from 1 to 8 up to the maximum load during the first loading cycle

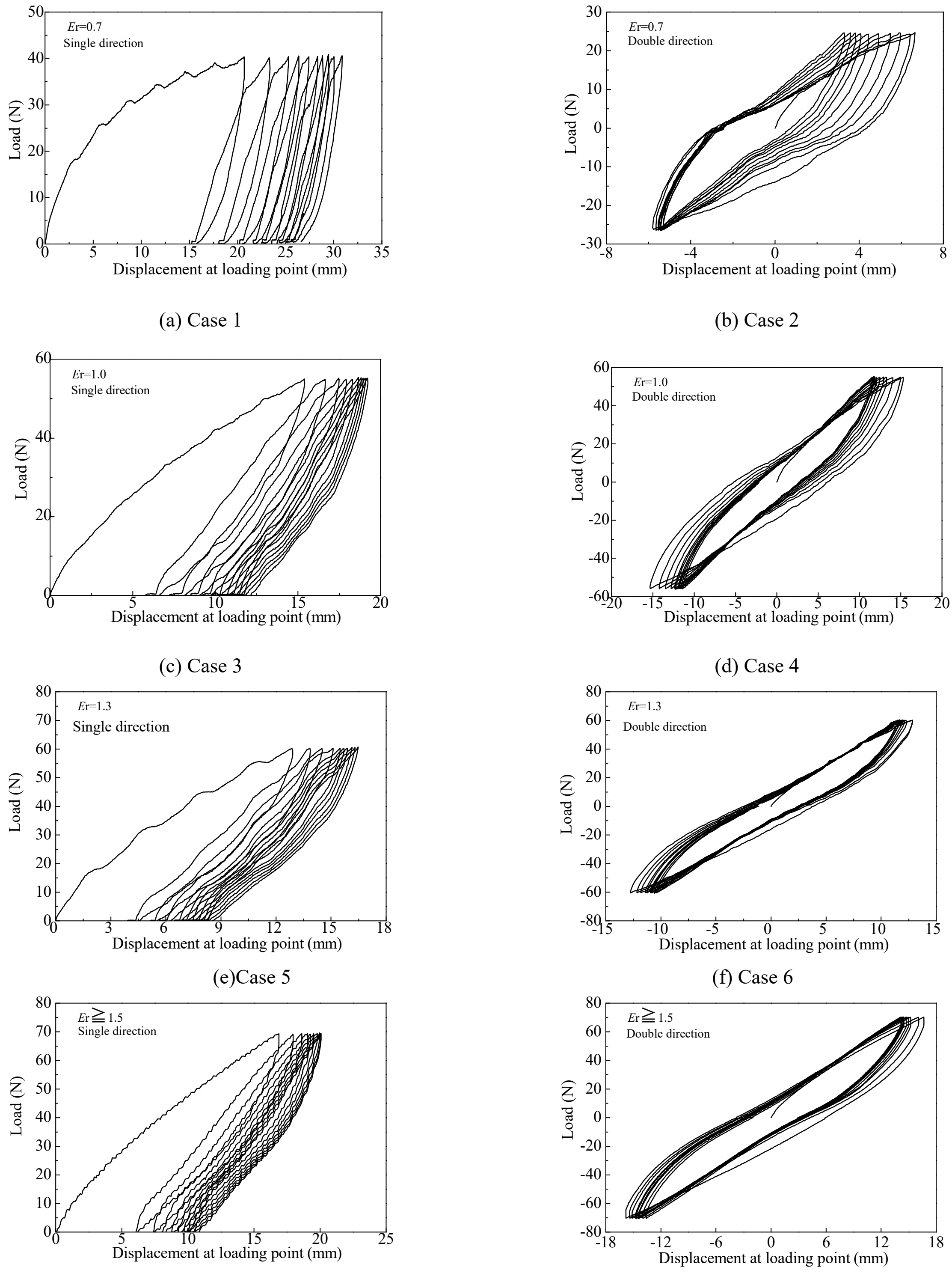
results, it is evident that with an increase in the number of loading cycles, the displacement at the loading point at the maximum load increases significantly for all cases in the single direction loading experiments. On the other hand, in the double direction loading experiments, it was found that the maximum and minimum displacements decreased with an increase in the number of loading cycles.

The relationship between the displacement ratio at the loading point (y_{0n}/y_{01}) and the number of loading cycles is shown in **Fig. 7**. In the figure, displacement changes at the maximum load (when double direction loading, both directional maximum loads) state are shown. The displacement ratio at the loading point refers to the value obtained by dividing the displacement at the *n*th loading cycle (y_{0n}) by the displacement at the first loading cycle (y_{01}). When double direction loading, there are two y_{01}. The maximum loads of each direction has each y_{01}. Same as y_{01}, there are two y_{0n} in a cycle. The displacement ratios in the case of double directional loading cases shown in the figure are calculated comparable pair of y_{0n} and y_{01}.

From **Fig. 7**, it is evident that in the single direction loading experiments at maximum load, the displacement at the loading point increases with an increase in the number of loading cycles regardless of E_r. Additionally, it was observed that cases with smaller E_r values tend to exhibit a higher rate of increase in displacement ratio. In the cases where $E_r \geq 1.0$, such as $E_r = 1.0$, 1.3, and 2.2, no significant differences in the ratio y_{0n}/y_{01} were observed. They were approximately from 1.19 to 1.28 at 10 cycles. In the case of $E_r = 0.7$, the displacement ratio y_{0n}/y_{01} was larger than other cases. It was 1.50 at 10 cycles.

In the double direction loading experiments, at maximum loads in both directions, the displacement ratio y_{0n}/y_{01} decreased with an increase in the number of loading cycles for all values of E_r. The displacement ratios y_{0n}/y_{01} in both directions were consistent across cases with $E_r \geq 1.0$, such as E_r =1.0, 1.3, and 2.5. The ratios y_{0n}/y_{01} were approximately 0.76 to 0.90 at maximum load at the first direction and about 0.74 to 0.86 at maximum load at the second direction, showing consistency regardless E_r. On the other hand, in the case of $E_r = 0.7$, the ratio y_{0n}/y_{01} was approximately 0.49 at maximum load in the first direction and about 0.96 at maximum load in the second direction.

In all experimental cases, as the number of loading cycles increased, the rate of change of the displacement ratio y_{0n}/y_{01} per loading cycle tended to decrease.



(a) Case 1 (b) Case 2

(c) Case 3 (d) Case 4

(e)Case 5 (f) Case 6

(g) Case 7 (h)Case 8

Fig. 6 Relationship between load and displacement at the loading point in Cases from 1 to 8.

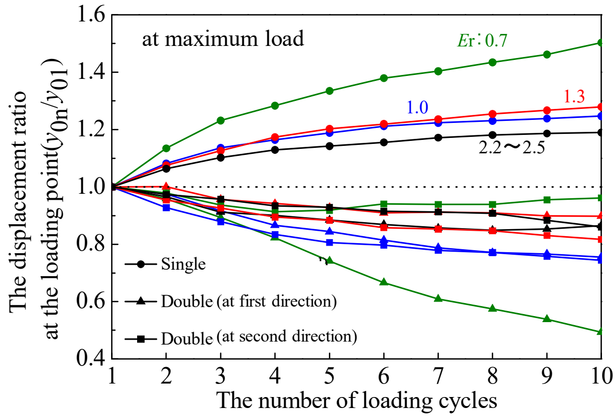


Fig. 7 Relationship between the displacement ratio y_{0n}/y_{01} when the maximum load applied and the number of loading cycle

Based on the results from **Fig. 7**, **Fig. 8** shows the relationship between the displacement ratio y_{0n}/y_{01} at the 10th loading cycle and the embedment ratio E_r. As can be seen from this figure, in both single direction and double direction repeated loading experiments, there are no significant change in y_{0n}/y_{01} by the change of E_r when E_r is larger than 1.0. However, when E_r is 0.7, y_{0n}/y_{01} is different from those in the case of E_r is larger than 1.0.

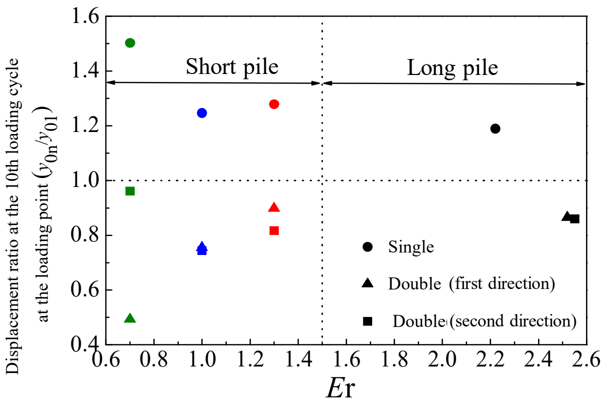


Fig. 8 Relationship between the displacement ratio y_{0n}/y_{01} at the loading point when the maximum load at 10th loading cycle and embedment ratio E_r

Some types of offshore structures may require consideration of the displacement of piles when the load is removed (0N). Similar analysis as displacement change according to repeated loading was conducted at load removed condition. **Fig. 9** shows the relationship between the displacement ratio y_{0n}/y_{01} and the number of loading cycles at the 0 load level.

From **Fig. 9**, it can be observed that in the single direction repeated loading experiments, the displacement ratio y_{0n}/y_{01} increased with an increase in the number of loading cycles in all values of E_r. The displacement ratio y_{0n}/y_{01} was approximately 1.70 to 1.95 at the 10th loading cycle when E_r was less than 1.5. It was approximately 1.76 at the same loading cycle when E_r was larger than 1.5. This indicates that the trend was similar for both short and long piles.

In the double direction repeated loading experiments, the displacement ratio y_{0n}/y_{01} was approximately 0.45 to 0.65 at the 10th loading cycle when E_r was larger than 1.0. However, the displacement ratio y_{0n}/y_{01} was approximately 0.13 at the 10th loading cycle when E_r was 0.7.

Based on the results in **Fig. 9**, **Fig. 10** shows the relationship between the displacement ratio y_{0n}/y_{01} of residual condition at the 10th loading cycle and the

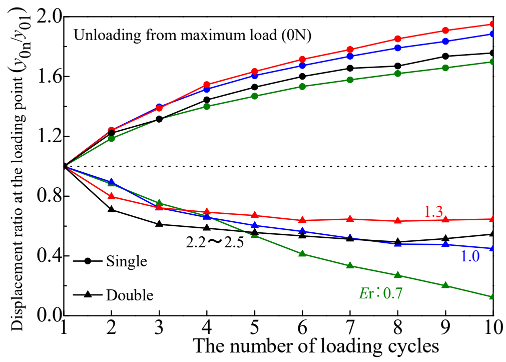


Fig. 9 Relationship between the displacement ratio y_{0n}/y_{01} when no load applied and the number of loading cycle

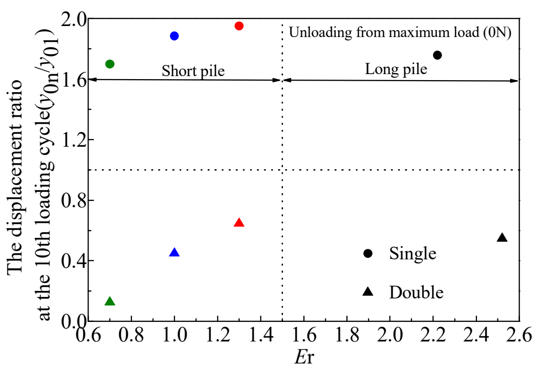


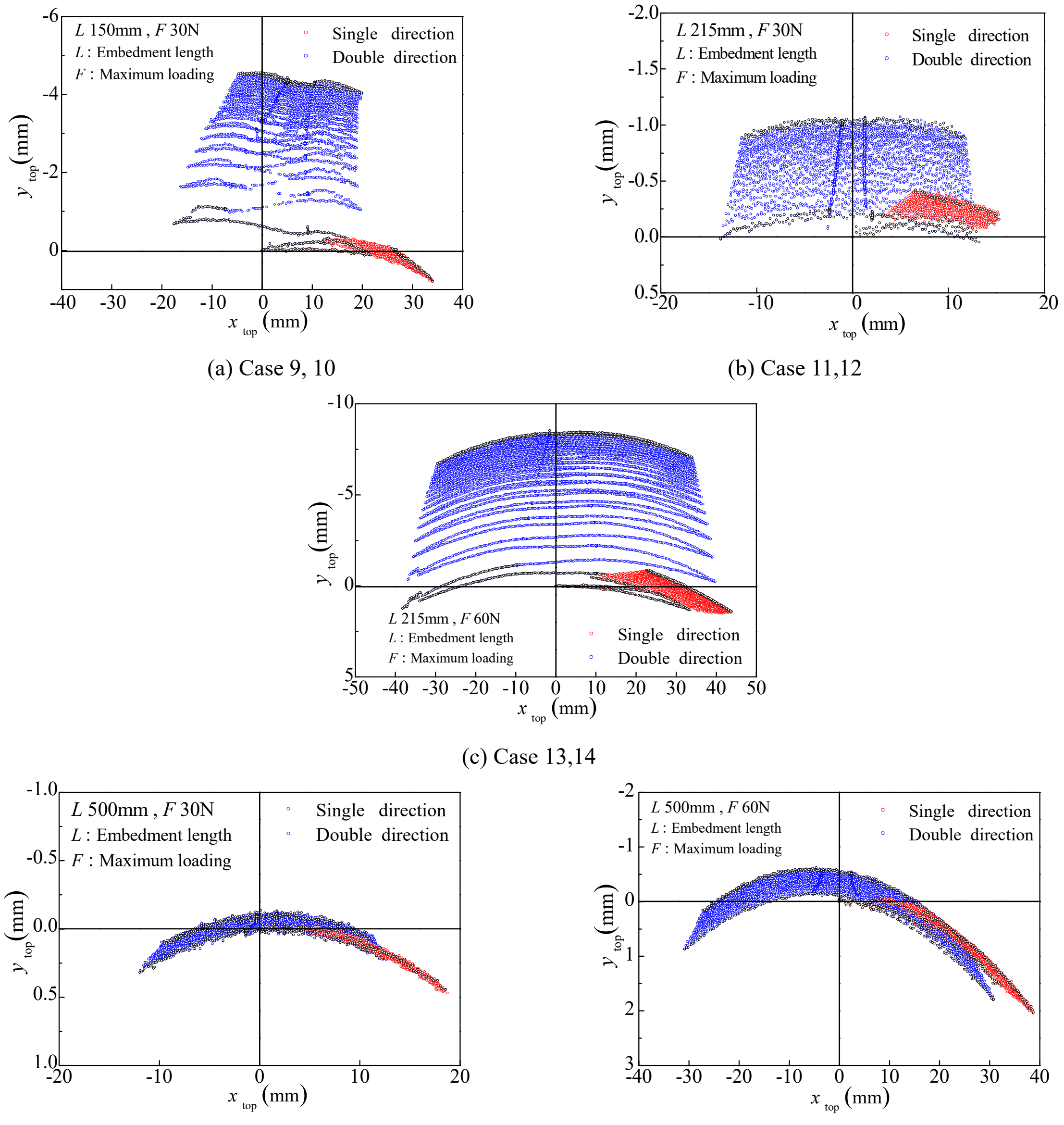
Fig. 10 Relationship between the displacement ratio y_{0n}/y_{01} at the loading point when no load at 10th loading cycle and the embedment ratio E_r

embedment ratio E_r. As already seen, y_{0n}/y_{01} at the 10th loading cycle was less affected by E_r even E_r was as less as 0.7 in single direction loading. The displacement ratio y_{0n}/y_{01} at residual condition at the 10th loading cycle was less affected by E_r when E_r was more than 1.0 in double direction loading. But y_{0n}/y_{01} at residual condition at the 10th loading cycle was small when E_r was 0.7 in double direction loading.

3.2. Regarding vertical displacement

Fig. 11 shows the displacement of the pile head in the cases of from Case 9 to Case 18. In **Fig. 11**, each figure has two experiment results which are single and double loading directions in the same embedment length and maximum load. In **Fig. 11**, positive horizontal displacement x_{top} was set to the first loading direction and positive vertical displacement y_{top} was set to the subsurface direction.

In the case of long pile conditions such as from Cases 15 to 18, no or less upward displacement was observed due to repeated loading. In the case of short pile conditions such as from Cases 9 to 14, relatively large upward displacement was observed. and large upward displacements were observed in double loading conditions, on the other hand rather small upward displacements were in single direction loading.



(a) Case 9, 10

(b) Case 11,12

(c) Case 13,14

(d) Case 15,16

(e) Case 17,18

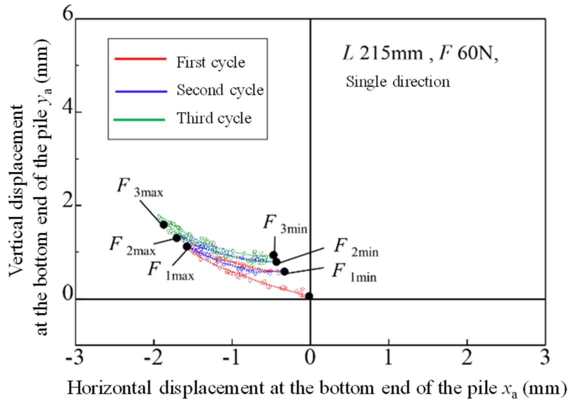
Fig. 11 Displacement of the pile head (Cases 9 to 18)

Furthermore, when comparing under the same maximum load conditions, it was confirmed vertical upward displacement increased in the cases with smaller Er values. When comparing under the same embedment ratio conditions, it was found that in the cases of double direction loading, vertical upward displacement was larger compared to the cases of single direction loading. It was observed that the upward displacement in a cycle was large in early stage of repeated loading in double direction loading when embedment ratio was less than 1.0, and as the number of loading cycles increased, the vertical upward displacement converged.

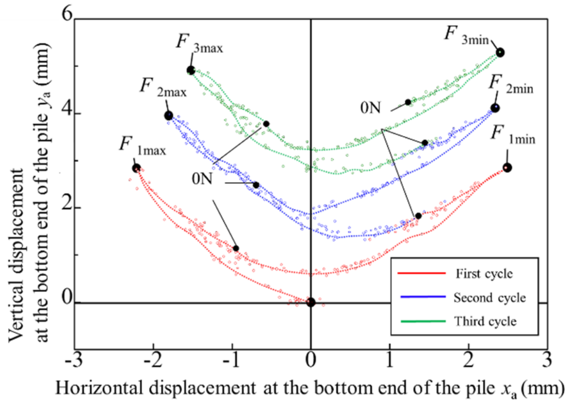
Fig. 12 shows the behavior of horizontal and vertical displacements at the bottom of the pile in the case with embedment length of 215 mm and a maximum load of 60 N in both single direction and double direction of repeated loading. In these figures, embedment ratio E_r was 0.977. In the single direction loading as shown in **Fig. 12** (a), the bottom end of the pile moved horizontally and vertically according to loading levels. The pile bottom end moved upward a little with repeated loading.

In the double direction loading as shown in **Fig. 12** (b), the bottom end of the pile moved horizontally and vertically both in first and second direction loading. Different from in the case of single direction loading, vertical upward displacement was rapidly increased. This is thought to be caused by the movement of the ground in contact with the pile where significant ground reaction forces are exerted, the pile is to move up and down. Because this movement is larger in double direction loading than single direction loading, it is considered that vertical displacement accumulated, especially during double direction loading. This effect is large in the case of small embedment ratio piles.

Focusing on the vertical displacement at the bottom of the pile, **Fig. 13** shows the relationship between the vertical displacement amount y_{an} - y_{a1} at the bottom of the pile when unloaded (0 N load) and the number of loading cycles for the case of maximum load 60 N. The vertical displacement at the bottom of the pile refers to the difference between the vertical displacement at the nth loading cycle y_{an} and the vertical displacement at the first loading cycle y_{a1}. From **Fig. 13**, it can be confirmed that conditions for easy to move upward in the vertical are



(a) Case 13



(b) Case 14

Fig. 12 Displacement at the bottom end of the pile

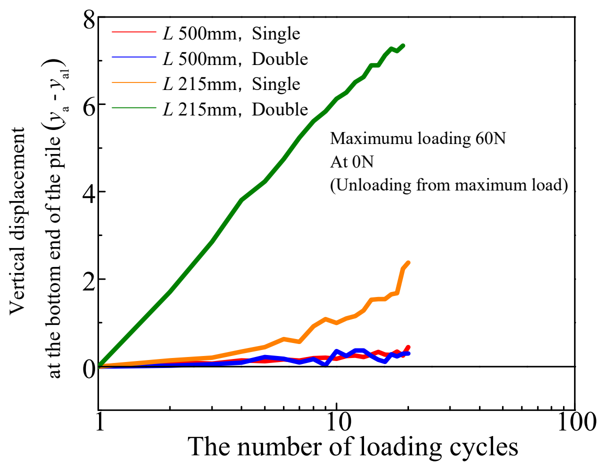


Fig. 13 Relationship between vertical displacement at the bottom end of the pile y_{an}-y_{a1} and the number of loading cycles

in the case of shorter piles rather than longer piles, and in the case of double direction loading rather than single direction loading. However, even in the cases where the embedment length of the pile is considered to be sufficiently long, which was embedment length of 500 mm with E_r of 2.27, in Fig. 13, there is still a possibility of the pile being pulled out depending on the loading method. Therefore, it is important to check the possibility of upward movement of the pile under repeated loading even in a long pile.

4. Conclusion

Effect of the embedment length of a pile to horizontal and vertical displacement of a pile under repeated horizontal loading was investigated in this research. Considering the pile embedment length in horizontal loading problem, it is to be considered in the concept of embedment ratio E_r. In this meaning, 'embedment length' in this report can be replaced 'embedment ratio.'

A single pile was horizontally loaded repeatedly in this research. As a result, it was found that short piles exhibited a greater rate of change in horizontal and vertical displacement compared to long piles, making them more susceptible to the effects of repeated loading. Furthermore, even with the same embedment length, significant differences in displacement behavior were observed depending on the loading directions.

Regarding the vertical displacement under repeated loading, even in the cases where the embedment length of the pile is considered to be sufficiently long, there is a possibility to be uplifted depending on the loading directions. Therefore, it is important to check the possibility of upward movement of the pile under repeated loading even in a long pile.

The problems discussed in this research are common for every pile constructed in any construction methods including press-in technology.

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