Effects of pile diameter and density of ground to the plugging of open-ended piles

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ABSTRACT

In these days, deep embedded and large diameter steel pipe piles have been widely used in port facilities in Japan for supporting large vertical load. In this study, the plugging phenomena was examined by changing the outer diameter of the pile, the wall thickness, and the density of the ground. As a result, the relationship between the inner stress ratio R_r and the inner soil height length change rate *IFR** did not varied by the pile outer diameter D or the diameter thickness ratio D/t. And the product of the wall friction coefficient μ and the earth pressure coefficient K_h was found not to be much influenced by the difference of the pile outer diameter and the relative density of the ground.

Keywords: open-ended piles; inner friction resistance; coefficient of horizontal earth pressure

1 INTRODUCTION

Deep embedded and large diameter steel pipe piles have been widely used in port facilities in Japan for supporting large vertical load, as growing size or changing structural types of port facilities. As a result, it is required that accurate estimation of the bearing capacity of a pile. As most design codes in Japan adopt a method of estimating the end bearing capacity of piles that does not consider the influence of the overburden pressure on the pile end, the issue of the plugging of a pile and the issue of the increase of the toe bearing capacity of a pile with the increase of the overburden pressure are mixed in the estimation of the bearing capacity of the large diameter and deep embedded open-ended piles. It makes the estimation for bearing capacity of large diameter and deep embedded open-ended piles complex problems. Therefore, the authors have tried to solve this problem by experimentally investigating the plugging mechanism of the open-ended pile through the pile penetration experiments of the model pile into the sandy ground (Kanbe et al. 2017). In this study, the plugging phenomena was examined by changing the outer diameter of the pile, the wall thickness, and the density of the ground.

2 PREVIOUS STUDY

Yamahara proposed the vertical stress distribution of the inner pile ground based on the similar stress balance as silo theory for explaining the plugging effect of open-ended piles. Its result can be written as Eq. (1) (Yamahara 1964a, b).

$$\sigma_v = \left(\frac{R_{fl,z=i}}{A_{in}} + \frac{\gamma_\tau D_{in}}{4\mu K_h}\right) \exp\left(\frac{4\mu K_h}{D_{in}}(-x)\right) - \frac{\gamma_\tau D_{in}}{4\mu K_h} \qquad (1)$$

where σ_v is vertical earth pressure of inner pile at the distance of x from the pile bottom at the penetration depth of $z=i$, $R_{fl,z=i}$ is vertical force acting on the base of the soil plug at the penetration depth of $z=i$, A_{in} is inner cross section of pile toe, μ is friction coefficient of interface between pile and soil, K_h is coefficient of horizontal earth pressure, γ_t is unit weight of inner soil, D_{in} is inner diameter of the pile.

Paikowsky et al. (1989) proposed the incremental filling ratio (*IFR*) as a parameter of plugging phenomena of an open-ended pile. *IFR* is defined as $IFR=dh/dz$, where h is inner soil height, z is pile penetration depth. *IFR* is 1 when pile is un-plugged, *IFR* is between 0 and 1 when pile is partially plugged, and *IFR* is 0 when pile is fully plugged.

Kikuchi examined the applicability of Yamahara's proposal (Kikuchi 2011). As a result, vertical stress distribution on a horizontal cross section did not satisfy his assumption, but the equation was applicable on average in the cross section and the value of μK_h was evaluated as about 0.34. Kikuchi (2011) also mentioned a certain limitation of small model pile experiments for discussing plugging phenomena because there was a big gap between his small model pile experimental results and an actual prototype pile experimental results (Schneider et al 2007) in the plugging phenomena.

Even small model piles were used for the experiments in this research, applicability of the experimental results to the prototype pile was discussed with conducting experiments by changing pile diameters, ratios of pile diameter to pile wall thickness.

3 OUT LINE OF EXPERIMENTS

Outer diameters of model piles were 50 mm and 101.6 mm. Closed ended piles and open-ended piles were used. Diameter, *D* and thickness, *t* of pile wall in open-ended piles were D/t= 12.5, 16.7, 25, 50. The piles were made of stainless steel. Open-ended piles had a sleeve at the toe of the piles to control the range of the area inner friction worked with changing sleeve length *l* as shown in Fig. 1. Model ground was made of dry sandy soil of Silica sand #5. The density of the soil particles of Silica sand #5 was 2.666 g/cm^3, the mean diameter was 0.59 mm, and the maximum and minimum void ratios were 1.062 and 0.689 respectively.

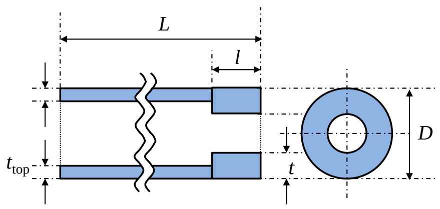


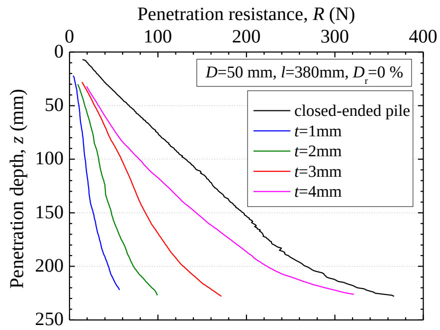
Fig. 1. Image of a pile used in this research.

When using model piles with an outer diameter of 50 mm, the model ground was prepared in a soil tank of 300 mm inner diameter. A soil tank with an inner diameter of 772 mm was used when using model piles with an outer diameter of 101.6 mm. The model ground was made of dry sand and the height was 270 mm and 800 mm in each soil tank. The model ground was prepared with sand of from 0% to 80% relative density with air pluviation method. A pile was penetrated to the ground at the velocity of 5 mm/min. The penetration resistance, penetration depth, and inner soil height were measured with external load cell, displacement transducer, tape-measure-type displacement transducer respectively. As outer friction resistance of a pile shaft was relatively small without when the relative density was 0%, outer frictional resistance was ignored.

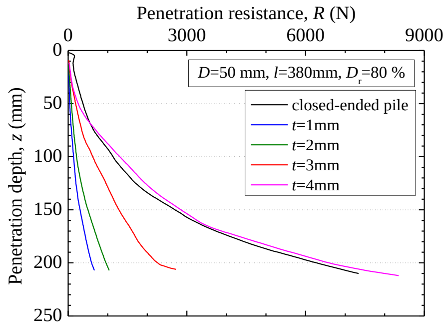
4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Plugging effect and plugging phenomena

Fig. 2 shows the relationship between penetration depth and penetration resistance of a pile with 50 mm outer diameter. Piles used were a closed ended pile and open-ended piles with different pile wall thickness. Sleeve length of open-ended piles were 380mm, which means pile wall thickness is the same along the pile axis. Fig. 2 (a) shows the cases with Dr of 0% and (b) shows the cases with Dr of 80%. According to these results, the penetration resistance of the pile differed greatly if Dr was different. It is also found that there was a certain relationship in the ratio of the penetration resistance of the open-ended pile to that of the closed-end pile due to the difference in the wall thickness of the pile.



(a) Dr=0%



(b) Dr=80%

Fig. 2. Relationship between penetration depth and penetration resistance for pile diameter of 50mm.

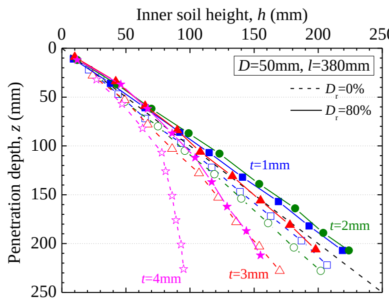


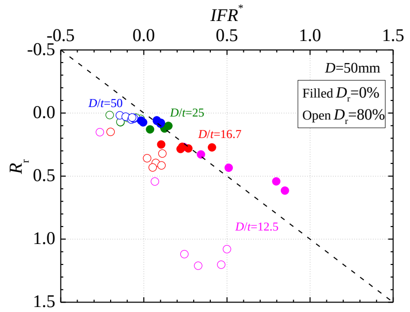
Fig. 3. Relationship between penetration depth and inner soil height.

Fig. 3 shows the relationship between the inner soil height *h* and the pile penetration depth *z* for the experimental cases shown in Fig. 2. From Fig. 3, as the pile wall thickness increased, the inner soil height became smaller than the penetration depth of the pile from the stage where the pile penetration depth was shallow. That is, it became difficult for soil to enter the pile when the pile wall thickness was large.

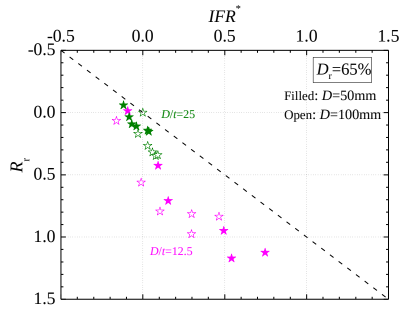
Since the plugging effect depends on the friction force acting between the inner soil of the pile and the inner surface of the pile, the increase in the toe resistance force of the pile due to this friction force will be appropriate. Based on this concept, the inner stress ratio R_r was defined as $R_r=q_{fl}/q_b$, where q_{fl} is the unit toe resistance because of inner friction force of the open-ended pile, q_b is the unit toe resistance of pile body. According to the experimental results reported by Kikuchi (2011), q_b was equally distributed over the entire bottom surface when the open-ended pile was completely plugged. Therefore, q_b was calculated from

$q_b=R_{close}/A$, where A is total cross-sectional area of a closed ended pile. Further, q_{fI} can be obtained from $q_{fI}=R_{fI}/A_{in}$, where R_{fI} is the frictional force of the inner surface of the open-ended pile, A_{in} is the inner cross section area of the open-ended pile. And R_{fI} was calculated from $R_{fI}=R_{open}-q_bA_p$, where A_p is the cross-sectional area of the body of open-ended pile.

As already mentioned, *IFR* has been proposed because the degree of increment of the inner soil height due to pile penetration relating to the pile plugging. However, *IFR* is defined as 0 when a pile is completely plugged, and 1 when it is not plugged at all. Therefore, the parameter *IFR** = 1 - *IFR*, which becomes 1 when a is completely plugged and 0 when it is not plugged at all, was used as an index of the plugging phenomenon. Here it is called inner soil height length change rate.



(a) Effect of relative density



(b) Effect of outer pile diameter

Fig. 4. Relationship between R_r and *IFR**

Fig. 4 shows the relationship between the inner stress ratio R_r and *IFR**. Fig. 4 (a) shows the relations when the pile of outer diameter *D* of 50 mm with sleeve length of *l*=380 mm in the two relative densities ground. The results for z/D = 1.0, 1.5, 2.0, 2.5 for each ground density are shown. D/t in Fig.4 is the ratio of the wall thickness to the outer diameter of the pile. According to the figure, when D_r was small, there was a 1:1 relationship between R_r and *IFR** regardless of the difference in D_r. However, when D_r was large, the R_r was larger than *IFR**. This tendency was more apparent when D/t was small.

On the other hand, Fig.4 (b) compares the relationships of the results in 101.6 mm outside diameter and in 50 mm outside diameter on ground with D_r of 65%. The relationships were in the middle of the case of each D_r in Fig.4 (a). The relationship between R_r and *IFR** of each pile seems to be the same even if the pile outer diameter was different. Thus, in the range of the experiment conducted here, relationship between R_r and *IFR** were not affected much by the outer diameter of the pile and were strongly influenced by the outer diameter/wall thickness ratio D/t and the relative density D_r of the ground. Considering the case of actual steel pipe piles, D/t is usually more than 50 and the influence of D/t was not as large as that in the experiment.

4.2 Evaluations of coefficient of earth pressure acting on the pile inner surface around the pile toe and vertical earth pressure distribution along the pile

When obtaining the vertical earth pressure using Eq. (1) from the experiments, the product of the earth pressure coefficient K_h acting on inside of the pile and the coefficient of friction μ between the soil and the inner wall of the pile is only unknown. The distribution of μK_h along the pile axis at a certain pile penetration depth was estimated with assuming that μK_h changes in the direction of the pile axis. The procedure is shown in Fig. 5. At first, at the certain penetration depth $z=i$, μK_h from the toe to height l_1 was estimated using Eq. (1) with using both R_{fI}/A_{in} obtained from the experiment of the pile with the shortest sleeve length l_1 and the vertical earth pressure equal to the overburden pressure at the height of l_1. This μK_h was set to μK_{h1}. Next, in the pile with a second shortest sleeve length l_2, μK_h from the toe to height l_1 was assumed as μK_{h1}, and μK_h between $x= l_1$ and $x= l_2$ was estimated so that σ_v at $x=l_2$ was equal to the overburden pressure. This μK_h was set to μK_{h2}. Such calculation was repeated sequentially up to a pile with a sleeve length of 380 mm.

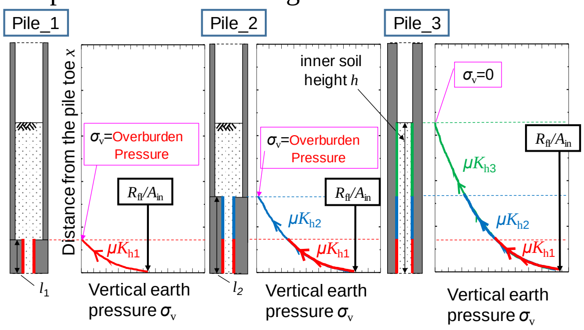
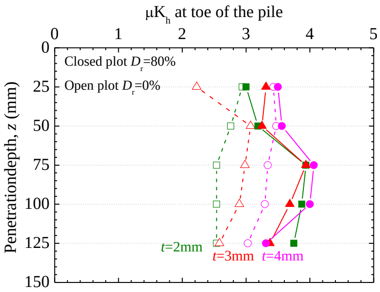


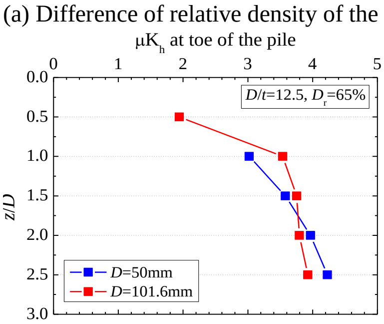
Fig. 5. Estimation method when μK_h is not constant.

Fig. 6 (a) shows the change of the μK_{h1} obtained from above method when the relative density is different for a pile with an outer diameter *D* of 50 mm. In this figure, solid lines show the results of D_r = 80%, and the broken lines show the results of D_r = 0%. The symbols plotted are changed according to the difference in wall thickness of the piles. According to these results, the value of μK_{h1} varied somewhat depending on the wall thickness of the pile, but μK_{h1} tended to become larger with larger D_r. In addition, it is understood that

μK_{h1} did not change so much even if the pile penetration depth changed. Fig. 6 (b) shows the change of μK_{h1} when the outer diameter of the pile differs. In Fig. 6 (b), the pile penetration depth was normalized with the pile outer diameter. The shortest sleeve length l_1 of a pile with an outer diameter D=50 mm and 101.6 mm is set to l_1/D=0.2. According to this figure, it is understood that regardless of the outer diameter of the pile μK_{h1} took almost the same value, and even if the pile penetration depth changes, it did not change very much. As shown in Fig. 7, μK_h is the largest near the toe of the pile and it rapidly decreases toward the upper side of the pile axis. From this reason, it can be said that μK_h near the toe of the pile is an important parameter in estimating the frictional force of the inner surface of the pile. If μK_h near the toe of the pile is not affected by the pile outer diameter or the density of the ground, estimation of the inner frictional force of the pile will be easy.



(a) Difference of relative density of the ground



(b) Difference of outer pile diameter

Fig. 6. Change of μK_{h1} according to pile penetration depth.

Fig. 7 shows distributions of μK_h along the pile axis when z/D=2. For the comparison, the cases with the pile outer diameter D is 50 mm and 101.6 mm are shown in this figure. In the figure, the distance x from the toe in the pile axis direction was normalized with the pile outer diameter D. In Fig. 8, μK_h was slightly larger when the pile outer diameter was 50 mm than that was 101.6 mm, but the difference was small. Also, comparing to μK_h near the toe of the pile, it is understood that μK_h was a very small when x/D exceeded 0.3. These results show that the distribution of μK_h was very similar at all depths and μK_h rapidly decreased as going above along the pile axis even if outer diameter of piles were different.

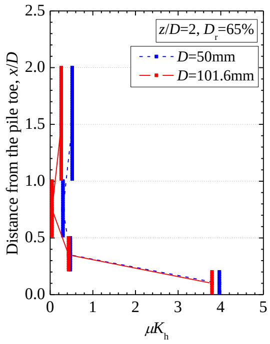


Fig. 7. Distribution of μK_h estimated from experimental results.

5 CONCLUSION

The effects of the difference of the pile outer diameter and the relative density of the ground on the plugging of the open-ended piles were investigated in this study. The relationship between the inner stress ratio R_r and the inner soil height length change rate *IFR** varied depending on the relative density of the ground, but the influence of the pile outer diameter D or the diameter thickness ratio D/t to the relationship was relatively small. It was found that μK_h is large near the toe of the pile, and μK_h is small at the upper part of the pile. In addition, μK_h was found not to be much influenced by the difference of the pile outer diameter and the relative density of the ground.

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