Effect of Pile Diameter on Plugging Phenomenon of Open-ended Piles

Mizue KANBE
Graduate Student, Department of Civil Engineering, Tokyo University of Science, Chiba, Japan
Email: 7616608@ed.tus.ac.jp
Yoshiaki KIKUCHI
Professor, Department of Civil Engineering, Tokyo University of Science, Chiba, Japan
Email: kikuchi_y@rs.tus.ac.jp
Taichi HYODO
Assistant Professor, Department of Civil Engineering, Tokyo University of Science, Chiba, Japan
Email: t.hyodo@rs.tus.ac.jp
Hiromu OTSUBO
Undergraduate Student, Department of Civil Engineering, Tokyo University of Science, Chiba, Japan
Email: 7614018@ed.tus.ac.jp
Hiroyoshi YAMAZAKI
Undergraduate Student, Department of Civil Engineering, Tokyo University of Science, Chiba, Japan
Email: 7614106@ed.tus.ac.jp

ABSTRACT

Nowadays deep embedded and large diameter steel pipe piles have been widely used in Japanese port facilities for supporting large vertical load, as growing sizes or changing structural types of port facilities. Estimation for bearing capacity of large diameter and deep embedded piles has been complex problems such that bearing capacity is increased because of deep embedment and plugging effect is decreased because of using large diameter piles. To investigate the inner friction force mechanism development with soil plugging of open-ended piles was the main aim of this study. In this research, open-ended piles with different pile outer diameters were penetrated into dry sand. The plugging situation in the model pile penetration experiment was evaluated from two viewpoints of the plugging phenomenon. As a result, it was found that if the ratio of the wall thickness to the pile diameter is the same, there is not much difference in the degree of plugging due to the pile diameter.

Key words: *Open-ended piles, End bearing capacity, Soil plugging, Inner friction*

1. Background

Steel pipe piles have been used for a long time in Japan's port facilities. Nowadays deep embedded and large diameter steel pipe piles have been widely used in port facilities for supporting large vertical load, as growing sizes or changing structural types of port facilities. Therefore, it is required to accurately estimate the end bearing capacity of one pile. According to the design standards of Japanese port structures, the design bearing capacity of the open-ended pile incorporates a plugging ratio. The plugging ratio is considered to be affected by pile diameter and embedment length to the bearing layer, detailed mechanism of the plugging has not been clarified.

As shown in **Fig. 1**, theoretically, the toe bearing resistance of an open-ended pile can be separated into the resistance of the annular part, R_p, and the inner friction between the pile wall and soil, R_{fI}. Considering this, the theoretical plugging effect, η, is written in **Eq. (1)**. (AIJ, 2001)

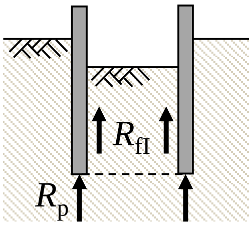


Fig. 1 Schematic diagram of the bearing capacity of an open-ended pile

$$\eta = \frac{R_p + R_{fI}}{R_{close}} \tag{1}$$

where R_{close} is the resistance of a closed-ended pile.

However, it is difficult to estimate the inner frictional resistance because the mechanism of the soil plugging of the open-ended pile is unknown. For this reason, a method for estimating the plugging ratio has not been adopted in practice.

In this study, the mechanism of inner friction force development with soil plugging of open-ended piles was investigated. In order to investigate the effect of the pile outer diameter on the plugging phenomenon of an open-ended pile, model piles with different pile outer diameters were penetrated into dry sand in this paper. The results of model pile penetration experiments were evaluated for the plugging situation from two viewpoints. One was the bearing capacity, the other was a phenomenon where plugging can be made.

2. Material and test methods

The model piles used in this study were made of stainless steel. One closed-ended pile and two open-ended piles had an outer diameter (D) of 50 mm and a length (L) of 380 mm. Apart from them, one closed-ended pile and two open-ended piles had an outer diameter of 101.6 mm and a length of 900 mm. For both open-ended piles with D of 50 and 101.6 mm, diameter-thickness ratio (D/t) was 12.5 and 25.

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. It was made of Tohoku silica sand #5. The density of the soil particles of Tohoku silica sand #5 was 2.658 g/cm^3, the mean diameter was 0.55 mm, and the maximum and minimum dry density were 1.718 g/cm^3 and 1.479 g/cm^3 respectively. The model ground was prepared with sand of 65% relative density. The particle size distribution of Tohoku silica sand #5 is given in **Fig. 2**. Internal friction angle of the sand measured by drained triaxial compression test under the confining pressure of 50 kN/m^2 was 40

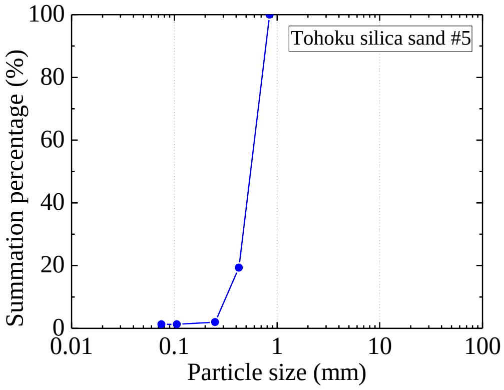


Fig. 2 Particle size distribution of Tohoku silica sand #5

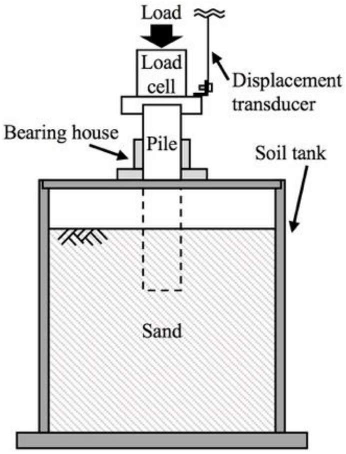


Fig. 3 Schematic diagram of installation method of measuring equipment

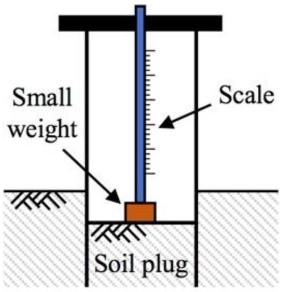
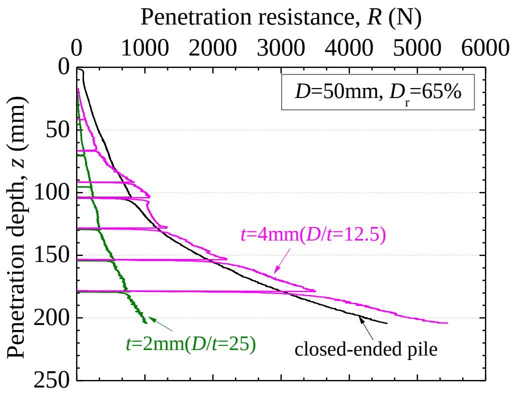


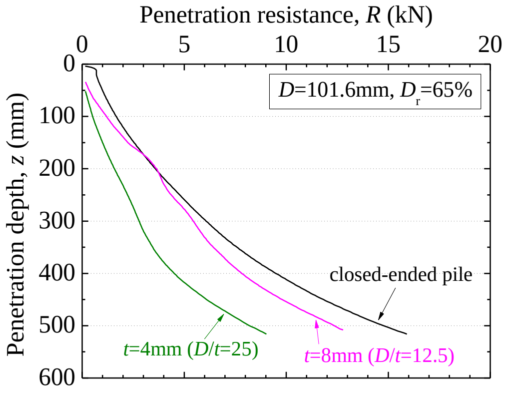
Fig. 4 The measurement method of inner soil height

degree at the relative density of 80%.

The pile was penetrated into the model ground at the rate of 5mm/min in experiments with a soil tank of 300 mm inner diameter, 30 mm/min in experiments with a soil tank of 772 mm inner diameter. No effects were observed in the difference of penetration rates in these series of experiments. The penetration resistance and penetration depth were measured using external load cell and displacement transducer respectively as shown in **Fig. 3**. When the open-ended pile with an outer diameter D of 50 mm was penetrated into the model ground, the inner soil height, *h*, was measured using a scaled-mark string connected to a small weight at the bottom by stopping penetration at 25 mm intervals as shown in **Fig. 4**. For open-ended piles with an outer diameter of 101.6 mm, inner soil height was measured with a tape measure type displacement transducer connected to a weight. Inner soil height was measured continuously by placing the weight on the soil surface in the open-ended pile and measuring the withdrawal amount of the wire with penetration of the pile.

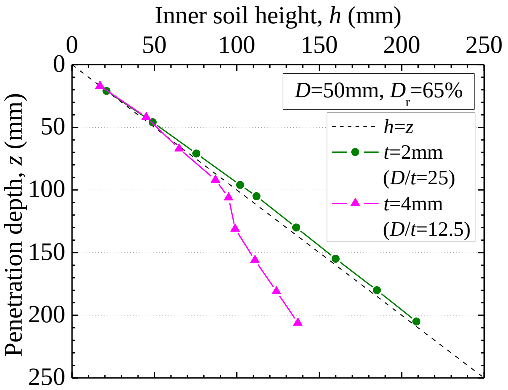


(a) *D* = 50 mm

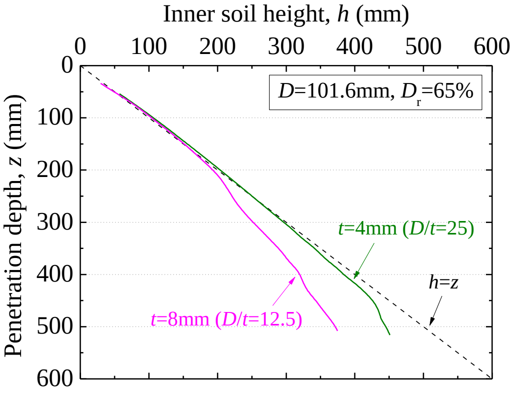


(b) *D* = 101.6 mm

Fig. 5 Relationship between the penetration depth and the penetration resistance



(a) *D* = 50 mm



(b) *D* = 101.6 mm

Fig. 6 Relationship between the penetration depth and inner soil height

3. Results and discussion

Fig. 5 (a) and (b) show the relationship between the penetration depth and the penetration resistance in an outer diameter of 50 and 101.6 mm. In the case of open-ended piles with outer diameter *D* of 50 mm as shown in **Fig. 5** (a), the inner soil height was measured by stopping penetration and released the load at around 25 mm intervals. The results indicate that there was a certain relationship between the ratio of the penetration resistance of open-ended pile to the penetration resistance of the closed-ended pile. The results also indicate that the relationship varied depending on the diameter-thickness ratio, regardless of the pile diameter. **Fig. 5** (a) and (b) show that the smaller the diameter-thickness ratio is, the lower penetration resistance at the same penetration depth becomes.

Fig. 6 (a) and (b) show the relationship between the penetration depth and the inner soil height in an outer diameter of 50 and 101.6 mm. When the tangential line of the z-h curve is in parallel with the dotted line (z=h), inner soil was unplugged. When the inner soil height was smaller than the penetration depth, there was a situation in which soil was difficult to be filled into the pile. The results show that the inner soil height was smaller than the penetration depth with the penetration depth more than twice the pile diameter (referred to as 2*D*) when the diameter-thickness ratio was small regardless of the pile diameter. When the diameter-thickness ratio is small, it was considered that a plugging phenomenon was occurring at the penetration depth deeper than 2*D*.

In this research, the soil plugging behavior of open-ended pile was evaluated from two viewpoints. One was a plugging effect to be evaluated from penetration resistance. The other was a plugging phenomenon which evaluates whether the inner soil had formed a plug from the relationship between the inner soil height and the penetration depth. The inner stress intensity ratio(R_r) was used to evaluate the plugging effect. R_r was defined by **Eq. (2)**.

$$R_r = q_{fI} / q_b \tag{1}$$

where q_{fI} is the resistance per unit area acting on the bottom of the inner soil of the pile, q_b is the resistance of the annular part per unit area.

The previous research suggests that the soil pressure distribution at the tip of the closed-ended pile is almost equally distributed load at the model experiment level (Kikuchi, 2011). In this paper, q_b was calculated from **Eq. (3)** using a measured value of penetration resistance of the closed-ended pile.

$$q_b = R_{close} / A \tag{2}$$

where R_{close} is the resistance of a closed-ended pile, A is the total area covered by the pile outer diameter.

q_{fI} was calculated by **Eq. (4)** and **Eq. (5)** using measured values of penetration resistance.

$$q_{fI} = R_{fI} / A_{in} \tag{3}$$

$$R_{fI} = R_{open} - q_b A_p \tag{4}$$

where R_{fI} is inner frictional resistance, A_{in} is internal area of open-ended pile, R_{open} is the resistance of an open-ended pile, A_p is annular area.

Since the degree of the change in the inner soil height with the penetration of the pile is related to the soil plugging, incremental filling ratio (*IFR*) (Lehane and Gavin, 2001) was defined as shown in **Eq. (6)**.

$$IFR = dh / dz \tag{5}$$

where *dh* is change of inner soil height for a penetration depth of *dz*.

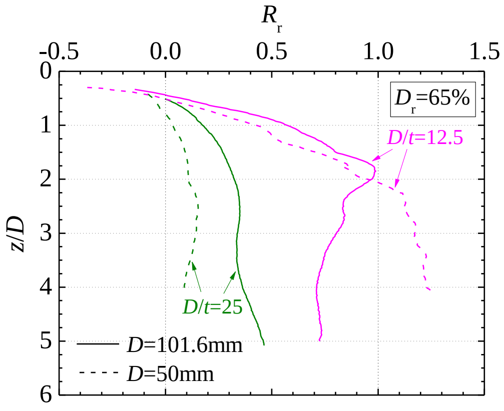


Fig. 7 Relationship between the penetration depth and R_r

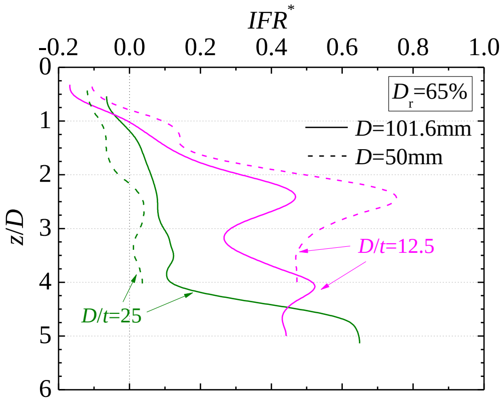


Fig. 8 Relationship between the penetration depth and IFR^*

As **Eq. (6)** implies, a fully-plugged open-ended pile produces a zero value of *IFR* due to no changes in the soil plug height respective its penetration depth. At the other extreme end, an unplugged open-ended pile produces 1 value of *IFR* due to an equal height of soil plug to its penetration depth. However, a fully-plugged open-ended pile produces 1 value of R_r, and an unplugged open-ended pile produces zero value of R_r. To clarify the relationship between the plugging effect and the plugging phenomenon, the plugging phenomenon was evaluated by IFR^* shown in **Eq. (7)**. A fully-plugged open-ended pile produces 1 value of IFR^*, and an unplugged open-ended pile produces zero value of IFR^*. In this paper, IFR^* was referred to as incremental filling ratio.

$$IFR^* = 1 - dh/dz \tag{6}$$

Fig. 7 shows the relationship between the penetration depth and R_r calculated from **Eq. (2)-(5)**. In **Fig. 7**, the penetration depth was normalized by the pile outer diameter. The result shows that R_r increased with penetration when the penetration was shallow. The result also shows that R_r became almost constant irrespective of the penetration depth when the model pile was penetrated into the ground more than about 2*D*. In addition, R_r is slightly bigger for larger diameter piles at any diameter-thickness ratio until the penetration depth reaches 2*D*.

Fig. 8 shows the relationship between the penetration depth and IFR^* calculated from **Eq. (7)**. In **Fig. 8**, the penetration depth was normalized by the pile outer diameter as in **Fig. 7**. The result indicates that the same tendency as R_r could be seen with IFR^*. In other words, the result shows that IFR^* increased until the penetration depth reached 2*D*, and it showed a generally constant value when it was penetrated deeper than 2*D*.

Fig. 7 and **Fig. 8** show that both R_r and IFR^* appeared to be affected by both the pile diameter and diameter-thickness ratio. In order to clarify the influence of the pile diameter and diameter-thickness ratio, the relationship between the diameter-thickness ratio and R_r or IFR^* was investigated as shown in **Fig. 9** and **Fig. 10**. The data when the penetration depth reached 2*D* was plotted in **Fig. 9** and **Fig. 10**. In addition, these figures also include past research results of penetrating model piles into grounds of different relative densities (Kanbe *et al.*, 2017).

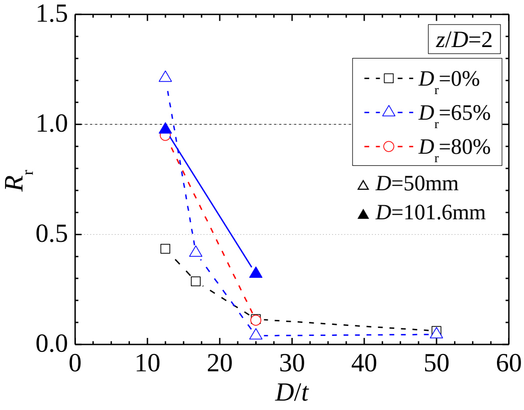


Fig. 9 Relationship between inner stress intensity ratio and diameter-thickness ratio

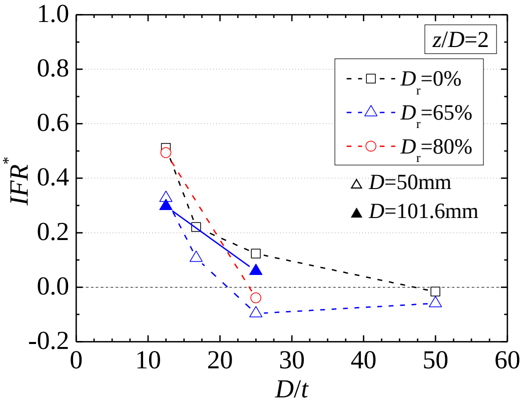


Fig. 10 Relationship between incremental filling ratio and diameter-thickness ratio

Fig. 9 shows that R_r tended to decrease as the diameter-thickness ratio increased in both cases of pile diameter of 50 and 101.6 mm. Focusing on the difference in pile diameter, **Fig. 9** shows that R_r became slightly larger as the pile diameter increased in both diameter-thickness ratio of 12.5 and 25. However, since the difference in R_r due to the pile diameter was smaller than the difference in R_r due to the diameter-thickness ratio, it was considered that the influence on R_r is larger in the diameter-thickness ratio than in the pile diameter. **Fig. 10** shows that IFR^* decreased with the diameter-thickness ratio as in R_r. Focusing on the difference depending on the pile diameter, **Fig. 10** shows that IFR^* decreased as the pile diameter increased when the diameter-thickness ratio was 12.5. **Fig. 10** also shows that IFR^* was less than zero with the small pile diameter and it was slightly more than zero with the large pile diameter. If IFR^* is less than zero, it means that the increment of the inner soil height is larger than the increment of the penetration depth. There are at least two factors that can affect the inner soil height. One is that mass of soil penetrated a little from the outside of the inner of the pile. The other is that the volume of soil changes after soil penetrating into the pile. When the diameter-thickness ratio was 25, it is difficult to judge which cause affected the difference in the tendency of IFR^* depending on the pile diameter only by this result.

As shown in **Fig. 9** and **Fig. 10**, there was a slight difference in tendency between *R*r and IFR^* due to differences in the pile diameter and the diameter-thickness ratio.

Fig. 11 shows the relationship between R_r and IFR^* to investigate how these relationships change. This figure includes the results at the penetration depth of 1*D*, 1.5*D*, 2*D*, 2.5*D*. **Fig. 11** also includes the past research results (Kanbe *et al*., 2017). On the dotted line, R_r and IFR^* are equal. As shown in Fig. 11, the past experiment results show that R_r and IFR^* had a one-to-one relationship in loose sands regardless of the difference in the diameter-thickness ratio. In addition, the past experiment results also show that R_r became larger than IFR^* in dense sand. The relationship between the overall R_r and IFR^* obtained from the experiment results this time was located between the past experiment results. This is probably because the relative density of the model ground was 65%. Focusing on the difference in the diameter-thickness ratio, it could be seen that the diameter-thickness ratio did not have much influence on the relationship between R_r and IFR^* although the values of R_r and IFR^* themselves varied depending on the diameter-thickness ratio. Focusing on the difference in the pile diameter, the relationship between R_r and IFR^* had almost the same trend regardless of the pile diameter at the diameter-thickness ratio of 12.5. When the diameter-thickness ratio was 25, it was considered that there was not much difference depending on the pile diameter although it could not be clearly judged because of the range of R_r varying somewhat by the pile diameter.

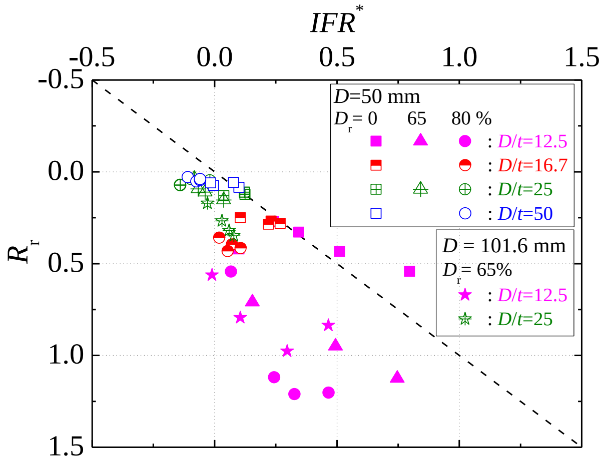


Fig. 11 Relationship between R_r and IFR^*

4. Conclusions

In this research, model experiments were conducted to penetrate open-ended piles with different pile diameters into the ground. The degree of the soil plugging in the experiment results was evaluated from two viewpoints. The first evaluation method was to judge the plugging effect based on the bearing capacity, which was evaluated by R_r. The other was IFR^*, which was to judge whether a soil plug was formed from a change in the inner soil height.

The results suggest that R_r slightly increased with the pile diameter, while IFR^* tended to decrease with the pile diameter. Although this tendency was seen, it was deduced that the effect of the diameter-thickness ratio on the soil plugging was larger than that of the pile diameter under this experiment condition.

The results also suggest that there was not much change in the relationship between R_r and IFR^* if the diameter-thickness ratio was the same even if the pile outer diameter was about two times different.

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