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The inner friction resistance and the resistance of an actual part of open-ended piles by the double-pipe model pile experiment

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ABSTRACT: A penetration experiment was conducted using a double-pipe model pile capable of measuring the inner friction resistance in isolation. The objective was accurately measuring the bearing capacity of open-ended piles and determining the range of machining that needs to be performed on the toe of the piles in order to plugging. The friction coefficient of the model pile was changed to verify the relationship between the inner friction resistance and the *IFR**, and how plugging at the toe is affected by the range and position of the where machining area. From the results, it can be concluded that a superior outcome cannot be achieved solely by increasing the friction coefficient around 0.5*D* from the end of the pile. To achieve effective plugging, the friction coefficient should be increased not only at the toe of the pile but across an area of at least 1.0*D* from the toe of the pile.

1 INTRODUCTION

Pile foundations have been used for a long time in the port facilities in Japan. In recent years, as port facilities increase in size and their structural types change, large-diameter steel pipe piles are being widely used to support large vertical loads. Therefore, steel pipe piles with a large diameter, including up to ϕ2,000 mm, are also used. For open-ended piles, such as steel pipe piles, it is the problem that the plugging effect decreases as the pile diameter increases.

According to Kikuchi (2011), there is a significant difference in the estimated bearing capacity depending on the difference in the estimation equations from areas where the pile penetration depth exceeds 60 m when the bearing capacity of the pile is estimated using internationally applied estimation equations.

According to the construction standards of Japan (Architectural Institute of Japan, 2001), as shown in Figure 1, the toe bearing resistance of an open-ended pile, which can be separated into the resistance acting on the annular part, R_{out}, and the inner friction between the pile wall and soil, R_{in}, can be theoretically represented as $R_{open}=R_{out}+R_{in}$ (Figure 1).

Considering this, the plugging effect η which is the ratio of the resistance of an open-ended pile and a closed-ended pile, is written as equation (1). However, it is difficult to measure R_{in} and R_{out} separately in actual piles, and it has not been possible to discuss the plugging effect quantitatively.

$$\eta = \frac{R_{open}}{R_{close}} = \frac{R_{out}+R_{in}}{R_{close}} \qquad (1)$$

The authors considered an estimation of the internal friction resistance R_{in} of open-ended piles to be a serious problem in the estimation of R_{open}. Therefore, we previously devised a method to estimate the inner friction resistance R_{in} of open-ended piles through a model pile penetration experiment on sandy ground.

If the inner friction resistance is not exerted in comparison with R_{close} with unplugging at the pile toe, the plugging effect may be insufficient. In such cases, a special pile is considered to promote plugging by machining the pile toe with cross-ribs. However, neither has a method to promote plugging by machining around the pile toe been systematized, nor has a rational method been developed.

Therefore, it is important to accurately estimate the bearing capacity of a pile and to clarify the method of machining the toe of a pile tip to promote plugging. In this study, penetration experiments were conducted using a double-pipe model pile, which can measure the inner friction resistance and the

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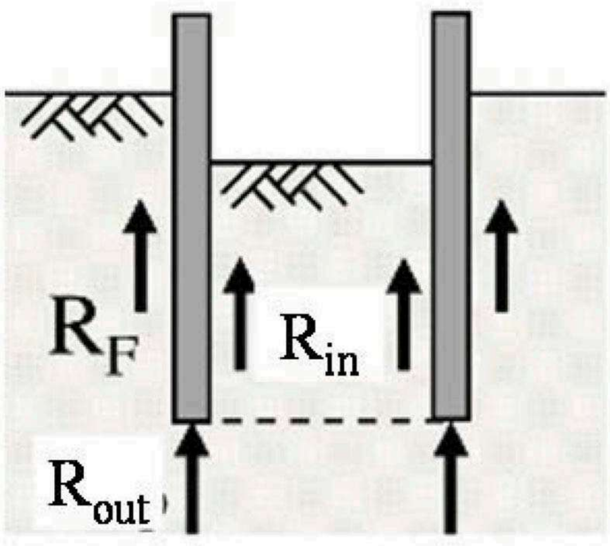

Figure 1. Schematic of the bearing capacity.

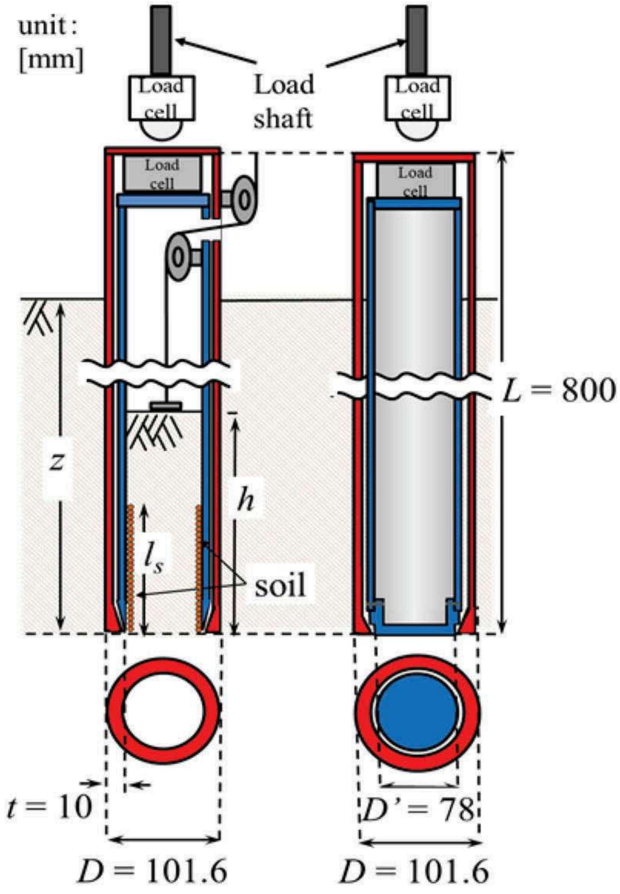

Figure 2. Diagram of the model piles.

resistance acting on the ring of the pile toe. Furthermore, the relationship between the inner friction resistance and IFR*, which was defined as 1 − *IFR*, was investigated. Definition of *IFR* is shown in equation (2). IFR* represents the state of plugging by the inner friction coefficients of the inner surface of a double-pipe model pile that are varied by attaching sand to the inner surface of the pile. The effects of the machining area and position of the sand on the acceleration of plugging were also studied.

2 MATERIAL AND TEST METHODS

The model piles used in this series of experiments are shown in Figure 2. Each model pile is comprised of both outer and inner pipes. The dimensions of the outer pipe of the model pile, shown in red, are as follows: outer diameter D = 101.6 mm, total length L = 800 mm, and pipe thickness t = 10 mm. The toes of the piles were formed as shown in Figure 2. The ratio of the outer diameter to the pipe thickness of the outer pile (D/t) was approximately 10.2. There were two types of inner pipes, open-ended and closed-ended. They are shown in blue in Figure 2. The outer and inner diameters of the open-ended pile were 88 mm and 80 mm, respectively, whereas the tip of the closed-ended pile had a diameter of D' = 78 mm. Both pipes were 4 mm thick and made of stainless steel. In the closed-ended pile, the attachment was screwed to the pile toe. When it was combined with an outer pipe, the positions of the pile toes were aligned. The inside of the outer piles was tapered at the pile shaft to prevent the inner and outer pipes from protruding from each other. Adhesive tape was applied to the pile tip clearances to prevent sand from entering between the piles.

Two load cells were used to measure the resistance of each pile individually. A load cell with a capacity of 30 kN was inserted between the upper part of the inner pipe and the outer pipe, through which the outer and inner pipes were rigidly connected. A load cell with a capacity of 49 kN was set between the loading shaft and top of the outer pile. The penetration resistance R_{in} acting on the inner pipe was measured directly by the load cell set between the piles. The penetration resistance acting on the outer pipe was calculated from the total resistance measured by the load cell set between the loading shaft and the top of the outer pipe and subtracting the load measured by the load cell set between the pipes. The penetration resistance acting on the outer pipe was the sum of the tip resistance of the outer pipe R_{out} and outer frictional resistance R_f. The outer frictional resistance R_f was estimated based on a previous study[2].

In this study, sand particles of Tohoku silica sand #5 (Table 1), which was used for the model ground, adhered to the inner surface of the inner pipe with epoxy adhesive, as shown in Figure 2. The friction coefficient of the inner surface was partially changed by this method in this series of experiments. The lengths of the attached sand particles, l_s, were 0, 20, 50, and 100 mm. The distance from the pile toe to the lower end of the sand-adhered part was either 0 or 50 mm. Table 2 shows the relationship between the experimental case names and the positions of the sand-adhered part.

Table 1. Soil properties of test sand.

Soil particle name	Tohoku silica sand #5
ρ_s	2.658 g/cm^3
ρ_{dmax}	1.718 g/cm^3
ρ_{dmin}	1.479 g/cm^3
D_{50}	0.6 mm
U_c	1.9
D_r	65 %

Table 2. Summary of sand-adhered part.

Type of pile	Case name	Sand-adhered part: Lower end from toe (mm)	Upper end from toe (mm)	Length l_s (mm)
Open-ended	S0-0	0	0	0
	S0-20	0	20	20
	S0-50	0	50	50
	S0-100	0	100	100
	S50-100	50	100	50
Closed-ended	Closed			

The model ground was prepared in a soil tank with an inner diameter of 772 mm, as depicted in Figure 3, and was made of dry Tohoku silica sand #5 (Table 2). The model ground was prepared with a relative density of 65 % and a ground height of 800 mm using an air pluviation method. The internal friction angle of the sand was ϕ_d = 35° when the relative density was 65 %.

The model pile penetrated the model ground statically at a speed of 30 mm/min, and the data measured included the total penetration resistance R, inner friction resistance R_{in}, and penetration depth z. The penetration depth was measured continuously using a displacement transducer, the capacity of which was 1000 mm. In the case of an open-ended pile, the displacement of the inner soil surface, h', was measured continuously using a displacement transducer, the capacity of which was 2000 mm. The inner soil height, h ($h = z - h'$), is the length from the pile tip to the soil surface inside the inner pile.

3 RESULTS AND DISCUSSION

3.1 *Inner soil height*

Figure 4 depicts the relationship between the inner soil height h and the penetration depth z in the open-ended pile penetration experiments. The values on both the X and Y axes are normalised by the outer diameter of the outer pile. When the increase in inner soil height h was almost equal to the increase in penetration depth, the soil could be easily intruded into the pile. Thus, it can be considered that the pile was not plugged. When the increment rate of the inner soil height was smaller than the pile penetration, the soil was less likely to enter the pile. In this case, it can be considered that the pile was partially plugged. When the inner soil height did not change during the penetration of the pile, the soil was never intruded into the pile. The pile was then perfectly plugged.

From Figure 4, the results suggest that no plugging occurs throughout the pile penetration

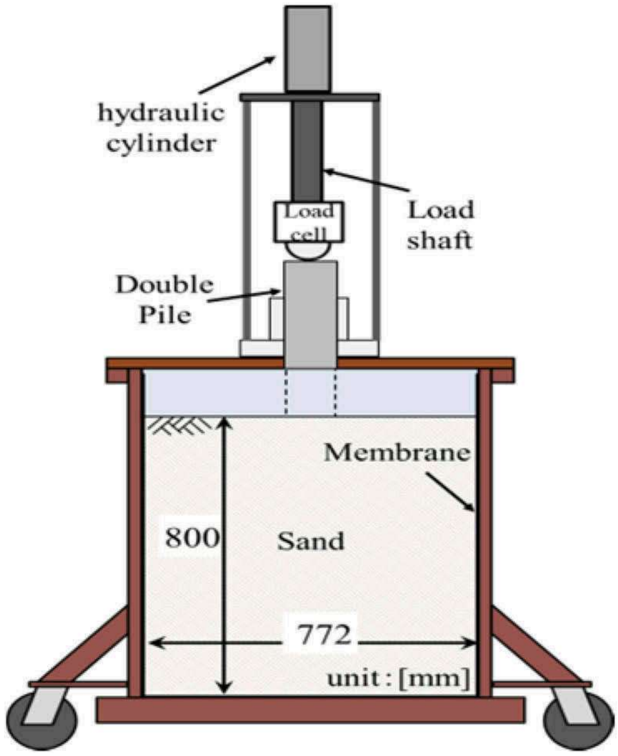

Figure 3. Diagram of the soil tank.

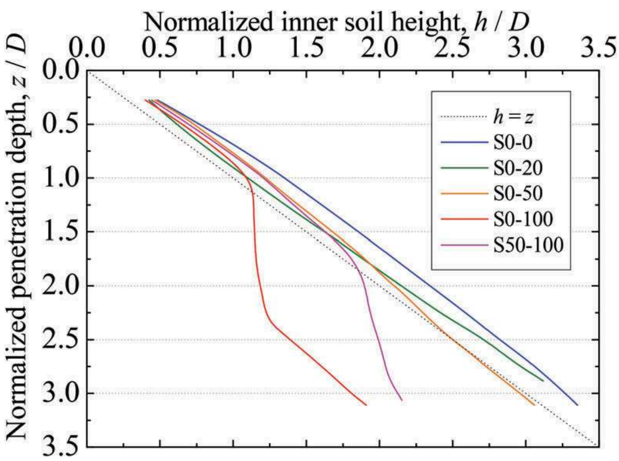

Figure 4. Relationship between h/D - z/D.

process in cases where the sand-adhered area was a small area of the inner surface of the pipes, such as in the cases of S0-0, S0-20, and S0-50. In the cases of S50-100 and S0-100, partially or perfectly plugging phenomena were observed during the pile penetration. Plugging can be considered to occur when the normalized penetration depth *z/D* ranged from 1.9 to 2.8 for S50-100 and from 1.1 to 2.3 for S0-100. In particular, a negligible soil height increment occurred during pile penetration within this range in the case of S0-100, which implies that near-perfect plugging occurs. In the case of S0-100 after the normalized pile penetration depth was further than 2.8, the pile was considered un-plugged.

In this study, the rate of change of inner soil height with penetration was compared with the state of plugging. The increment of soil length per increment of pile penetration depth, IFR^*, was used as an index to evaluate the plugging phenomena. It is expressed by the following formula:

$$IFR^* = 1 - \frac{\Delta h}{\Delta z} \tag{2}$$

The parameters Δh and Δz indicate the increment in inner soil height and pile penetration depth, respectively. $IFR^* = 1$ indicates that no soil enters the pile during penetration and plugging occurs. $IFR^* = 0$ indicates that the amount of soil equivalent to the penetration depth penetrates the inner pipe, and no plugging occurs. Therefore, a small IFR^* value indicates less plugging, and a high value indicates more plugging.

There are other indices for examining pile plugging, such as PLR = h/z. Usually, the pile is not plugged; then, *PLR* = 1. When this index was applied to the case S0-100, *the PLR* was less than one at the pile penetration depth deeper than $z/D > 1.1$. As seen in Figure 5, the plug could be destroyed after the penetration depth of $z/D > 2.3$. At that condition, *PLR* was still smaller than one. Thus, *PLR* is a less important parameter for the plugging index than *IFR* or IFR^*.

In this report, the relationship between $q_{in\text{-}open}/q_{in\text{-}close}$ and IFR^* is considered. The effects of the formation situation of plugging on the inner friction resistance are also discussed in this report.

3.2 *Penetration resistance*

$R_{in\text{-}open}$ is the resistance of the inner friction of the open-ended pile, and $R_{in\text{-}close}$ is the resistance acting on the inner pipe of the closed-ended pile. In the case of the closed-ended pile, $R_{in\text{-}close}$ is the resistance at a radius of 39 mm from the centre of the pile tip. It is not possible to compare the resistance measured in the inner pipe between $R_{in\text{-}open}$ and $R_{in\text{-}close}$ because of the different cross-sectional areas at the tip of the inner pipe. Therefore, to discuss the resistance per unit cross-sectional area, $q_{in\text{-}open}$ is defined as $R_{in\text{-}open}$

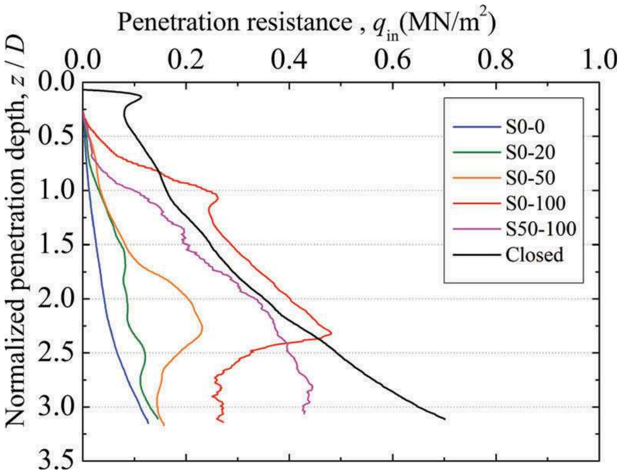

Figure 5. Relationship between q_{in} - z/D.

divided by the internal area of the inner pipe (i.e., $(D{-}2t)^2/4$), and $q_{in\text{-}close}$ is defined as $R_{in\text{-}close}$ divided by the cross-sectional area at the end of the inner pipe (i.e., $\pi(D')^2/4$). By converting the resistance per unit cross-sectional area using this approach, it is possible to compare and discuss them. The relationship between the unnormalized penetration resistance and depth ($R_{in\text{-}open} - z$, $R_{close} - z$) has also been described in a previous paper[3].

Figure 5 depicts the relationship between the inner friction resistance per unit area, $q_{in\text{-}open}$ or $q_{in\text{-}close}$, and the normalized penetration depth, *z/D*. In Figure 5, although the value of $q_{in\text{-}close}$ was relatively larger than that of $q_{in\text{-}open}$ at the beginning of the pile penetration. When the soil adhered area was large, $q_{in\text{-}open}$ tended to increase rapidly after the penetration depth was greater than $z/D = 0.5$. However, a significant difference in $q_{in\text{-}open}$ was observed between S0-50 and S50-100, where the soil adhered area was the same size. In S0-100, $q_{in\text{-}open}$ sharply increased up to the pile penetration depth of $z/D = 1.1$. From Figure 4, it was evident that the pile was plugged at this point. In the case of S0-100 $q_{in\text{-}open}$ was larger when the pile penetration depth ranged from 1.1 to 2.3. The $q_{in\text{-}open}$ of this case sharply decreased at the pile penetration depth of $z/D = 2.3$. At this point, the pile plug was destroyed and IFR^* was almost zero. In S50-100, the plugging occurs in a similar manner, $q_{in\text{-}open}$ sharply increases from $z/D = 0.8$ until $z/D = 1.2$, and once $q_{in\text{-}open}$ matches $q_{in\text{-}close}$, it remains approximately the same as $q_{in\text{-}close}$. In this pile penetration range, $z/D = 0.8 - 1.2$, plugging did not occur, as depicted in Figure 4. In addition, after *z/D* exceeds 1.7, plugging is formed and $q_{in\text{-}open}$ is relativity smaller to $q_{in\text{-}close}$. The difference in the relationship between the formation situation of plugging viewed from the behaviour of inner soil height and $q_{in\text{-}open}$ and $q_{in\text{-}close}$ is complex.

Comparing S0-20 and S0-50, the $q_{in\text{-}open}$ were almost the same until the pile penetration depth was $z/D = 1.5$. After $z/D = 1.5$, the $q_{in\text{-}open}$ of S0-50 was larger than that of S0-20, and both values were almost the same when the pile penetration depth z/D was close to 3.0. In these cases, the inner soil heights were almost the same for the full pile penetration depth. When the plugging effect was small, IFR^* was not an effective parameter for presenting the plugging situation. The authors considered that the effect of the change in friction angle in the inner pile along the pile axis was not even along the pile axis and was more effective in increasing the inner friction if the friction angle of the area near the pile toe increased. The value of $q_{\text{in-open}}/q_{\text{in-close}}$ also increases when h/D was nearly 1.8. Figure 5 does not show a sharp decrease in $q_{\text{in-open}}$ after the disintegration of the plugin S0-100.

Figure 6 shows the relationship between the ratio of inner soil resistance ($q_{\text{in-open}}/q_{\text{in-close}}$) and the normalized inner soil height (h/D), which is normalized by the outer diameter of the outer pile. For S0-100, where complete plugging occurred, and the $q_{\text{in-open}}/q_{\text{in-close}}$ value was the highest shortly after the point where the inner soil height (h/D) reached 1.0, that was, the point at which complete plugging occurred. Then, the value of $q_{\text{in-open}}/q_{\text{in-close}}$ sharply decreased as the inner soil height (h/D) increased when the plug was destroyed. A similar phenomenon occurred in the case of S50-100, which was the other case where plugging occurred. In this case, $q_{\text{in-open}}/q_{\text{in-close}}$ reached almost 1.0 when h/D was almost 1.3. At that h/D, plugging occurred. Thereafter, as h/D increased, a smaller change in the ratio occurred up to 1.8. h/D.

Figure 6 shows a sharp decrease relative to the increase in h/D immediately after the highest value is reached in the case of S0-100, but the resistance ratio was almost constant from h/D of 1.3 to 1.8 in the case of S50-100. The reason for this difference in the behaviour of $q_{\text{in-open}}/q_{\text{in-close}}$ between the cases that were both plugged in this manner was that S0-100 plugged perfectly, but S0-50 was incompletely plugged.

Figure 7 depicts the relationship between $q_{\text{in-open}}/q_{\text{in-close}}$ and IFR^*. Although there was variance in the relationship in each case, $q_{\text{in-open}}/q_{\text{in-close}}$ began to

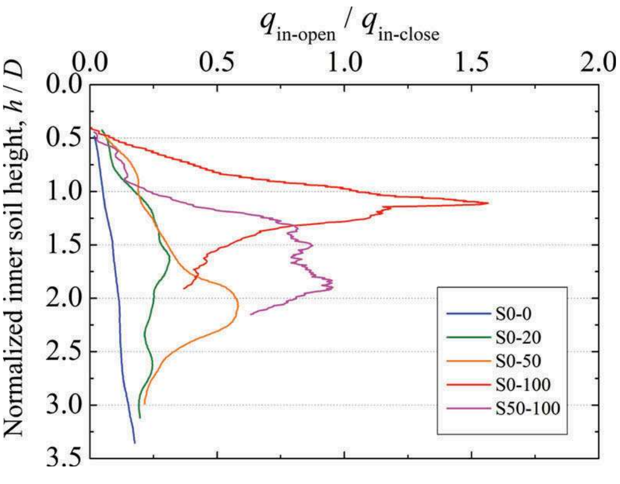

Figure 6. Relationship between $q_{\text{in-open}}/q_{\text{in-close}} - h/D$.

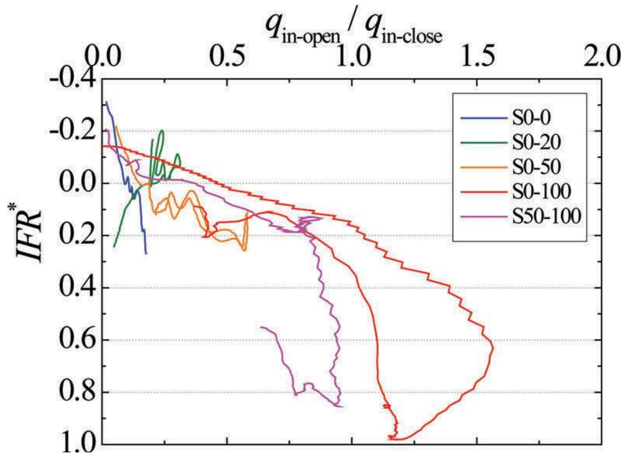

Figure 7. Relationship between $q_{\text{in-open}}/q_{\text{in-close}}$ and IFR^*.

increase after IFR^* reached approximately –0.1. The figure shows that until IFR^* reached 0.2, $q_{\text{in-open}}/q_{\text{in-close}}$ increased relative to IFR^* increase. IFR^* reached more than 0.2 in only two of the cases, S0-100 and S50-100. In these cases, $q_{\text{in-open}}/q_{\text{in-close}} > 0.9$ was maintained, although the values of $q_{\text{in-open}}/q_{\text{in-close}}$ varied. In the cases of S0-100 and S50-100, IFR^* decreased to some extent in the pile penetration depth. From these experimental results, the authors found that the values of $q_{\text{in-open}}/q_{\text{in-close}}$ were different whether IFR^* increased or decreased.

Even if the values of IFR^* were similar, the ratio of inner friction resistance was different; thus, further studies are required to estimate the ratio of the inner friction resistance circumference when IFR^* is above a certain value.

The relationship between the ratio of inner friction resistance and plugging at the pile toe was discussed. Therefore, the effect of the change in the range or position wherein the friction coefficient of the inner surface of the pile was changed on the IFR^* and the inner friction resistance must be considered.

Figure 8 depicts the relationship between IFR^* and the penetration depth when normalized by the outer diameter of the pile (z/D). In S0-0, S0-20, and S0-50, the results show that processing the end of the pile had most no effect on IFR^*. For example, S0-0, wherein no processing was performed, exhibited a higher value below $z/D = 1.0$ than that of S0-20, wherein processing was performed across an area extending 20 mm from the end. In S0-100, the case with the largest processed area, the IFR^* value increased sharply immediately after penetration, demonstrating the effect of processing. In S50-100, IFR^* began to increase sharply only after z/D exceeds 1.5, despite having a processed area of the same size as that of S0-50. From Figure 4, it can be observed that the inner soil height, h/D, was the same at $z/D = 1.5$, as it was previously, from which it can be presumed that the outcome was affected by processing an area that is at a distance from the pile end. Past research has indicated that the inner friction resistance of an

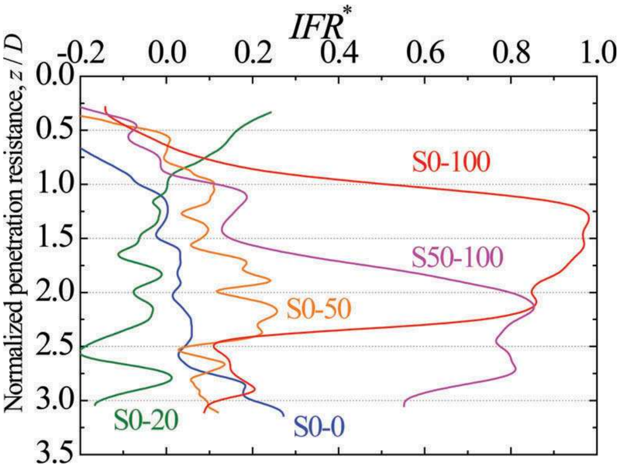

Figure 8. Relationship between IFR^* and z/D.

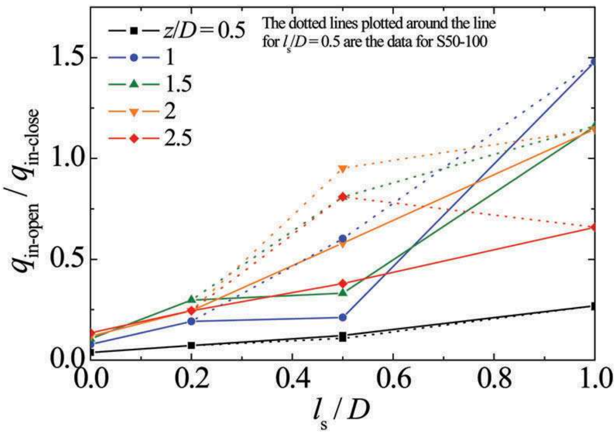

Figure 10. Relationship between l_s^*/D and $q_{\text{in-open}}/q_{\text{in-close}}$.

open-ended pile is noticeable near the pile end; thus, it can be presumed that it is important to change the friction coefficient at a distance from the pile end in some cases and the end in other cases for easy plugging.

Figure 9 depicts the relationship between l_s/D (the area of the inner surface of the pile that is processed, l_s, divided by the outer diameter of the pile, D) and h (the inner soil height when a specific penetration depth is reached). The dotted lines plotted around the line for $l_s/D = 0.5$ are the data for S50-100. From Figure 9, it can be observed that plugging was not facilitated until z/D reached 0.5 – 1.0, regardless of the processed area. There is no difference in the state between $l_s/D = 0.0$ and $l_s/D = 0.2$ after $z/D = 1.5$ but plugging occurs at the end. Note that when l_s/D = 0.5 for S0-50, the state remains the same as that at $l_s/D = 0.2$ until $z/D = 2.0$; however, a notable degree of plugging occurs at the same l_s/D value (i.e., l_s/D = 0.5) for S50-100.

Figure 10 depicts the relationship between l_s/D and the ratio of inner friction resistance, $q_{\text{in-open}}/q_{\text{in-close}}$. From Figure 10, the difference between $q_{\text{in-open}}/$

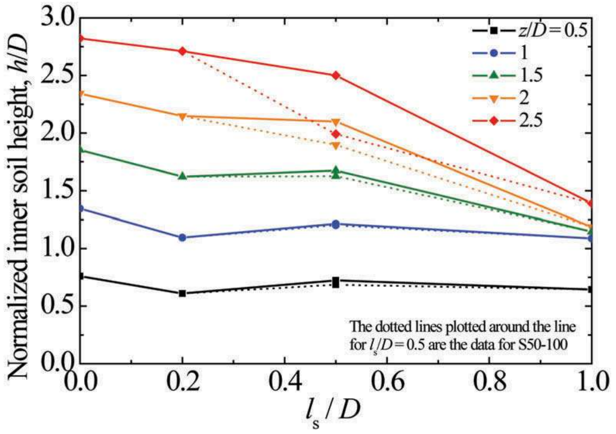

Figure 9. Relationship between l_s^*/D and h/D.

$q_{\text{in-close}}$ was small when the relative penetration depth was less than z/D = 0.5. However, as the relative penetration depth increased, *the* $q_{\text{in-open}}/q_{\text{in-close}}$ increased only in the case of l_s/D = 1. It can be observed that the $q_{\text{in-open}}/q_{\text{in-close}}$ values are larger for $l_s/D = 0.5$ in the case of S50-100, as depicted by the dotted line, in comparison with that in the case of S0-50 with the same $l_s/D = 0.5$. Thus, it can be presumed that increasing the coefficient of inner friction in the section of approximately 1D from the pile toe or 0.5D from the pile toe to 1D may affect the acceleration of plugging.

4 CONCLUSIONS

In this study, a penetration experiment was conducted using a double-pipe model pile to measure the inner friction resistance, $q_{\text{in-open}}$, and the resistance acting on the ring of the pile toe. The sand was applied to the inner surface of the double-pipe model pile to change the friction coefficient, and the relationship between the inner soil height and IFR^*, which represents the plugging effect, was verified. Furthermore, the effect of the area and position where the sand was applied on the plugging at the pile end was verified.

The relationship between the ratio of inner friction resistance, $q_{\text{in-open}}/q_{\text{in-close}}$, and IFR^* indicated that when the plug at the pile end disintegrated and IFR^* sharply decreased, $q_{\text{in-open}}/q_{\text{in-close}}$ was lower than that when IFR^* increased as a result of plugging. This may be the result of a historical effect occurring during an increase in IFR^*.

This study investigated the effect of changing the area and position where the friction coefficient was changed in the pile on the IFR^* and inner friction resistance. Based on the results, it can be presumed that no effect was achieved by only increasing the friction coefficient at approximately 0.5D from the pile end. To achieve effective plugging at the end, the friction coefficient should be increased near the pile end as well as across an area of at least

1.0*D* from the end. It was also found that processing the area from 0.5 to 1.0*D* from the pile end facilitates plugging more effectively than processing the area from 0 to 0.5*D*.

Future research is necessary to determine whether the same phenomenon occurs during plug reformation. Furthermore, it would be useful to quantify indices, such as the friction coefficient in the pile, inner friction resistance, and IFR^*.

There were many differences in the actual field and this kind of small-scale experiment. For example, the pile diameter to pile wall thickness ratio D/t used in the experiment was quite large compared to the actual field. The ratio of pile diameter to soil particle must be an important parameter, but the authors did not discuss this point. The stress level was significantly different between the field and this experiment. Furthermore, the maximum penetration depth was only approximately 3*D*; thus, it is not established whether a plug forms again after the initial plug disintegrates.

According to these limitations in laboratory experiments, the conclusions extracted from this research cannot be applied directly to the field. However, the conclusions might provide useful information for planning larger-scale model experiments or field experiments. The authors believe that this research provides useful information to readers preparing further research.

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