Evaluation of the vertical bearing capacity of steel pipe piles driven by the vibratory hammer method with water and cement milk jetting

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ABSTRACT

The RS method is a new pile driving method that is well suited to the construction of foundations in port areas. In such areas, oftentimes an impact hammer cannot be used because the noise and ground vibration caused by the hammer are problematic for neighboring industrial plants and residential areas. However, the bearing capacity of piles driven by vibratory pile driving with water jetting or cement milk jetting is uncertain, although these methods can decrease the noise and ground vibration compared to the impact hammer. The RS method drives the pile using a vibratory hammer with water jetting and forms a soil cement block on the tip with cement milk jetting. In this paper, we show the bearing performance by analyzing the axial loading for 600 ~ 1300mm diameter piles driven by the RS method. It was found that the bearing capacity of the test piles was determined by the soil resistance, and the strength of the soil cement block, which was estimated by an unconfined compression test, is much higher. This result indicates that the soil cement block is well-constructed, and if a pile is driven into soil that is harder than the soil used in the test, it is possible the pile will even have higher bearing capacity. Furthermore, the feature of the resistance mechanism of piles driven by the RS method is believed to be the high shaft resistance in the soil cement block.

Keywords: steel pipe pile, static axial bearing capacity, vibratory pile driving with water jetting, soil cement block instruction

1. INTRODUCTION

With the existing pile driving methods used to construct the foundation in port and harbour areas, it is difficult to obtain high bearing capacity with low noise and ground vibration. The impact hammer, which is the most popular method, has the disadvantage that its produces high noise and ground vibration. Therefore, it is difficult to apply this method near industrial plants and residential areas. To solve this problem, the water jetting vibratory hammer method, or ‘JV method’, has been adopted. However, the bearing capacity of piles driven by the JV method tends to be lower than that of piles driven by an impact hammer because the water jetting decreases the soil strength. On the other hand, the cement milk jetting vibratory hammer method, or ‘CJV method’, can reinforce the shaft resistance by cementing the soil around the pile. In a foundation, the pile tip resistance of a pile driven by the CJV method is as low as that of pile driven by the JV method, whereas the shaft resistance with the CJV method is reported to be about six times higher than the JV method (Uezono et al., 2002).

The RS method, a new pile driving method, has the potential to achieve high bearing capacity with low noise and ground vibration. This method can reduce the noise and ground vibration through the use of a driving procedure that is similar to the JV method, and high bearing capacity can be obtained through the construction of a soil cement block on the pile tip and shaft with cement milk jetting (Kikuchi et al., 2007). In this paper, we provide an outline of this method, as well as observations on and an evaluation of the vertical bearing capacity of piles driven by this method.

2. OUTLINE OF THIS METHOD

The procedure for the RS method is shown in Figure 1. First, a pile is driven by a vibratory hammer with water jetting, which is the same as in the JV method. When the pile reaches the target depth of about three times the outer diameter of the steel pile from the top of the bearing stratum, the water jetting is switched to cement milk jetting. The vibratory hammer then
continues vibrating and moves up to about the top of the bearing stratum. After that, the pile is driven down about twice the outer diameter of the steel pile by the vibratory hammer along with cement milk jetting. In this procedure, cement milk is mixed with the soil to construct a soil cement block on the pile tip. If the pile needs high shaft resistance, this method can be used to fill in cement milk around the pile by raising the cement jetting pipes from the pile tip to the ground surface. With this procedure, piles can be driven with low noise and ground vibration.

There are two types of the pile tip specifications. ‘Type-A’ has a jet nozzles and rib plates that are set around the outer side on the pile tip, as shown in Figure 2(a). These outer rib plates increase the diameter of the soil cement block, as shown in Figure 3(a). The other ‘Type-B’ is shown in Figure 2(b). Type-B has a rib plate to divide the pile cross section, and the jet nozzles are set around the outer side of the pile and on the inner rib plate. Type-B is recommended for large piles with a diameter of over 1000mm because the water jetting on the inner rib plate can excavate the central area of the pile and the cement jetting on the rib plate can make a soil cement plug inside of the steel pile, which is difficult to achieve by jetting around the outer side of the pile.

It is important to make high strength soil cement and create a soil cement plug in order to achieve high bearing capacity. The authors made a test boring inside of 600mm and 800mm diameter Type-A piles and 1300mm and 1600mm diameter Type-B piles and confirmed that a soil cement plug was formed (Kikuchi et al., 2007, Morikawa et al., 2014). Also, both the Type-A and Type-B piles have slip keepers inside the pile tip that can resist the push-out force when the piles are loaded vertically.

3 THE AXIAL LOADING TEST

3.1 Test method

Static axial compression load tests were performed in accordance with The Japanese Geotechnical Society’s manual (2002) on piles driven by the RS method. Table 1 shows the test conditions. The range of the pile diameters in the test was 600 – 1300mm. The test piles in Cases 1 – 3 (Kikuchi et al., 2007) were Type-A, which has outer rib plates on the pile tip, while the test pile in Case 4 (Mizutani et al., 2014) was Type-B because of the large 1300mm pile diameter. Also, the test pile in Case A (Takahashi et al., 2000) was driven by an impact hammer.

It is possible to compare the bearing capacity of Cases 1, 2, 4 and A as the piles were driven on the same ground conditions and were driven on neighboring sites. As a representative of these cases, the profile of the ground condition for Case 4 is shown in Figure 4. In this case, the bearing stratum begins at G.L.-13.4m, has an SPT-N value of over 50, and a bearing stratum of fine sand. The geological condition of Case 3 is different from the other cases in that the bearing stratum is made up of sandy gravel.

The bearing capacity is determined by the relationship between the load and pile displacement. In the tests, the axial force and pile displacement at each depth was calculated from the value measured by the strain gauges attached to each pile section.

| Case | Case 1 | Case 2 | Case 3 | Case 4 | Case A |
|------|--------|--------|--------|--------|--------|
| Dp  (mm) | 600 | 800 | 1000 | 1300 | 800 |
| Pile tip | Type-A | Type-A | Type-A | Type-B | - |
| Driving method | RS method | RS method | RS method | RS method | Impact hammer |
| Bearing stratum | Fine sand N≥50 | Fine sand N≥50 | Sand gravel N≥50 | Fine sand N≥50 | Fine sand N≥50 |
| Pile edge depth | G.L.-18.0m | G.L.-18.0m | G.L.-19.0m | G.L.-16.0m | G.L.-15.2m |

Dp: Diameter of the steel pipe pile
### 3.2 Test results

The difference in bearing capacity is shown in Figure 5, which shows the relationship between the jacking load and pile head displacement. The jacking load and initial gradient in Cases 1–4 are higher than that in Case A. The main results of this test are shown in Table 2. The technical terms concerning bearing capacity are defined as follows. The end resistance in Cases 1–4 is the axial force on the steel pile cross section at a point twice the pile diameter up from the steel pile edge face as shown in Figure 4, and the end resistance in Case A is the axial force on the steel pile cross section at a point five times the pile diameter up from the steel pile edge face. The pile tip is the same position as this cross section. The shaft resistance is the value calculated by subtracting the end resistance from the jacking load. The second limit resistance is the resistance at which the pile tip reaches 10% of the steel pile diameter. In this paper, the bearing capacity is defined as the second limit resistance of the pile end.

The end resistance of a pile per unit area is the value calculated by dividing the second limit resistance by the pile area. In Cases 1–3, the pile area has two meanings. One is the cross section of the soil cement block, and the other is the closed section of the steel pipe. The outer rib plate in Type-A can increase the diameter of the soil cement block, and its cross section is assumed to be about twice that of the closed section of the steel pipe. In the Cases 4 and A, the pile area means the closed section of the steel pipe. Also, Case 3 finished when the pile tip was about 4% of the steel pile diameter because the reaction force was larger than estimated and the pulling resistance of the reaction piles reached the limit.

To evaluate the shaft resistance, we calculated the maximum average strength of the skin friction per unit of area, which is the difference of the adjacent axial forces. Figures 6 and 7 show the relationship between the average strength of the skin friction per unit of area and the average N value of each section. In these figures, the design line of the pile driven by the impact hammer (Japan Road Association, 2012) is shown because it was not possible to distinguish the test value of that from the Takahashi et al (2000). Also, the design line of a cast-in-place concrete pile (Japan Road Association, 2012) is included as a reference. From this figure, it is obvious that the skin friction per unit of area in the RS-method is substantially larger than that of design line of the impact hammer pile, and it is comparable to or higher than the design line of the cast-in-place pile. This result suggests that the shaft area of the pile driven by the RS method is filled with soil cement, and the adhesion between the pile and the soil is sufficiently strong.

To analyze the end resistance, it was necessary to consider the differences in the pile area, expansion effect of the outer rib plate, and failure mode. The next section contains a discussion about the failure mode, bearing mechanism, and differences between the RS method and impact hammer.

![Fig. 4. Soil conditions and pile setting](image_url)

![Fig. 5. Jacking load and pile head displacement](image_url)

| Case | Case 1 | Case 2 | Case 3 | Case 4 | Case A |
|------|--------|--------|--------|--------|--------|
| $Q_t$ pile top [kN] | 15,000 | 13,124 | 22,000 | 19,500 | 4,500 |
| End resist. [kN] | 6,199 (0.1Ds) | 8,767 (0.1Ds) | 13,306 (0.04Ds) | 10,992 (0.1Ds) | 3,700 (0.1Ds) |
| $q_t$ [kN/m²] | 21,924 | 17,441 | 16,950 | 8,281 | 7,361 |
| $q_e$ [MPa] | 19.1 | No data | 16.6 | 16.6 | - |
| $q_s$ | 37.3 | ~ | 19.0 | 38.5 | - |

$D_s$: Diameter of the steel pipe pile  
$q_t$: Second limit resistance  
$q_e$: Second limit resistance per unit of area  
$q_s$: Unconfined compression strength
4 DISCUSSION ABOUT THE END BEARING CAPACITY

4.1 Estimation of the failure mode
Two failure modes have been assumed for the pipe end during the load test. One is that the soil cement block breaks, and the other is that the soil resistance under the soil cement block reaches its yield stress before the soil cement block itself breaks.

One way to estimate the failure mode is comparing the second limit resistance per unit area with the strength of the soil cement block. We conducted boring tests into the soil cement block and performed an unconfined compression test of the boring cores. The results shown in Table 2 are the maximum and minimum values from a number of tests. As can be seen in these results, the unconfined compression strength of the boring core, \( q_c \), is higher than second limit resistance per unit area. Therefore, the failure mode of the loading test is considered to be when the soil resistance reaches the yield stress before the soil cement block breaks. In other words, a pile driven by the RS method in soil conditions that are as hard as the soil cement block may be able to obtain higher end bearing capacity than test results show in this paper.

4.2 Estimation of the bearing mechanism
To consider the differences in the pile diameter with and without the expansion diameter effect of the outer rib plates, Figure 8 shows the normalized relationship between the end resistance and pile end displacement. The horizontal axis is the end resistance, \( R_t \), normalized by the second limit resistance of the pile end, \( Q_s \), and the pile end displacement, \( L \), normalized by the pile diameter, \( D \). In Cases 1 and 2, the pile diameter means the diameter of soil cement block, which has been widened by the outer rib plate. Because the expanded area of the soil cement block is estimated to be about twice the closed area of steel pipe, the diameter of the soil cement block is assumed 1.4 times the steel pile diameter. In Cases 4 and A, the pile diameter is assumed to be equal to the steel pile diameter.

The difference of the bearing mechanism between RS method and impact hammer causes the differences seen in the lines graphed Figure 8. When the normalized end resistance is small, the normalized pile end displacement in Cases 4 (RS method) is smaller than that of Case A (impact hammer). After the line in Case 4 reaches the yield point, the normalized pile end displacement increases rapidly. The reason for this is considered to be the influence of the skin friction around the soil cement block. As shown in Figure 6, the skin friction of the piles driven by the RS method is much higher than that of the impact hammer. As a result, when the skin friction around soil cement block increases, the normalized pile end displacement remains small. After the skin friction reaches the maximum value, only the bottom resistance of the soil cement block continues to maintain resistance. However, the bottom resistance depends on the soil resistance, so as the soil resistance approaches the yield stress, the normalized pile end displacement increases rapidly.

When comparing Cases 1, 2, and 4, Case 4’s gradient after the yield point is slightly sharper than other cases. The reason for this is considered to be that the ratio of the skin friction area to the bottom resistance area in Case 4 is higher than that of other cases, as shown in Table 3. The expanded bottom area of the soil cement block in Cases 1 and 2 is thought to result in higher bottom resistance than Case 4 and the normalized pile end displacement is increases at a slower pace.
In the case of the impact hammer (Case A), the normalized pile end displacement after the yield point increases as a slower pace than that of the RS method (Cases 1, 2 and 4) because a plug in the pile end develops as the pile end displacement increases. Incidentally, the plug resistance depends on the pile diameter (The Overseas Coastal Area Development Institute of Japan, 2009). If the pile diameter in Case A of 1300mm is the same as Case 4, it will become difficult to develop the plug resistance and the normalized end resistance will reach the 1.0 upper limit more rapidly. Therefore, the bearing capacity of the RS method has the potential to be higher than that of the impact hammer when comparing the same pile diameters.

5 CONCLUSIONS

This paper introduces a new pile driving method (RS method) that has the potential to provide suitable performance in port areas, and the bearing capacity and its mechanism were evaluated through the performance of axial loading tests.

As a result of the tests, the shaft resistance of the pile driven by the RS method was superior to that of the pile driven by an impact hammer and comparable to or higher than that of the design line of a cast-in-place pile. The high shaft resistance implies that the soil cement around pile shaft is well-constructed and the adherence between the pile and soil is therefore.

The possible failure modes are either the limit of the soil resistance or a break in the soil cement block. By researching the strength of the soil cement block, it was possible to assume which failure mode will occur.

A feature of the end bearing mechanism of the RS method is considered to be the high skin friction of the soil cement block. When the axial load is comparability small, the skin friction prevents pile end displacement. After the skin friction reaches its limit, the pile end displacement is comparability large because only the bottom of the soil cement block resists the load. In contrast to this, a plugging pile driven by an impact hammer develops along with the pile end displacement and restricts the increase in pile end displacement.

From the observations and evaluations in this paper, it is shown that piles driven by the RS method have potentially higher bearing capacity than those driven by an impact hammer. However, the influence of pile diameter, load transfer mechanism from the steel pipe to soil cement block and characteristic features of the different soil conditions still need to be studied.

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