# Soil resistance of steel pipe piles during vibratory hammer installation

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## ABSTRACT

In this paper, we attempted to evaluate the soil resistance during the installation and the bearing capacity after curing time of the steel pipe piles by vibratory hammer installation. Four steel pipe piles with diameter of 114.3mm and length of 11m were constructed for the test. Three piles were installed by a vibratory hammer with different penetration rates. One pile was installed by a drop hammer. Dynamic measurement with axial pile head strain and acceleration were performed during installation. As the calculation method of the soil resistance for vibratory hammer installation, we adopted two methods, the single-mass model analysis method and the CASE method (Rausche et al., 1985) based on the one-dimensional wave theory. We attempted to separate the soil resistance into the shaft and the toe from the shape of the soil resistance – displacement curve. Static load tests were performed on all test piles with curing time of 1 day, 28 days and 180 days after installation.

**Keywords:** Steel pipe pile, Vibratory hammer, Single mass model, CASE method, Soil resistance

## 1 INTRODUCTION

The vibratory hammer installation is the pile construction method that is widely used because it has low soil resistance during installation and is easy to control accuracy of positioning. However, recently, in Japan, the design formula for piles installed by vibratory hammer has disappeared in the design standards, because the bearing capacity of piles installed by vibratory hammer is lower than that of piles driven by impact hammer. In this paper, we attempted to evaluate the soil resistance during the installation and bearing capacity after curing time of the pile by vibratory hammer installation.

## 2 SOIL RESISTANCE OF VIBRATORY HAMMER INSTALLATION

A pile constructed with a vibratory hammer penetrates the ground while repeating a cycle of vibrating up and down. Figure 1 shows the soil resistance that the pile receives during one vibration cycle.

① The cycle starts with the point when the pile is pulled up as zero. First, the pile penetrates the ground through which the pile passed in the previous cycle. The soil resistance at this time is the upward shaft resistance of the ground disturbed by the construction.

② Next, the pile toe penetrates into the deep ground that was not reached in the previous cycle. In addition to the shaft resistance, the soil resistance at this time is the toe resistance of the undisturbed ground.

③ The pile is then pulled up after reaching the maximum depth of this cycle, ending the cycle. The soil resistance at this time is the downward shaft resistance.

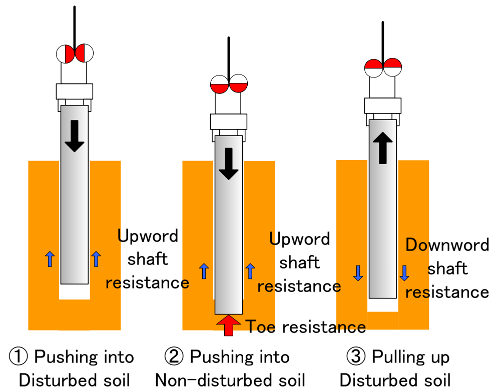


Fig. 1. Vibratory hammer cycle.

Figure 2 shows the time history of the acceleration, velocity, displacement and soil resistance of a pile in one typical cycle. Figure 3 shows the soil resistance - displacement relationship in one typical vibratory cycle. If the curve shown in Figure 3 is obtained by dynamic measurement, the soil resistance during vibratory installation can be grasped. By reading the values in stages ①, ②, and ③ from the curve, the soil resistance during installation can be evaluated separately for the shaft and the toe.

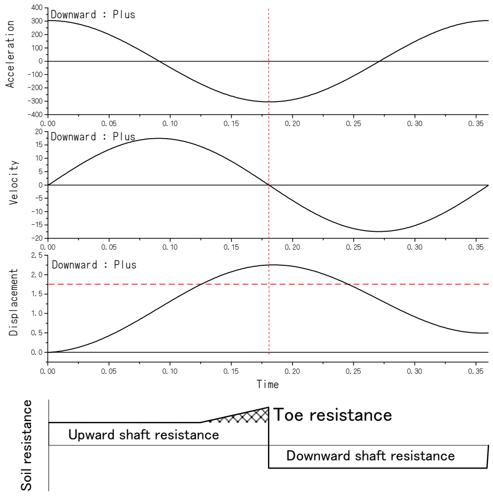


Fig. 2. Time history of Vibratory hammer cycle.

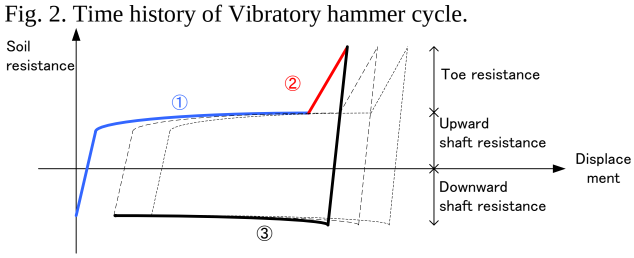


Fig. 3. Soil resistance vs. displacement relationship.

## 3 CALCULATION METHOD FOR SOIL RESISTANCE OF DYNAMIC MEASUREMENT

As the calculation method of the soil resistance, we adopted two methods, the single-mass model method and the CASE method based on the one-dimensional wave theory.

(1) Single-mass model method

The soil resistance is calculated by considering the pile body as a single mass point and subtracting the inertial force of the pile body from the axial force.

$$R_{soil}(t) = F_v(t) - m \cdot \alpha(t) \quad (1)$$

R_soil (t): Soil resistance, Fv (t): Axial force,
m: Pile mass, α (t): Acceleration

(2) CASE method

CASE method has developed as a resistance evaluation method for impact hammer installation. The sum of the downward input wave before the half round trip (L / c) of the target time and the upward reflected wave after L/c at the pile head is obtained as the soil resistance.

$$R_{soil}(t) = F_d(t - L/c) + F_u(t + L/c) \quad (2)$$

Fd (t - L / c): downward input wave before the half round trip (L / c)

Fu (t + L / c): upward reflected wave after the half round trip (L / c)

Rausche(2002) described that CASE method can be applied to vibratory installation. He described that single mass model method is homogeneous in a way that ignores the wave propagation time of CASE method. CASE method is more suitable for handling elastic pile bodies. However, single mass model method has the advantage that it can be applied to data with a low measurement frequency.

## 4 SITE TEST

### 4.1 Pile Installation test

Four steel pipe piles with a diameter of 101mm and a length of 11m were constructed for the test. Figure 4 shows the soil profile and N value of the test ground with a test pile. The upper soil layer was cohesive soil and lower soil layer was sandy soil. Strain gages were instrumented to separate the bearing capacity into the upper shaft, lower shaft and the toe for static load test. The test piles were installed to the depth of 10.1m. Three piles were installed by a vibratory hammer with different penetration rates, VS, VM, VL pile. One pile was installed by a drop hammer, D pile. The reason for changing the penetration rate is that the difference in the amount of vibration applied to the soil around the pile affects the soil resistance during installation and bearing capacity after curing time. In this paper, VM pile is excluded from the comparison. Because VM pile had a sharp increase in soil resistance at a depth of about 9m. This clearly behaves differently from the other two vibratory piles.

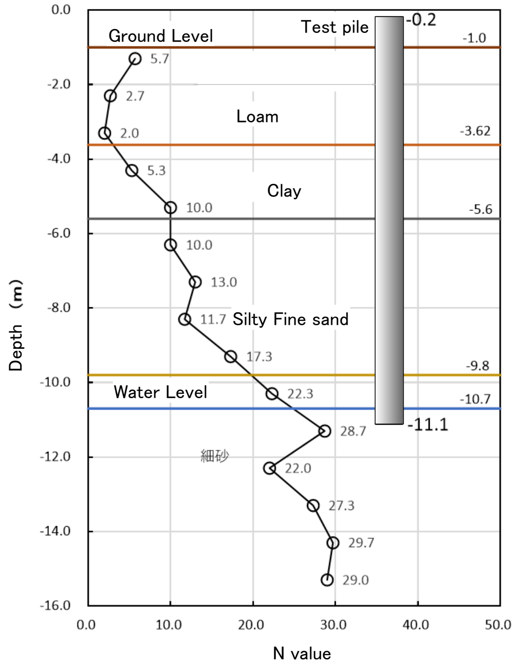


Fig. 4. Soil profile of the test site.

Table 1. Test pile specification.

| Test pile | Size | Hammer | Installation time |
|---|---|---|---|
| VS | Diameter: 114.3mm | Vibratory | Short |
| VM | Thickness:6mm | | Medium |
| VL | Length:10.9m | | Long |
| D | Embedded:10.1m | Drop | |

Table 2. Installation time.

| Test pile | Time (sec) | Rate (m/s) |
|---|---|---|
| VS | 1072 | 9.4 |
| VM | 2767 | 3.7 |
| VL | 3464 | 2.9 |

Dynamic measurement with axial pile head strain and acceleration were performed during installation. Figure 5 shows a time history curve of acceleration, velocity, displacement and axal force at a depth of 10.1 m of VS pile as an example of dynamic measurement results. Velocity and displacement are integral values of acceleration. The frequency of the vibratory hammer was 18.6 Hz. The round number of the wave propagation to the 10.1m length pile is 7.6. This calculated the compression and tension behaviors as one cycle each. Figure 6 shows the results of calculating the soil resistance by the above two methods, single mass model method and CASE method. It can be seen that when the two are overlapped, they almost match.

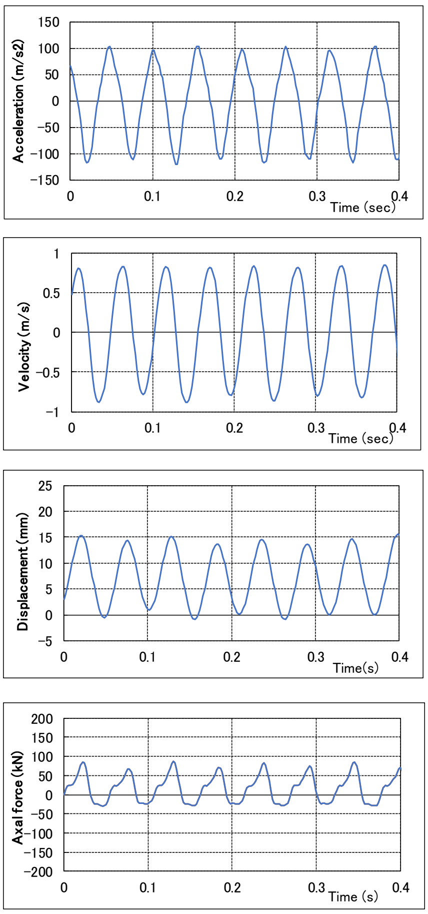


Fig. 5. Time history curves of dynamic measurement.

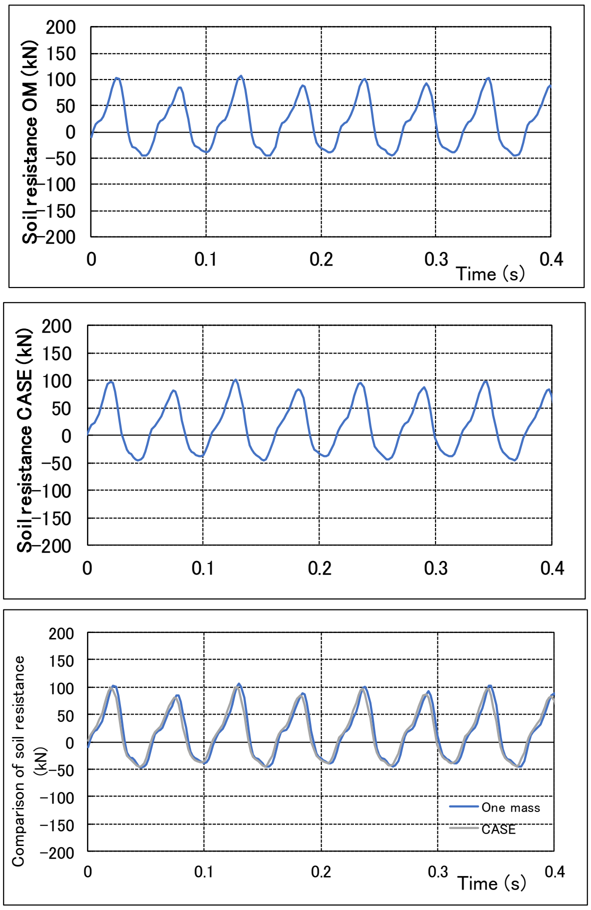


Fig. 6. Comparison of time history curves of soil resistance.

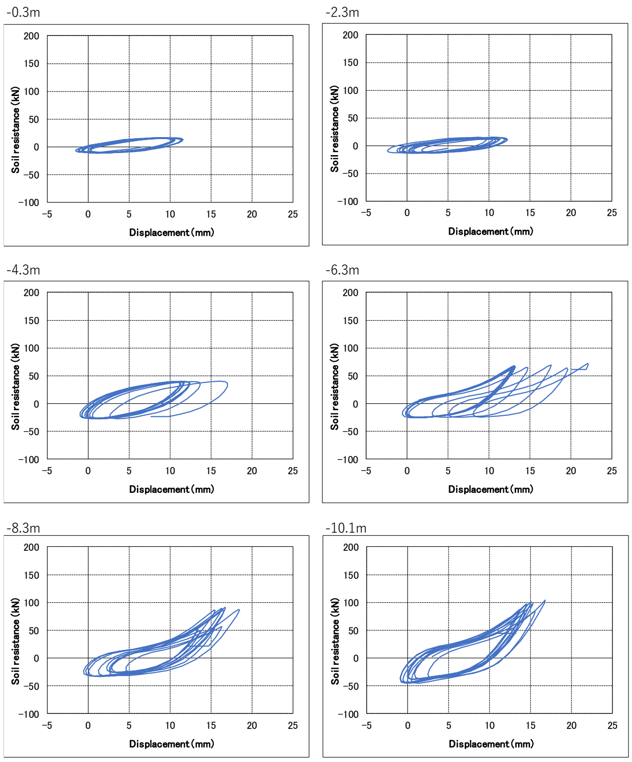


Fig. 7. Soil resistance – displacement relationship curve.

Figure 7 shows the soil resistance - displacement curves for each 2 m depth of VS pile resulted from CASE method. According to them, it has a flat elliptical shape at a shallow depth, and it can be seen that there is only small shaft resistance. It is shown that the thickness of the ellipse increases and the shaft resistance increases as the depth increases. When the pile tip reaches the hard layer, a protrusion like a horn appears on the curve. This horn is the tip resistance.

Figure 8 shows the soil resistance - displacement curve at a depth of 10.1 m of VS. We can read from this figure that the soil resistance is 100 kN, of which the shaft is 20 kN and the toe is 80kN. Furthermore, the soil resistance at the maximum displacement can be read as a static resistance.

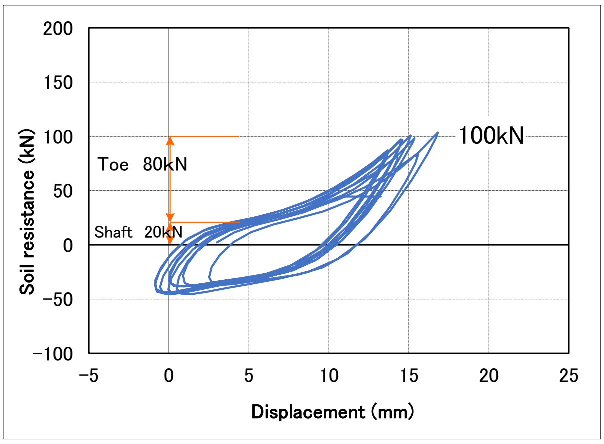


Fig. 8. Separating soil resistance into shaft and toe.

Figures 9 and 10 show the distribution of the soil resistance separated into shaft and toe of the vibratory test piles obtained by the above method in the depth direction. The calculated soil resistance curve trends were in good agreement with the N values in the ground survey results.

Figure 11 shows the distribution in the depth direction of the soil resistance of vibratory test piles plus D pile of which the soil resistance was calculated by normal CASE method without damping reduction.

Looking at Figure 11, it can be seen that the slower the penetration rate, the lower the resistance. Also, the soil resistance of D pile is larger than that of vibratory. When the static resistance by CAPWAP analysis of D pile with a depth of 10.1 m is plotted, the static resistance is larger than that of the VS pile. It can be inferred that this result is due to the fact that the drop hammer pile has less soil turbulence than the vibratory hammer.

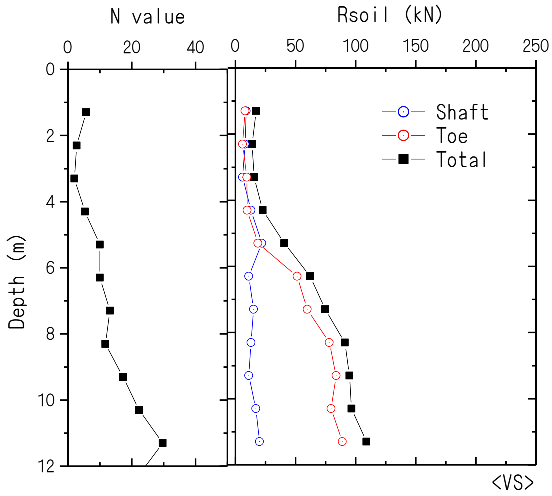


Fig. 9. Distribution of the soil resistance, shaft and toe(VS).

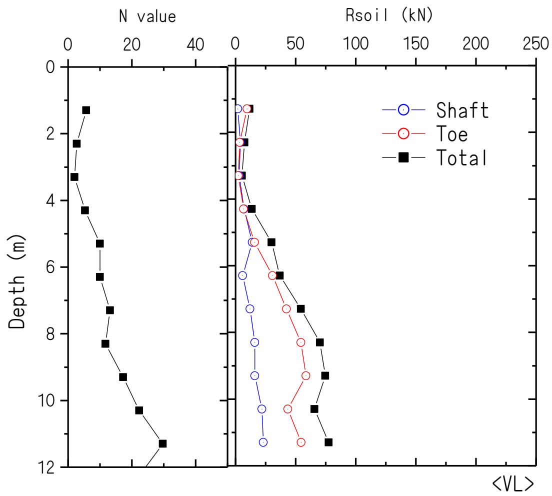


Fig. 10. Distribution of the soil resistance, shaft and toe(VL).

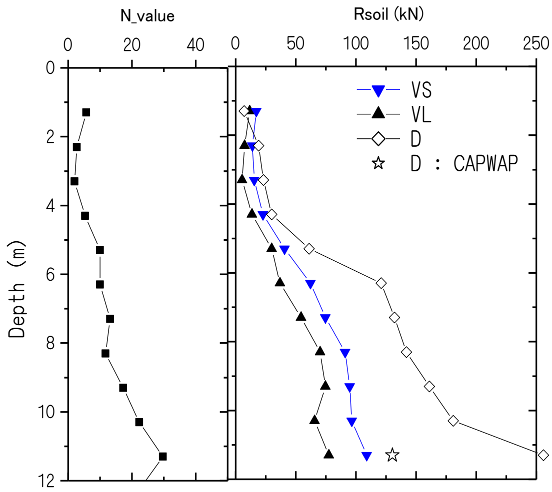


Fig. 11. Comparison of distribution of the soil resistance.

## 4.2 Static load test

Static load tests were carried out to evaluate the bearing capacity. The load test was conducted on the same test pile 1 day, 28 days and 180 days after installation. Figure 11 shows the load - displacement relationship curve of the pile head in the load test after 1 day. A section with low rigidity can be seen at the beginning of the curve of both of the vibratory piles. This is thought to be due to the loosening of the toe ground due to vertical movement of vibratory hammer. The test piles this time have a diameter of 114 mm and a length of 10.9 m, which is smaller than general piles. It is highly possible that the small diameter and light weight of the pile emphasized the looseness of the ground at the pile toe.

Figure 12 shows the curves of the load tests after 28 days. Since the same pile is tested, the effect of loosening of the toe ground are not seen.

The bearing capacity after 28 days was 168 kN for the D pile. VS pile was 83% of D pile and VL pile was 75%. The larger the amount of vibration, the lower the bearing capacity tends to be. The bearing capacity is the load when the amount of settlement at the pile toe reaches 10% of the pile diameter.

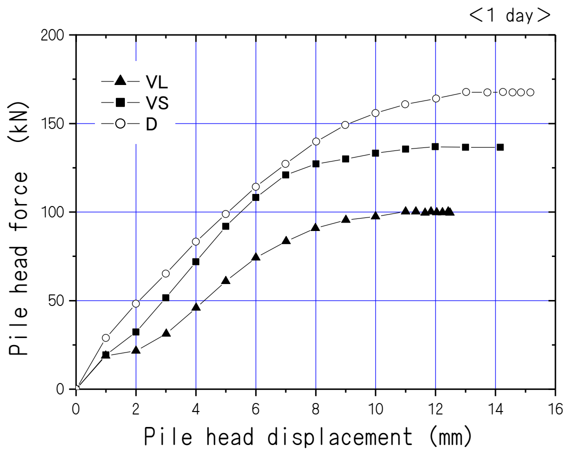


Fig. 11. Load – Displacement curves 1 day after installation.

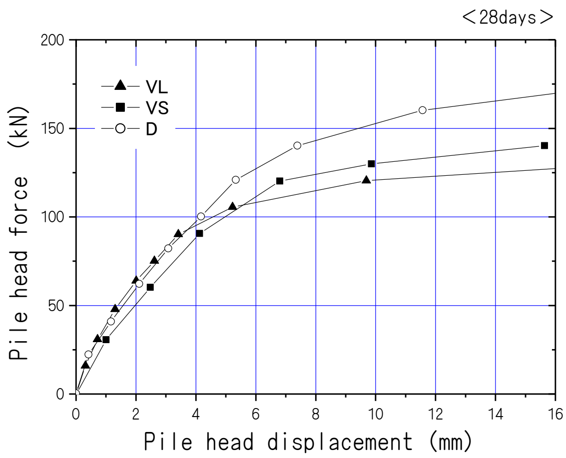


Fig. 12. Load – Displacement curves 28 days after installation.

Figure 13 shows the change in bearing capacity over time. According to it, there is no significant change in the bearing capacity of D pile and VS pile from 1 day to 180 days. However, the VL pile gradually increased over time and became equivalent to the VS pile after 180 days. The soil surround pile that was greatly disturbed by the vibratory installation may be recovered over time.

Figure 14 shows the change in shaft resistance of the sand layer at depth of 5.7m to 10.7m. According to it, the shaft resistance of the sand layer is larger in VL and VS than in D. In addition, the rate of increase after the curing period was higher for the piles installed by vibratory hammer. Photo 1 shows the test piles dug out after the tests. According to it, sandy soil adheres firmly to the surface of VL pile, while no soil adheres to D pile installed by the drop hammer. It is estimated that the sandy soil around the pile was compacted by the vibration of the vibratory hammer.

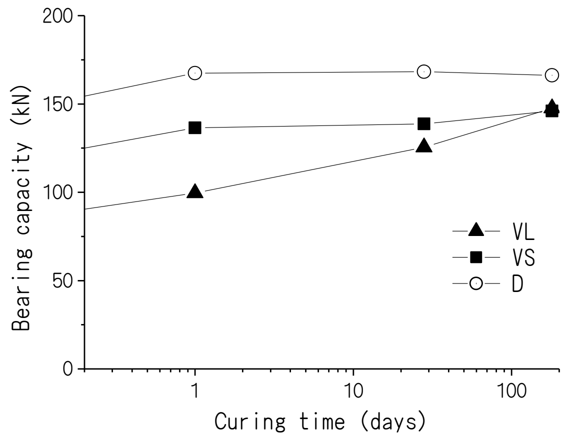


Fig. 13. Change in bearing capacity over time.

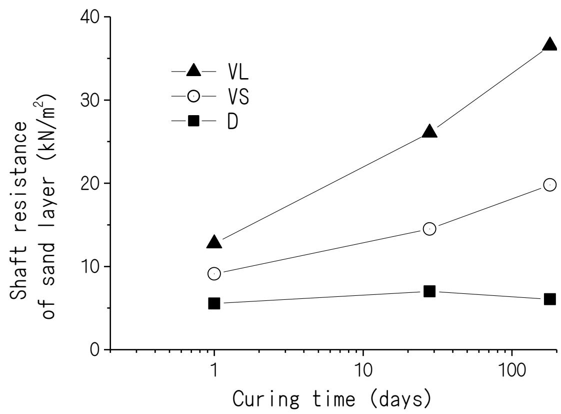


Fig. 14. Change in Shaft resistance of sand layer over time.

VL pile

D pile

Photo. 1. The surface of the test piles after loading tests.

## 5 CONCLUSIONS

The conclusion is as follows.
- Soil resistance during installation by vibratory hammer can be obtained by CASE method and Single mass model method using the data of dynamic measurement.
- By drawing a soil resistance-displacement curve, soil resistance can be evaluated separately for the shaft and the toe.
- The bearing capacity of piles with vibratory installation was 80% of that of piles with a drop hammer.
- The bearing capacity of the pile that was given a large vibration was low immediately after installation, but it became the same as that of a pile that was given a small vibration six months later.
- In this test, it is presumed that the sandy soil around the test pile was compacted by the vibration of the vibratory hammer and the shaft resistance increased.

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