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EVALUATION OF VERTICAL BEARING CHARACTERISTICS FOR SOIL-CEMENT COMPOSITE PILES

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ABSTRACT: There are several pile construction methods with relatively small construction machinery that are suitable for construction in narrow urban spaces and areas with low overhead clearance. The Top-drive Boring Hole (TBH) method, which has a machine height of 4.5m, is often used. The Boring Hole (BH) pile method can handle narrow spaces and low overhead clearances better than the TBH method. However, because the BH pile method is a direct circulation method, mud cakes easily form on the hole walls, and slime tends to accumulate at the pile tip. Such challenges related to the construction method, bearing capacity and settlement need to be resolved for pile construction in narrow urban spaces. Pile construction in narrow urban spaces and for existing structures to strengthen the seismic resistance is subjected to constraints on the construction site and process. Therefore, a method for soil-cement composite pile construction was developed that uses a compact mechanical agitator for pile foundations of lightweight structures. In this study, static compression load tests on soil-cement composite piles that were constructed with the developed ground improvement construction method were carried out to evaluate the vertical bearing characteristics. Furthermore, it was evaluated the performance of vertical bearing characteristics on the soil-cement composite piles to compare the evaluation method as shown in the design specifications in Japan.

Keywords: Soil-cement composite pile, Compression load test, Bearing capacity, Evaluation method

1. INTRODUCTION

There are several pile construction methods with relatively small construction machinery that are suitable for construction in narrow urban spaces and areas with low overhead clearance. The Top-drive Boring Hole (TBH) method, which has a machine height of 4.5m, is often used. However, there are many cases where even these construction machines are interfered with by architectural limitations and existing structures. In particular, piles near railway tracks or on rail platforms are currently constructed after temporary construction is carried out to ensure construction space. The Boring Hole (BH) pile method can handle narrow spaces and low overhead clearances better than the TBH method. However, because the BH pile method is a direct circulation method, mud cakes easily form on the hole walls, and slime tends to accumulate at the pile tip. This lowers the bearing capacity of the piles, so subsidence is more likely to occur. Such challenges related to the construction method, bearing capacity and settlement need to be resolved for pile construction in narrow urban spaces.

Pile construction in narrow urban spaces and for existing structures to strengthen the seismic resistance is subjected to constraints on the construction site and process. Especially, this pile is subjected to the lack of bearing capacity due to the increase of superstructure weight by strengthening the superstructure. Furthermore, noise and industrial waste need to be considered with regard to their effects on the surrounding environment. Therefore, a method for soil-cement composite pile construction combined with soil cement ground improvement was developed that uses a compact mechanical agitator for pile foundations of lightweight structures. The construction machine is a mechanical agitator with an attached vibrating mechanism and improved drilling capacity. This

Fig. 1 Construction machine of soil-cement composite pile.

developed machine can be used to realize pile construction in narrow spaces where construction is usually difficult. This method is characterized by having no need to drill up to a fixed depth as in the pre boring pile construction method. Instead, soil is agitated along with the cement milk at the original position. This greatly reduces the spoil generated by pile construction. In this method, the drilling rod of the developed machine is sent down to the bearing stratum; after agitating and mixing, the pile is composed of segmental steel pipes that are connected with bolts on flanges.

Although the soil-cement composite piles are generally designed as temporary structures [1], the purpose of this study is to design the soil-cement composite piles as the permanent foundation structures. In this study, static compression load tests on the soil-cement composite pile (i.e. H section steel piles with soil-cement ground improvement) that were constructed with mechanical agitator ground improvement method were carried out to evaluate the vertical bearing capacity. Furthermore, it was evaluated the performance of vertical bearing capacity on the soil-cement composite pile to compare the evaluation method as shown in the design specifications in Japan.

2. SUMMARY OF SOIL-CEMENT COMPOSITE PILE CONSTRUCTION

In this construction method, strength of the soil cement is in the ranges of 1000～5000kN/m^2. The H section steel piles were used to be fabricated from JIS standard steel piles to ensure a low cost and certain level of quality. The typical construction process with this method is described as follows;

1) Excavate to the bearing stratum, carry out agitation and mixing, and lay the soil cement as the ground improvement structure. During this time, carry out drilling so that the rod will reach a predetermined depth.

2) Build H section steel pile joints in the ground improvement structure, which is in loose and poorly lithified soil.

3) After the pile construction is completed, fix the pile head before the soil-cement hardens.

The above construction can be carried out using only the developed construction machine shown in Fig. 1 The planar dimensions of the construction machine are extremely compact: a 1.55m width and 2.32m length. In addition, the construction machine is 3.0m tall, including the leader. Thus, construction is possible even with low overhead clearances. The machine has a vibration mechanism to improve the agitation and mixing capability. The results of construction test showed that even strong sandy stratum with an N value of about 40–50 can be agitated and mixed [2].

Fig. 2 Pile tip shape of soil-cement composite pile.

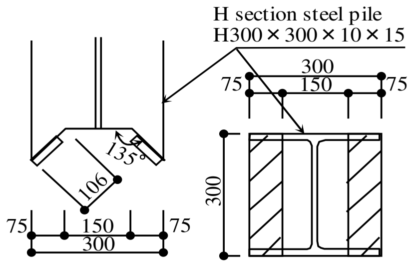


Fig. 3 Scale of soil-cement composite pile tip.

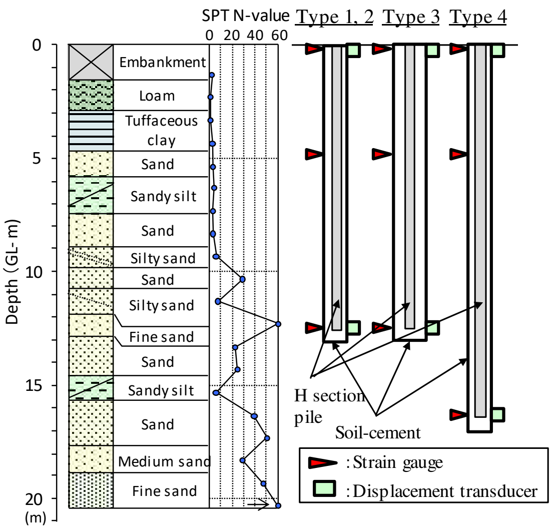


Fig. 4 Soil profile and test piles.

Table 1. Specifications of test piles.

	Pile diameter (mm)	Pile length (m)	Strength of soile-cement (kN/m^2)
Type 1	600	14.0	1000
Type 2	600	14.0	3000
Type 3	800	14.0	1000
Type 4	600	17.0	1000

In order to increase the end bearing capacity, two plates were attached to the tip of the H section steel pile. Fig. 2 and Fig. 3 shows the tip shape of the H section steel pile. As shown in Fig. 2 and Fig. 3, two plates were attached to the tip of the H section steel pile with an inclination of 135deg. from the horizontal direction.

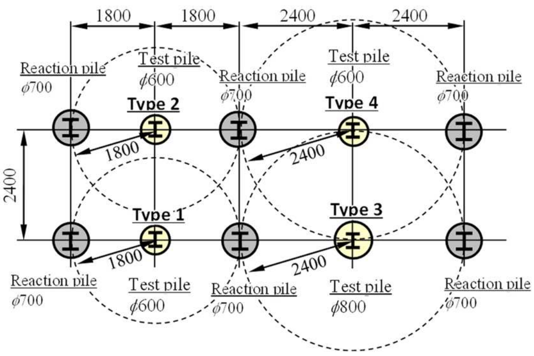


Fig. 5 Arrangement of test piles and reaction piles.

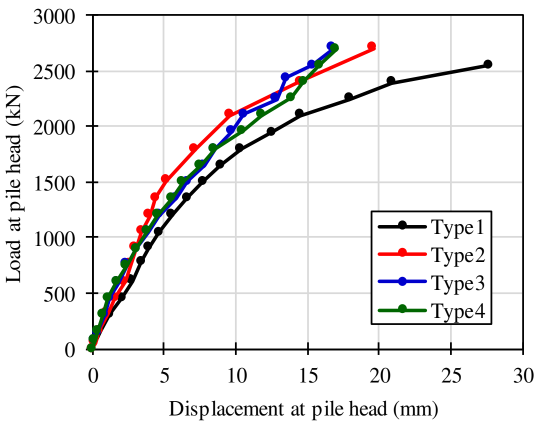


Fig. 6 Relationships between load and displacement at pile head.

3. IN-SITU FULL SCALE COMPRESSION LOAD TEST

The soil profile and test piles indicates in Fig. 4. The test ground was composed of loam and tuffaceous clay up to about GL −5.0 m and sandy silt and medium sand, fine sand below that. Four piles were constructed for the static load test with the soil cement diameter, pile length, and soil cement strength as parameters.

Table 1 presents the specifications of the test piles. The bearing stratum was adopted to be N=20 and 40 from the results of ground investigation; the test piles were embedded in the bearing stratum. The test piles were pre-drilling soil-cement column diameter of 600mm and 800mm, H section steel shape of H-300×300×10×15. The target strength of the pre-drilled soil cement as the improved ground structure was 1000kN/m^2 with the test pile of Type 1, 3, 4 and 3000kN/m^2 with the test pile of Type 2. In the core strength test carried out after the load test, the average strengths with the all of the test piles were over the target strength, respectively.

The arrangement of test piles and reaction piles presents in Fig. 5. Four test piles and six reaction piles were constructed. Similar to the test piles, six reaction piles were also constructed as the H section steel pile with soil cement by the same construction method as the test piles. The distance between the test piles and the reaction piles were set based on the influence range as described in the Japanese Geotechnical Society ("Methods for vertical load test of piles") [3], the distance are 3D=1800, 2400 (mm). Here, D means the pile diameter such as soil cement diameter.

The static load test was carried out based on the standards of the Japanese Geotechnical Society ("Methods for vertical load test of piles") [3]. A stepwise multi cycle loading system was employed with a new load holding period of 30min, hysteretic load holding duration of 2min, and zero load holding duration of 15min. The measured parameters were the pile head load, pile head and pile tip displacements, and strain of the H section steel. The pile tip displacement was measured with the pipe-in pipe method (i.e. double steel tube method). In order to evaluate the shaft friction of each stratums and the end bearing capacity, the strain were measured at the tip of pile, the boundary of each soil stratums and top of pile.

4. RESULTS OF IN-SITU FULL SCALE COMPRESSION LOAD TEST

Figure 6 shows the relationships between the load and displacement at the pile head. The maximum loads were 2500kN for Type 1 and 2700kN for Type 2~Type 4. For all of the piles, the curve was steep from the initial of loading; and all of the piles possessed a large initial stiffness. The gradient of the curve then changed with the loading and reached the maximum load. For the test piles of Type 2~Type 4, a larger N value for the bearing stratum, a larger pile diameter and a longer pile length meant a higher stiffness.

The axial force distribution of each test piles is plotted in Fig. 7. The axial force was calculated by considering only the H section steel. The strain of H section steel obtained from the load test was multiplied with the Young's modulus and the cross-sectional area of H section steel. It can be seen that the larger the load at pile head, the larger the axial force difference for each measure point. Therefore, this means that the shaft friction is mobilized along the pile shaft.

The relationships between the shaft friction and local pile displacement which was obtained by dividing this axial force difference by the circumferential area are shown in Fig. 8. The improved diameter of the soil cement (i.e. outer

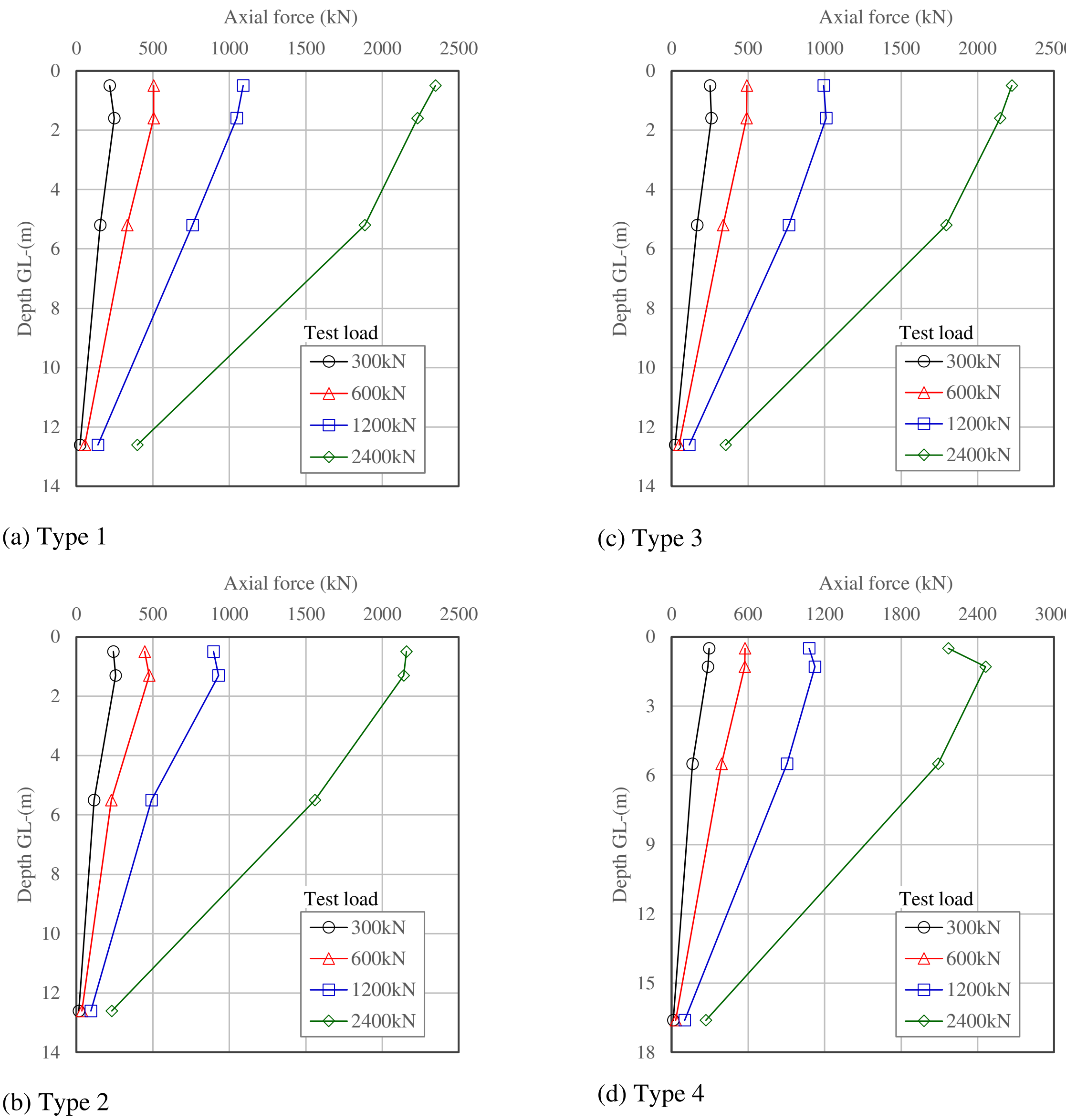
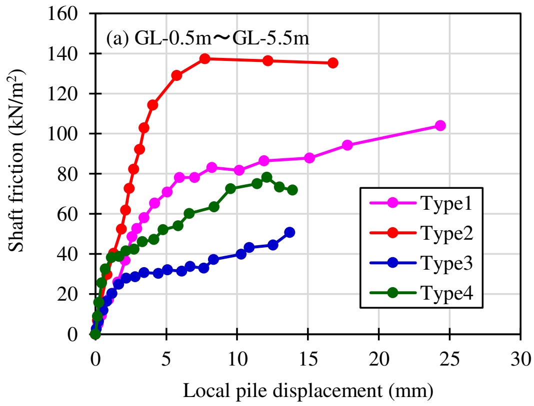


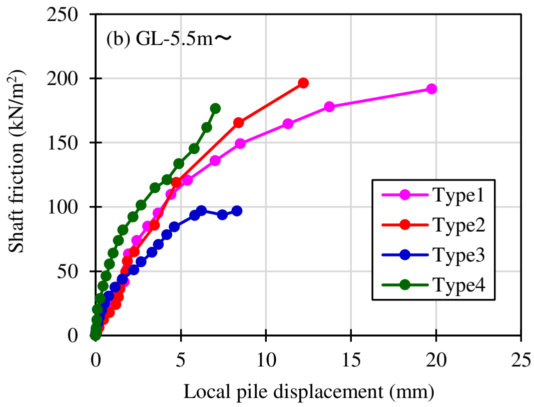
Fig. 7 Distribution of axial force

diameter of soil cement column) was used when calculating the circumferential area of the pile. Fig. 8(a) shows that a maximum shaft friction of 50 ~ 140kN/m^2 was reached in clayey soil stratum. In comparison, the average value for the unconfined compressive strength of the corresponding section of the ground was 57kN/m^2. Thus, it can be concluded that the shaft friction was more than the undrained shear strength of the ground (=28kN/m^2). In the sandy ground stratum, it is observed that the maximum shear strength is 100~200kN/m^2. Therefore, it is said that the shaft friction of the corresponding section shows the large value.

The end bearing capacity was calculated by dividing the axial force reaching the pile tip by the envelope area of the H section steel (BxH) as shown in Fig. 9. The relationships between the end bearing capacity and displacement at pile tip indicates in Fig. 10. The reference displacement of pile tip is 10% of the diameter of the equivalent circle area which is equal to the envelope area of H section steel pile when the end bearing capacity is evaluated. However, the maximum displacement at pile tip does not reach the reference displacement in this load test. Thus, the end bearing capacity is evaluated at the maximum displacement at pile tip. The end capacity of 3000~6600kN/m^2 is examined in this load test. The trend indicates that the end bearing capacity is gradually increasing because the displacement at pile tip is small and does not reach the reference displacement to evaluate the end bearing capacity. In addition, the end bearing capacity of the test pile Type 3 indicates the largest value of four test piles. This means that the large end bearing capacity is mobilized due to the large diameter of the pile.



(a) Clayey soil: GL-0.5m~GL-5.5m.



(b) Sandy soil: GL-5.5m~.

Fig. 8 Relationships between shaft friction and local pile displacement.

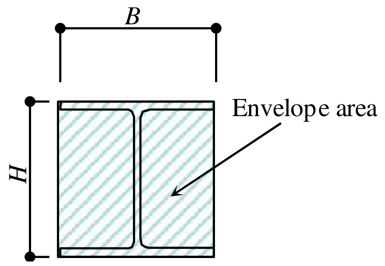


Fig. 9 Pile tip area (Envelope area).

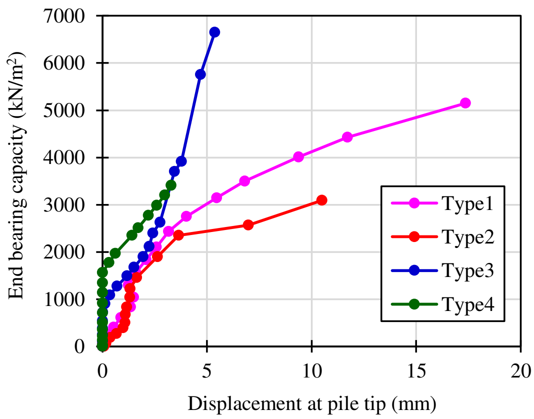


Fig. 10 Relationships between end bearing capacity and displacement at pile tip.

5. EVALUATION OF VERTICAL BEARING CAPACITY

The end bearing capacity which was obtained from the developed soil-cement composite pile is compared to the calculated end bearing capacity as shown in the design specification of Japan. In this study, the calculated value is estimated by the Design Standards for Railway Structures and Commentary (Railway Technical Research Institute, 2012) [4] because the developed soil-cement composite pile is applied to the railway structure. The estimation equations of bearing capacity for the steel pipe soil-cement pile and cast in-situ pile are used in this study. The estimation equations are described as follows;

1) Steel pipe soil-cement pile

Shaft friction for sandy soil:

$$\gamma_{fk} = 7N \leq 200(\mathrm{kN/m^2}) \tag{1}$$

Shaft friction for clayey soil:

$$\gamma_{fk} = 10N \leq 200(\mathrm{kN/m^2}) \tag{2}$$

End bearing capacity for sandy soil:

$$q_{tk} = 150N \leq 10000(\mathrm{kN/m^2}) \tag{3}$$

2) Cast in-situ pile

Shaft friction for sandy soil:

$$\gamma_{fk} = 3N \leq 150(\mathrm{kN/m^2}) \tag{4}$$

Shaft friction for clayey soil:

$$\gamma_{fk} = 6N \leq 150(\mathrm{kN/m^2}) \tag{5}$$

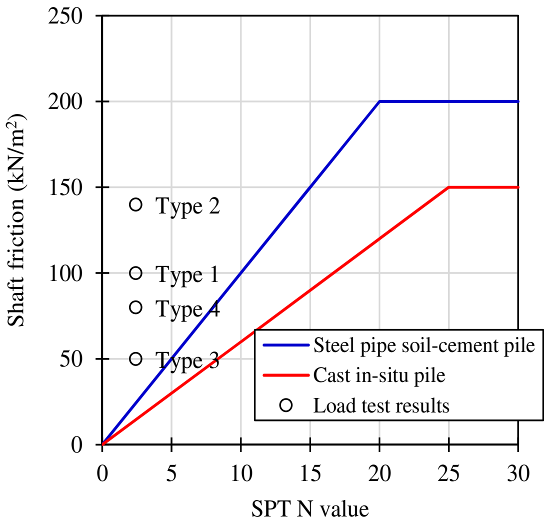
End bearing capacity for sandy soil:

$$q_{tk} = 60N \leq 3500(\mathrm{kN/m^2}) \tag{6}$$

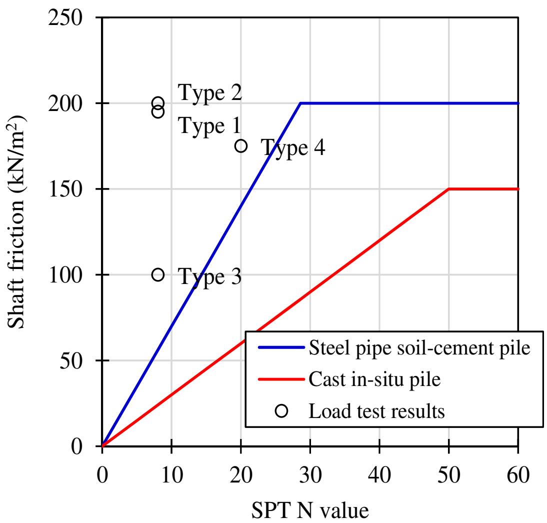
Where,

N: SPT (Standard Penetration Test) N value

The relationships between shaft friction and SPT N value for clayey soil and sandy soil indicate in Fig. 11. The estimated values from Eqs. (1), (2), (4) and (5) are also plotted in Fig. 11. Here, the shaft friction was calculated using average STP N value which is corresponded each soil layer. According to Fig. 11(a), the shaft friction which is obtained from the load test is larger than the estimated value from the design specification. It is said that the developed soil-cement composite pile has the enough shaft friction for the clayey soil. From Fig. 11(b),



(a) Clayey soil.



(b) Sandy soil.

Fig. 11 Relationships between shaft friction and SPT N value.

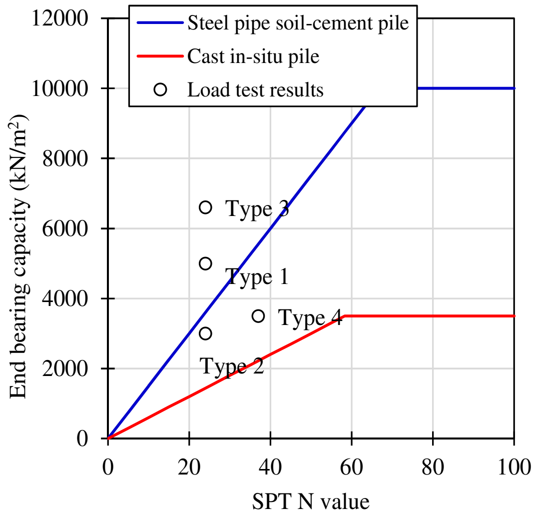


Fig. 12 Relationships between end bearing capacity and SPT N value.

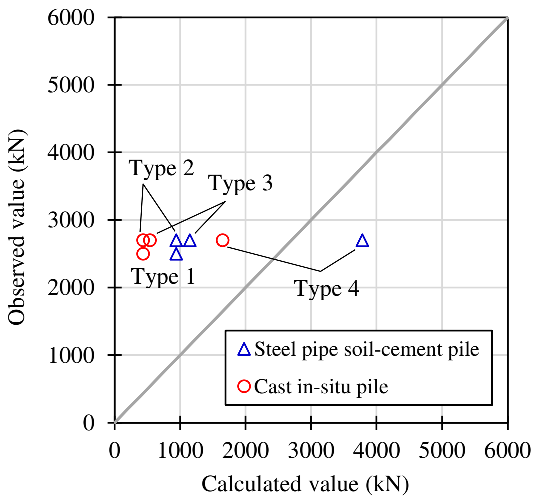


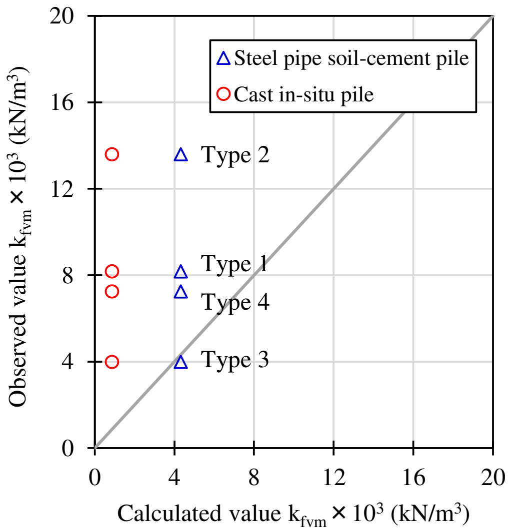
Fig. 13 Relationships between observed bearing capacity and calculated bearing capacity.

compared to the shaft friction from the load test and that from the design specification, the shaft friction of load test shows the large value. Therefore, it is also said that the shaft friction of the developed soil-cement composite pile has the enough shaft friction for the sandy soil.

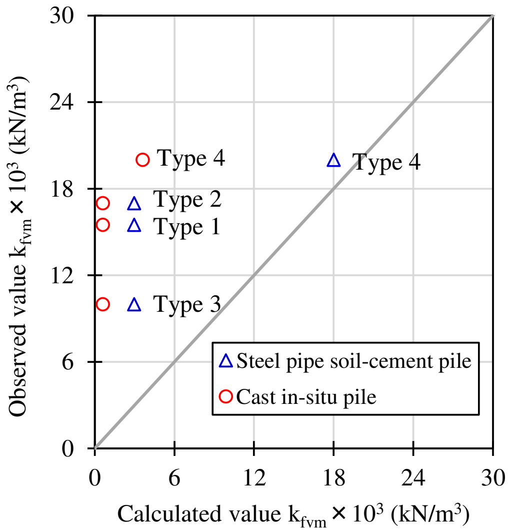
The relationships between end bearing capacity and SPT N value for sandy soil are plotted in Fig. 12. The estimated values from Eqs. (3) and (6) are also plotted in Fig. 12. It is seen that the end bearing capacity of Type 1 and Type 3 from the load test is larger than that of the estimated value. However, the end bearing capacity of Type 2 and Type 4 from the load tests is lower than that of estimated value for the steel pipe soil-cement pile although the end bearing capacity of load test shows the large value for the cast in-situ pile. This means that the end bearing capacity does not mobilize because the displacement at the pile tip is too small.

The relationships between observed bearing capacity and calculated bearing capacity are plotted in Fig. 13. Here, the calculated bearing capacity is evaluated by Eqs. (1) ~ (6). The trend indicates that the bearing capacity which was obtained from the load test is larger than the calculated value.

The relationships between observed value and calculated value on the coefficient of vertical subgrade reaction for the pile shaft indicate in Fig. 14. Here, the observed values about coefficient of vertical subgrade reaction at the pile shaft are evaluated as the secant gradient at the reference displacement (10mm) by the relationships between shaft friction and local pile displacement such as Fig. 8. As shown in Fig. 14, the observed value on the



(a) Clayey soil.



(b) Sandy soil.

Fig. 14 Relationships between observed value and calculated value about coefficient of vertical subgrade reaction at circumference of pile.

coefficient of vertical subgrade reaction at the pile shaft are larger than the calculated values for both the Steel pipe soil-cement pile and the Cast in-situ pile.

Figure 15 presents the relationships between observed values and calculated values on the coefficient of vertical subgrade reaction at the pile. The observed values about coefficient of vertical subgrade reaction at the pile tip are defined as the secant gradient at the reference displacement (10mm) by the relationships between end bearing capacity and displacement at the pile tip as plotted in Fig. 10. It is seen that the observed values of all piles on the coefficient of vertical subgrade reaction at the pile tip are larger than the calculated value for

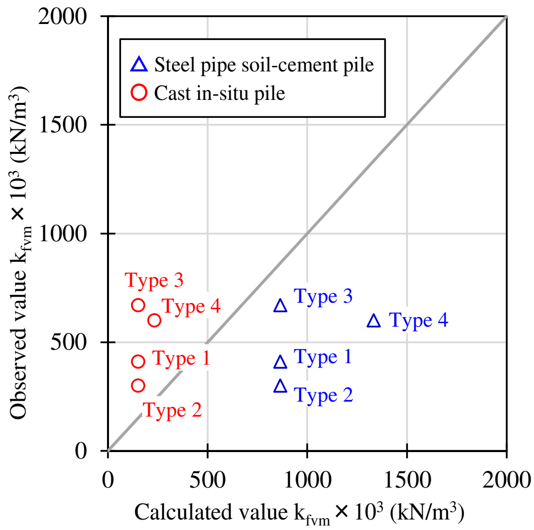


Fig. 15 Relationships between observed value and calculated value about coefficient of vertical subgrade reaction at pile tip.

the cast in-situ pile. However, the observed values of all piles on the coefficient of vertical subgrade reaction at the pile tip are smaller than the calculated value for the steel pipe soil-cement pile. The strength of soil-cement is 1000kN/m^2~ 3000kN/m^2 for the soil-cement composite pile which is developed in this study. Compared to the soil-cement strength of soil-cement composite pile and that of steel pipe soil-cement pile, the soil-cement strength of soil-cement composite pile is lower than that of steel pipe soil-cement pile which is generally used in the practical engineering field. Therefore, the elastic modulus for the soil-cement at pile tip shows the low value. In addition, it may be assumed that the compression displacement of H section steel at the tip is predominant the displacement of end bearing stratum.

6. CONCLUSIONS

The static compression load tests on the soil-cement composite pile (i.e. H section steel piles with soil-cement ground improvement) that were constructed with the mechanical agitator ground improvement method were carried out to evaluate the vertical bearing capacity in this study. Furthermore, it was evaluated the performance of vertical bearing capacity on the developed soil-cement composite pile to compare the evaluation method as shown in the design specifications in Japan. The following findings were obtained from this study.

1) According to the compression load test, both the shaft friction and the end bearing capacity has

the enough performance on the vertical bearing capacity.

2) It is concluded that the shaft friction of the load test is larger than the estimated shaft friction which is calculated by the design specification in Japan.

3) Compared to the end bearing capacity which is obtained from the load test and that of estimated value from the design specification in Japan, the end bearing capacity of the load test shows the large value. However, the partial results are lower than the estimated value. This means that the end bearing capacity is gradually increasing because the displacement at the pile tip is too small.

4) According to comparing to the observed value and the calculated value about coefficient of vertical subgrade reaction, the observed value at the pile shaft is larger than the calculated value. However, the observed value at the pile tip is lower than the calculated value of the steel pipe soil-cement pile. It can be said that the deformation characteristics of pile tip depends on the strength of soil-cement at the pile tip.

There are some research issues to address in the future. More vertical load tests to examine the vertical bearing behavior will be carried out. Moreover, it is needed to confirm the performance of pile body such as the bond strength and the effect of reinforcing pile tip. We will tackle the research issues described as the above sentence in the future.

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