Study on the Horizontal Bearing Performance of Steel Tubular Piles Installed by the Gyropress Method and the Press-in Method Assisted with Water Jetting

Naoki SUZUKI
Construction Solutions Department, Giken Ltd., Japan
Email: suzuki.n@giken.com
Yasumasa KIMURA
Construction Solutions Department, Giken Ltd., Japan

ABSTRACT

In this paper, the results of static horizontal loading tests of steel tubular piles installed by the Gyropress Method and the Press-in Method assisted with water jetting were collected, and these horizontal bearing performances were evaluated. As a result, the following were drawn: 1) Load-displacement curves of the Press-in Method assisted with water jetting and the Gyropress Method were consistent with the Weibull distribution curve, when the deformation index m=1.0. The average yield displacement normalized by the pile diameter with the Gyro Method is consistent with the average values of 4.1 – 4.5 % for steel tubular piles installed by other construction methods, and that with the WJ Method gives smaller value than the average of other construction methods; 2) The coefficient of horizontal subgrade reaction calculated backward from the displacement at the loading point showed somewhat larger value than the design value when the reference displacement was set at 1 % of the pile diameter in the case of the Gyro method. On the other hand, for cases constructed by the WJ method, the average of measured k_H is regarded fairly consistent with designed k_H, but the variation of them are large; and 3) In the case of group piles, δ_g - k_H curves were better fitted than δ_g / B - k_H curves. The calculated backward k_H approximately coincides with the design k_H when the horizontal displacement at the ground surface is about 15 mm.

Key words: *Horizontal subgrade reaction, Rotary press-in, Water jet system, Horizontal loading tests, Steel tubular pile*

1. INTRODUCTION

1.1. Background

As means to evaluate coefficients of horizontal subgrade reaction, two methods have been suggested: one based on the *in-situ* horizontal loading tests; and horizontal resistance calculation equation based on the results of existing horizontal loading tests. It is often the case that the latter is adopted. For the coefficient of horizontal subgrade reaction is evaluated from the deformation modulus of the ground and the pile diameter, as well as it is evaluated in a non-linear relationship that is inversely proportional to square root of the ground deformation. It is prescribed that the reference coefficient of horizontal subgrade reaction be one when the horizontal subgrade deformation of pile is 1 % of the loading width (JRA, 2017).

Although it is considered that the horizontal bearing performance is affected by the construction method, it has not necessarily been clearly evaluated in the currently available design methods. For example, in the standard of Ports and Harbours Association of Japan (PHAJ, 2007), though it has been described that attention must be paid to the effect of the construction method, especially when the construction might have loosened the surrounding ground, how to evaluate the effects is not concretely presented.

The Press-in Method is one of the construction methods for the foundation works with steel tubular piles.

In the method, already installed piles are held by the Silent Piler, a hydraulic pressing-in/extracting machine for piles, and the next pile is pressed into ground by a static load, using the extraction resistance of already installed piles.

The Press-in Method used in stiff ground include the Press-in Method assisted with water jetting (termed WJ Method hereinafter) and the Press-in Method with rotary cutting (termed Gyro Method hereinafter) (IPA, 2015). These methods penetrate piles/sheet piles into ground, reducing the resistant force during construction sufficiently small. It has been verified that the reduced ground resistance at the time of pile/sheet pile installation will recover with time (Shepley & Bolton, 2013). In addition, it is said that Vibration hammer method with water jetting for gravel ground affects the surrounding ground in the range of up to 30 cm from the outer surface of the pile (Technical Committee on Vibration Hammer Method, 2015). However, knowledge on the bearing performance especially in the horizontal direction has not been sorted out.

In addition, the Press-in Method are often used when building continuous walls because the Silent Piler use already installed piles as reaction force. For foundations with large widths, researches on horizontal resistance of structures such as diaphragm walls and large-diameter caisson piles have been carried out, but few have been conducted on continuous walls with steel tubular piles.

1.2. Objectives

The objective of this paper is to understand the horizontal resistance characteristics of the Gyro and WJ Methods, and to check the effect of foundation width to their horizontal bearing performance .

2. METHODS

2.1. Overview

Among the piles penetrated into ground by the Gyro and WJ Methods, the results of static horizontal loading tests were collected, and their bearing performance were evaluated.

The data used were 6 cases from the Gyro Method and 3 cases from the WJ Method. In addition, a set of data from Bored Pile Method that was tested at the same site were used for comparison. The specifications of each testing pile are summarized in **Table 1**.

where,

D: Pile diameter, B: Foundation width

n: Number of piles, L_d: Embedded depth of pile

h: Height of loading point

β: Characteristic value of foundation (**Eq. 3**), and

N_{value}: Average N-value from the ground surface to β^{-1}.

First, bearing performance was approximated by the Weibull distribution curve, and evaluated (Uto *et al.* 1982). The relationship between the yield displacement and the foundation width was then checked. After that, the coefficient of lateral ground reaction force was calculated backward from the displacement at the loading point. The calculated coefficients were sorted out for each construction method and were compared with the design values. Lastly, the effect of wall width by continuous walls, which is a characteristic of the Press-in Method, to the coefficient of subgrade reaction was checked.

2.2. Piling Method

Constructions by the Gyro Method and the WJ Method were carried out as follows; In the Gyro Method, cutting bits were attached to each pile toe and the pile was installed with rotary cutting. The number of bits of each test are shown in **Table 1** A water pipe was attached inside the steel tubular pile, and water was supplied, near the pile toe location, toward the circumferential as well as outside directions. The amount of water flow is described as ‘flow outside’ + ‘flow inside’ the steel tubular pile in **Table 1** (tests D & E).

In the WJ Method, water jetting pipes were attached outside the steel tubular pile, and the penetration was completed spurting water to the load bearing layer. The amount of water flow is described as the maximum flow per pipe times the number of pipes in **Table 1** (tests G, H and I). Note that in all the test piles calculated βL_d were bigger than 2.25, and that the evaluation and analysis were carried out, assuming that the piles were embedded to semi-infinitely long depth.

2.3. Site and Ground Conditions

Fig. 1 shows soil classification and SPT *N-value* at each location of pile loading tests. SPT N averaged over the depth from the ground surface to calculated β^{-1} is shown in **Table 1** The β^{-1} were obtained from **Eqs. (3)** to **(7)**.

Table 1. Pile conditions

test	Means*	D	thick-ness	n	water flow	Bit No.	Curing	B	L_d	h	N_{value}	βL_d	Notes	Refs.
unit	-	mm	mm	-	L/min	-	days	m	m	m	-		-	-
A	Bored	600	12	1	-	-	14	0.6	9	0.5	9.1	3.4		
B	Gyro	600	12	1	unknown	3	24	0.6	9	0.5	9.1	3.4		IPA (2014)
C	Gyro	600	12	3	unknown	3	17	2.2	9	0.5	9.1	3.2		
D	Gyro	1,000	22	1	20+40	6	29	1	10	2.4	9.9	2.4		
E	Gyro	1,000	12	1	20+40	6	26	1	10	2.4	9.5	2.7		
F	Gyro	1,000	12	4	unknown	6	over 29	4.75	14	2.4	9.1	5.0	Reaction force pile in test D	
G	WJ	800	12	1	325x4	-	over 8	0.8	36.5	0.6	3.3	8.8		Omori *et al*. (2003)
H	WJ	800	12	1	900x4	-	224	0.8	51	0.6	3.5	12.6	Ground improvement (pre-vertical loading)	Fujiwara *et al*.(2015)
I	WJ	800	12	1	900x2	-	unknown	0.8	15.5	0	5.2	4.3	Filled-in concrete	
J	Gyro	800	16	1	unknown	4	28	0.8	17.5	0.25	8.4	4.7		IPA (2014)

Notes: * Bored: Bored Pile Method; Gyro: Gyropress Method assisted with rotary cutting (Gyro Method);
WJ: Press-in Method assisted with water jetting (WJ Method)

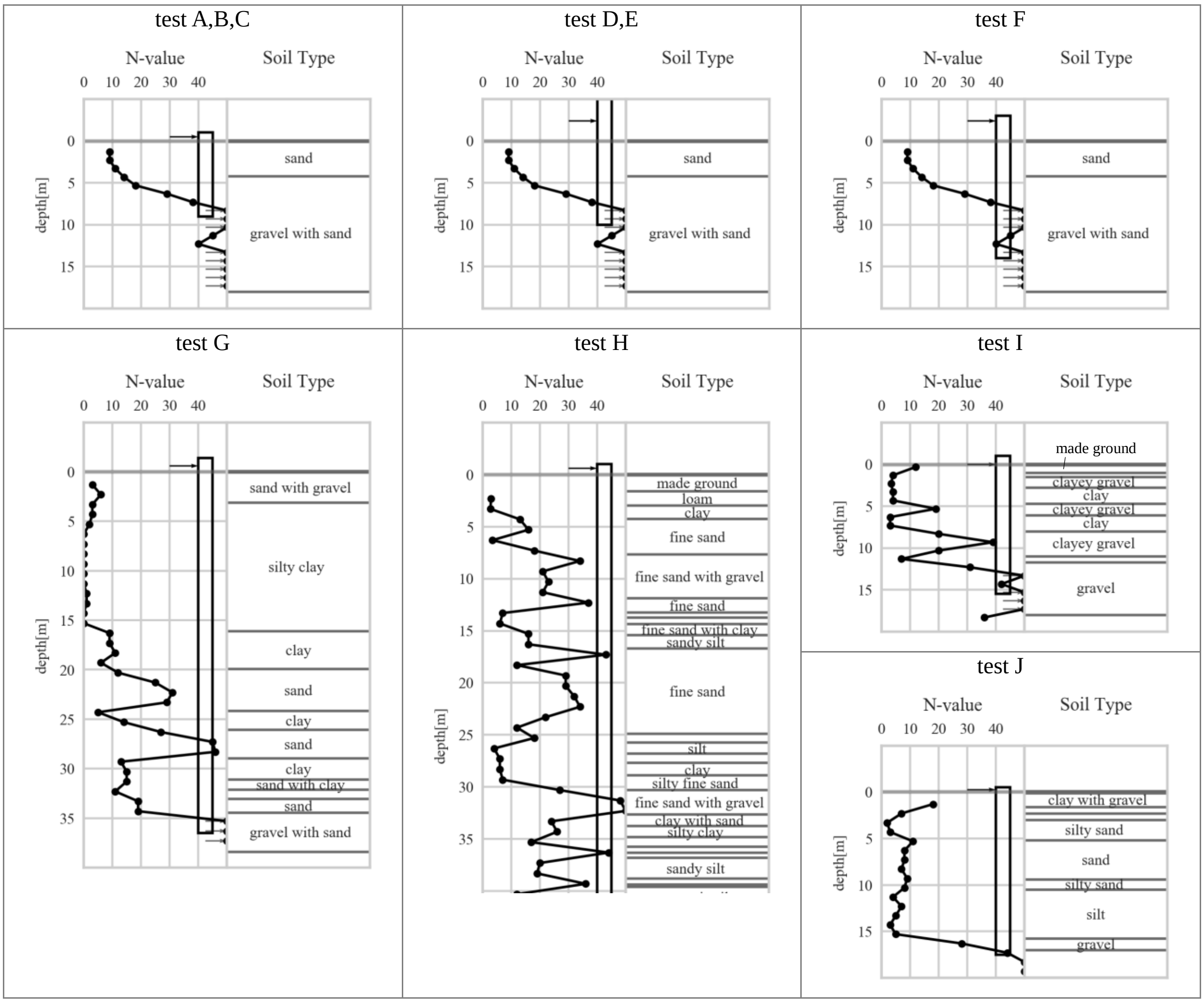


Fig. 1 Site Profiles

2.4. Test Condition

Loading tests were carried out according to one-directional loading tests in the step loading method standardized by the "Method of horizontal loading tests of piles (Japan Geotechnical Society (JGS 1831))". The following are the ones that require attention, such as those different from the above test method and those that have special field conditions.

Test F was used as the reaction pile for test D and was 13 m away from the center of the pile in test D. As for the direction of deformation, test D was in the influence range of about 5 times the foundation width. This was ignored since the pile width in test D was small compared with the foundation width in test F.

In test H, the soil about 300 mm around the pile was improved by permanent grout after the pile installation (Fujiwara *et al*. 2015). Though there might be little effect on the horizontal resistance, the result of test H was used as a reference. In addition, horizontal loading test was performed after vertical loading test.

Finally, in test I, the soil inside the steel tubular pile was excavated after the pile installation, and the void was filled with concrete from the pile toe for a length about 5 times the pile diameter. It was also ignored, judging that the situation inside the steel tubular pile would not affect the horizontal resistance.

2.5. Analysis Method

2.5.1. Coefficient of Horizontal Subgrade Reaction

Assuming the ground is simulated by elastic springs, and that the coefficient of horizontal subgrade reaction is constant in the depth direction, horizontal displacement at the ground surface and that at the loading point are given by **Eqs. (1)** and **(2)**, respectively. Ground deformation modulus was estimated by the *N*-value as in **Eq. (7)** to evaluate all the tests by the same method, not using the results of the hole horizontal loading tests.

$$\delta_g = \frac{1+\beta h}{2EI\beta^3} P_o \tag{1}$$

$$\delta_p = \frac{(1+\beta h)^3 + 1/2}{3EI\beta^3} P_o \tag{2}$$

$$\beta = \sqrt[4]{\frac{k_H B}{4EI}} \tag{3}$$

$$k_H = k_{H0} (B_H / 0.3)^{-\frac{3}{4}} \tag{4}$$

$$k_{H0} = \frac{1}{0.3} \alpha E_0 \tag{5}$$

$$B_H = \sqrt{\frac{B}{\beta}} \tag{6}$$

$$E_0 = 2800N \tag{7}$$

where,

E: Elastic modulus of steel
I: Moment of inertia of area for foundation
k_H: Coefficient of horizontal subgrade reaction
B_H: Equivalent loading width of foundation
E_0: Elastic modulus of ground
P_o: horizontal load,
δ_g: Ground deformation, and
δ_p: Deformation at loading point

Note that in addition to the pile stiffness at each sectional stiffness, that of steel members to protect monitoring instruments were added.

2.5.2. Yield Deformation of Ground

For the estimation of elastic range on the horizontal behavior of piles, there are different methods, including one to estimate from the point at which residual displacement abruptly increases in step loading, one to use a point at which displacement increases while keeping a constant load, or one that uses reference displacement in the Weibull distribution curve (**Eq.8**).

Though the first method is often used from performance required for lateral resistance, there are drawbacks such as dependency on the number of steps in repeated loading. Though the estimated value of the second method is presumed to correspond to the creep limit of the ground, all the records of the change over time were not left. As for the third method, according to Okahara *et al*. (1989) in which the characteristic value of ground displacement δ_{gs} obtained from the Weibull distribution curve is regarded as the yield displacement of the ground δ_{gy}, comparing with the point at which the residual displacement abruptly increases in step loading. Therefore the same assumption was adopted, though δ_{gs} and δ_{gy} are different in a precise sense and clear points which residual displacement abruptly increases in step loading could not be found around the displacement δ_{gs}.

Note that in fitting the result of the load test with the load control by the Weibull distribution curve, the result at the small displacement amount are emphasized too much.

Therefore, displacement at each step was weighted among the results of step loading tests so that the residual sum of squares became minimum (Nakatani *et al*. 2009a).

$$\frac{P_o}{P_{ou}} = 1 - e^{-\left(\frac{\delta_g / D}{\delta_{gs} / D}\right)^m} \tag{8}$$

where,

P_{ou}: Ultimate horizontal bearing capacity

δ_{gy}: Yield deformation of ground ($=\delta_{gs}$)

δ_{gs}: Characteristic value of ground deformation, and

m: Deformation index

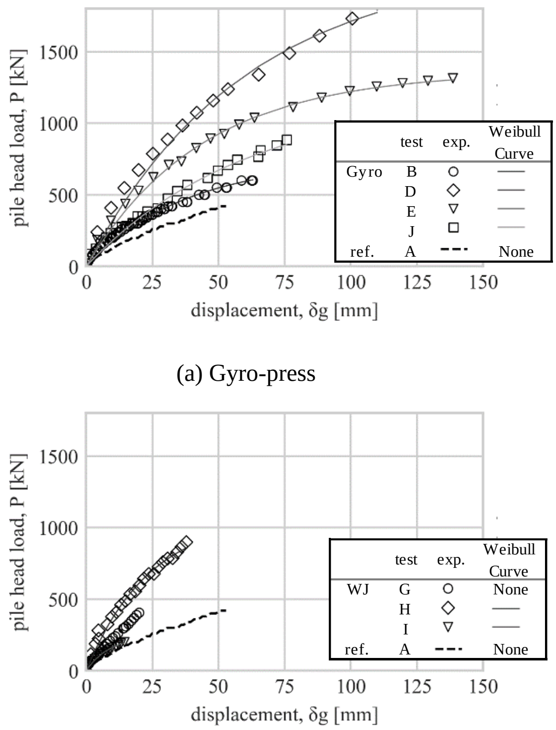
3. RESULTS AND ESTIMATION

3.1. Load-Displacement Curves

Weibull distribution curve is described by the three variables of deformation index m, maximum load P_{ou} and characteristic value of ground deformation δ_{gs}. When all the variables were changed in data fitting, calculated yield displacement became remarkably large. Consequently, final fitting was carried out fixing the index m = 1, which is often used in the approximation of the Weibull distribution curve (e.g. Okahara *et al*. 1989, Nakatani *et al*. 2009b).

Fig. 2 shows load-deformation results and Weibull distribution curves at each loading test for each construction method. The results with the application of the Weibull distribution curve are shown in solid lines, while ones installed by Bored Pile Method are shown by dotted lines. In addition, since in the data fitting of test G, the maximum ground displacements in the loading tests were smaller than 1.1 times δ_{gs}, it was judged that the estimation accuracy was low and was excluded from the evaluations. Note that as described later, the cases for single piles were used here in order to exclude the effect of foundation width for multi number of piles (tests C and F in this paper. Termed pile groups hereinafter). It may be seen that the load-displacement curves are relatively consistent when m = 1 is assumed, and that loosening of ground due to construction is not identified especially in the initial displacement.

Next, the relationship between the yield displacement δ_{gy} and the pile diameter D is shown in **Fig. 3** The result of test H was shown for reference because of permanent grout. A broad correlation between δ_{gy} and D is noticeable in the Gyro method. Statistical values δ_{gy}



(a) Gyro-press

(b) Water-jet

Fig. 2 $P - \delta_g$ Curve (m=1) for single pile

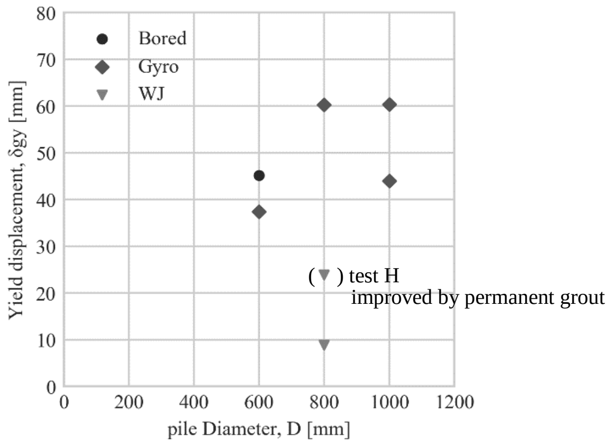


Fig. 3 Relationship between δ_{gy} and D

Table 2. Statistics of δ_{gy} / D

means	num	M	SD	CV	GM	GSD
Gyro	4	6.0%	1.3%	0.21	5.9%	0.22
WJ*	2	2.1%	1.3%	0.64	1.8%	0.70
(test I)	1	1.1%	-	-	1.1%	-

Notes: M:mean, SD: standard deviation, CV:coefficient of variation, GM:geometric mean, GSD:geometric standard deviation

*: including test H in which ground was improved by permanent grout

normalized by *D* are listed in **Table 2** for each construction method. Though there were few test data, geometric means for single pile was 5.9 % for the Gyro Method, while it was 1.1 or 1.8 % for the WJ Method. The results suggest that compared with the average values of 4.1 – 4.5 % for steel tubular piles installed by other construction methods (**Fig. 4**), the value of Gyro Method shows a little larger, whereas that of WJ Method shows somewhat smaller. However, since the yield displacement 1.1% is larger than the most frequent value in **Fig. 4** and the reference value 1.0% (JRA, 2017), it is too early to declare that WJ Method has a clear influence on the yield displacement.

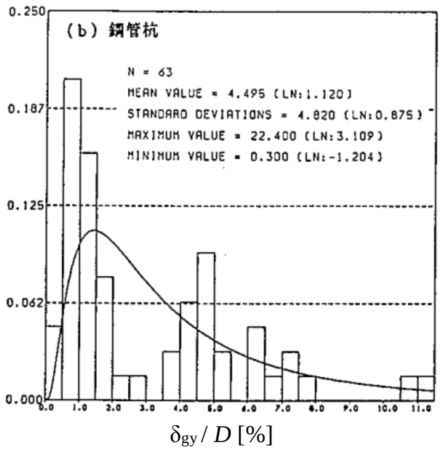
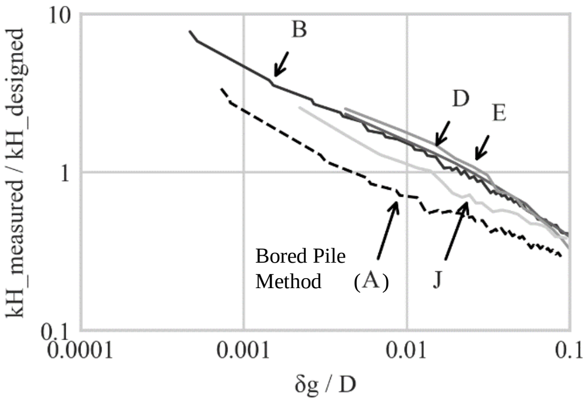


Fig. 4 Relative frequency distribution of δ_{gy} / D for steel tubular piles (Okahara *et al*. 1989)

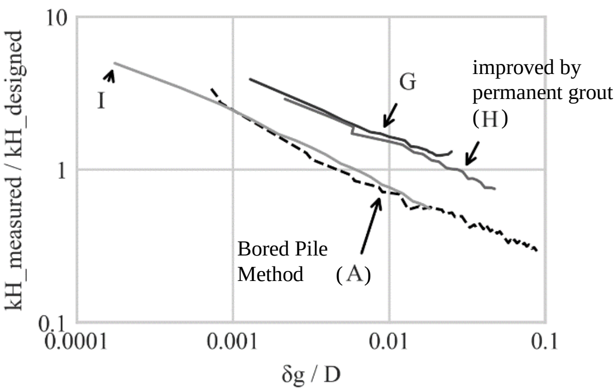
3.2. Back Calculated coefficient of Subgrade Reaction

The relationship between normalized coefficient of horizontal subgrade reaction k_H and the normalized horizontal displacement at the ground surface is shown in **Fig. 5**. Here, k_H calculated backward from the displacement at the loading point with the assumption that ground is represented by elastic springs was normalized by the design $k_{H,}$ which is given as **Eq. (4)**, while the horizontal displacement at the ground surface was normalized by the pile diameter.

In this section, only the cases of single piles were also used to exclude the effects of foundation width. Calculated backward k_H where the ground displacement normalized by the pile diameter is 1 % is larger than the design k_H for all the cases constructed by the Gyro Method (**Fig. 5a**). On the other hand, for cases constructed by the WJ method, the average of k_H where δ_g/D = 1% are regarded fairly consistent with the design k_H, but the variation of them seem large (**Fig. 5b**).



(a) Gyro-press



(b) Water-jet

Fig. 5 Relationship between normalized k_H and δ_g /B

3.3. Effect of Foundation Width

Next, the effect of foundation width was checked, using the test data with different pile diameters or different number of piles at the same test location (tests B to F). Note the data used here are all constructed by the Gyro Method. Note that in test F, the displacement at the loading point was not measured, so k_H was calculated backward from the horizontal displacement at the ground surface.

It is known that in a continuous pile foundation, horizontal resistant force is reduced by mutual interference among piles. In the case of a group of piles as

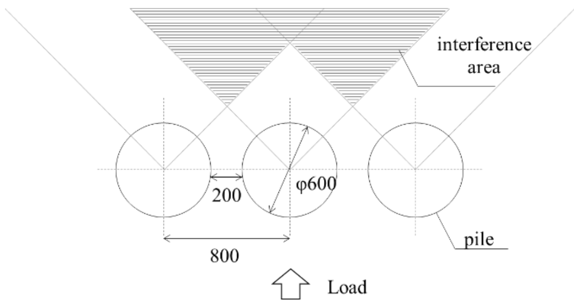
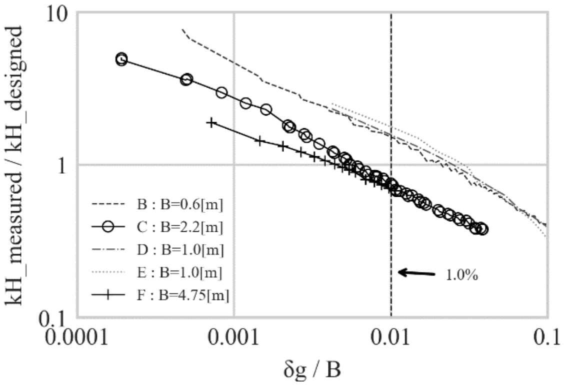
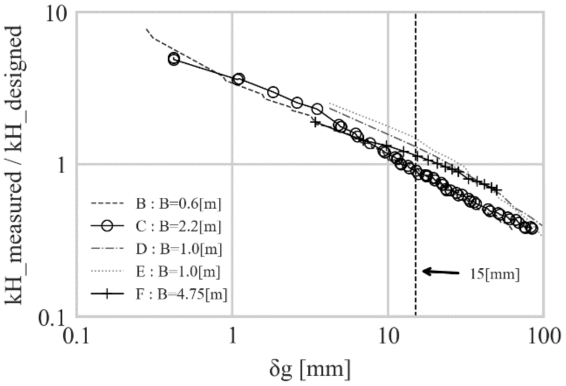


Fig. 6 Image diagram of interference by pile groups



(a) arranged by δ_g/B



(b) arranged by δ_g

Fig. 7 Effect of foundation width on normalized k_H

shown in **Fig. 6**, it is expected that the load shared by the center pile would be smallest because of the interferences from both sides. However, there were little apparent differences between the center pile and the side pile when the distribution of bending moment in the depth direction were looked at. Consequently, it was judged here that the steel tubular piles were behaving as an integrated body.

As in the previous section, **Fig. 7a** shows the relationship between the calculated backward k_{H} normalized by the design k_{H} and δ_{g} normalized by the foundation width *B*, and **Fig. 7b** shows the relationship between the normalized k_{H} and δ_{g}. It may be seen in **Fig. 7a** that the normalized k_{H} of pile group is smaller than that of single pile when δ_{g} is normalized by pile diameter, and the difference between them is large. On the other hand, it is seen from **Fig. 7b** that the relationship between k_{H} and δ_{g} of the group pile is relatively the same with that of the single pile when δ_{g} is evaluated by themselves. Furthermore, the calculated backward k_{H} approximately coincides with the design k_{H} when the horizontal displacement at the ground surface is about 15 mm (e.g. ASPP 2007).

Shimomura and Suzuki (2016) have reported that for large diameter pile foundations, the calculated backward k_{H} tends to be smaller than the design k_{H} . It is inferred for steel tubular pile foundations with small stiffness as in this study that the same thing applies.

Consequently, for steel tubular pile continuous walls, it is considered proper that the reference displacement used to calculate ground reaction force is not one proportional to the pile diameter but that a constant value should be used.

4. CONCLUSIONS

From the results of the study, the following have been checked:

- Load-displacement curves of the WJ and the Gyro Method are consistent with that obtained from the Weibull distribution curve for a displacement index *m* = 1.0.
  The average yield displacement normalized by the pile diameter with the Gyro Method is consistent with the average values of 4.1 – 4.5 % for steel tubular piles installed by other construction methods, and that with the WJ Method gives smaller value than the average of other construction methods.
- The coefficient of horizontal subgrade reaction calculated backward from the displacement at the loading point showed somewhat larger value than the design value when the reference displacement was set at 1 % of the pile diameter in the case of the Gyro method. On the other hand, for cases constructed by the WJ method, the average of measured k_{H} is regarded fairly consistent with designed k_{H}, but the variation of them seem large.
- In the case of group piles, δ_{g} - k_{H} curves were better fitted than δ_{g} / *B* - k_{H} curves. The calculated backward k_{H} approximately coincides with the design k_{H} when the horizontal displacement at the ground surface is about 15 mm.

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REFERENCES

Association of Steel Pipe Pile (ASPP). 2007. Design Manual of Cantilever Steel Sheet Pile Retaining Walls. (in Japanese)

Fujiwara, M., Tanigawa, J., Tsuchiya, M. and Murata, K. 2015. Countermeasures against Installation of Long Steel Pipe Piles and Quality Assurance of Bearing Capacity by Load Tests, Proceedings of 70th JSCE Annual Meeting, Section IV, No. 015, pp. 29-30. (in Japanese)

International Press-in Association (IPA). 2014. Design and Construction Manual of Steel Tubular Pile Earth Retaining Walls by Gyropress Method (Rotary cutting Press-in). (in Japanese)

International Press-in Association (IPA). 2015. Design and Construction Manual of the Press-in Method. (in Japanese)

Japan Geothechnical Society (JGS). 2010. Standards of Japanese Geotechnical Society for Lateral Load Tests of Piles. (in Japanese)

Japan Road Association (JRA). 2017. Specifications of Highway Bridges and Explanation, IV: Substructures. (in Japanese)

Matsui, N., Suzuki, T., Hirata, S. and Kimura, Y., 2009. Bearing Capacity Performance of Pressed-in Steel Tubular Piles by Rotary Cutting (Gyropress Method); Part 2: Lateral bearing capacity, Proceedings 64th JSCE Annual Meeting, III-130, pp. 259-260 (in Japanese).

Nakatani, S., Shirato, M. and Yokomaku, K. 2009a. Study on Axial Deformation Characteristics of Pile, Technical note of PWRI, No. 4139. (in Japanese)

Nakatani, S., Shirato, M., Kono, T., Iochi, H. and Kirikoshi, T. 2009b. Geotechnical Criterion for Elastic Limit of Horizontally-Loaded Pile, Technical Note of PWRI, No. 4151. (in Japanese)

Okahara, M., Takagi, S., Nakatani, S., Taguchi, K. and Sakamoto, A., 1989. Investigation on Lateral Resistance Characteristics of Piles with the Use of Loading Test Data, Technical Note of PWRI, No. 2721. (in Japanese)

THE PORTS & HARBOURS ASSOCIATION OF JAPAN (PHAJ). 2007. Technical Standards and Commentaries for Port and Harbour Facilities in JAPAN, Last Volume. (in Japanese)

Technical Committee on Vibration Hammer Method. 2015. Design and Construction Manual for Vibration Hammer Method. (in Japanese)

Shepley, P. and Bolton, MD. 2014. Water Supply to a Geotechnical Centrifuge for Pile Jetting in Sand, Physical Modelling in Geotechnics - Proceedings of the 8th International Conference on Physical Modelling in Geotechnics, pp. 281-287.

Shimomura, S. and Suzuki, Y. 2016. Coefficient of Lateral Ground Reaction Force of Single Pile in Sandy Ground Based on the Results of Lateral Loading Tests of Wide Range Pile Diameters, Architectural Institute of Japan, Technical Report, Vol. 22, pp. 919-924. (in Japanese)

Shimomura, S. and Suzuki, Y. 2017. Coefficient of Lateral Ground Reaction Force of Single Pile in Clay Ground Based on the Results of Lateral Loading Tests of Wide Range Pile Diameters, Architectural Institute of Japan, Technical Report, Vol. 23, pp. 93-98. (in Japanese)

Uto, K., Fuyuki, M. and Sakurai, M. 1982. Compilation Method of the Results of Pile Loading Tests, The Foundation Engineering & Equipment, Vol. 10, No. 9, pp. 21-31. (in Japanese)