Evaluation of Bearing Capacity of a Small-Diameter Spiral Pile Subjected to Combined Load Using Model Tests

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ABSTRACT

A spiral pile is a useful pile because it has high resistance against vertical load such as push-in and pull-out loading, but it also has a problem that its horizontal resistance is relatively small, comparing to a steel pipe pile with the same diameter. In addition, the conventional design has the following problems; 1) unifying effect of the surrounding ground by the revolving press-in has not been considered for safety design, 2) evaluation method for bearing capacity against combined load is not established, and 3) inclination effect of loading has not been clarified.

In the previous research (Isobe and Yamauchi, 2017), a simple method is proposed to consider the unifying effect of the surrounding ground due to the revolving press-in, based on the various loading test results such as push-in, pull-out and lateral loading tests for the spiral piles in soft clay ground. Then, the bearing capacity of the spiral pile subjected to combined load was investigated with the numerical analysis method. In this paper, in order to verify this analysis, model tests have been carried out in which model piles were revolving press-in a dry silica sandy ground and then loaded at some arbitrary angles.

***Key words:* spiral pile, bearing capacity, combined loading, loading test, FEM**

1. Introduction

Recently, demand for renewable energy has been increasing and commercial photovoltaic power generation have become popular. In order to reduce production costs, the photovoltaic power generation facilities have to be massively invested even in the areas of poor conditions, like lands full of slopes, though inexpensive. In general, solar power generation equipment is constructed based on concrete spread foundations, but for effectively utilizing those aforementioned bad grounds, some techniques such as steel pipe piles with a small diameter, spiral piles, and batter piles are applied (Araki, 2013, Sato et al., 2015 and Hirata et al., 2005). In particular, the spiral pile is a useful pile form because of the high resistance to the vertical load (push-in and pull-out), but there are the following problems; 1) unifying effect of the surrounding ground by the rotary press fitting has not been considered for safety design, 2) evaluation method for bearing capacity against combined load is not established, and 3) inclination effect of loading has not been clarified.

In this study, combined loading tests on a single screw pile were conducted in the pull-out direction. The bearing capacity obtained by the model experiments is compared with the bearing capacity calculated by the proposed evaluation method in previous research (Isobe and Yamauchi, 2017). Because the screw pile used in this tests was fitted with a spiral blade on the circumferential surface of straight pile using glue, loading tests were conducted for the straight pile with sand adhered on the circumferential surface in the same manner for comparison.

2. Outline of previous study

In the previous research, vertical and horizontal loading tests were performed on a spiral pile, which was subjected to twisting processing to flat steel pile and constructed on soft viscous ground. Based on these results, correction coefficients were set for the parameters such as pile diameter, soil strength and bending stiffness of the pile by adapting the conventional vertical bearing capacity evaluation formula and Chang's equation to calculate horizontal resistance characteristics of the spiral pile.

Subsequently, three-dimensional elasto-plastic finite element analysis with Drucker-Prager type of yield function was carried out in consideration of correction coefficients. As a result, it reproduced the bearing capacity of a spiral pile against the combined load in the vertical and horizontal directions by the same analysis method. In this study, the ultimate resistance was defined as the load at a time when the vertical or horizontal displacement of loading point reaches the displacement of 10% of pile diameter.

Relationship between vertical and horizontal ultimate resistance for each loading angle based on the simulation results shown in **Fig. 1** is an elliptical shape with the long side in the vertical load direction. The numbers shown in this figure mean the loading angle (0 degree is horizontal loading), positive and negative value indicate pulling-out direction and pushing-in direction, respectively. It was suggested from **Fig. 1** that the bearing capacity curve of the spiral pile subjected to combined load can be shown on the elliptical shape calculated from bearing capacity subjected to load at 90, 0 and -90 degrees.

3. Outline of model test

3.1. Model pile

A miniaturized spiral pile was originally planned to be used for the small-scale model tests, but it did not have enough rigidity to carry out the loading test in the small-scale model tests. Therefore, in this series of tests, using the screw pile having the spiral structure similar to that of the spiral pile, the effect of the spiral structure on the bearing capacity of the pile was investigated. The screw pile has a shape with a spiral blade attached to the circumferential surface of the straight pile by glue. The winding direction of a spiral blade is right, the pitch of the spiral blade is 15 mm, and the blade adheres to the entire pile excluding the tip. Thus, the diameter of the screw pile was set to 1.3 mm considering the spiral blade. The loading tests were performed on the screw pile and the straight pile to compare the influence of the blades.

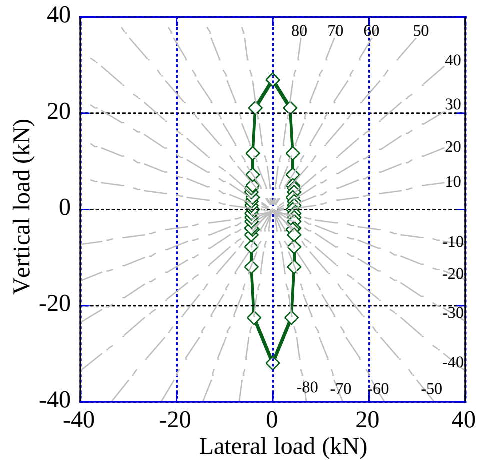

Fig. 1 Bearing capacity curve of spiral pile based on the numerical analysis results (Isobe and Yamauchi, 2017)

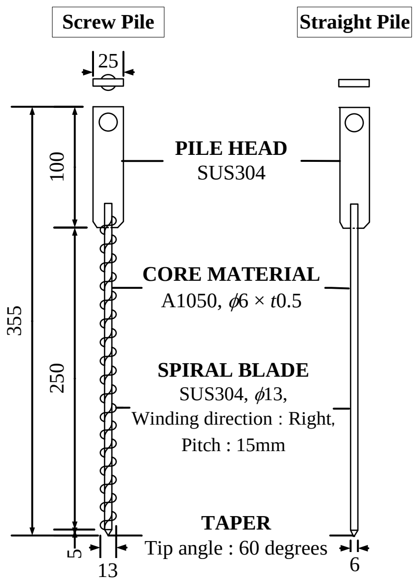

Fig. 2 Model pile

First, bending tests were carried out for the screw pile and the straight pile with a total length of 165 mm to investigate the influence of the blades on the flexural rigidity in air. In these bending tests, the pile head was fixed and the load was applied on the pile tip, measuring the bending strain on the pile by strain gauges installed on the circumference of pile. **Fig. 3** shows that maximum strains were observed at around 20 mm from the pile head in both piles, and no difference is found between them. It is, therefore, considered that the influence of the spiral blade on the flexural rigidity of the model pile is little. Based on the results, the flexural rigidity of both piles, *EI* can be regarded as 0.0053 (kN-m^2).

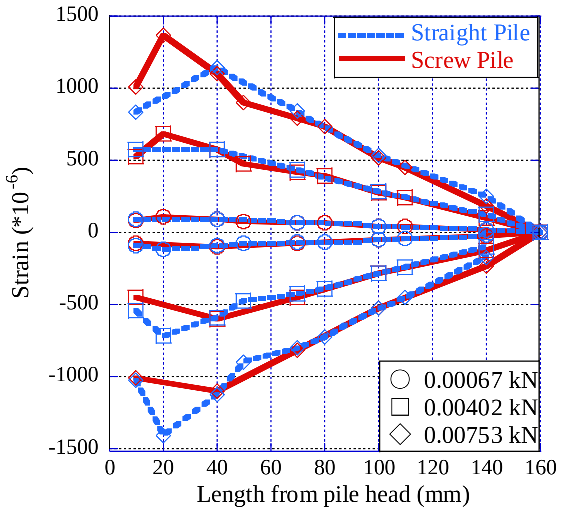

Fig. 3 Bending strain distribution on the model piles

3.2. Model test procedure

3.2.1. Model ground preparation

The soil chamber is a rectangular structure with depth of 250 mm, width of 700 mm and height of 500 mm as shown in **Fig. 4** and **Fig. 5.** The model ground material with the relative density, D_r of 70% was achieved with dry sand (Silica No. 7) by pluviation in air from height of 300 mm.

3.2.2. Penetration of model pile

Loading tests were carried out on piles constructed vertically to the flat model ground. The straight pile was installed to prescribed depth by press-in on the pile head. For the screw pile, the penetration assist device, in which revolving press-in is applied on the spiral pile head in predetermined directions with the removable guides, and the direction of penetration can be freely adjusted, is used (**Fig. 4**). The penetration direction is fixed by the penetration assist device during the operation, and the pile head is rotated along the spiral direction of screw pile and penetrated. According to the reference[2)], the screw pile can be constructed with less disturbing the ground by press-in at the speed that length of penetration per one rotation is equal to the length per one pitch of the screw pile. In these model tests also, the same speed is applied.

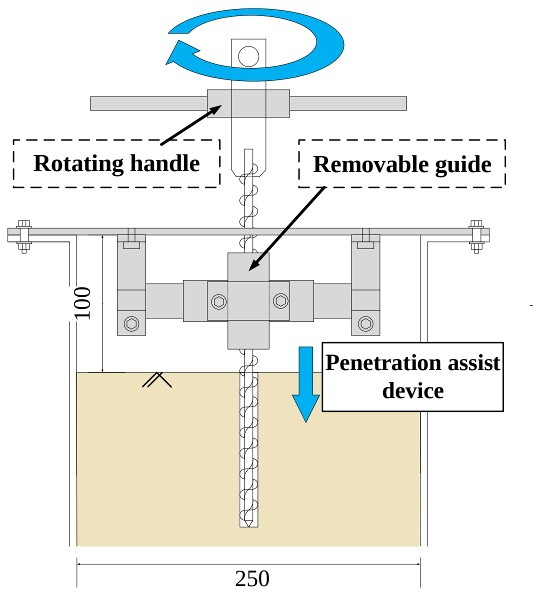

Fig. 4 Penetration of the screw pile

3.2.3. Loading Procedure

A loading device shown in **Fig. 5** can set optional loading angle in the range of 0 to 90 degrees. Pull-out loading are applied by the loading motor up. The tensile load applied to the pile head was measured by the load cell attached between the motor and the pile head. The lateral and vertical displacement and load of the pile head are measured at 90 mm from the ground surface because there is little difference in the displacement of the model pile at the ground surface and the measurement point considering that the rigidity of the pile is high and there is little effect on the displacement by the deformation of the pile. The pile head and loading motor was connected by a wire, and a pulley is installed at an optional position between them to vary loading directions. As with the previous study, the ultimate bearing capacity against combined loading was defined as the load at a time when the lateral or vertical displacement at the loading point reaches 10% of pile diameter at the loading point. The combined loading of 0, 30, 45, 60, 75, 80, and 90 degrees was tested three times each.

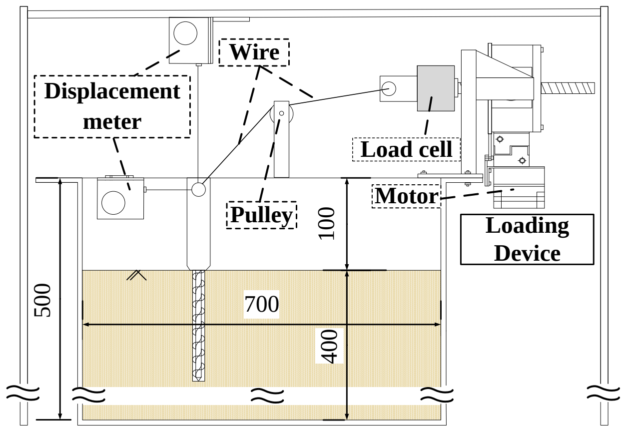

Fig. 5 Loading device

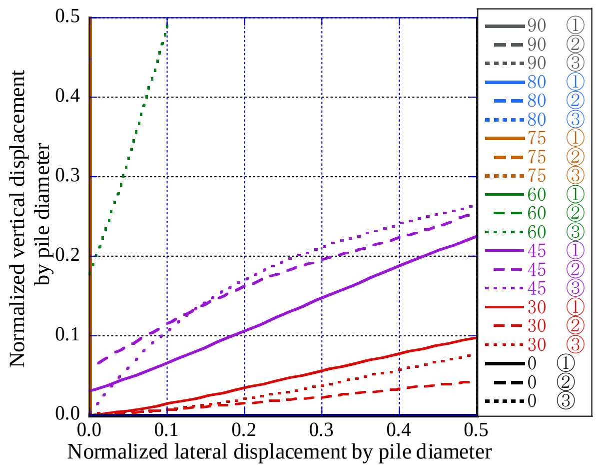

Fig. 6 Vertical displacement- lateral displacement for the straight pile

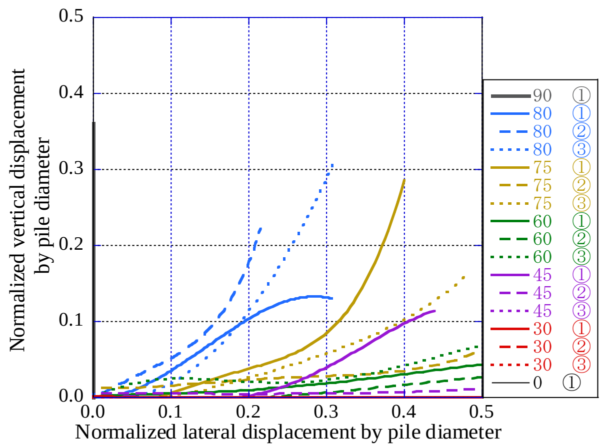

Fig. 7 Vertical displacement- lateral displacement for the screw pile

4. Test Results

Figs. 6 and **7** show vertical displacement - lateral displacement for the straight pile and the screw pile, respectively. As shown in **Fig. 6**, for the straight pile, lateral displacement is dominant in the case of loading direction close to horizontal (0 and 30 degrees) and vertical displacement is dominant in the case of loading direction close to vertical (60 to 90 degrees). Therefore, ultimate bearing capacity was judged by the lateral displacement in the cases of the loading direction of 0 and 30 degrees, and was judged by the vertical displacement in the cases of the loading direction of 60 to 90 degrees. In the case with the loading angle of 45 degrees, the intermediate behavior was observed unlike other cases. Therefore, the bearing capacity of the straight pile with the loading angle of 45 degrees is judged by both vertical displacement and horizontal displacement. As shown in **Fig. 7**, for the screw pile, the increase of the vertical bearing capacity due to the spiral blade was observed, so that vertical displacement did not occur much at all load angle. Thus, for the screw pile, the ultimate bearing capacity was judged based on the horizontal displacement.

Fig. 8 shows vertical load – vertical displacement for the straight pile in the cases with the loading angle of 45 to 90 degrees, and **Fig. 9** shows lateral load – lateral displacement for the straight pile in the cases of the loading angle of 0 to 45 degrees. The horizontal axis indicates the displacement normalized by the pile diameter (6 mm). According to **Fig. 8**, in the case of the loading angle of 60 to 90 degrees, the maximum values were observed in the range of the normalized displacement of 0.1 to 0.3, after that the resistance shows a tendency to keep constant. Thus, the pile was considered to be withdrawn in the vertical direction.

The case with the loading angle of 45 degrees shows a different tendency from the cases with the loading angle of 60 to 90 degrees, due to the influence of the lateral subgrade reaction, resulting in the continuing increase of the resistance. Also in **Fig. 9**, larger resistance was observed in the case with the loading angle of 45 degrees due to the influence of the vertical resistance, comparing to the results for the loading angle of 0 degree. Therefore, it is found that the variation of the results in the case with the loading angle of 45 degrees is considered to be due to the mutual influence of vertical and lateral resistance during loading.

Fig.10 shows lateral load – lateral displacement of the screw pile. In this figure also, the displacement was normalized by the pile diameter (the outer diameter of the blade, 13 mm). In the displacement range of 0.1 (= 10%*D*) or less, as the loading angle is closer to lateral direction, the bearing capacity becomes larger.

Fig. 11 shows the lateral load – lateral displacement for the straight and spiral piles subjected lateral loading (the loading angle of 0 degree). According to this figure, within the range of the criterion displacement (10% of the spiral pile diameter, 1.3 mm), no significant difference in the relationship was observed. It infers that there was little difference in their flexural rigidity and loading width in the same as the result of the bending test to both piles.

Figs. 12 and **13** show the bearing capacity against the combined loading for the straight pile and the screw pile, respectively. The ratio of V / H (V: bearing capacity of 90 degrees, H: bearing capacity of 0 degree) is 2.26 for the straight pile and 9.15 for the screw pile, respectively. Since there is no difference in the bearing capacity of both piles subjected to only lateral load, the vertical bearing capacity in pulling-out direction was increased by about 4 times by the spiral blade. The influence on improvement of vertical bearing capacity by spiral blade is remarkable.

Figs. 14 and **15** respectively show the bearing capacity curve of the straight pile and the screw pile normalized by the vertical bearing capacity of 90 degrees and the lateral bearing capacity of 0 degrees. The bearing capacity envelopes also were shown in the same figure based on the method shown in the previous research (Isobe and Yamauchi, 2017). It was found that the average bearing capacity against the combined loading for the straight pile was in the envelope and the average value for the screw pile was outside of the envelope. It is assumed that the area where the spiral blade passes through the surrounding ground was slightly disturbed during the installing operation. On the other hand, for the straight pile, the surrounding ground was densified during the installation procedure. However, the influence was not considered in the estimation method. Thus, it was thought that the different tendency was observed due to the difference of how to install.

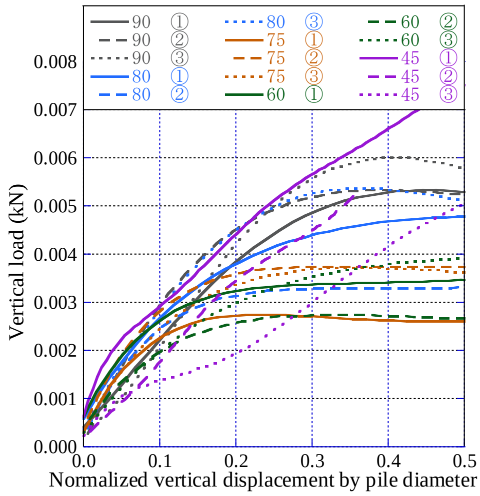

Fig. 8 Vertical load – vertical displacement for the straight pile

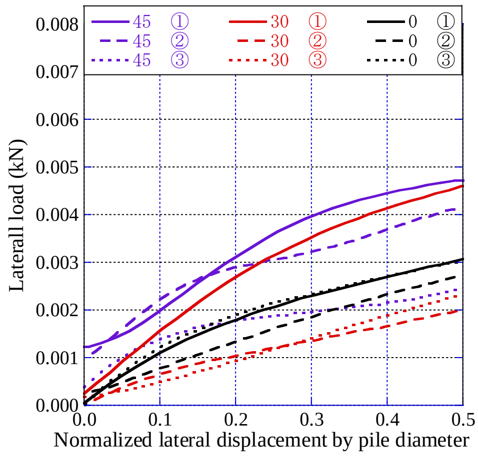

Fig. 9 Lateral load – lateral displacement for the straight pile

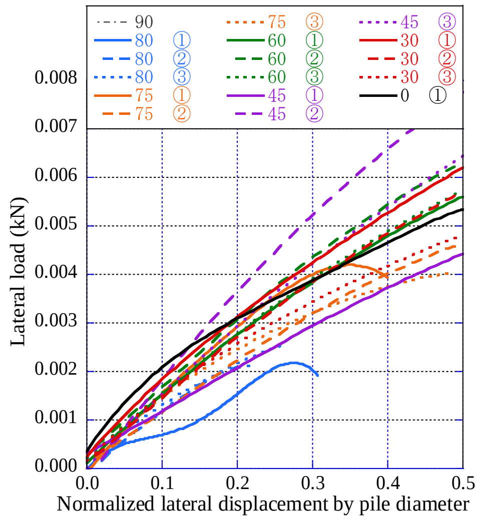

Fig. 10 Lateral load – lateral displacement for the screw pile

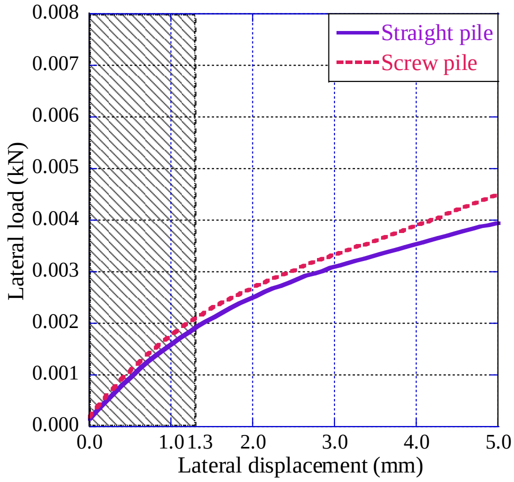

Fig. 11 Lateral load – lateral displacement for both the straight pile and the screw pile

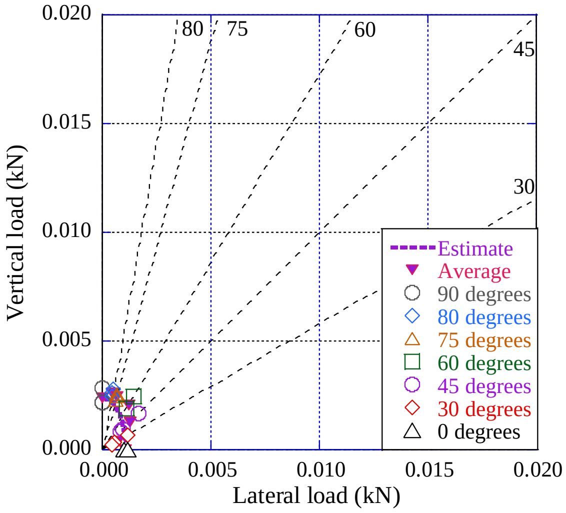

Fig. 12 Bearing capacity envelope for the straight pile

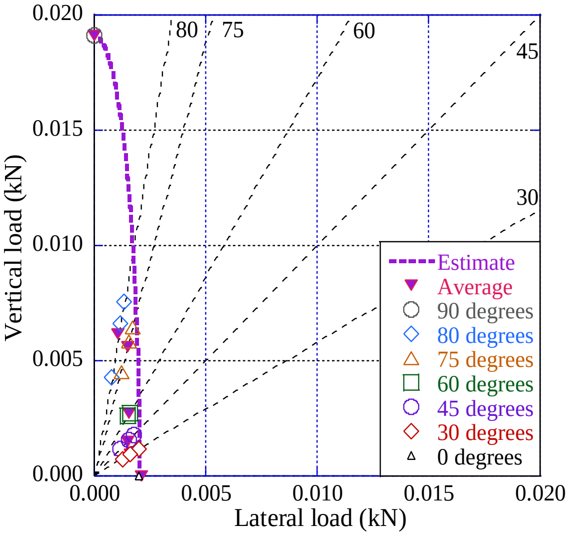

Fig. 13 Bearing capacity envelope for the screw pile

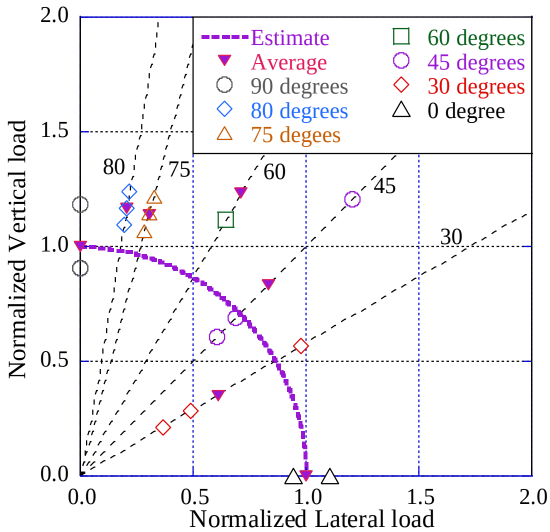

Fig. 14 Normalized bearing capacity envelope for the straight pile

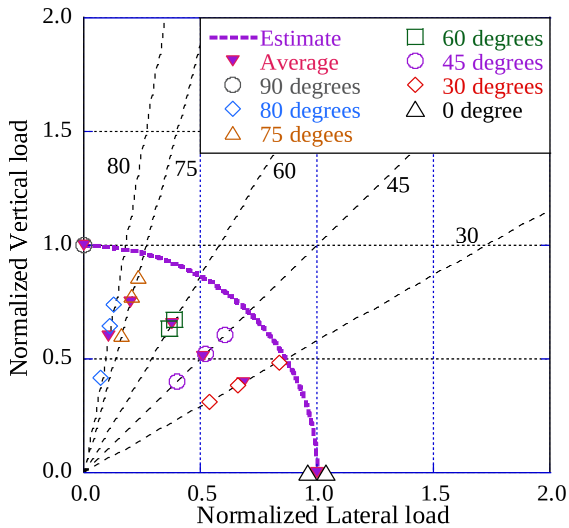

Fig. 15 Normalized bearing capacity envelope for the screw pile

5. Discussion

5.1. Inverse calculation of friction resistance angle between ground and pile

The friction resistance angle between the surrounding ground and the pile was inversely calculated from the bearing capacity in the direction of vertical pulling-out for the straight pile obtained from the model test. The general vertical bearing capacity formula of a pile is as follows;

$$R_u = q\,A + \tau\,L\,f \tag{1}$$

where, R_u: ultimate vertical bearing capacity (kN), q: ultimate bearing capacity of ground of pile tip (kN/m^2), A:

area of pile tip (m^2), τ: skin frictional force per unit area (kN/m^2), L: pile length in this study (m), f: circumferential length of pile (m). Since the bearing capacity of pile tip is not involved in evaluating the pull-out resistance, the first term of right side of **Eq. (1)** is assumed to be 0.

$$\tau = R_u / f L \quad (2)$$

Skin frictional force per circumference area, τ is obtained by the following equation;

$$\tau = 0.5\, \gamma L K_0 \tan\delta \quad (3)$$

where, γ: unit volume weight of the ground (kN/m^3), K_0: coefficient of earth pressure at rest (Jaky's equation, 1 - sinϕ), δ: friction resistance angle between ground and pile. **Eq. (4)** is derived by combining **Eqs. (2)** and **(3)**.

$$\tan\delta = R_u / (0.5\, \gamma\, (1-\sin\phi)\, L^2 f) \quad (4)$$

Substituting the values in **Table 1,** δ is 37.4 degrees for the straight pile and 70.4 degrees for the spiral pile. Thus, the increase due to the spiral blade can be confirmed. However, since the frictional resistance angle between ground and screw pile which was inversely calculated is not a realistic value, it is necessary to make a realistic assumption of slip surface by pulling-out force in dry sandy ground.

5.2. Inverse calculation of lateral ground reaction coefficient

The lateral ground reaction coefficient k_h is inversely calculated from **Eq. (5)** using the characteristic value of pile β obtained by the equation shown in **Eq. (6)**.

$$\beta = (k_h D / 4\, EI)^{1/4} \quad (5)$$

$$y_t = \frac{1}{2EI\beta^3}(c_1 + c_2) \quad (6)$$

$$c_1 = \frac{H}{\Delta}\left[(1 - sin2\beta l)e^{-2\beta l} - e^{-4\beta l}\right] \quad (7)$$

$$c_2 = \frac{H}{\Delta}\left[1 - (1 + sin2\beta l)e^{-2\beta l}\right] \quad (8)$$

$$\Delta = 1 - 2(2 - \cos 2\beta l)e^{-2\beta l} + e^{-4\beta l} \quad (9)$$

where, β: characteristic value of pile (m^{-1}), D: pile diameter (m), EI: flexural rigidity (kN-m^2), y_t: displacement at the pile head (m), H: lateral load (kN), l: pile length (m).

First, for the straight pile, using criterion displacement y_t = 0.6 mm and the bearing capacity of the straight pile subjected to only lateral load H = 1.059*10^{-3}(kN) and substituting the values in **Table 2**, lateral ground reaction coefficient k_h is calculated as follows;

$$k_h = 4841 \text{ (kN/m}^3\text{)}$$

Then, for the screw pile, the lateral displacement of the pile head is evaluated by **Eq. (6)** using the inversely calculated k_h. Incidentally, as can be seen in **Fig. 11**, the load-displacement relationship of the straight pile and the screw pile are similar in the measurement range (0 mm < y < 1.3 mm). In order to compare both piles under similar conditions, the value of the lateral loading H and the displacement y were set 1.059*10^{-3} (kN) and 0.6 (mm) as the same value of the above calculation, respectively.

The calculated displacement of the pile by substituting the inverse calculated k_h into **Eqs. (5)** and **(6)**,

$$\beta = 7.24 \text{ (m}^{-1}\text{)}$$

$$y_t = 0.29 \text{ (mm)}$$

However, the target displacement of y_t is 0.6 mm. So, it is necessary to set the correction coefficient ξ for the pile diameter so as to decrease β. The modified β in consideration of ξ is expressed by the following;

$$\beta' = (k_h\, \xi D / 4\, EI)^{1/4} = \xi^{1/4} \beta \quad (7)$$

Based on the above calculation, the obtained correction coefficient for the pile diameter, ξ is 0.46. That is, in dry sandy ground, if the outer diameter of the spiral blade is evaluated as pile diameter, it leads to overestimation of the horizontal resistance. It is, therefore, necessary to evaluate using the pile diameter excluding the spiral blade portion, which is equal to the pile diameter of the straight pile.

In the previous research, it was necessary to estimate the vertical and horizontal bearing capacity for the spiral pile installed in soft viscous ground by using the assumed pile diameter larger than the actual pile diameter. This was due to the fact that the spiral pile and the surrounding ground were integrated. On the other hand, in dry sandy ground, it was confirmed that the effect of integrating screw pile with the surrounding ground can't be expected against the horizontal load.

Table 1. Summary of information concerning inverse calculation of friction resistance angle between ground and pile

	Unit		Straight pile	Screw pile
R_u	kN	Ultimate Vertical bearing capacity	0.002	0.019
A	mm^2	Area of pile tip	28.27	132.73
L	mm	Pile length	255.00	
f	mm	Peripheral length of pile	18.85	40.84
γ	kN/m^3	Unit volume weight of ground	13.33	
K_0		Coefficient of earth pressure at rest	0.36	
δ	°	Friction resistance angle between ground and pile	37.40	70.40

Table 2. Summary of information concerning inverse calculation of level ground reaction coefficient

	Unit		Straight pile	Screw pile
D	m	Pile diameter	0.006	0.013
EI	kN-m^2	Flexural rigidity	0.006	
y_t	mm	Displacement of pile head	0.60	
H	kN	Lateral load	0.001	
L	m	Pile length	0.255	
β	m^{-1}	Characteristic value of pile	5.964	7.236
kh	kN/m^3	Lateral ground reaction coefficient	4841	

6. Conclusion

The following conclusions are obtained from this study;

1) The bearing capacity in the vertical direction is increased by the spiral blade, but there is not much influence on the bearing capacity in the horizontal direction in dry sand.
2) The horizontal resistance of the screw pile was expected to increase by integration with the surrounding ground in the soft viscous ground, but in the dry sandy ground there was no effect of integration with the surrounding ground. It is, therefore, necessary to evaluate the shape excluding spiral blade.
3) The influence of the ground disturbance during the installation operation and the type of ground was not considered in the proposed estimation method in the previous research (Isobe and Yamauchi, 2017), resulting in the errors for the estimation of the bearing capacity against the combined loading.

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