Bearing Capacity Recovery Rate of Square Steel Tubular Pipe Piles Based on Loading Test Results

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ABSTRACT

Several vertical loading tests were performed to establish the bearing capacity design formula of the square steel tube pile. At the same time, the relations between the bearing capacity of each pile and the final press-in force of each pile construction were measured. The set-up rate which is determined by the ratio of the bearing capacity and the final press-in force were calculated. The average set-up rate of 8 test piles is obtained around 2.3 both for the sandy ground and the clayey ground. Also the minimum value of the set-up rate is around 1.6 both for sandy and clayey ground. The minimum set-up rate of 1.6 is applied to the press-in construction control method to ensure each pile bearing capacity performance.

Keywords: *Steel pipe pile, Loading tests, Bearing capacity, Set-up rate, Construction control method*

1. Outline of this paper

This paper represents the bearing capacity design formula and the press-in piling construction control method of a newly developed square tubular steel pile called Kakuske-pile.

First we introduce the outline of Kakuske-pile and explain the several loading tests results in order to establish the design bearing capacity formula of Kakuske-pile.

Secondly, the bearing capacity recovery rate after piling construction date will be discussed from a viewpoint of the piling construction control.

Finally, DEM trial simulation will be applied to Kakuske –pile press-in construction procedure. As DEM modeling analysis for piles has not yet been a fully developed technique, the calculation results may not give us enough information to explain the set-up phenomena.

1.1. Introduction

In Japan there are several types of steel piles such as H-shape steel piles, round pipe steel piles, steel-concrete composite piles, and screw type steel piles and so on. Square tubular steel pipes have not been applied to foundation piles although some square precast concrete piles have been used for building foundations. Kakuske-pile which is made of square tubular steel pipe by press-in piling method was developed recently.

This paper describes the design bearing capacity formulation of Kakuske-pile and its construction control methods. The set-up rate which is defined by the ratio between the ultimate bearing capacity and the final press in resistance at the end of construction will be discussed based on the loading tests results.

2. Loading tests of Kakuske-piles

2.1. Test piles

To establish the design bearing capacity formula of the square tubular steel piles by press-in piling construction, 8 vertical loading tests have been performed in different construction sites. The test pile properties are shown in **Table 1** and **Table 2**. The pile toe of Kakuske-pile is closed ended by steel flat plate shown in **Fig. 1**, **Fig. 2** is the press-in piling construction site for houses.

Table 1. Loading test piles on sandy ground

NO	Site	Width (mm)	Wall thickness (mm)	Cross section area (mm^2)	Depth of pile toe (m)	Soil property at pile toe	N-value at pile toe
S-3	KR	100	3.2	100	15	Clayey fine sand	11.9
S-4	KR	125	2.3	156	5.8	Clayey fine sand	6.5
S-5	MK	50	1.6	25	5.5	Clayey fine sand	6
S-6	BD	125	3.2	156	8.73	Fine sand	3.4
S-7	NB	100	2.3	100	6.3	Clayey gravel	29.9

Table 2. Loading test piles on clayey ground

NO	Site	Width (mm)	Wall thickness (mm)	Cross section area (mm^2)	Depth of pile toe (m)	Soil property at pile toe	N-value at pile toe
C-3	KR	50	1.6	25	4	Clay	1.6
C-4	MK	125	3.2	156	7.65	Clay	5.6
C-5	NB	125	2.3	156	4.3	Clay	1.4

Fig. 1 Pile Tip of Kakuske-pile

Fig. 2 Press-in pile driver

2.2. Ground condition

Loading tests sites' ground conditions are shown in **Fig. 3** to **Fig. 6**. 8 loading tests of Kakuske-piles are performed in 4 test sites. The lengths of each test pile is represented next to the boring logs.

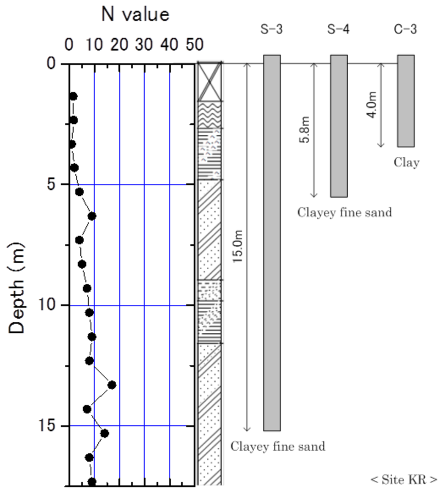

Fig. 3 SPT results of Loading test site KR

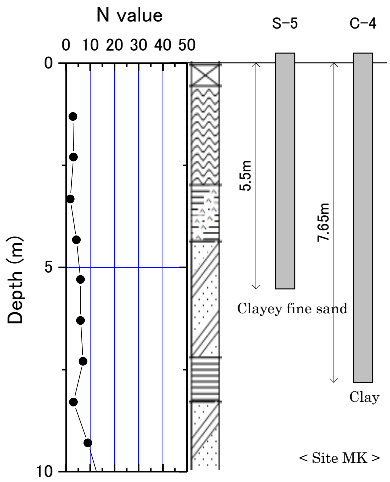

Fig. 4 SPT results of Loading test site MK

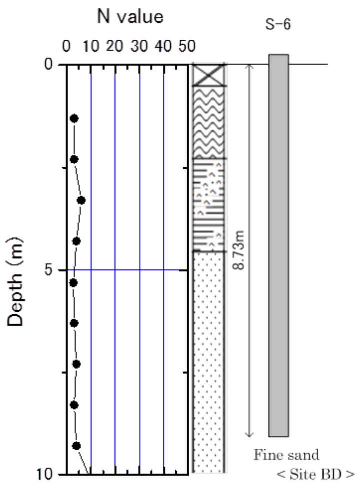

Fig. 5 SPT results of Loading test site BD

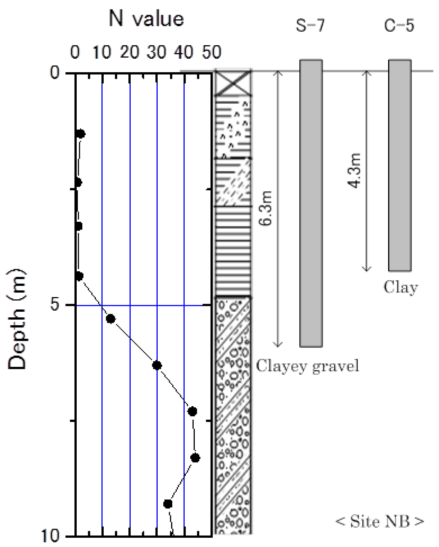

Fig. 6 SPT results of Loading test site NB

2.3. Test pile press in construction

Test piles of Kakuske-pile are pressed into the ground by ordinary piling machines which are equipped with 100-200kN hydraulic jacks. **Fig. 5** is a photograph of a construction scene at a loading test site.

Fig.7 Kakuske –pile driver

3. Loading tests results of Kakuske-piles

3.1. Load – Settlement Relations

Vertical static loading tests are performed according to the Japanese pile loading test standard(JGS,2012). The ultimate bearing capacity of pile toe is determined by measured axial force by strain gauges corresponding to the settlement of 10% equivalent diameter D of the piles. D can be calculated by D=2B/$\sqrt{\pi}$

Observed P-S relations are normalized by the following calculations.

$$\overline{P} = \frac{P_t}{N \times B^2} \qquad (1)$$

$$\overline{S} = \frac{S_t}{0.1 \times B} \times \frac{\sqrt{\pi}}{2} \qquad (2)$$

Where,

P_t: Axial force transferred to the pile tip

S_t : Pile toe settlement

B: Width of square pipe pile

$\overline{N}$: Averaged SPT –N value at the pile toe:

Normalized P-S relations at the pile tips are plotted in **Fig. 8** for sandy ground tests, **Fig. 9** for clayey ground. The ultimate bearing capacity equation for the pile tip is formulated as below.

$$R_a = q_p * A_p = \frac{\alpha}{3} * \overline{N} * A_p \qquad (3)$$

R_a : Allowable design capacity at pile toe kN

q_p : Pile tip capacity of allowable base kN/m^2

A_p : Pile tip effective area in m^2

$\overline{N}$:Averaged N value around the pile tip

α :Pile bearing capcity factor to N value

After **Fig. 8** and **Fig. 9** the bearing capacity factor of pile tip in Eq. (3) can be determined as 410 for sandy stratum and 450 for clayey bearing stratum as minimum value.

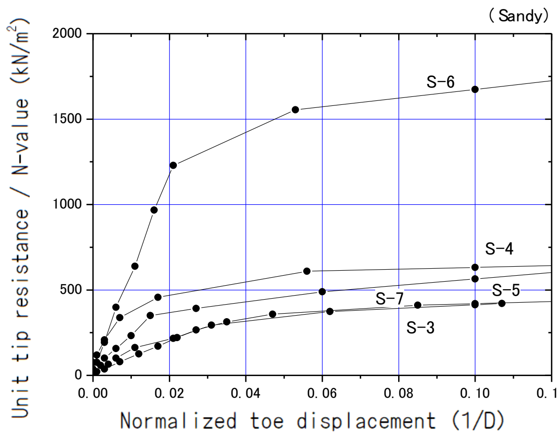

Fig. 8 Normalized P-S curves of sandy ground

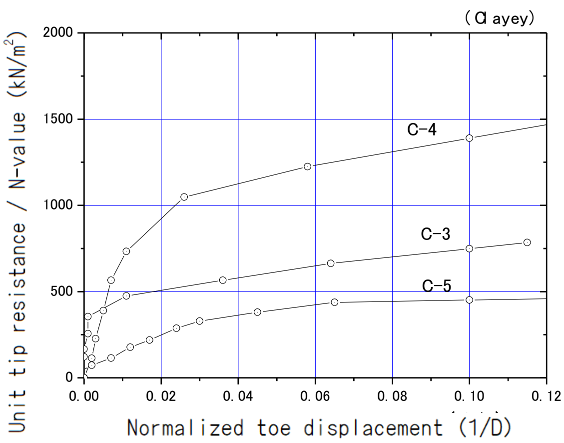

Fig. 9 Normalized P-S curves of clayey ground

3.2 Set-up rate between Bearing Capacity and the final press-in resistance

In **Table 3** and **Table 4**, the set-up rate which indicates the recovery rate of the bearing capacity after pile installation as defined by **Eq. (4)**.

$$SUR = \frac{R_u}{R_{EOD}} \tag{4}$$

SUR : Set-up rate

R_u : Ultimate bearing capacity of pile top (kN)

R_{EOD} : Final press in resistance at EOD (kN)

In **Table 3** and **Table 4** press-in resistance at EOD is measured by the hydraulic pressure gauge. Also, SLT denotes the static loading test.

From Fig.10 and Fig.11 the average set up rate for sandy ground was 2.3 and the minimum value of them was 1.59. Also the average set-up rate for clayey ground was 2.18 and the minimum value of them was 1.63.

Bearing capacity recovery rate of each pile with days after driving are plotted in **Fig. 12.** There seems to be quite small correlations between them.

The set-up rate must have some tendency with the duration days,permeability of soils, and the pile diameter. In **Fig. 13** the set-up rate is plotted to the days/D^2 ,in the same manner as proposed by Randolph & Wroth(1979).

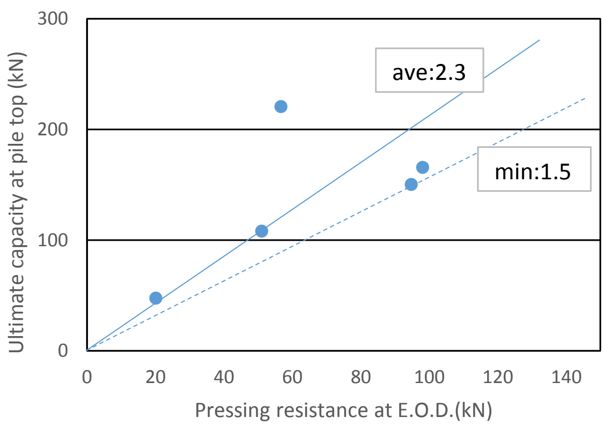

Fig. 10 Set-up Rate relations of sandy ground

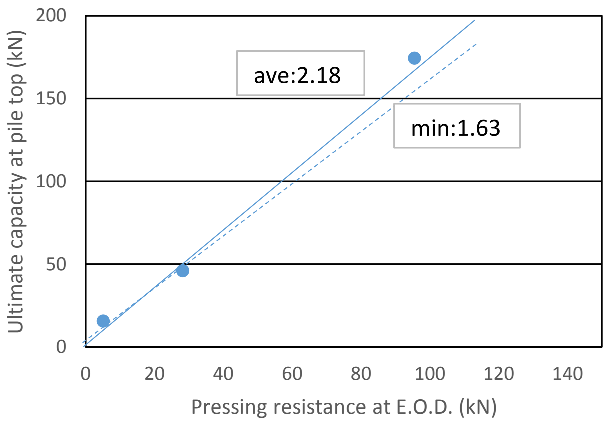

Fig. 11 Set-up Rate relations of clayey ground

Table 3. loading test summary of sandy ground

Sandy soil

	Width (mm)	Equivalent diameter (mm)	Wall thickness (mm)	Toe depth (m)	Soil property	Press-in resistance at E.O.D.(kN)	Ultimate capacity of SLT(kN)	Set up rate	Instration date	SLT date	Aging time (days)	Toe resistance (kN)	N-value at pile toe	α
S-3	100	113	3.2	15.00	Clayey fine sand	56.6	220.6	3.90	2015/5/26	2015/6/25	30	49.2	11.9	413
S-4	125	141	2.3	5.80	Clayey fine sand	51	108	2.12	2015/5/25	2015/9/25	123	64.2	6.5	632
S-5	50	56	1.6	5.50	Clayey fine sand	20.1	47.4	2.36	2015/5/29	2015/6/24	26	8.5	6.0	565
S-6	125	141	3.2	8.73	Fine sand	94.7	150.3	1.59	2015/5/27	2015/6/30	34	89.7	3.4	1674
S-7	100	113	2.3	6.30	Clayey gravel	98	165.8	1.69	2015/6/4	2015/6/10	6	125.6	29.9	420
							ave	2.33						
							min	1.59						

Table 4. loading test summary of clayey ground

Clayey soil

	Width (mm)	Equivalent diameter (mm)	Wall thickness (mm)	Toe depth (m)	Soil property	Press-in resistance at E.O.D.(kN)	Ultimate capacity of SLT(kN)	Set up rate	Instration date	SLT date	Aging time (days)	Toe resistance (kN)	N-value at pile toe	α
C-3	50	56	1.6	4.00	Sandy clay	5.1	15.7	3.08	2015/5/25	2015/6/26	32	3.1	1.6	749
C-4	125	141	3.2	7.65	Clay	95.5	174.4	1.83	2015/5/29	2015/6/23	25	121.5	5.6	1389
C-5	125	141	2.3	4.30	Clay	28.2	46.1	1.63	2015/6/4	2015/6/9	5	9.9	1.4	451
							ave	2.18						
							min	1.63						

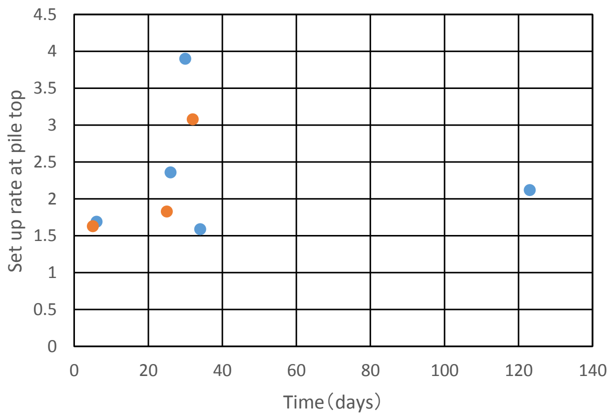

Fig. 12 Set-up rate to aging days

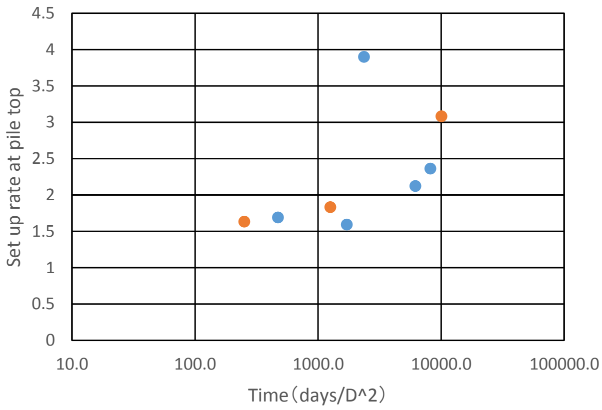

Fig. 13 Set-up rate to aging days/D^2

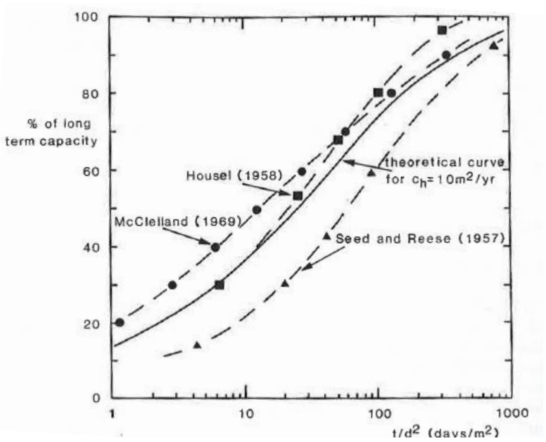

Fig. 14 Pile bearing capacity recovery rate with days

By **Fig. 13** we understand that the slightly better correlation between the set-up rate and the characteristic days. According to Randolph &Wroth, the pile set-up phenomenon can be calculated by the consolidation theory . They plotted the bearing capacity recovery rate as in **Fig. 14** by using the consolidation coefficient of 10m^2/year. Fujita&Ueda(1971) summarized many static loading test results from a viewpoint of the set-up rate, and formulated the bearing capacity recovery rate as in Eq. (5)., and the maximum set-up limited by 2.0.

$$\beta = 50(1 + 0.5\ell ogT) \quad (5)$$

β : Bearing capacity recovery rate (%)

T : Duration time after pile driving until SLT (days)

3.3 Press-in piling construction control method for Kakuske –pile

By considering the static loading tests and the set-up phenomena, we understand that the press-in piling resistance at EOD is strongly related to the bearing capacity after aging. After **Fig. 13** and other test results, reliable set-up rate is around 2 to 3.

The most advantage of the press-in piling construction method is that the simple and direct measurement of the final resistance of EOD of each pile . That is, Kakuske-piles are surely installed by observing their capacity at EOD. And multiplying the SUR$_c$ to the final press-in resistance, we could ensure the long-term capacity of the pile. Here, we choose 2.5 as SUR$_c$ for a construction control method.

$$R_{EOD} \geq \frac{R_{ud}}{SUR_c} \quad (5)$$

$$R_{ud} = 3 \times R_a \quad (6)$$

R_{EOD} : Final press in resistance at pile top at EOD

R_{ud} : Design ultimate bearing capacity at pile top

R_a : Allowable bearing capacity at pile top

SUR_c :Construction control set up rate (=2.5)

4. DEM simulation of pile press-in construction.

Recently DEM is considered to be effective method to understand the soil pile interaction problem such as pile driving. Here we tried to see how the press-in resistance varies with press-in velocity and the soil void ratio.

Model piles dimensions are shown in Table 5, DEM modeling factors such as particle elastic modulus, friction coefficient, dumping factor and so on are set after H.Kuwabara *et al.*,(2002).

Table 5. DEM press in piling model dimensions

Pile width	Soil model width	Dia. of perticle	penetration depth
125mm	1250mm	6.25mm	1000mm

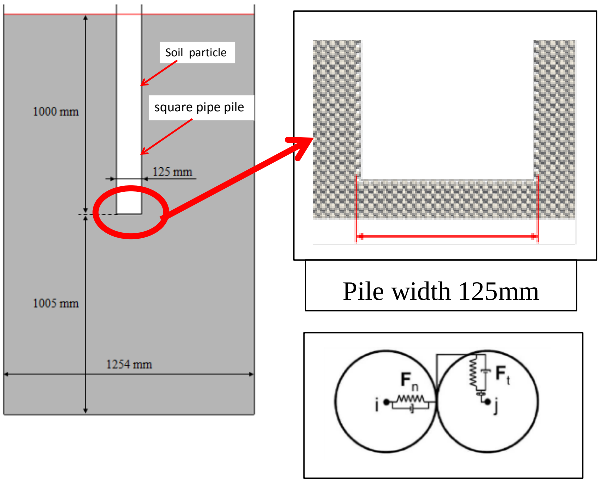

Fig. 15 Configuration of DEM simulation model

The configuration of the simulation pile and particle ground is shown in **Fig. 15**. As the soil was modeled by 6mm diameter, the pile tip is contacted by 20 particles.

Press-in penetration analyses were done by three different conditions as in **Table 6** by opensource DEM code called LIGGGHTS,2011(Kloss *et al.*,2012).

Table 6. DEM press in analysis conditions

case	particle size	press in velocity	comment
case-1	6.25mm	1.5m/min	quick pressing
case-2	6.25mm	0.5m/min	slow pressing
case-3	6.25mm&3.12mm	1.5m/min	dense sand

Fig. 16 and **Fig. 17** represent the relations between press in resistance and penetration length. It is clear that the penetration velocity does not have much impact to the resistance, i.e. bearing capacity. On the other hand, the particle arrangement has affected to the resistance much. **Fig. 18** shows the stress distribution around the pile toe. Slightly larger stress concentration was observed in case 3 after press-in piling, after press in piling.

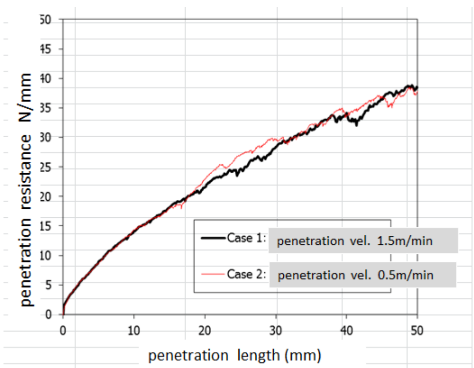

Fig. 16 Penetration resistance with displacement

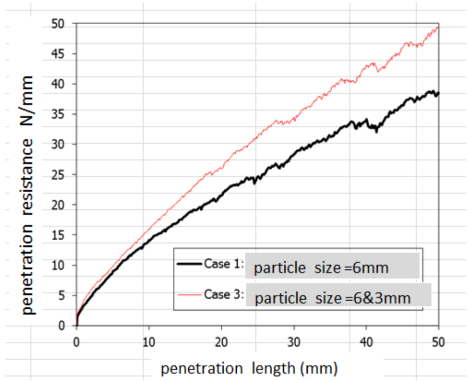

Fig. 17 Penetration resistance with displacement

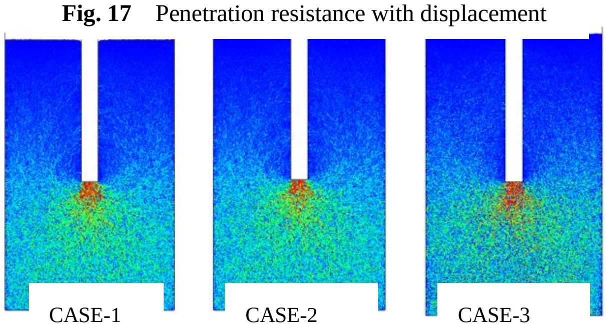

Fig. 18 DEM stress distribution around tip at EOD

5. Concluding & remarks

1) Bearing capacity design formula of square steel tubular pile was developed, by several SLT results.
2) Kakuske-pile press in piling control method was proposed by the set-up consideration based on consolidation process.
3) DEM analysis applied to the press in piling to see the velocity affection to the resistance.

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