Bearing Capacity and Driving Efficiency of Ecological Screw Pile: "Tsubasa Pile

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Abstract:

"Tsubasa PileTM" developed by JFE Steel is a steel screw pile which has the tip shape of two types, wing tip diameter of 1.5 to 3.0 times of the steel pipe, and an enlarged pile head structure for soft ground. This wide range of products makes it possible to select suitable specifications acoording to ground conditions. It has been increasingly used in various fields by taking advantage of large bearing capacities and environmentallyfriendliness such as driving without removing any soil and non-use of cement milk. In addition, JFE Steel is developing new technologies including the use of batter piles and the utilization of geothermal heat.

1. Introduction

In the evolution of foundation piles, various construction methods have been developed and used at actual construction sites. However, in the relationship between pile construction and the environment, focus of attention has been on problems such as noise and vibration during construction, treatment of surplus soil, groundwater pollution, etc. JFE Steel developed "Tsubasa PileTM," which is a screwed steel pipe pile with a toe wing mounted on the leading toe, in response to these issues. Because "Tsubasa PileTM" not only provides large bearing capacity (vertical bearing capacity, uplift resistance), but also has the important merit of being an ecological product, this innovative line of steel pipe piles has been adopted in diverse fields, including building foundations, highway bridge foundations, railway bridge foundations, and others, and is continuing to extend its sales record. This report describes the features of "Tsubasa PileTM."

2. Features of "Tsubasa PileTM"

2.1 General Items

2.1.1 Structure

"Tsubasa PileTM" is a steel pipe pile with a toe wing mounted on the leading toe of the steel pipe. The wingshaped part comprises two intersecting semicircular flat steel plates having a diameter 1.5 to 3.0 times the diameter of the steel pipe. Two types of tip shapes are available, one in which the hole (1/2 the diameter of the pipe) in the center of the wing is open and the steel plates intersect at the outer surface of the pipe, and the other in which the tip is completely closed and the plates intersect at the center of the pipe. These two types have been commercialized under the trade names "Tsubasa PileTM" (Open end) (**Fig. 1**) and "Tsubasa PileTM" (Closed end) (**Fig. 2**).

The "Tsubasa PileTM" line is also available as an



Fig. 1 Composition of "Tsubasa Pile[™]"(Open end)

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Fig. 2 Composition of "Tsubasa PileTM" (Closed end)



Photo 1 Enlarged pile head (Dp: 800 mm+1 200 mm)

Enlarged head type (**Photo 1**), in which the diameter of the steel pipe at the pile head is increased than that at the pile end part (maximum of 1.6 times larger is possible) and is joined by welding by way of a steel disk. This type can be used in soft ground, etc. where large horizontal resistance is necessary.

The specifications of these products have been standardized for each pile diameter and toe wing enlargement ratio based on experiments and finite element method (FEM) analysis, and can be selected corresponding to the conditions at the site.

2.1.2 Construction machinery

Placement of "Tsubasa PileTM" does not require special construction machinery, but rather, can be performed with construction machinery in general use. The machinery used differs, depending on the pile diameter and ground conditions, but is roughly classified as shown in **Fig. 3**. Views of the respective construction machinery are shown in **Photo 2**. As the general practice, with small diameter piles, the pile head part is rotated, and with large diameter piles, the pile body (casing) is rotated.

2.2 Range of Application

"Tsubasa PileTM" has received performance evaluations by General Building Research Corporation of Japan in the building construction field, by the Public

							D_{p}	(mn	n)						
100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600
								1	1	1					
	Bas	e ma	chine	ry											_
	Casing machinery														





Photo 2 Construction machinery

Works Research Center in the highway field, and by the Railway Technical Research Institute in the railway field¹⁻⁵). The range of application in these respective fields is shown in **Table 1**. Although the values differ in each field, this is because the timing and standards when "Tsubasa PileTM" was evaluated were different, and does not mean that this pile cannot be used in other fields of application.

2.3 Differences between Open End Type and Closed End Type

"Tsubasa PileTM" is available in two types, the open end type and the closed end type, and can be applied taking advantage of their respective features. Outlines of the two types are presented below.

2.3.1 Open end type

Practical application of the open end type began in 2007 with the aim of improving workability.

Because soil can enter the pipe during pile construction, this open end type features excellent workability in large-diameter piles (φ 700 mm and larger) and is particularly suitable for ground with a hard intermediate layer.

2.3.2 Closed end type

The closed end type was first use in practical applications in 1999 and now has an extremely large record of use. With a simple, high rigidity structure, it can be manufactured at low cost. The closed end type is mainly used in small- and medium-diameter piles (φ 609.6 mm and smaller).

2.4 Construction System

Construction of "Tsubasa PileTM" is performed by

Tumo	Field	Dian	neter	Max donth (m)	Upper row: Pile diameter (mm) Lower row: Magnification of toe wing			
Туре	Field	Min. (mm)	Max. (mm)	Max. depth (m)				
	Duilding	114.2	1 200	07	114.3-609.6			700-1 200
	Bunung	114.5		07	1.5-3.0		1.5-2.0	
On an and	Deed buildee	219.5	1 600	77	318.5–1 200		1 300–1 600	
Open end	Road bridge	318.5		//	1.5–2.0		1.5	
	Railway	400	1 600		400–1 600			
	bridge			_	1.5			
	Duilding	114.3	1 200	60	114.3–267.4	318.5-	-508.0	600-1 200
	Bunung				2.0-3.0	2.0-	-2.5	1.5-2.0
Closed and	Pood bridge	219.5	1 200	60	318.5–1 200			
Closed ella	Koad blidge	318.3	1 200	00	1.5–2.0			
	Railway	400	800		400-800			
	bridge	400		_	2.0			

Table 1	Scope of	application
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using general construction machinery. However, special know-how is necessary for reliable construction at diverse construction sites. A "Tsubasa PileTM Technical Society" was organized by JFE Steel and 9 pile construction companies (number as of May 2012) and is working to improve technical capabilities.

3. Ecological Construction Features

3.1 Environmental Impacts

3.1.1 No earth removal construction

When turning driving force (torque) is applied to "Tsubasa PileTM" at the ground surface, the pile pene-



Photo 3 Ground surface after construction



Fig. 4 Movement of soil during construction

trates the ground because the toe wing exerts a propulsion effect like that of a wood screw. In this process, soil corresponding to the volume of the pile is moved by the following (1) and (2). As a result, absolutely no soil is excavated aboveground from pile construction through the completion of construction (**Photo 3**).

- (1) Accompanying rotation of the toe wing, the soil below the wing is moved to above the wing, and inside the pile pipe, in the case of the open end type.
- (2) Soil that has been moved to above the wing is compacted laterally by the pipe.

The process of the above-mentioned soil movement during construction is shown schematically in **Fig. 4**.



Fig. 5 Investigation points



Fig. 6 Soil investigation results



Fig. 7 Measurement of noise and vibration

An example comparing the measured ground density and *N*-value around the pile before and after construction is shown in **Fig. 5** and **Fig. 6**. From the fact that density and the *N*-value increased at points near the pile (A, B) after construction, it can be understood that the ground around the pile undergoes compaction accompanied by the pile construction.

As merits of no earth removal construction, not only is the cost of treating surplus soil zero, there is no effect on vehicular traffic in the area because dump trucks are not necessary for disposal of the soil, and construction is also possible at former factory sites, etc., where the ground may be affected by soil pollution.

3.1.2 No use of cement milk

In order to realize a large toe bearing capacity, the general practice with conventional piles requires construction of foot protection bulb in the support layer, and in the case of cast-in-place piles, the full length of the pile is constructed of concrete. In either case, pollution of the groundwater by cement milk is unavoidable.

However, with "Tsubasa PileTM," absolutely no cement milk is required because the toe bearing capacity is supplied by the rigidity of the toe wing itself. Therefore, piles can be constructed without polluting the groundwater, and construction is possible in areas that use well water and areas where river bed water or confined (artesian) water exists.

3.1.3 Low noise/low vibration

Because "Tsubasa PileTM" is constructed by screwing a steel pipe into the ground, low noise/low vibration construction is possible, without generating the loud



Fig. 8 Geothermal air-conditioning system

impact noise associated with conventional pile-driving. **Figure 7** shows the results of measurements of noise and vibration (4 sites) during actual pile construction. In all cases, it can be understood that the values are substantially lower than the limit values (noise: 85 dB, vibration: 75 dB).

3.2 Development to New Applications

With the closed end type, added value can be given to ordinary support piles by utilizing the space inside the pipe after construction is completed. The following are actual examples of value-added applications.

3.2.1 Geothermal heat utilization air-conditioning system

The temperature in the ground is almost constant throughout the year, being lower than atmospheric temperature in summer and higher in winter. Efficient airconditioning is possible if geothermal heat can be used as a heat source for a heat pump system. However, the high cost of installing such systems, for example, the cost of excavation, etc., is an issue. A geothermal heat utilization air-conditioning system which greatly reduces installation costs is possible by using "Tsubasa PileTM" as both a foundation pile and a pile with a heat-exchange function. A schematic diagram is shown in **Fig. 8**.

3.2.2 Treatment of surplus soil from construction

At construction sites, generation of surplus soil from various processes other than pile construction is possible. If this surplus soil is placed inside "Tsubasa PileTM" after pile construction, disposal is possible without discharging the surplus soil off-site. This can significantly reduce soil transportation and treatment costs.

4. Bearing Capacity Performance of "Tsubasa PileTM"

An extremely large toe bearing capacity can be expected with "Tsubasa PileTM" because bearing capacity is supplied by the surface area of the toe wing, which has a diameter 1.5 to 3.0 times that of the pile pipe. Bearing capacity performance comprises two types,

namely, vertical bearing capacity (compressive load) and uplift resistance (tensile load). These two types of bearing capacity are confirmed by large-scale load tests, respectively. However, because the standards differ depending on the field of application, the equations used in evaluations also differ. Since the highway field (open end type, closed end type) and the railway field (open end type) use similar construction methods, a unified bearing capacity equation has been proposed as "screwed steel pipe pile"^{6,7)}.

4.1 Vertical Bearing Capacity (Compressive Load)

A combined total of 36 static axial compressive load tests was performed with open end type and closed end type "Tsubasa PileTM," and a design vertical bearing capacity equation was established based on the test results. The conditions of the compressive load tests are shown in **Fig. 9**.

Outlines of the design equations in each field are presented in Sections 4.1.1 to 4.1.3. The common symbols are given below:

- *R*_u: Ultimate vertical bearing capacity of pile head (kN)
- D_p : Diameter of pile (m)
- D: Diameter of enlarged pile head part (m)
- $D_{\rm w}$: Diameter of toe wing (m)
- $D_{\rm wi}$: Inner diameter of toe wing (m), $D_{\rm wi} = 0.5 D_{\rm p}$
- $L_{\rm s}$: Total length in contact with sandy ground (m) However, excludes the section $1D_{\rm w}$ from the pile toe.
- $L_{\rm c}$: Total length in contact with clay ground (m) However, excludes the section $1D_{\rm w}$ from the pile toe.
- L_i : *i*th layer thickness considering surface frictional force (m)
- Ψ : Circumference of pile (m)
- $\Psi = \pi \cdot D_p$ (General part of conventional type/ enlarged pile head type piles)
- $\Psi = \pi \cdot D$ (Enlarged pile head part of enlarge pile head type pile)



Fig. 9 List of compressive load tests

4.1.1 Building construction field

Vertical bearing capacity is evaluated by using the following equation as a standard.

$$R_{\rm u} = \alpha \cdot \overline{N} \cdot A_{\rm p} + (\beta \cdot \overline{N_{\rm s}} \cdot L_{\rm s} + \gamma \cdot \overline{q_{\rm u}} \cdot L_{\rm c}) \cdot \Psi$$
(1)

α: Bearing capacity coefficient of pile toe (common to sand and gravel)

Open end type (α =150), Closed end type (α =132)

 β : Surface friction coefficient of pile in sandy ground

Open end type and closed end type (β =2.0)

- γ : Surface friction coefficient of pile in clay ground Open end type and closed end type (γ =0.5)
- \overline{N} : Mean value of number of blows in standard penetration test of ground in range of $1D_w$ below and $1D_w$ above pile toe (times) Open end type: $12 \le \overline{N} \le 60$ Closed end type: $13 \le \overline{N} \le 60$
- $A_{\rm p}$: Effective cross-sectional area of toe of foundation pile

Open end type:

$$A_{\rm p} = (1.40 - 0.25 \times D_{\rm w}/D_{\rm p}) \times \pi/4 \times (D_{\rm w}^2 - D_{\rm wi}^2)$$

Closed end type: $A_{\rm p} = \pi/4D_{\rm w}^2$

 $\overline{N_s}$: Mean number of blows in standard penetration test for sandy soil (times) Open end type: 2 ≤ $\overline{N_s}$ ≤ 30

Closed end type: $4 \le \overline{N_s} \le 30$

 $\overline{q_u}$: Mean value of uniaxial compressive strength of clay ground (kN/m²) Open end type: 23 ≤ $\overline{q_u}$ ≤ 200

Closed end type: $43 \le q_u \le 200$

4.1.2 Highway field

Vertical bearing capacity is evaluated using the following equation as a standard. This is the equation for the screwed steel pipe pile and is the same for both the open end type and the closed end type.

$$R_{\rm u} = q_{\rm d} \cdot A_{\rm w} + \Psi \cdot \Sigma \left(L_i \cdot f_i \right)$$
(2)

 q_d : Ultimate bearing capacity of pile toe (kN/m²) By type of ground: Sandy, 120N for 1.5× wing, 100N for 2.0× wing,;

Gravel, 130N for $1.5 \times$ wing, 115N for $2.0 \times$ wing,

- *N*: *N*-Value of ground at pile toe ($N \le 50$)
- $A_{\rm w}$: Projected area of wing (m²) $A_{\rm w} = \pi/4D_{\rm w}^2$
- f_i : Maximum surface frictional force of *i*th layer, considering surface frictional force (kN/m²) Sandy soil: $3N (\leq 150)$ Clay soil: *c* or $10N (\leq 100)$

- c: Viscosity (kN/m²)
- N: N-Value of ground at pile surface

4.1.3 Railway field

Vertical bearing capacity is evaluated using the following equation as a standard. For the open end type, this is the equation for the screwed steel pipe pile.

- q_{tk} : Standard bearing capacity of pile toe (kN/m²) (Open end type) 150N ($\leq 10~000$) (Common for sand and gravel)
 - *N*: Minimum *N*-value of the section $1D_p$ above and $3D_p$ below pile toe
 - (Closed end type) sand: $75N (\leq 6\ 000)$,
 - Gravel: $75N (\leq 7500)$
- N: N-Value in vicinity of pile toe
- A_t : Area of pile toe (m²)
 - Open end type: $A_t = \pi/4 \times (D_w^2 - D_{wi}^2)$
 - Closed end type: $A_t = \pi/4D_w^2$
- $r_{\rm fk}$: Standard surface bearing capacity (kN/m²) (Open end type) Sandy soil: 2.5N (≤100), Clay soil: 5N (≤100) or 0.3c (≤100) (Closed end type) Sandy soil: 2N (≤100), Clay soil: 4N (≤100)
 - *N*: *N*-Value of ground at pile surface, *c*: Viscosity (kN/m²)

4.2 Uplift Resistance (Tensile Load)

A combined total of 10 tensile load tests was performed with the open end type and closed end type of "Tsubasa PileTM." A design uplift resistance equation was established based on the results of these tests. The conditions of the tensile load tests are shown in **Fig. 10**.

Outlines of the design equations in the respective fields are presented in Sections 4.2.1 to 4.2.3. The common symbols are as follows:

- R_t : Ultimate uplift resistance of pile head (kN)
- D_p : Diameter of pile (m)
- D: Diameter of enlarged pile head part (m)
- $D_{\rm w}$: Diameter of toe wing (m)
- $L_{\rm s}$: Total length in contact with sandy ground (m) However, excludes the section $2D_{\rm w}$ from the pile toe.
- $L_{\rm c}$: Total length in contact with clay ground (m) However, excludes the section $2D_{\rm w}$ from the pile toe.
- Ψ : Circumference of pile (m)
 - $\Psi = \pi \cdot D_p$ (General part of conventional type/ Enlarged pile head type piles)
 - $\Psi = \pi \cdot D$ (Enlarged pile head part of enlarge



Fig. 10 List of tensile load tests

Table 2 Uplift coefficient, β

Internal friction angle of support layer, φ	Uplift coefficient, β
35°	2.16
36°	2.40
37°	2.65
38°	2.89
39°	3.14
40°	3.38
41°	3.77
42°	4.16
43°	4.55
44°	4.93
45°	5.30

pile head type pile)

- γ_i : Effective unit weight of soil of *i*th layer from ground surface higher than support layer (kN/m³)
- L_i : Thickness of *i*th layer from ground surface higher than support layer (m)
- y: Effective unit weight of soil of support layer (kN/m³)
- *H*: Penetration depth to height that the local shear fracture region extends above the wing (m) Assuming $H \leq 2.5D_w$ (Highway field) Assuming $H \leq 1D_w$ (Railway field)
- β : Uplift coefficient. Expresses the coefficient of resistance of the shear fracture plane; A value corresponding to the internal friction angle of the support layer is applied (**Table 2**).
- φ : Internal friction angle of support layer (°)

4.2.1 Building construction field

Uplift resistance is evaluated using the following equation as a standard. This equation is the same for the open end type and the closed end type.

$$R_{t} = \kappa \cdot \overline{N_{t}} \cdot A_{tp} + (\lambda \cdot \overline{N_{s}} \cdot L_{s} + \mu \cdot \overline{q_{u}} \cdot L_{c}) \cdot \Psi$$
(4)

κ: Bearing capacity coefficient of pile toe (common to sand and gravel)

$$\begin{split} \kappa &= 63 \ (0.114 \ 3 \leq D_{\rm p} \leq 0.609 \ 6) \\ \kappa &= 44 \ (0.7 \leq D_{\rm p} \leq 1.2) \end{split}$$

 λ : Surface frictional force coefficient of pile in sandy ground

$$\lambda = 0.05 \ (0.114 \ 3 \le D_p \le 0.609 \ 6)$$

$$\lambda = 0.03 \ (0.7 \le D_{\rm p} \le 1.2)$$

 $\mu :$ Surface frictional force coefficient of pile in clay ground

$$\begin{split} \mu &= 1.02 \; (0.114 \; 3 \leq D_{\rm p} \leq 0.609 \; 6) \\ \mu &= 0.71 \; (0.7 \leq D_{\rm p} \leq 1.2) \end{split}$$

 $\overline{N_t}$: Mean value of the number of blows in standard penetration test of ground in range of $2D_w$ above pile toe (times)

$$12 \le N_{\rm t} \le 60$$

$$A_{tp}$$
: Area of protruding toe wing (m²)

$$A_{\rm tp} = \pi/4 \times (D_{\rm w}^2 - D_{\rm wi}^2)$$

- $\overline{N_s}$: Mean value of the number of blows in standard penetration test of sandy ground (times) $6 \le \overline{N_s} \le 30$
- $\overline{q_u}$: Mean value of uniaxial compressive strength of clay ground (kN/m²) $50 \le \overline{q_u} \le 200$

4.2.2 Highway field

Uplift resistance is evaluated using the following equation as a standard. This equation is the same for the open end type and the closed end type.

$$R_{t} = \pi \cdot D_{w} \cdot (\Sigma \gamma_{i} \cdot L_{i} + \gamma \cdot H/2) \cdot H \cdot \beta \cdot \tan \varphi + \Psi \cdot \Sigma (L_{i} \cdot f_{i})$$
(5)

It should be noted that the first term in Eq. (5) is the anchor effect of the pile toe. The mechanism of the anchor effect (uplift resistance) attributable to the toe wing is considered to be as shown in **Fig. 11**. The second term is the same at that for vertical bearing capacity.



Fig. 11 Anchor effect of toe wing

4.2.3 Railway field

Uplift resistance in the railway field is evaluated by Eq. 6, which is the same as Eq. (5) in Section 4.2.2. However, the closed end type is considered to be expressed by only the second term.

$$R_{\rm t} = \pi \cdot D_{\rm w} \cdot (\Sigma \gamma_i \cdot L_i + \gamma \cdot H/2) \cdot H \cdot \beta \cdot \tan \varphi + \Psi \cdot \Sigma (L_i \cdot r_{\rm fk})$$
(6)

4.3 Application to Batter Piles

Batter pile construction is comparatively easy because "Tsubasa PileTM" penetrates the ground by a screwing action. Since horizontal displacement can be suppressed by using batter piles, substantial cost reductions, such as reduction of the number of piles, etc., can be expected, depending on the load conditions.

This section describes the outline of a construction test which was carried out using a crawler type pile

Table 3 Specification of test

Туре	Inclination Diangle (°)		Diameter (mm)	Magnification of toe wing	Depth (m)	Support layer
Open end	pen end 15		600	2.0	21.51	Gravel



Fig. 12 Soil profile and pile shape



Photo 4 Construction test of batter plie

Table 4	Measurement	of	inclination	angle
	modouronnon	<u> </u>	monnation	angio

Donth (m)	Inclination angle (°)						
Depui (iii)	Direction of slope	Direction of perpendicular to slope					
0.0	15.0	0.4					
7.25	15.0	_					
9.87	15.0	0.2					
9.87	15.0	0.5					
15.00	15.0	0.2					
21.51	15.2	0.0					

driver, which is a general type of construction machinery. Piles up to approximately $\varphi 600$ mm were constructed. The test conditions are shown in **Table 3**, the soil profile and pile shape are shown in **Fig. 12**, and views of the construction test are shown in **Photo 4**.

In this test, the control target value of the inclination angle was set at $15^{\circ} \pm 0.5^{\circ}$, and piles were placed while measuring the angle periodically.

The results of measurements are shown in **Table 4**. A nearly constant angle was maintained during construction, confirming the applicability of "Tsubasa PileTM" to batter piles. Similar construction is also possible with whole circumference rotary machines, and "Tsubasa

PileTM" already has a record of application in actual construction by this method.

5. Conclusion

This report described the features of "Tsubasa PileTM," centering on environmental aspects and bearing capacity. Although "Tsubasa PileTM" has a construction record which already exceeds 500 projects, the authors will continue to work to increase these results in the future.

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