A study on the bearing capacity of steel pipe piles with tapered tips

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\section*{ABSTRACT}

The problem that occurs during open-ended steel pipe pile installation is that soil enters the pipe and develops frictional resistance that further prevents soil intrusion, causing plugging and increased piling resistance. The steel pipe pile with tapered tip (tapered tip pile) restrains plugging and piling resistance. To apply the tapered tip pile as end-supported piles, it is essential to clarify the bearing capacity mechanism suitable for tapered shapes. In addition, it is not possible to apply the bearing capacity mechanism of the flat tip pile (straight pile). The purpose of this paper is to reveal the piling performance and the bearing capacity by experiment and to propose the bearing capacity model based on the mechanism in a fully plugged mode. Experiments were conducted on model-tapered pipe piles installed in sands with different soil conditions to investigate the effects of the pile shape on piling performance and bearing capacity. Extending the combination theory of Prandtl and cavity expansion, bearing capacity model and formula incorporating shape parameters were derived. Theoretical values were good agreement with the experimental results.

\textbf{Keywords:} tapered piles, end bearing capacity, prandtl theory, sands

\section*{1 INTRODUCTION}

The problem during open-ended piles installation is that soil enters piles and develops frictional resistance that further prevents soil intrusion, causing plugging and increased piling resistance. The tapered tip piles that we have proposed control the amount of soil entering piles, pressure of pile tip, and plugging. Thus, reducing piling resistance and improving piling has been considered.

As piles support structures, its bearing capacity has to be clarified. The bearing capacity of straight piles is calculated from empirical formula that is supported by many accumulated data (Japan Road Association 2014a). However, the tapered tip piles whose tip shapes have changed cannot be supported by these data. Therefore, it is necessary to propose the bearing capacity formula based on the bearing capacity mechanism in a fully plugged mode. End bearing capacity of straight piles is divided into resistance of two parts: the pipe wall and the inner soil part (David et al. 2000). But, end bearing capacity of tapered tip piles is divided into resistance of three parts: the tapered part, the pipe wall, and the inner soil part. The inner soil part comprises two failure modes: partially plugged and fully plugged. Inner soil is broken in case of a partially plugged mode. Soil under a pile is broken in case of a fully plugged mode. In many cases, piles are used in a fully plugged mode. In a fully plugged mode, the pipe wall is integrated into the inner soil part.

The purpose of this paper is to reveal the piling performance and the bearing capacity by experiment and to propose the bearing capacity model based on the mechanism in a fully plugged mode. But we do not cover the mechanism with a partially plugged failure mode.

\section*{2 OUTLINE OF THE TAPERED TIP PILE}

The tapered tip piles are shown in Figure 1. These shapes are uniquely determined by two parameters either from opening ratio $\alpha$, taper angle $\beta$, or taper length $l$. $\alpha$ and $\beta$ is defined as follows

\begin{equation}
\alpha = \frac{D_t}{D} \times 100
\end{equation}

\begin{equation}
\beta = \tan^{-1}\left(\frac{l}{(D - D_t)/2}\right)
\end{equation}

Here, $D$ is the pipe shaft diameter and $D_t$ is the tip diameter shown in Figure 1.
3 REVIEW OF PREVIOUS STUDY

3.1 Bearing capacity theory of straight piles

There are three bearing capacity theories of straight piles; Prandtl, cavity expansion, and a combination of Prandtl and cavity expansion.

Prandtl theory regards soil as a rigid-plastic body (Terzaghi 1943 and Meyerhof 1956). Without considering the effect of compressibility and horizontal stress in soil, slip surface is occurred. Terzaghi proposed that a wedge under a pile tip pushes a logarithmic spiral slip surface that was suppressed by a vertical soil pressure, similar to a theory for shallow foundation. Meyerhof proposed that a logarithmic spiral slip surface was developed on the upper side of pile tip.

Cavity expansion theory regards soil as a uniform isotropic elastic-plastic body (Vesic et al. 1977 and Yamaguchi 1973). The cavity is regarded as a three-dimensional sphere or a two-dimensional cylinder. The ultimate pressure necessary to inflate the cavity is the bearing pressure of pile tip.

The combination theory consists of Prandtl theory and cavity expansion theory (Vesic 1972 and Takano et al. 1979). Similar to Prandtl theory, the wedge under a pile tip pushes the logarithmic spiral slip surface. The outside area of the logarithmic spiral slip surface is based on the cavity expansion theory.

3.2 Bearing capacity theory of tapered piles

Theories of tapered pile such as the cone tip of cone penetration test (CPT) and piles that taper toward the distal end from the pile head (full-length tapered pile) were proposed.

For the cone tip, the combination theory of Prandtl and cavity expansion was proposed (Salgado 2003). The cone tip same as the wedge pushed the logarithmic spiral slip surface and the outside area was based on the cavity expansion theory. This theory was almost same as the straight pile theory.

For the full-length tapered pile, the cylindrical cavity expansion theory was proposed (Manandhara et al. 2013 and Tominaga et al. 2006). This theory is considered below. As cylinder inflates, the pile diameter is gradually expanding with piling. The pile displaces soil particle. Horizontal stress of soil is increased.

4 EXPERIMENTAL DETAILS

The purpose of this experiment is to understand the piling performance and bearing capacity of the tapered tip piles.

4.1 Experimental equipments

A soil tank and a piling-loading machine are shown in Figure 2 and its specifications are given in Table 2. To capture the effect of the taper shape on the bearing capacity, five test piles were used. The pipe shaft diameter \( D \) is 76.3 mm. The opening ratio \( \alpha \) is 70%-100% (Straight). The taper length \( l \) is 22.9 mm. The pipe thickness \( t \) is 3.2 mm. Four bits are mounted at the pile tip.

| Table 1. Experimental equipments |
|----------------------------------|
| Soil Tank | Inner Diameter (mm) | Height (mm) |
| Piling-Loading Machine | Maximum Vertical Force (kN) | Maximum Torque (kN·m) | Rotational Speed (rpm) | Maximum Stroke (mm) |
|-------------------------|-----------------|---------------|-----------------|-----------------|
| Test Pile | 482 | 736 |
| Loading Machine | 100 | 6.5 | 0-10 | >1000 |

Fig. 2. Experimental equipments

4.2 Test piles

Test piles are shown in Figure 3 and its specifications are given in Table 2. To capture the effect of the taper shape on the bearing capacity, five test piles were used. The pipe shaft diameter \( D \) is 76.3 mm. The opening ratio \( \alpha \) is 70%-100% (Straight). The taper length \( l \) is 22.9 mm. The pipe thickness \( t \) is 3.2 mm. Four bits are mounted at the pile tip.

| Table 2. Test piles |
|---------------------|
| Pile ID | Shaft Diameter \( D \) (mm) | Opening Ratio \( \alpha \) | Tip Diameter \( D_1 \) (mm) | Taper Length \( l \) (mm) | Pile Thickness \( t \) (mm) |
| Straight | 100 | 76.3 | - |
| 95-0.3 | 95 | 72.5 |
| 90-0.3 | 90 | 68.6 | 22.9 | 3.2 |
| 80-0.3 | 80 | 61.0 |
| 70-0.3 | 70 | 53.4 |
4.3 Soil conditions
Soil conditions are shown in Table 3. Soil was produced by vibration compaction while falling in air. Soil pressure conditions are listed in Table 4. Soil was pressurized to a predetermined pressure by the water at the top and side surface of the soil tank.

Table 3. Soil conditions (lode silica sand No. 7)

| Density of soil particle, $\rho_s$ (g/cm$^3$) | 2.653 |
| Mean grain size, $D_{50}$ (mm) | 0.1823 |
| Coefficient of uniformity, $U_c$ | 1.553 |
| Maximum void ratio, $e_{\text{max}}$ | 0.981 |
| Minimum void ratio, $e_{\text{min}}$ | 0.576 |
| Maximum dry density, $\rho_{\text{dmax}}$ (g/cm$^3$) | 1.683 |
| Minimum dry density, $\rho_{\text{dmin}}$ (g/cm$^3$) | 1.339 |
| Relative density, $D_r$ (%) | $\geq 80$ |

4.4 Measurement
To capture the effect that the tapered shape on the piling efficiency, the torque and vertical load were measured during the piling test. To capture the effect of tapered shape on the bearing capacity, vertical load was measured during the vertical bearing capacity test. In addition, to capture the effect of plugging on the piling efficiency and the bearing capacity, inner soil height and piling depth were measured.

4.5 Piling and loading conditions
The piling and loading conditions are given in Table 5. The piling and loading process were repeated multiple times using test piles listed in Table 2. In the piling process, the rotation speed was 4 rpm and the vertical speed was 10 mm/min. In the loading process, the vertical speed was 2 mm/min. Cases A and B were repeated three times to 8.0D. Cases C and D were repeated twice to 6.0D.

Table 5. Piling and loading conditions

| Test | Vertical Speed (mm/min) | Rotation (rpm) | Depth (D) |
|------|-------------------------|----------------|-----------|
| Rotation and Press in | 10 | 4 | 0.0-3.8 |
| Loading | 2 | 0 | 3.8-4.0 |
| Rotation and Press in | 10 | 4 | 4.0-5.8 |
| Loading | 2 | 0 | 5.8-6.0 |
| Rotation and Press in | 10 | 4 | 6.0-7.8 |
| Loading | 2 | 0 | 7.8-8.0 |

5 RESULTS AND DISCUSSION
The relation between depth and inner soil height, and the vertical load and torque of Case C is shown in Figure 4. The tapered tip piles are compared with the straight pile with respect to the opening ratio.

5.1 Plugging
During the open-ended pile installation, soil enters the pile and develops frictional resistance to prevent further soil intrusion, causing the piling resistance and bearing capacity increase.

The function of the degree of plugging, which is called the incremental filling ratio ($IFR$) has been proposed (Paik et al. 2004). $IFR$ is the ratio of the increment of inner soil height to the increment of pile penetration depth and is defined as follows

$$IFR = \frac{\Delta h}{\Delta z} \times 100(\%) \quad (3)$$

Here, $\Delta h$ is increment of inner soil height ($h$) and $\Delta z$ is increment of pile penetration depth ($z$).

If $IFR$ is applied to the tapered tip piles, $IFR$ is calculated smaller than the actual degree of plugging. The reason is that the opening area of pile tip and the volume of soil entering the pile are small. We proposed a new function called the incremental filling ratio volume ($IFR_v$), which is the ratio of multiplying increment of the inner soil height to straight area to multiplying the increment of pile penetration depth to the tip opening. $IFR_v$ is the function to correct the soil volume and is defined as follows

$$A_{ps} = \frac{[(D - 2t)^2\pi]}{4} \quad (4)$$

$$A_{pt} = \frac{[(\alpha/100 \times D - 2t)^2\pi]}{4} \quad (5)$$

$$IFR_v = \frac{\Delta hA_{ps}}{(\Delta zA_{pt})} \times 100(\%) \quad (6)$$

![Experimental results (Case C)](image-url)
In this paper, if $IFR_v$ is 20 or less, inner soil is regarded as fully plugged mode.

The depth at which the fully plugged occurred is given in Table 6. As the opening ratio decreases, the depth increases in all cases. Case C is shown as a representative example. The depth increases by 1.3D in 95-0.3 “opening ratio 95%,” and increases by 2.0D in 90-0.3 “opening ratio 90%,” and increases by 2.9D in 80-0.3 “opening ratio 80%,” compared with the straight “opening ratio 100%.” Furthermore, 70-0.3 “opening ratio 70%” is not plugged even at 6.0D. Moreover $IFR_v$ of 70-0.3 at 6.0D is 41%.

The slope of the inner soil height between 3.0D and the origin is shown in Figure 4. As the opening ratio decreases, the slope decreases in all cases.

Based on these results, it is understood the tapered tip piles inhibit generation of plugging.

Table 6. Depth at which fully plugged occurred (all cases)

| Depth (D) | Soil conditions |
|-----------|-----------------|
| Straight  | A    | B    | C    | D    |
| 95-0.3    | 4.1D | 4.2D | 2.9D | 3.2D |
| 90-0.3    | 4.5D | 4.5D | 4.2D | 4.4D |
| 80-0.3    | -    | -    | 5.8D | 5.8D |
| 70-0.3    | 5.7D | 7.0D | 6.0D | 6.0D |

5.2 Piling performance

In the rotation and press-in method, piling resistance is evaluated by a vertical force and torque. The vertical force and torque of Case C are shown in Figure 5. As a representative example, Figure 5 shows the results of straight pile and 70-0.3 at 2.0D, 3.8D and 5.8D.

At 2.0D, Figure 5 shows state in which two piles are partially plugged. The vertical force increases by 1.1 kN and the torque increases by 0.07 kNm in 70-0.3, as compared with those of the straight pile. This is because the resistance of the tapered tip part is dominant.

At 3.0D, Figure 5 shows the state in which the straight pile is fully plugged. The vertical force decreases by 1.9 kN and the torque decreases by 0.02 kNm in 70-0.3, as compared with those of the straight pile. This is because the tapered tip piles decrease the generation of plugging, as described in Section 5.1.

At 5.8D, Figure 5 shows the final state. The vertical force and the torque of the straight pile are almost similar to those at 3.0D. This is because the fully plugged occurs and the resistance surface is not developed. The vertical force decreases by 1.0 kN and the torque decreases by 0.01 kNm in 70-0.3, as compared with the straight pile, for the same reason at 3.0D.

These results indicate that the tapered tip piles reduce the piling resistance than the straight pile because the tapered tip piles decrease the generation of plugging.

5.3 Bearing capacity

The bearing capacity is shown in Table 7. The bearing capacities of the tapered tip piles are in the range –20% to +10% in all cases, as compared with those of the straight pile. Case C is shown as a representative example. The bearing capacity decreases by 96% in 95-0.3, decreases by 89% in 90-0.3, and decreases by 91% in 80-0.3, and increases by 104% in 70-0.3, as compared with those for the straight piles.

Thus, the bearing capacity of the tapered tip piles and the straight pile is equivalent. Although the tapered tip piles decrease plugging and the bearing capacity by plugging decreases, the tapered tip parts compensate for the bearing capacity.

Table 7. Bearing capacity (all cases)

| Bearing Capacity (kN) | Soil conditions/Test conditions |
|-----------------------|-------------------------------|
| A                     | B    | C    | D    |
| Straight 95-0.3        | 16.5 | 21.6 | 37.5 | 55.2 | 14.1 | 22.3 |
| 90-0.3                | 16.7 | 21.2 | 38.3 | 50.9 | 13.5 | 23.9 |
| 80-0.3                | 17.7 | 23.5 | 41.2 | 57.6 | 12.5 | 20.8 |
| 70-0.3                | -    | -    | 40.2 | 52.0 | 14.7 | 21.6 |

6 BEARING CAPACITY THEORY OF STEEL PIPE PILES WITH TAPERED TIPS

Tapered tip pile is a middle shape of the straight pile and the cone tip of CPT. The bearing capacity model of the tapered tip piles is used a combination theory of Prandtl and cavity expansion.

6.1 Bearing capacity model

The bearing capacity model of the tapered tip piles is shown in Figure 6. From the pile to the logarithmic spiral surface is Prandtl theory area. The outside area of the logarithmic spiral slip surface is the cavity expansion theory area. The total bearing capacity $R$ is the addition of the inner soil part resistance and the tapered tip resistance from Figure 6 and Equation 7.

$$R = R_t + R_s$$  \hspace{1cm} (7)

Here, $R_t$ is the tapered part resistance and $R_s$ is the inner soil part resistance.
In Prandtl theory area, our model is extended from Vesic model proposed for a straight pile (Vesic 1963). In our model, there are three assumptions. The tapered tip part is regarded as the wedge. The tapered tip part and the wedge under inner soil are continuous. The logarithmic spiral slip surface is an integral.

In cavity expansion theory area, the ultimate pressure $p_d$ should be calculated from initial soil strength by using cavity expansion. But calculation of $p_d$ is not performed in this paper and is subject to future study. As per our assumptions, the ultimate pressure $p_d$ is calculated from the bearing capacity of the straight pile using the Vesic model, as shown in Figure 7. $p_d$ is defined as follows

$$q_b = R/A$$

$$A = (D^2 \pi)/4$$

$$p_{lim} = q_b \tan(\pi/4 + \varphi/2)$$

$$p_d = p_{lim}/e^{2\theta \tan \varphi}$$

Here, $R$ is the bearing capacity of the straight pile, $q_b$ is the bearing capacity pressure, $A$ is the cross-sectional area of straight pile, $\varphi$ is the internal friction angle, $\theta$ is $1.9\varphi$ and $p_{lim}$ is the line segment BC pressure.

6.2 Bearing capacity model of the inner soil part

The bearing capacity model of the inner soil part is shown in Figure 8.

(a) Relation of the inner soil part pressure $q_{bs}$ and the line segment BC pressure $p_{lims}$

Depending on the geometric force balance, relation of $q_{bs}$ and $p_{lims}$ is derived.

$$q_{bs} = p_{lims} \tan(\pi/4 + \varphi/2)$$

(b) The line segment BC pressure $p_{lims}$. Depending on the logarithmic spiral, relation of $p_{lims}$ and $p_d$ is derived.

$$p_{lims} = p_d e^{2\theta \tan \varphi}$$

Here, $\theta_s$ is the angle shown in Figure 8.

(c) The inner soil part pressure $q_{bs}$

By substituting Equation 13 into Equation 12, the relation of $q_{bs}$ and $p_d$ is derived.

$$q_{bs} = p_d e^{2\theta \tan \varphi} \tan(\pi/4 + \varphi/2)$$

(d) The inner soil resistance $R_s$

By multiplying the inner soil part area $A_s$ to $q_{bs}$, $R_s$ is calculated.

$$A_s = (\alpha^2 D^2 \pi)/4$$

$$R_s = A_s q_{bs}$$

6.3 Bearing capacity model of the tapered tip part

The bearing capacity model of the tapered tip part is shown in Figure 9.

(d) Relation of the tapered part pressure $q_{bt}$ and the tapered surface pressure $p_{limt}$

Depending on the geometric force balance, the relation between $q_{bt}$ and $p_{limt}$ is derived.

$$q_{bt} = p_{limt} (1 + tan \beta tan \delta)$$

Here, $\delta$ is friction angle between piles and soil.

(e) The tapered surface pressure $p_{limt}$

Depending on the logarithmic spiral, the relation between $p_{limt}$ and $p_d$ is derived.

$$p_{limt} = p_d e^{2\theta \tan \varphi}$$

Here, $\theta_t$ is shown in Figure 9.

(f) The tapered part pressure $q_{bt}$

By substituting Equation 18 into Equation 17, the relation between $q_{bt}$ and $p_d$ is derived.

$$q_{bt} = p_d e^{2\theta \tan \varphi} (1 + tan \beta tan \delta)$$

(g) The tapered part resistance $R_t$

By multiplying the tapered part projected area $A_t$ to $q_{bt}$, $R_t$ is calculated.

$$A_t = [(1 - \alpha^2) D^2 \pi]/4$$

$$R_t = A_t q_{bt}$$
6.4 Comparison of experimental results and theoretical values

To indicate the probability of theoretical values calculated from the bearing capacity model, the theoretical values were compared to the experimental results in section 5.

Calculation conditions of the theoretical values are listed in Table 8. The ultimate pressure $p_d$ was used as a value obtained by calculating back from the resistance of the straight pile.

Comparison of experimental results and theoretical values is shown in Figure 10. Regardless soil pressure conditions, the theoretical values can be good agreement with the experimental results. Therefore, the bearing capacity model of tapered tip pile was able to prove the probability.

### Table 8. Calculation conditions of the theoretical values

| Internal friction angle | 41.0 |
|-------------------------|------|
| Friction angle between piles and soil $\delta$ | 0.54$\varphi = 22.1$ |

| Pile ID | 70-0.3 80-0.3 90-0.3 95-0.3 Straight |
|---------|--------------------------------------|
| The opening ratio $\alpha$ | 70 80 90 95 100 |
| The taper angle $\beta$ | 63.4 71.6 80.5 85.2 90.0 |

7 CONCLUSION

The tapered tip piles can reduce the piling resistance than straight piles because the tapered tip piles decrease plugging generation.

The bearing capacity of the tapered tip piles and the straight pile is equivalent. Although the piles decrease plugging and the inner soil part resistance decreases, the tapered part resistance compensates for the bearing capacity.

The bearing capacity model of tapered tip pile was proposed as a combination theory of Prandtl and cavity expansion. The theoretical values were consistent with the experimental results.

As future study, the ultimate pressure is should be calculated by using cavity expansion theory.

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