Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Study on the effects of bored precast pile toe shape on vertical bearing capacity

Genki Yanagi
Nihon University, Narashino, Japan, cige21193@g.nihon-u.ac.jp

Shuichi Shimomura
Nihon University, Narashino, Japan, Shimomura.shuichi@nihon-u.ac.jp

Yuki Domyo
TENOX, Tokyo, Japan, domyo-y@tenox.co.jp

ABSTRACT: A bored precast pile is installed using a construction method that enhances vertical bearing capacity by forming an enlarged grouted base at the pile toe. This base is created through soil mixing with cement milk, effectively increasing the pile toe diameter and thereby enhancing the vertical bearing capacity. Therefore, the enlarged grouted base serves as a critical factor in improving the pile's vertical bearing capacity. The vertical bearing capacity of the pile is primarily influenced by the geometry and strength of the pile toe and the enlarged grouted base. In particular, a precast pile installation method with concurrent augering, where the pile is embedded while the surrounding soil is simultaneously excavated, is widely used in Japan. In this method, the pile toe shape significantly affects not only the vertical bearing capacity but also the constructability. However, limited research has been conducted on how pile toe geometry affects the vertical bearing capacity. In this study, vertical loading tests using a pressurized tank were conducted on model steel pipe piles, with the pile toe shape set as a variable, in order to improve constructability. The effects of the pile toe shape on the vertical bearing capacity and the failure mode of the grouted base were investigated. The results clarified the relationship between the pile toe shape and the vertical bearing capacity.

1 INTRODUCTION

Among the various methods of installing bored precast piles, the embedded pile construction method has become the mainstream approach because it is environmentally friendly and produces low noise and vibration.

In this method, soil and cement milk are mixed and stirred at the pile toe to form an enlarged grouted base, effectively increasing the pile toe diameter and enhancing the vertical bearing capacity.

The enlarged grouted base is therefore an essential factor for improving the vertical bearing capacity of the pile.

Generally, when the pile toe has a hollow cylindrical shape, its closure condition greatly affects the pile bearing capacity.

Previous studies (Kurachi et al., 1992) classified the failure modes of grouted bases into two types: wedge splitting failure and punching shear failure (Figure 1).

Punching shear failure has been reported to cause a significant reduction in bearing capacity.

Pile vertical bearing capacity depends on the pile toe shape as well as the geometry and strength of the enlarged grouted base. Furthermore, to improve constructability, the use of a tapered pile toe may be considered to reduce penetration resistance when embedding the pile into the soil and soil-cement mixture. However, limited knowledge is available regarding its influence on vertical bearing capacity. In this study, piles with tapered toes were used, and the vertical bearing capacity and failure mode of the grouted base were investigated experimentally using a pressurized soil tank. Additionally, the influence of the

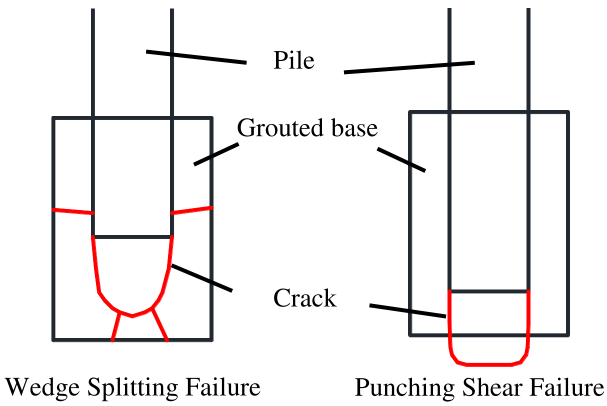


Figure 1. Failure mode.

inner filling length was examined to evaluate the closure condition of the pile toe.

2 EXPERIMENTAL CONDITIONS

Table 1 presents the experimental conditions. Figures 2, 3, and 4 show the outline of CASE 1, a photograph of CASE 1, and a photograph of the toe of the model pile, respectively. A steel pipe scaled to approximately one-eighth of the actual size was used as the model pile. The steel pipe had a pile diameter of d = 101.6 (mm), a wall thickness of 15 (mm), and a pile length of 280 (mm).

Two types of pile toe shapes were used: flat and tapered.

The enlarged grouted base had a diameter of 150 (mm), and the embedded length of the pile was set as 0.5d.

The experiments were conducted in four CASEs by varying the following parameters: pile toe shape [flat or taper], length of the grouted base below the pile toe [L_G], and inner filling length [L_I].

Table 2 lists the mixing conditions for both the enlarged grouted base and inner filling section. The target compressive strength was 10 (N/mm²), and the mix proportions were determined through preliminary mix tests. The specimens were prepared through sealed curing at 20 ± 3 (°C) indoors.

3 EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 5 shows the experimental apparatus. The pressurized tank was a steel cylinder with an internal diameter of 795 (mm) and a height of 1000 (mm). Teflon sheets, grease, and membranes were applied to the inner wall of the tank to reduce friction with sand.

The experimental procedure is as follows:

- Toyoura sand was prepared using the air pluviation method as the model ground to achieve a relative density of 85 (%).
- The specimen was placed 100 (mm) from the ground surface to the top of the grouted base.
- A rubber sheet and a loading plate were placed on the ground surface, and an overburden pressure of 300 (kPa) was applied to the plate

Table 1. Experimental conditions.

CASE	Pile diameter [d] (mm)	Pile wall thickness (mm)	Pile length (mm)	Grouted base diameter (mm)	Embedded length (mm)	Pile toe shape	L_G scale	L_G (mm)	L_I scale	L_I (mm)
1	101.6	15	280	150	50.8	Flat	2.0d	203.2	2.5d	254
2						Taper	2.0d	203.2	2.5d	254
3						Taper	2.5d	254	2.5d	254
4						Flat	2.0d	203.2	1.5d	152.4

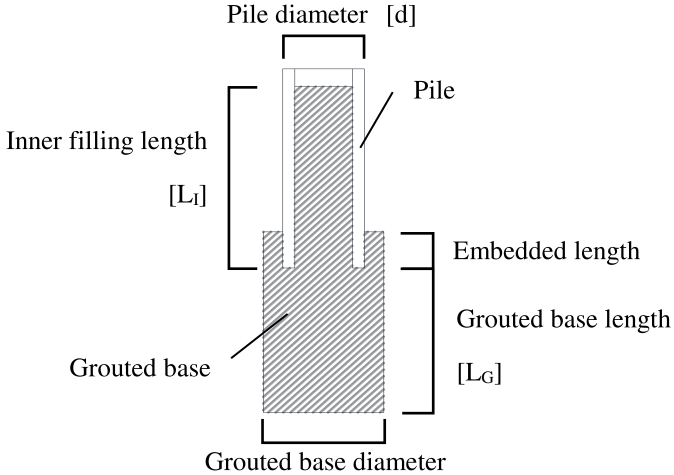


Figure 2. Outline of CASE 1.

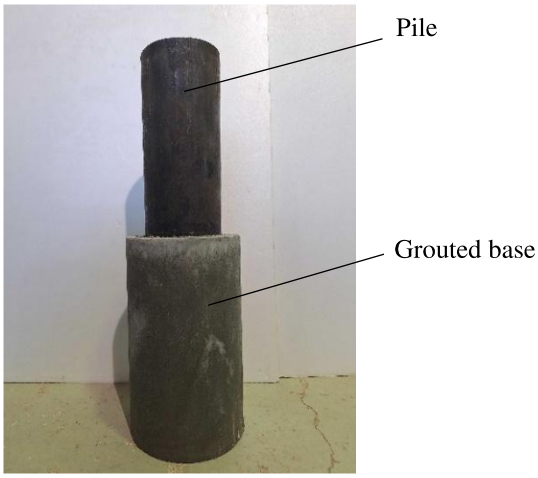


Figure 3. Photograph of the CASE 1.

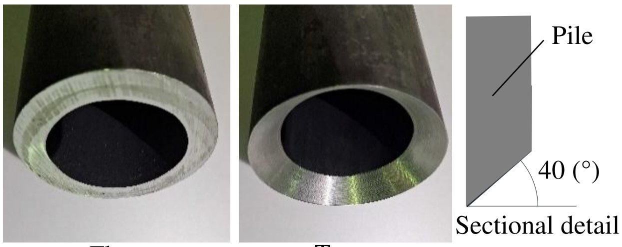


Figure 4. Photograph of the toe of the model pile.

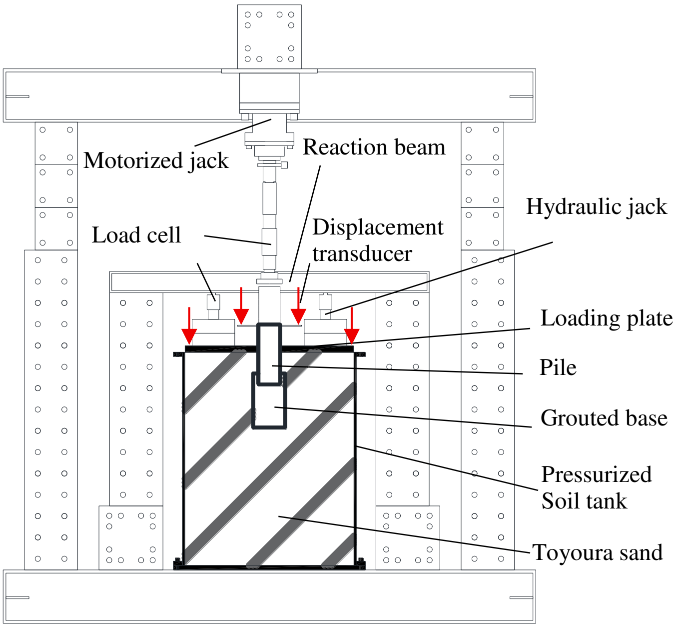


Figure 5. Experimental apparatus.

using a hydraulic jack.

- A motorized jack was installed at the pile head to apply vertical loading at a rate of 1 (mm/min). Displacement was measured at four points on the pile head and two points on the loading plate using displacement transducers.
- Unloading was initiated when the average displacement of the pile head reached 20 (mm). After unloading, the specimen was removed, and the failure mode was observed.

4 RESULTS

Figure 6 shows the pile head load–displacement curves.

In CASEs 1 and 2, which had different pile toe shapes, similar behavior was observed up to approximately 150 (kN); however, the load declined sharply at 152 (kN) in CASE 2.

Comparing CASEs 2 and 3 with different grouted base lengths [L_G], the maximum load increased slightly in CASE 3, which had a longer L_G.

Table 2. Mixing conditions.

Soil specimen		Cement slurry		
Tohoku Silica Sand No. 5 (g)	**Water (g)**	**OPC (g)**	**Water (g)**	**W/C (%)**
8000	1570	3308	1654	50

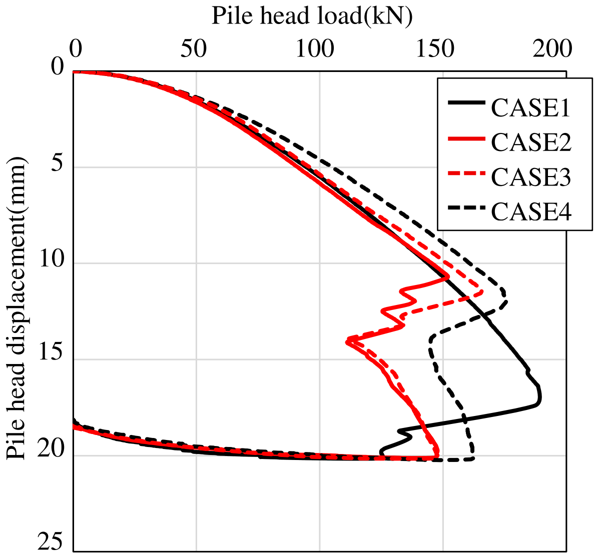


Figure 6. Pile head load–displacement curve.

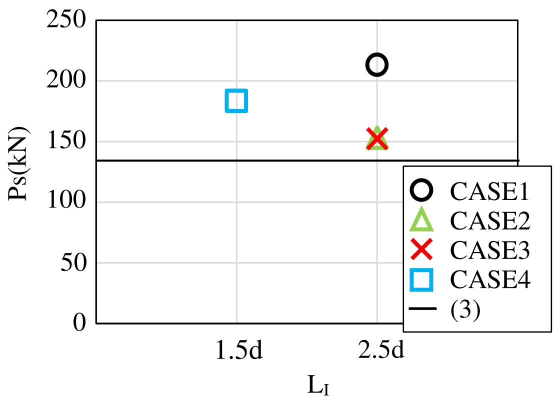


Figure 7. P_S-L_I relationship.

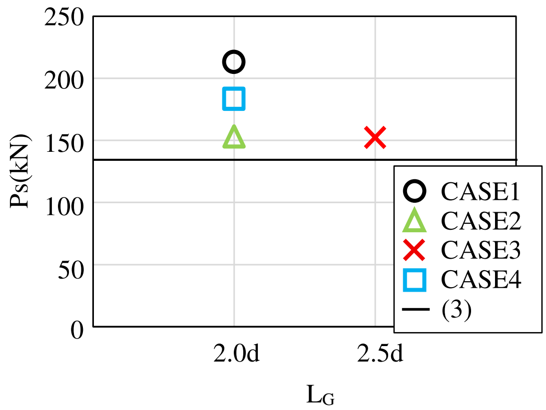


Figure 8. P_S-L_G relationship.

Comparing CASEs 1 and 4, which have different inner filling lengths [L_I], CASE 4, exhibited a smaller maximum load.

The unconfined compressive strength of the grouted section was normalized to evaluate the bearing capacity characteristics derived from the maximum load.

The normalized strength is calculated as follows:

$$P_S = \frac{P_{max}}{0.18 \cdot q_u{}^{(0.8-q_u/2000)}} \cdot 0.18 \cdot 10^{(0.8-10/2000)} \tag{1}$$

where P_S (kN), P_{max} (kN), q_u (N/mm^2) denote the normalized strength, maximum load, and unconfined compression strength, respectively.

Furthermore, the bearing strength based on the "AIJ Standard for Structural Design and Construction of Prestressed Concrete Structures" is evaluated as follows (Architectural Institute of Japan, 2022):

$$F_n = 1.8\sigma_B{}^{(0.8-\sigma_B/2000)} \cdot \sqrt{A_C/A_1} \tag{2}$$

where F_n (N/mm^2), σ_B (N/mm^2), A_C (mm^2), and A_1 (mm^2) denote the bearing strength, compressive strength of concrete, supporting area, and bearing area, respectively.

To compare formulas (1) and (2), σ_B in formula (2) was replaced with q_u to derive estimation formula (3).

$$P_{se} = 1.8q_u{}^{(0.8-q_u/2000)} \cdot \sqrt{A_C/A_1} \cdot A_1 \cdot 10^{-3} \tag{3}$$

where P_{se} (kN) is the estimated value.

Figures 7 and 8 show the P_S-L_I and P_S-L_G relationships.

Comparing CASEs 1 and 2, the P_S of CASE 1 was approximately 70 (kN) greater than that of CASE 2.

Although the tapered-type pile toe exhibited lower strength than the flat type, the measured value exceeded the estimated one.

In CASEs 2 and 3, P_S remained almost constant regardless of the grouted base length [L_G].

Comparing CASEs 1 and 4, CASE 1 with a longer infill length [L_I] showed a larger P_S.

Figures 9 - 12 show the wedge formation and peripheral cracking of the grouted base observed in CASEs 1 - 4.

In all CASEs, a wedge was formed across the entire cross-section of the pile toe, confirming that internal confinement was achieved regardless of the pile toe shape, L_G, or L_I.

Additionally, in every case, lateral cracks were observed near the pile toe along the outer periphery.

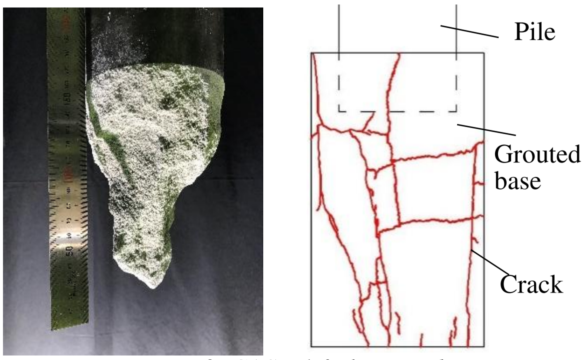


Figure 9. CASE 1 failure mode.

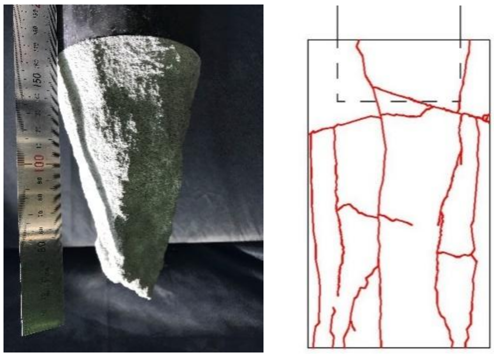


Figure 10. CASE 2 failure mode.

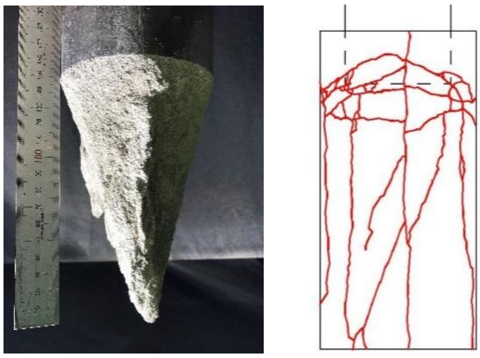


Figure 11. CASE 3 failure mode.


Figure 12. CASE 4 failure mode.

Table 3 shows the failure mode cross-section and bottom cracking of the grouted base.

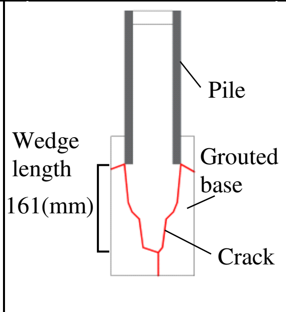
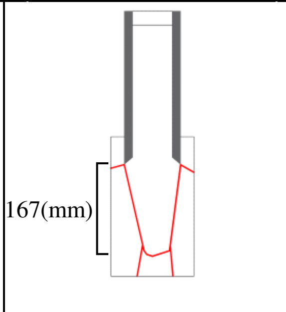
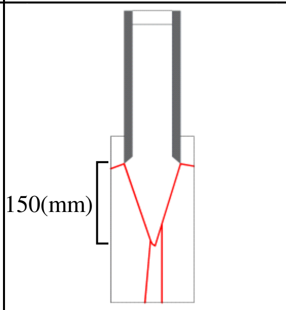
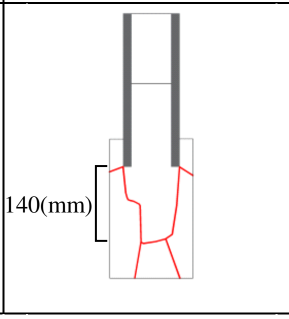
In CASE 1, splitting occurred vertically, whereas in CASEs 2 - 4, the grouted toe failed in a pull-out-like mode.

Although CASEs 2 to 4 exhibited similar failure patterns, CASE 4 exhibited a higher bearing capacity than the other CASEs. Figure 13 shows the results of the elastic FEM analysis when a vertical load of 100 kN was applied to the pile head. While stress is dispersed at the pile toe for the flat-type pile, stress concentrates at the sharp toe of the tapered-type pile, and the stress on the outer side of the pile also increases. This suggests that the tapered-type pile reached failure earlier.

However, the difference in the shape of the pile toe did not appear clearly in the failure mode.

These results suggest that, to achieve the same bearing capacity and failure mode as the flat-type pile toe, the grouted base length [L_G] should be increased in the tapered type.

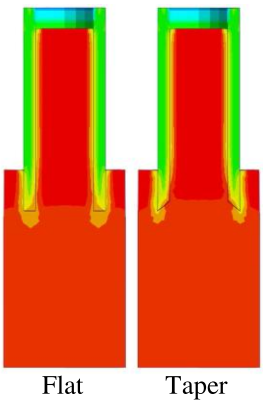
Table 3. Failure mode cross-section and bottom cracking of the grouted base.

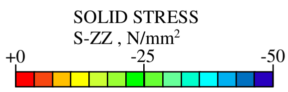
	Failure mode cross-section	**Bottom cracking of the grouted base**
CASE 1		
CASE 2		
CASE 3		
CASE 4		

5 CONCLUSIONS

In this study, model tests were conducted with the pile toe shape, grouted base length [L_G], and inner filling length [L_I] as parameters to investigate their effects on the vertical bearing capacity of the pile and failure mode of the enlarged grouted base. The findings are summarized as follows:

- Under the conditions of this experiment, it was confirmed that even when the pile toe has a tapered form, the bearing capacity exceeds the value predicted by existing evaluation formulas.
- When the pile toe is tapered, a longer grouted base length [L_G] is required to achieve a bearing capacity comparable to that of a flat toe.
- When the grouted base length [L_G] is 2.0d or greater, punching shear failure did not occur regardless of the pile toe shape.
- The failure strength increases with increasing inner filling length [L_I].





Pile	Young's modulus	E(kN/m^2)	2.05×10^8
	Poisson's ratio	v	0.3
	Unit weight	γ (kN/m^2)	78.5
Grouted base	Young's modulus	E(kN/m^2)	1.0×10^7
	Poisson's ratio	v	0.2
	Unit weight	γ (kN/m^2)	23
	qu	(kN/m^2)	1.0×10^4
	Pile head load	P(kN)	100
	Boundary conditions	Vertical displacemer	Fix

Figure 13. Results of Elastic FEM Analysis

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