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AXIAL COMPRESSIVE CAPACITY OF SHORT TAPERED PILES IN SAND

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The cross section of tapered piles gradually decreases along the vertical direction. The pile material distribution is more efficient. Due to the depth and breadth of research, tapered piles have not been widely applied in engineering. Therefore, the tapered short pile is the object of study in this paper. In order to reveal the bearing mechanism, the behavior of tapered piles under axial compressive loading in sand is studied. The results can provide support for engineering applications. The results show that the vertical bearing capacity of the tapered short pile is much higher than that of the short straight pile. And the tapered pile has the best cone angle. During the loading process, the cavity effect is generated, and the radial expansion zone is formed.

Keywords: tapered piles; bearing mechanism; cavity expansion; short pile

1. Introduction

The tapered pile is also called the wedge pile. The cross section of tapered piles gradually decreases along the burial depth. Compared with the equal section pile, the distribution of the tapered pile material is more efficient [1, 2].

Liu Jie and Wang Zhonghai [3] studied the long wedge pile with small cone angle under vertical load. The study shows that the average bearing capacity of the tapered pile is about 80% higher than that of the equal section pile in the clay. Jiang Jianping et al. [4] carried out static load tests for large diameter tapered piles and equal diameter piles. It is found that the bearing capacity of the tapered cast-in-place pile increases and the settlement decreases under the same volume condition compared with the same diameter pile. Wang Youqing and Wang Xianwei [5] analyzed the bearing capacity of tapered piles in consideration of soil compaction effect during loading. It is shown that the squeezing effect produced by the loading of tapered piles can significantly increase the bearing capacity. Chen Haohua et al. [6] divided the tapered pile bearing process into elastic deformation stage and plastic extrusion failure stage and analyzed the variation law of the increase coefficient of ultimate bearing capacity of tapered piles. Wang Wenbo et al. [7]

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considered the influence of construction disturbance and studied the dynamic response of tapered pile. Fahmy A and El Naggar M H [8] studied the axial performance of the helical tapered pile, and analyzed the performance of the tapered pile. Based on the theory of cavity expansion, Zhou Hang et al. [9] studied the squeezing effect of tapered piles. A comparative study on penetration resistance of jacked tapered piles and uniform section piles was conducted by Yang Qingguang et al. [10]. Zhang Keneng et al. [11] studied the piling effects of static piling in soft clay ground with tapered pile. Cao Zhaohu et al. [12] studied the installation effect of tapered piles in transparent soils. The results show that the radius of influence due to tapered pile installation is about 1.2 times that of the equal diameter pile.

The above research shows that the vertical bearing capacity of long tapered piles is obviously better than that of equal section piles. Limited by the width and depth of its research, the theory of computation and analysis of tapered piles is not yet mature. At present, the engineering application of conical pile is very tentative and has not been widely applied. Moreover, the bearing mechanism of short pile is different from that of long pile. Therefore, it is of great practical significance to study the bearing mechanism of short tapered piles. In this paper, the tapered short pile in sand is taken as the research object. The bearing mechanism of short tapered pile in homogeneous site is studied.

2. Finite element models

In order to study the bearing mechanism of short tapered pile and make the problem universal, this paper chooses the tapered pile to be buried in homogeneous sand. In order to make the research object comparable, seven kinds of conical piles are selected in this paper. Their average diameter is 200 mm, and the pile length is 3 m. The dimensions are shown in Table 1.

Table1

Size of pile

	Diameter of pile top D_{top}/mm	Diameter of pile tip D_{tip}/mm	Average diameter of piles $D_{average}$/mm	cone angle/°	Length of piles/mm
Pile-1	200	200	200	0	3000
Pile-2	210	190	200	0.191	3000
Pile-3	220	180	200	0.382	3000
Pile-4	230	170	200	0.573	3000
Pile-5	240	160	200	0.764	3000
Pile-6	250	150	200	0.955	3000
Pile-7	260	140	200	1.146	3000

3. Geometric model

In this paper, axisymmetric model is used to simulate the axial bearing mechanism of tapered piles. Pile element and soil element are simulated by axisymmetric four node element. The model size is shown in Fig. 1. The distance from the right boundary to the axis of the soil is $10D_{\text{average}}$. The distance between pile tip and bottom boundary is $5D_{\text{average}}$. The two sides of the soil are radial restrained and vertical free. The boundary of the soil bottom is restricted by radial direction and vertical constraint. The top boundary of the soil is a free boundary.

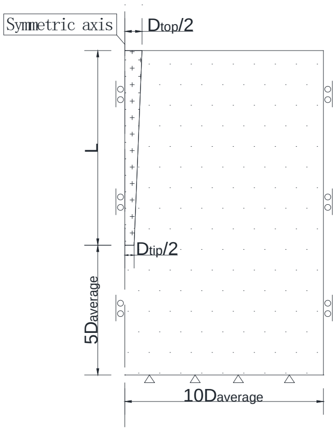


Fig. 1 Geometric model

4. Material properties

The soil is simulated by isotropic ideal elastoplastic model. The Mohr-Coulomb criterion is used to simulate the plasticity and failure criteria of soils. Poisson's ratio v_s and Young's modulus E_s are used to define the elasticity of soil. Cohesion c, internal friction angle φ and expansion angle ψ are used to define the plasticity of soil. The values of soil parameters are shown in Table 2.

Table 2

Soil parameters

Cohesion c (kPa)	Internal friction angle φ (°)	Expansion angle ψ (°)	Poisson's ratio v_s	Young's modulus E_s (MN/m^2)	Unite weight γ_s (kN/m^3)	Earth pressure coefficient K_s
1	32	0.1	0.3	70	18	0.47

The pile is made of concrete and simulated by linear elasticity. The Young's modulus E_p is 20GPa, Poisson's ratio v_p is 0.15 and the bulk density is 25kN/m^3.

5. Pile-soil interface model

The normal direction of pile-soil contact is hard contact. Normal pressure is not transmitted when there is gap between pile and soil. Normal pressure is transmitted when there is no gap compression. Normal pressure is not limited when there is contact. The tangent behavior of pile-soil contact is simulated by Coulomb friction model, and the friction coefficient is 0.625.

6. Loading sequence

First, considering the initial stress state that has been completed in the construction of the pile, the stress balance is carried out. Then, the vertical loading is applied to the top of the pile. The ultimate bearing capacity of piles is generally desirable when the vertical displacement of pile top is 20~30 mm. Considering that the analysis of short piles is carried out in this paper, 20 mm vertical displacement is applied to the top of the pile and the corresponding bearing capacity is taken as the ultimate bearing capacity.

7. Results and discussions

7.1 Relationship between load and settlement

The load-settlement curve of pile is a comprehensive reflection of the bearing behavior of pile-soil system and a macroscopic response of the bearing mechanism and bearing mode of pile-soil system. The relationship between vertical displacement and vertical load of pile top is shown in Fig. 2 -load settlement curves.

As can be seen from Figure 2, the load-settlement curve is divided into three stages: (1) initial linear stage; (2) transition stage; (3) nonlinear increase stage.

At the initial stage (vertical displacement $\delta < 0.001$ m), the Load-settlement curves of equal-diameter pile 1 and tapered pile-2~7 are basically the same. In the nonlinear increasing stage, the bearing capacity of tapered pile-2~7 is obviously larger than that of equal diameter pile-1 under the same vertical displacement. And with the development of loading process, the gap between them is bigger and bigger.

In engineering, it is generally considered that the vertical displacement δ and pile diameter D ratio δ / D =10%, pile failure. Therefore, the vertical force of vertical displacement δ =0.02m is the ultimate bearing capacity of pile, as shown in Table 2.

The ultimate bearing capacity of equal-diameter pile-1 is 45.76 kN, and that of tapered pile-2 is 62.11 kN. Although the cone angle of pile-2 is only 0.191 degrees, the ultimate bearing capacity of tapered pile-2 is 30% higher than that of equal-diameter pile-1. This is consistent with the results of the existing literature [13].In order to show the relationship between the ultimate bearing capacity of tapered pile and equal diameter pile more intuitively, the ultimate bearing capacity of the pile is normalized based on the ultimate bearing capacity of the equal diameter pile. The normalized bearing capacity of the pile is shown in Table 3 and Figure 3. With the increase of the cone angle, the ultimate bearing capacity of the pile increases, this further proves the advantage of the vertical bearing capacity of the tapered pile. Figure 3 shows that the increase of ultimate bearing capacity is not linear with the increase of cone angle. Normalized ultimate bearing capacity of piles 5, 6 and 7 are not significantly different, which are 1.85, 1.88 and 1.90 respectively. It shows that tapered pile has optimal cone angle.

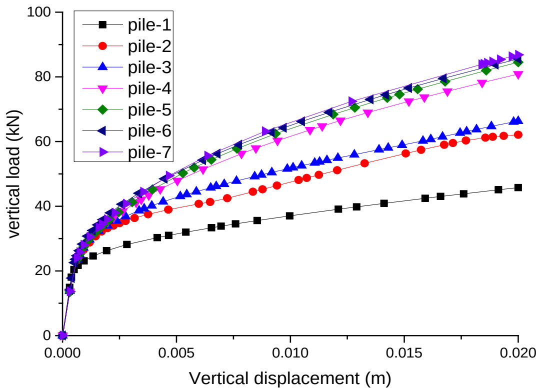


Fig. 2 Load settlement curves

Table 3

Piles ultimate compressive capacity

	Ultimate bearing capacity/kN	Normalization of ultimate bearing capacity
Pile-1	45.76	1.00
Pile-2	62.11	1.36
Pile-3	66.34	1.45
Pile-4	80.88	1.77
Pile-5	84.53	1.85
Pile-6	85.54	1.88
Pile-7	86.83	1.90

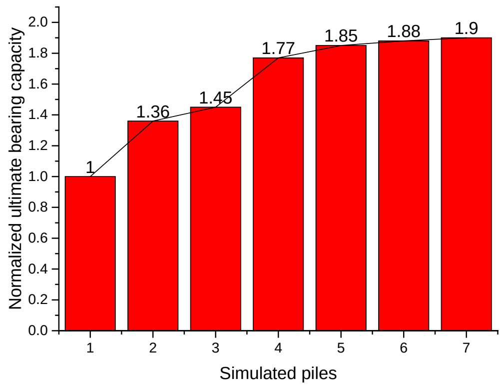


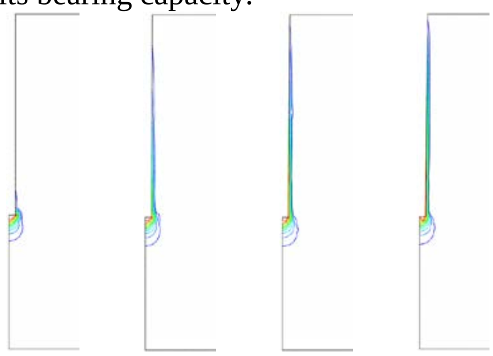
Fig. 3 Normalized ultimate capacity

7.2 Displacement contours

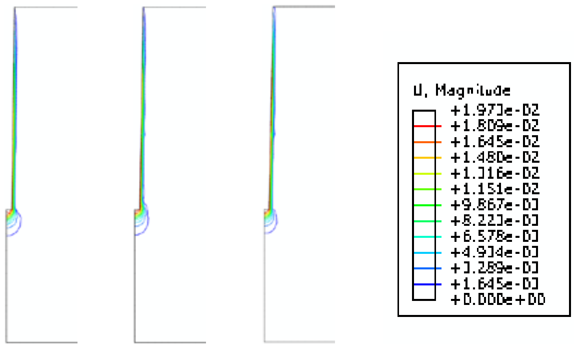
In order to further reveal the load transfer mechanism of pile-soil load transfer, the displacement contours of pile 1-7 are extracted when the vertical displacement of pile top is 0.02m, that is, when the bearing capacity reaches the ultimate capacity, as shown in Fig. 4.

Fig. 4 shows that the displacement profiles of both equal-diameter and short tapered piles are concentrated in the soil near the pile tip. However, the displacement profile of the short equal-diameter pile-1 does not extend to the ground. The displacement profiles of 2-7 tapered piles gradually extend to the ground with the increase of the cone angle. When the cone angle exceeds a certain value (pile 5-7), the displacement profiles extend to the ground.

This trend is consistent with the existing literature [14, 15]. This shows that the bearing mechanism of tapered pile includes cavity expansion along the pile body, thus increasing its bearing capacity.



(a) pile-1 (b) pile-2 (c) pile-3 (d) pile-4



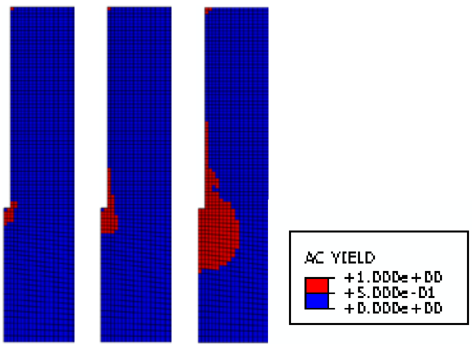
(e) pile-5 (f) pile-6 (g) pile-7

Fig. 4 Soil displacement contours at vertical pile of displacement of 0.02m

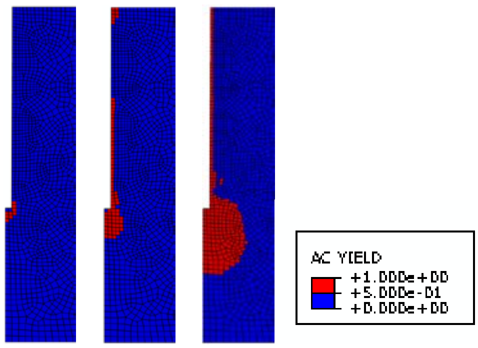
7.3 Yielding process

In order to further study the bearing mechanism of short tapered piles, Fig. 5 shows the yielding process of the soil around pile-1~7. Due to space limitation, only three pictures of the initial loading stage, the middle loading stage and the later loading stage are selected, and only the soil around the pile is intercepted.

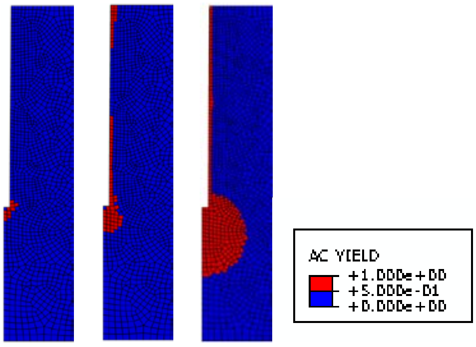
As can be seen from Fig. 5, the soil element around the tapered pile (pile-2~7) yielded at the later loading stage, while the equal diameter pile (pile-1) did not. Considering the yielding process of short tapered piles, the resistances of pile tip acts first. Then, the yield area develops along the pile body and the pile side resistance plays a role. Finally, the yield zone expands radially, forming a large radial expansion zone, so that the load is transferred to a wider range of soil. However, there is no radial extended yield zone along the pile body in equal diameter pile.



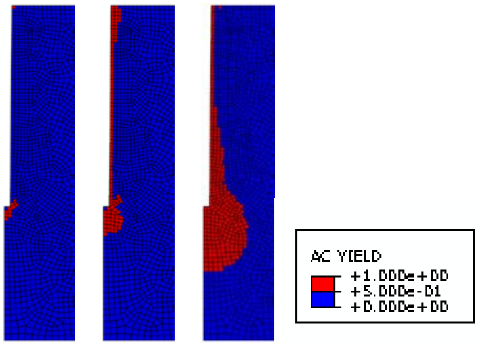
(a) pile-1



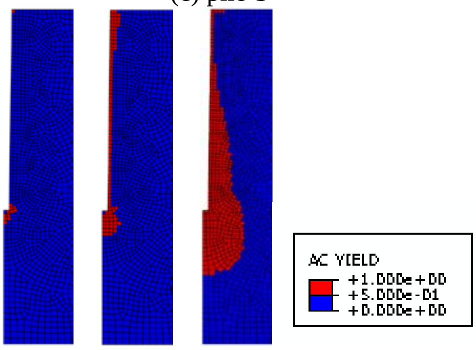
(b) pile-2



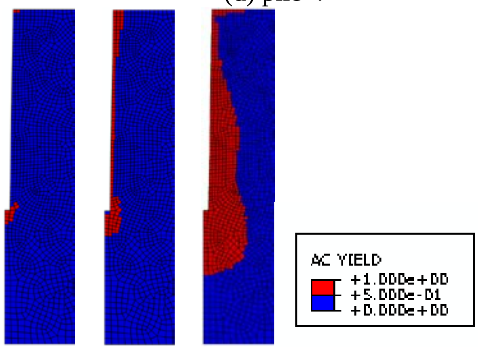
(c) pile-3



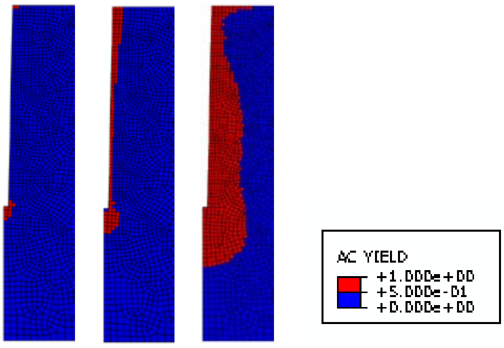
(d) pile-4



(e) pile-5



(f) pile-6



(g) pile-7

Fig. 5 Yield progress with loading

8. Conclusions

Based on the analysis of existing literatures, this paper studies the bearing mechanism of short tapered piles and draws the following conclusions:

(1) Compared with equal diameter pile, the vertical bearing capacity of tapered pile increases obviously, and increases with the increase of conical angle.

(2) Tapered pile has optimal cone angle.

(3) During the loading process, the cavity expansion effect is produced, and the radial expansion zone is formed, which improves the bearing capacity of the tapered pile.

(4) Because the purpose of this study is to reveal the general law of the bearing mechanism of short tapered piles in sand, the conclusions in this paper can only be used for qualitative analysis. In order to predict the bearing capacity of short tapered piles, model tests will be carried out in future research.

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