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Theoretical Study for the Influence of Section Form on Compressive Failure State of Concrete Expanding-Plate Piles

Yongmei Qian*, Ye Zhang, Wei Tian, Qingyu Cheng

Jilin Jianzhu University, Changchun 130118, China
654675316@qq.com

Due to the difference of construction equipment for concrete expanding-plate pile (CEP), there are certain differences for the section forms of CEP expanding plate, and also the actual section form and current theoretical model shall differ. On the basis of FEM analysis, this paper studies the failure state of soil around pile under vertical pressure with the section form of expanding plate changing, and further determines its effect on CEP compressive bearing capacity, so as to verify the reliability of current research and provide theoretical basis for CEP design.

1. Introduction

CEP piles are widely accepted for its good bearing capacity, applicability and economy, causing extensive research by scholars at home and abroad. Considering the importance of construction equipment and technique for CEP construction, CEP research must combine the related theory with actual construction equipment (Shen et al., 2008). The previous research only studied the longitudinal symmetry of plate type, i.e. CEP with straight surface and sharp-angled plate end in Figure 1; however, in actual construction, it tends to be circular-arc plate end with non-longitudinal symmetry piles formed by Drilling/Expanding Machine and Squeezing Equipment, and to be curved surface as shown in Figure 2, showing the difference between theoretical research and actual construction.

Considering that different CEP plate section forms are developed with different construction techniques such as drill-expanding and squeezing (Wang et al., 2013; Qian and Cheng, 2015), this paper studies the influence of different plate section types on CEP compressive-resistance failure state. Based on FEM analysis and ANSYS software program modelling, it changes the section form of bearing plate to determine the influence of pile-soil effect, soil shear failure and sliding failure of section form on CEP under the vertical pressure, in order to lay a good theoretical foundation for improving the ultimate compressive bearing capacity of single CEP pile by means of strength theory and slip-line theory research.

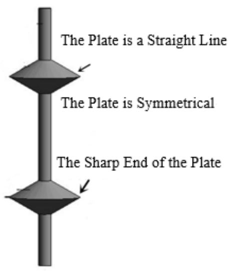

Figure 1: Plate form in theory

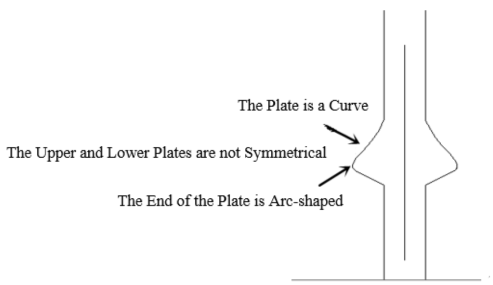

Figure 2: Plate form in actual construction

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2. Establishment of finite element model (FEM)

This paper uses ANSYS Software to establish the pile-soil model for half-section pile and get it loaded, obtaining the pile-top displacement-load curve of the four different section forms, and the pile-soil interaction diagram/pile-top displacement. Then, it makes comparative analysis for these above, which shall lay the foundation for the comparative analysis of indoor undisturbed soil small-scale semi-section pile test in the future.
In FEM analysis, the Drucke-Prager elastic-plastic model was used for the soil. Based on the actual undisturbed soil, it could set up the material props and make unit conversion; it is worth noting that the FEM units should be uniform so as to compare test results and simulation ones. See detailed parameters in Table 1, showing that it keeps axi-symmetrical when it interacts between soil mass and concrete pile.

Table 1: Parameter list of pile-soil material

Material	Poisson Ratio	Cohesion (*Kpa*)	Elastic Modulus (K*pa*)	Friction Angle (°)	Expansion Angle (°)	Density (*t/mm*^{3})	Friction Coefficient of Pile and Soil
Concrete	0.3	--	3.0e4	--	--	2.5e-9	0.4
Clay	0.35	16.4	30	18.29	18.29	1.5e-9	0.4

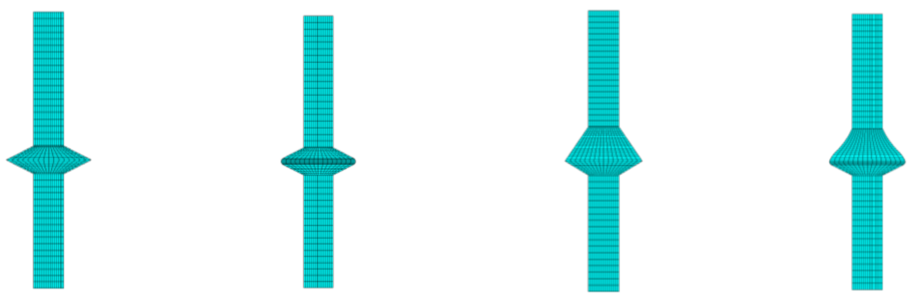
2.1 Plate-type determination and ansys modelling

2.1.1 Plate-type Determination of simulation pile

The plate-type of simulation pile depended on existing theoretical research and formed types in actual construction. One type is actual plate-type by the Drilling-Expanding AIO Machine invented by Zhang Baocheng, the second type for the type formed by new-model Squeeze Equipment, the third type for the type in previous theoretical research; Combining these three plate types with another pile, it analyzed and determined the plate types of four piles in this paper. In Figure 3, pile 1# uses the plate type in previous theoretical research, longitudinal-symmetry expanding plate and sharp-angular plate end; Pile 2# for comparison pile with longitudinal-symmetry expanding plate and arc end; Pile 3# for plate type by squeezing equipment with non-longitudinal-symmetry expanding plate and sharp-angled type end; pile 4# for plate type by Drilling-expanding AIO Machine with longitudinal-symmetry expanding plate and arc end, which is most widely used now. It is necessary to keep other variables of the four piles the same for comparison, thus, the same pile diameters of the four piles are determined by construction tools. The 27°slope angle for CEP is confirmed according to the slope angle in actual construction, because the plate dimension and shapes are based on the slope angle for many construction equipments. To ensure uniform slope angle, the plate diameter of concrete expanding piles with sharp angle end must be 127mm more than that with arc end.

2.1.2 ANSYS Modelling

Respectively establish two-dimensional (2D) coordinate system of pile and soil mass according to plate type, and then achieve ANSYS Software model (Chen, 2015; Peng, 20000; Shen et al., 2008; Tran et al., 2012) by rotating 180°. In Figure 3 apply the set parameters to pile and soil; note that under pressure for the pile, the soil mass on the plate and the plate may break up in actual construction, so there must reserve 10mm clearance between upper part of bearing plate and soil mass.



Pile 1# *Pile 2#* *Pile 3#* *Pile 4#*

Figure 3: Shape of Simulation Pile

Because this simulation was made to analyze the pile-soil interaction principle, and stress distribution/failure status of pile and soil by applying vertical pressure to CEP, it must be ensured that the soil range around the piles is large enough to eliminate the effect of pile-soil on the CEP; according to simulation pile dimension and previous research, it is determined that the radius range of soil mass is 5000mm, and height 8000mm.

2.2 Model Mesh Generation and Contact area Definition

2.2.1 Mesh Generation

Mesh generation is crucial for simulation accuracy, so proper-size/proportion mesh must be marked in the corresponding locations of soil and pile model. Mapping is adopted for mesh generation, i.e. certain encryption should be made in the bearing plate and its corresponding soil model location in order to better observe the failure status of the soil mass in bearing plate.

2.2.2 Definition of contact area

Generally regarded as the non-linear activity, the contact issue was divided into two basic types: contact between soft bodies, contact between soft body and rigid body. For contact of rigid body and soft body, one or more faces of the contact areas were taken as rigid bodies. Generally, it could be supposed as contacts of rigid body and soft body when soft material and rigid material made contacts. The contact type of rigid body and soft body was applied in this model, with rigid concrete expanding-plate pile and soft soil-around pile (Chaloulos et al., 2013). To ensure mutual contacts between two surfaces, it needed to connect the pile body of target surface and the contacted soil around pile when establishing one pair of contacts, which was very important for simulation success, therefore, accurate selection of the contact faces must be made. The contact mode between faces used in simulation modelling should be consistent with the contact between two units in practical engineering.

2.3 Boundary Constraints Condition and Simulation Capacity Load

Table 2: Simulation Parameters of 1# and 2# Pile

Number of pile plates n	1	Height of pile plates H	836	Cohesion of the soil around the pile c	0.000000174
Bearing capacity to expand the diameter of the plate D	2000	The distance between the plates S	0	The internal friction Angle of the soil around the pile Φ (radian)	0.319
The diameter of the main pile d	900	The cantilever length of the diameter of the plate Ro	688/820	Pitch angle of the plate Θ (radian)	2.041
Pile length L	8307	The range of compressive stress on the plate La	0	ƒ side	0.00007
The distance between the pile and the top of the pile L1	5600	The lower part of the plate increases the range of compressive stress Lb	2752/3280	The Severet of the pile γG	0.000000025
The distance of the pile from the end of the pile L2	3440	Increasing coefficient γ	1.1	ƒ end	0.0005

Table 3: Simulation parameters of 3# and 4# pile

Number of pile plates n	1	Height of pile plates H	1427	Cohesion of the soil around the pile c	0.000000174
Bearing capacity to expand the diameter of the plate D	2000	The distance between the plates S	0	The internal friction Angle of the soil around the pile Φ(radian)	0.319
The diameter of the main pile d	900	The cantilever length of the diameter of the plate Ro	688/820	Pitch angle of the plate θ(radian)	2.041
Pile length L	8307	The range of compressive stress on the plate La	0	ƒ side	0.00007
The distance between the pile and the top of the pile L1	5600	The lower part of the plate increases the range of compressive stress Lb	2752/3280	The Severet of the pile γG	0.000000025
The distance of the pile from the end of the pile L2	3440	Increasing coefficient γ	1.1	ƒ end	0.0005

Implant the pile in soil, and then compress/combine them in each node to make them a whole. In order to ensure the conformity between FEM simulation and actual situation, it was necessary to make constraints for soil sample boundary, including the constraints perpendicular to the surface on the vertical face of half-section pile

and soil mass, the constraints in the direction X, Y, Z on half cylindrical hook face, and that vertical to bottom face.
Table 2 and Table 3 lists the parameters of simulation pile, and Table 2 is about pile 1# and 2# with longitudinal-symmetric concrete expanding pile, since with different pile plate end shape, their cantilever length and pressure stress range shall be slightly different. This paper studies the compression bearing capacity of single plate, so the plate distance and pressure-stress range should be 0. Unit conversion has been made to all numbers in the Table 3.
Table.3 lists 3# and 4# pile with non-longitudinal symmetrical pile plate end, which could increase the height of upper plate, and change the cantilever length and lower plate stress range; while the lower plate stress range of pile 1# and 2# remains the same, because their plate height is the same.
Put the four groups of parameters above into the calculation formula of CEP ultimate compression bearing capacity, and then get the ultimate compress bearing capacity of the four piles. Although this formula was only applicable to 1# pile (the plate type for theoretical research), the bearing capacity of the other three piles calculated in the former formula could be important for reference in this paper (Qian et al. 2014); the formula result was the bearing capacity for the whole pile, while this paper studies that of half-section pile, thus, the bearing capacity of half-section pile can be gained after dividing the formula result by two.

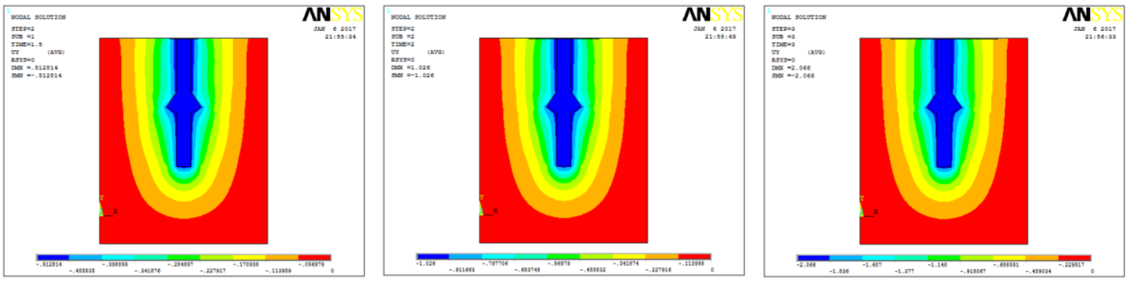
2.3.1 Simulation loading

Surface load is used in this paper, so it is necessary to convert the ultimate compressive bearing capacity to surface load which can be obtained with the ultimate bearing capacity divided by pile head area of half-section pile. Step-by-step loading is adopted for the four piles [16], starting with 0.5Mpa and adding 0.5Mpa every time. For convenience of comparison with actual CEP, surface load was converted into KN, starting with 158KN and add 158KN every time. By means of ANSYS software, it made calculation and records of the pile displacement, shear stress and soil around pile status etc.

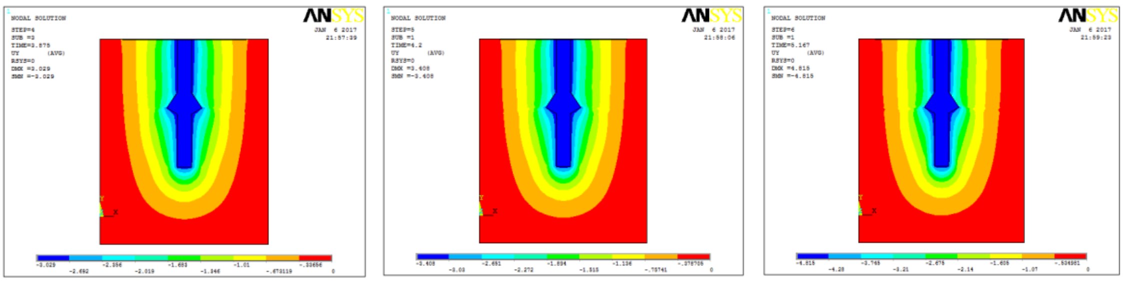
3. FEM result analysis

3.1 Displacement results analysis

Make step-by-step loading for the load value calculated by CEP compression bearing capacity formula. For comparing the failure status of the four piles, make loading of 150KN every time for four piles, and find that some piles cannot be re-loaded when uploading at step 7. For better comparison, load all piles with same loads, i.e. to step 7, and then extract the loading displacement chart for pile 3# at every step as shown in Figure 4.



The first step to load *The second step to load* *The third step to load*



The fourth step to load *The fifth step to load* *The sixth step of loading*

Figure 4: Loading Displacement Chart of Pile #3 at Every Step

Extract respectively the displacement charts in Y direction at maximum load for the four piles, load the shear stress along the pile body and soil around pile/the shear stress at maximum load, and then select the displacement chart at maximum load as shown in Figure 5. For better comparison, make charts of the corresponding displacement at max load as shown in Figure 6 so as to further compare and analyze effect of different plate forms on compressive failure of concrete expanding piles.

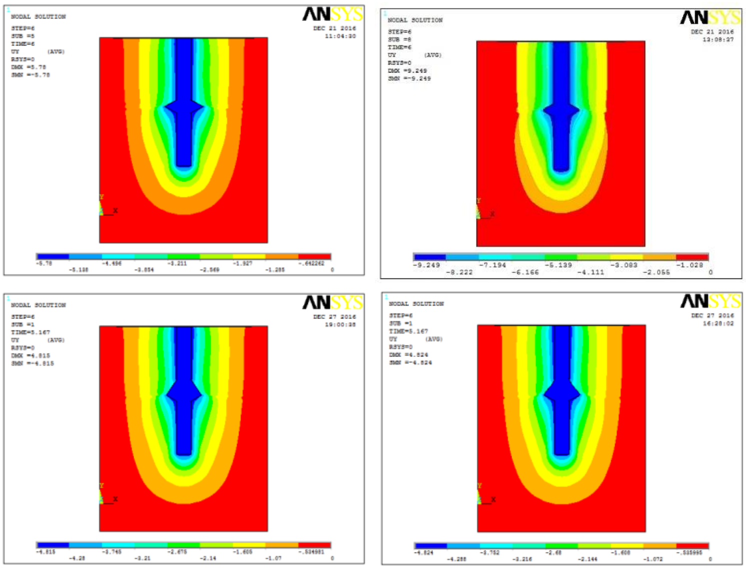


Figure 5: Vertical displacement chart of pile-soil model for different pile types of concrete expanding piles

Figure 5 shows that relative slip happens between concrete expanding piles and soil around pile, and reaches the maximum displacement when CEP is compressed with ultimate bearing capacity.
The comparison above could conclude that it had no effect on the displacement under ultimate pressure of concrete expanding pile whether the expanding plate was longitudinal-symmetric and upper plate was direct with the precondition that the main pile diameter of CEP remained the same; it also found that in the condition of consistent lower grade angle, the sharp-angled plate end had less displacement than arc end under ultimate pressure, because it caused CEP with the sharp-angled plate end to have larger effective diameter than with arc end in order to ensure same slope angle of the four piles. Thus, it could be assumed that the CEP plate section shape has little impact on its vertical displacement.

3.2 Stress result analysis

To compare the shear stress changes of pile bodies and expanding plate, select the points on pile top, upper plate and lower plate etc of the four piles, and then draw the line graph of stress values in X/Y direction as shown in Figure 6.

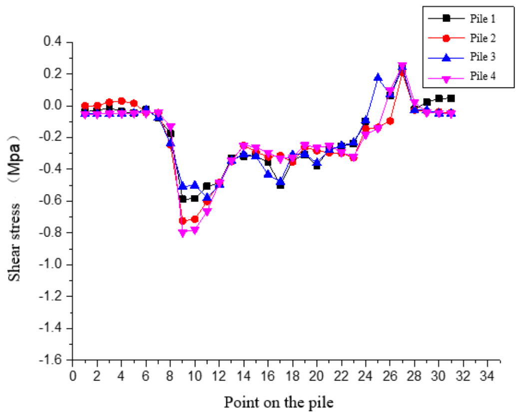


Figure 6: Shear stress curve graph in x/y direction

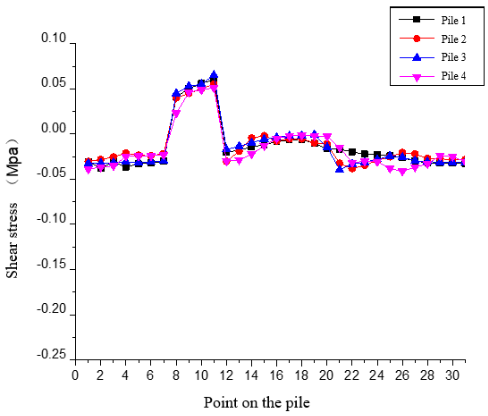


Figure 7: Shear stress curve chart in x/y direction

Figure 7 shows that the shear stress curve trend of the four piles is almost the same; under vertical pressure for

concrete expanding pile, abrupt change of shear stress occurs to the expanding plate: the shear stress at plate end of four piles presents decreasing trend, and especially at lower location of expanding pile, it is decreasing more obviously, mainly because there exist more pile-side resistance for the lower expanding plate. By comparison it is found that the shear stress of pile 1# and 3# with sharp-angle plate end has almost the same change trend, while the shear stress of pile 2 and 4# with arc end is consistent with the changes.
For convenience of observing the shear stress change of soil around pile, choose the shear stress values of soil and pile contact surface, organize and draw a line chart with these values of soil around pile and pile contact surface of the four piles as shown in Figure 7.
It can be seen in Figure 7 that the shear stress of the four pile changes conformably in the condition of consistent vertical pressure, although the location of selected points isn’t the same; abrupt change occurs to the expanding plates for all four piles respectively, and the shear stress of soil around pile at lower plate location decreases, which tells the higher pile side resistance there.
By comparing Figure 6 and 7, it is found that the shape of plate end basically has no impact on shear stress of pile body and pile-soil contact face in XY direction, and also the symmetry of expanding plates and shape of upper plate has no effect on them.

4. Conclusion

On the basis of ANYSYS software analysis, it has the following:
(1) Conclusion for the effect of plate end shape on CEP compression failure mechanism:
At same load, the CEP displacement with sharp-angle end is higher than that with arc end, which means that the CEP with sharp-angle plate end has better bearing capacity than that with arc end, but considering that the former has larger effective plate diameter, the plate diameter has higher impact on the bearing capacity of concrete expanding pile. Therefore it is concluded that plate shape end has little impact on the CEP compression bearing capacity, but with the same slope angle, the CEP bearing capacity with arc end is 0.8-0.9 times of that of sharp-angle end, and they have the same pile-soil failure mode and state, following the principle of slip failure.
(2) Conclusion for the effect of expanding plate shape and non-symmetry expanding plate on compression failure of concrete expanding pile. Comparing the two piles with linear expanding plate and curved plate, it is found that they have the same failure status of soil around pile, and shear stress trend, so we can see that it has no effect whether the expanding plate is longitudinal symmetric and linear or curved.
This paper improves the theoretical defects for concrete expanding plate, promoting the application of concrete expanding pile in some degree.

Acknowledgements

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