Article no. 33

THE CIVIL ENGINEERING JOURNAL 3-2020

DEM STUDY ON THE PENETRATION OF JACKED PILES INTO LAYERED SOFT CLAY

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ABSTRACT

In order to explore the variation law of soil particle displacement and pile force around piles during penetration process, the DEM (Discrete Element Method) model is used to test the penetration of pile foundation in layered soft soil foundation. The variation law of pile penetration force, radial pressure at pile-soil interface, friction resistance at pile side, displacement field and force field between particles during penetration process is analyzed. Research shows: (1) The penetration force increases with the increase of penetration depth and pile diameter. The increase of pile diameter is beneficial to overcome the influence of unfavorable strata. (2) At the same penetration depth, with the continuous penetration of the pile body, the radial pressure gradually decreases, showing a significant degradation phenomenon. The reason for the degradation of lateral friction is essentially the degradation of the radial pressure. (3) The distribution of contact force chain in different soil layers is similar, but the range of action is different. The contact force in silt layer is obviously larger than that in silty clay layer. The compressive stress of the soil at the end of the pile transfers radially with tensile stress. With the increase of pile diameter, the compressive stress and tensile stress in soil layer are gradually increasing, and the influence range of compressive stress and tensile stress is also gradually increasing. (4) The displacement of the soil below the pile tip is triangular, and the soil at the pile tip is squeezed around under the action of the pile tip. The influence range of particle displacement in each soil layer is different, and the influence range of particle displacement in silt layer is obviously smaller than that in silty clay layer.

KEYWORDS

DEM; Clay; Pile; Force; Displacement

INTRODUCTION

Jacked pile technology has the advantages of low noise and clean construction, and is widely used in engineering construction. The problem of pile penetration and its influence have been concerned for a long time in engineering and academic fields[1-3]. The mechanical problems of jacked piles can be divided into the penetration stage and the use stage according to the working conditions. The mechanical problems in the two stages are different, but both are complex. During the penetration stage of jacked pile, the pile tip strongly squeezes the soil, the displacement of the soil changes from small deformation to large deformation, and the pore water pressure changes drastically, which causes the mechanical properties of the soil to change. The pile side produces a reaction force, and this force is affected by many factors, such as the compressive modulus of the soil, the composition of soil particles, the depth of the soil layer, etc. The jacked pile is often subjected to cyclic loads during the use stage. Soils will weaken under the action of cyclic loading, which will affect the bearing capacity of the pile.

There are three main theories that can be used to analyze the mechanics of jacked piles: cavity expansion theory[4], strain path method[5], and limit equilibrium method[6], but each method has its limitations in application. For example, the cavity expansion theory ignores the influence of depth on the bearing capacity, and strain path method can only work on non-deformable soil, the limit equilibrium method uses the assumed slip line as the failure surface, and different assumed slip lines will cause large differences in the calculation results.

Because of the imperfect theory, many scholars[7-8] use experimental methods to explore the penetration force of jacked piles, which are mainly divided into macro-tests and meso-tests. Macro-tests mostly use piles with sensors to perform penetration tests in a model box or on-site and collect data in real time. To study the pile-soil interaction on the meso scale, some scholars[9] used meso-tests methods, such as CT, white light interferometer, etc., to test the porosity and contact area of soil particles under force.

Soil material is neither ideal elastomeric material nor ideal plastic material but is cemented or extruded by granular particles. Due to the granular characteristics of soil, the traditional continuum method and finite element method cannot reveal the microscopic mechanism of soil deformation and the law of force transfer in essence. Compared with the finite element method, the particle flow discrete element method has greater advantages. There are series of independent motions between the particle elements, which can reveal the macro-mechanics mechanism from the micro-particle element level. Particle flow software can effectively simulate discontinuous problems such as separation and cracking of media, and it is more and more widely used in geotechnical engineering. Cundall[10] (1971) put forward the concept of discrete element method for the first time. It is also the earliest application of discrete element method[11] to solve and study rock mechanics problems. At present, numerical simulation of particle flow is widely used in sand and rock[12-15]. However, when simulating clay, it is difficult for particle flow to be used in clay due to the small particle size requirement, the large number of particles in the model and the complexity of parameter calibration. The author repeatedly calibrates clay parameters and simulates the process of static pressure pile penetrating into clay soil by DEM to explore the change law of macro and micro physical quantities.

ESTABLISHMENT AND PENETRATION OF DEM JACKED PILE MODEL

Formation of Layered Soft Clay Foundation

The traditional rainfall method relies on the self-weight balance of particles to form the soil layer. Different self-weight results in different initial stress fields of the soil layer. Therefore, this paper uses the Grid Method proposed by Duan & Cheng[16] to generate soil layers. GM method divides the model of soil sample into many small areas. When the soil particles are generated, they are generated in order from left to right and from bottom to top. Finally, the soil model with controllable compactness and porosity is generated.

The size of the model is 450 mm *700 mm (width *height). Twelve layers of particles are generated, and 119880 soil samples are generated. The height of each layer is 5 cm, and the upper seven layers of simulated clay layers have particle sizes ranging from 0.45 mm to 0.7 mm. The lower five layers are sand layers with particle sizes ranging from 1.22 mm to 1.67 mm, and the initial porosity of soil samples is 0.25. Considering that the gravity field is affected by size, the acceleration of gravity of soil particles is increased to 40 G. The process of particle formation is shown in Figure 1. $GM_{i\text{-}j}$, I are expressed as the number of rows in the grid, J is expressed as the number of columns in the grid. It is convenient to observe particle movement and distinguish the soil layer with horizontal and vertical color bands.

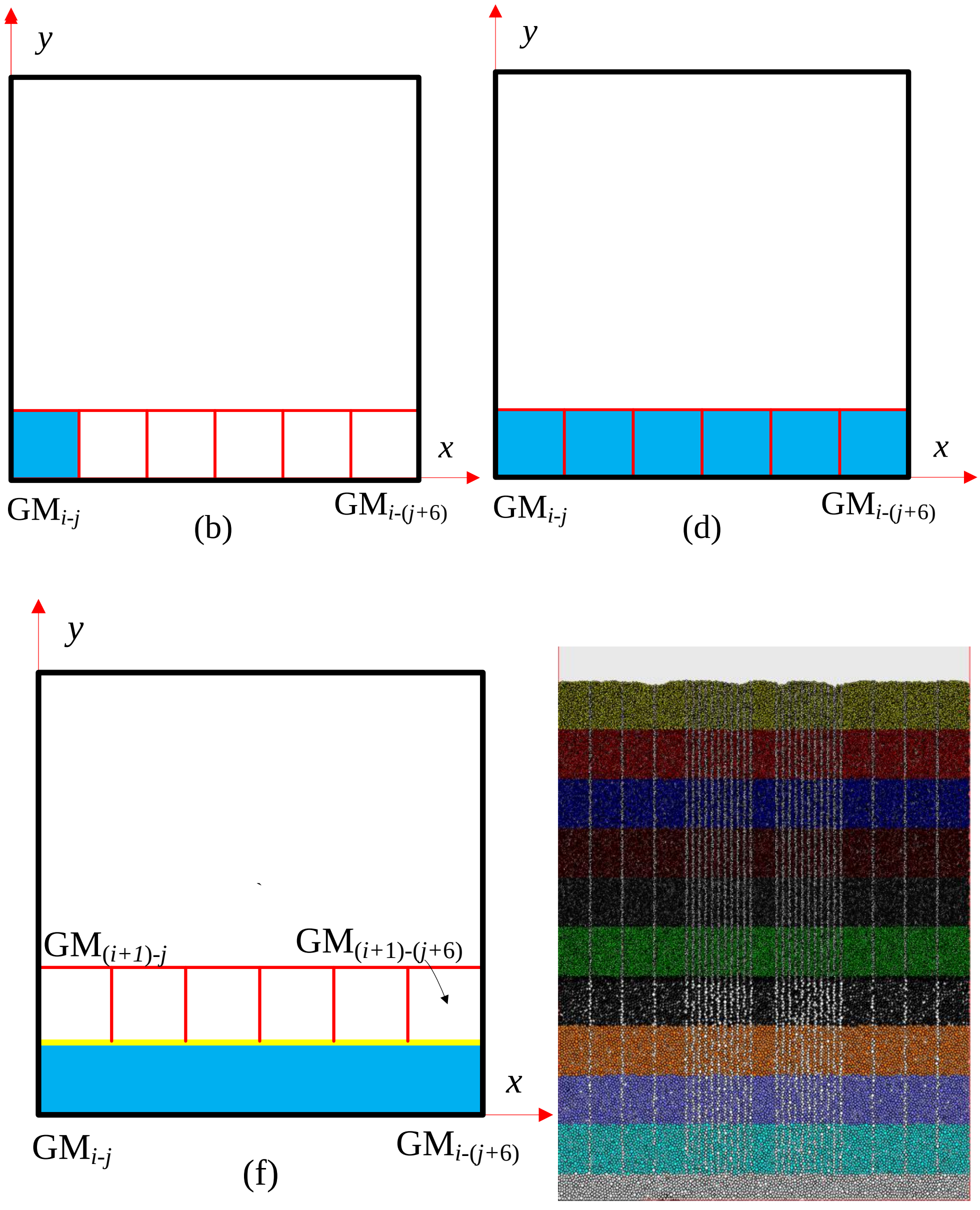


Fig. 1 - Graphics of soil samples generated by GM method

According to the relevant research[17-19], the contact and parameters between particles are assigned. The meso-physical parameters of soil particles are listed in Table 1.

Tab. 1 - Soil meso-parameters

NO.	Density / (kg/m³)	Soil classification	Normal contact	Tangential contact	Normal bond	Tangential bond	friction coefficient
1	2720	Silty clay	1e7	1e7	500	250	0.27
2	2710	Silty soil	5e7	5e7	500	250	0.756
3	2720	Silty clay	1e7	1e7	1000	500	0.32
4	2720	Silty clay	1e7	1e7	1000	500	0.46
5	2710	Silty soil	5e7	5e7	500	250	0.79
6	2720	Silty clay	1e7	1e7	1000	500	0.502
7	2710	Silty soil	5e7	5e7	500	250	0.78
8~12	2650	Sand	8e8	8e8	/	/	0.5

Pile Penetration

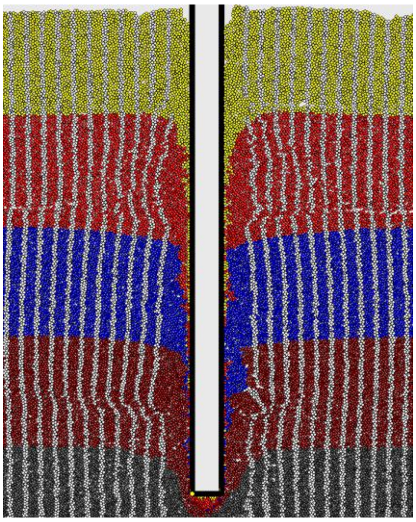


Fig. 2 - Pile driving process

Three sizes of piles are generated in the already formed soil particle model. The length of the pile is 30 cm, and the diameter of the pile is 10 mm, 15 mm and 20 mm. This kind of pile is composed of particles that can extract force and displacement. The penetration force of the pile top is increased from 0kN by 50kN each time, and the changes in force and displacement are monitored. When the pile body is completely penetrated into the soil particles, the loading is stopped.

DOI 10.14311/CEJ.2020.03.0033

ANALYSIS OF DEM TEST RESULTS

Pile-pressing Force Analysis

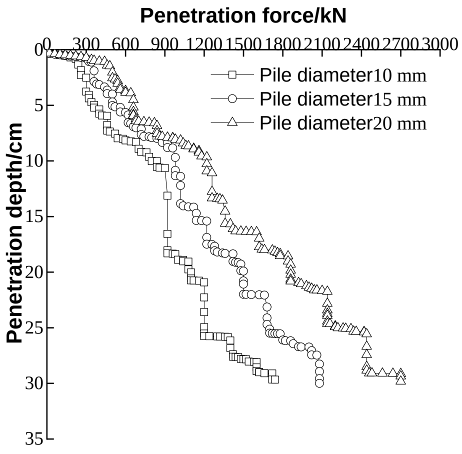


Fig. 3 - Curve of penetration force with penetration depth

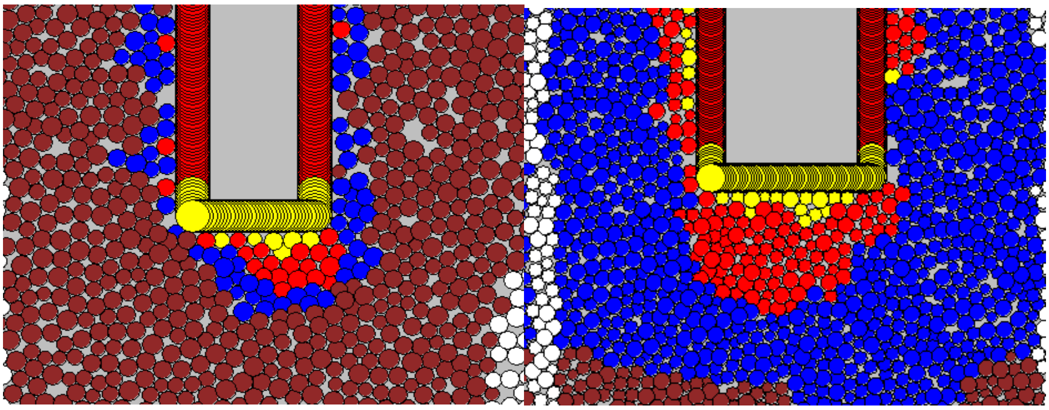
From Figure 3, it can be seen that with the increase of penetration depth, the penetration force increases gradually, and with the increase of pile diameter, the pile-pressing force increases gradually. The variation law of the curve also reflects the difference in the soil layer. From the point of view of the specific soil layer, the force of pile end increases rapidly and the displacement hardly changes when the pile end is not penetrated into the soil layer at the initial penetration stage. With the increase of penetration force, the penetration force keeps stable and the displacement increases sharply after piercing the soil layer at the pile end.

When the end of the pile penetrates into the silt layer, the penetration force increases rapidly and the penetration displacement increases slowly. When penetration into the silty clay layer, the penetration force remains stable and the penetration displacement increases rapidly.

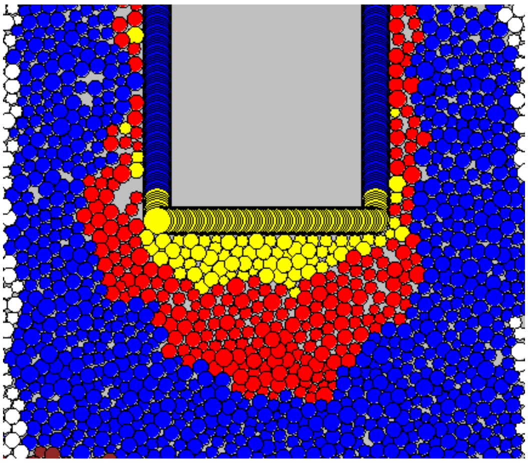
When the pile tip is located in the depth of 10 cm~20 cm, 25 cm~30 cm (silty clay layer 3, 4, 6), there is also a phenomenon of the rapid increase of pile driving displacement. Because the penetration force is still large after crossing the overlying soil layer, the displacement of the third, fourth and sixth layers of the soft soil layer increase sharply.

During the penetration process, when the pile tip is located in the soft soil layer, the displacement will increase sharply, which will be restrained with the increase of pile diameter. This shows that with the increase of pile diameter, unfavorable soil can be overcome to a certain extent. The specific reasons are as follows: Figure 4 shows that the increase of pile diameter will cover more soil particles, and part of the particles at the end of the pile is composed of upper soil particles, which have been compressed and consolidated during penetration. When the end of the pile is located in soft soil, the increase of pile diameter will increase the proportion of consolidated soil particles at the end of the pile, which shows that the displacement at the end of the pile decreases.

DOI 10.14311/CEJ.2020.03.0033



(a) Pile diameter 10 mm *(b) Pile diameter 15 mm*



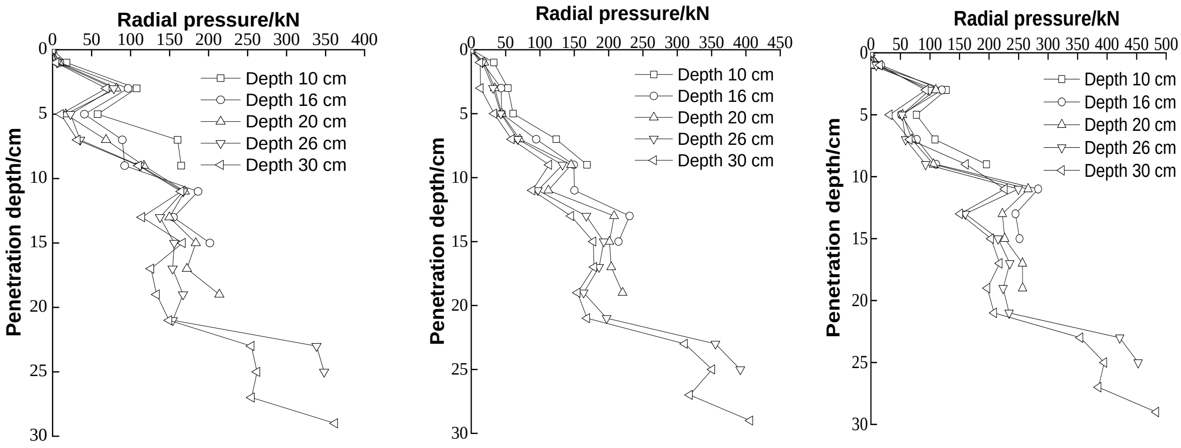
(c) Pile diameter 20 mm

Fig. 4 - Particle forms of incidental soil under different pile diameters

Analysis of Radial Pressure and Pile Side Friction

Each particle composing the pile can monitor the force change in real time, and extract the soil pressure monitored by the pile side particle at each depth from the DEM., the curve of the radial pressure on the pile side with penetration depth is drawn, as shown in Figure 5.

DOI 10.14311/CEJ.2020.03.0033

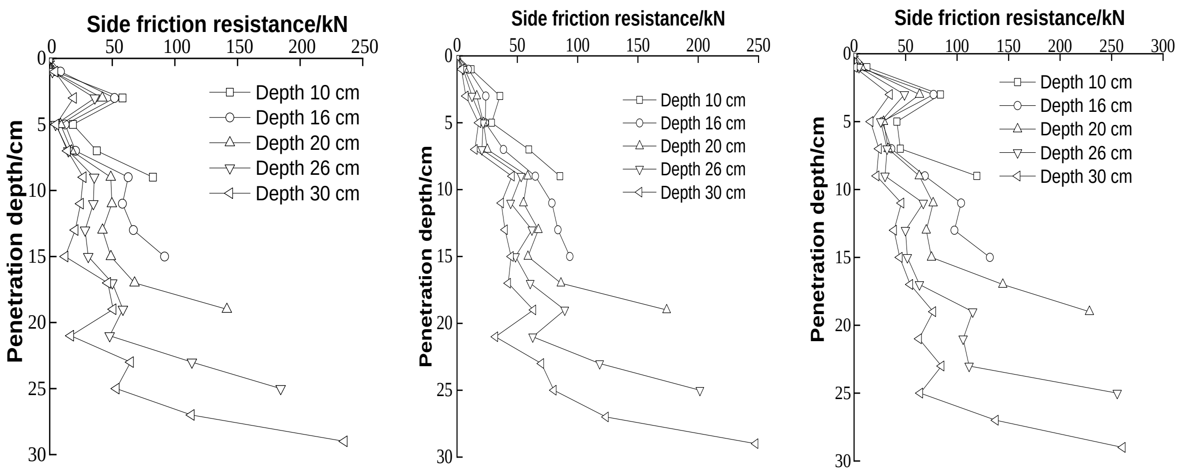


(a) Pile diameter 10 mm *(b) Pile diameter 15 mm* *(c) Pile diameter 20 mm*

Fig. 5 - Curve of radial earth pressure with penetration depth

From Figure 5, it can be found that with the increase of penetration depth, the soil pressure on the pile side increases gradually; the increase of pile diameter has no significant effect on the trend of soil pressure increase; when the pile side is located at the depth of 10 cm~20 cm, 25 cm~30 cm (silty clay), the soil pressure increases slightly with the depth fluctuation; When the pile side is located in the depth of 5 cm~10 cm and 20 cm~25 cm (silt), the soil pressure increases obviously with the depth. With the increase of penetration depth, the earth pressure at the same depth decreases slightly.

The frictional resistance of each section of the pile side during penetration into the soil is monitored, and the curve of frictional resistance of pile side with penetration depth is drawn as shown in Figure 6.



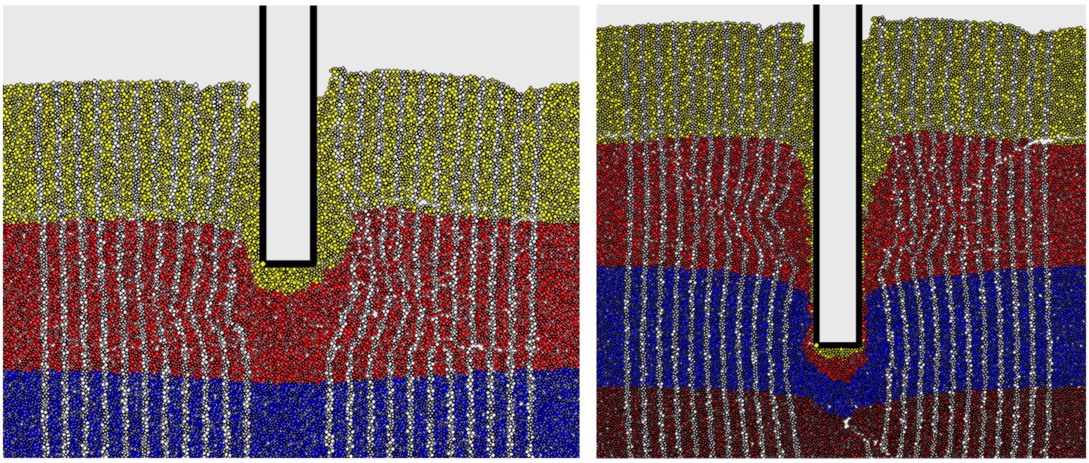
(a) Pile diameter 10 mm *(b) Pile diameter 15 mm* *(c) Pile diameter 20 mm*

Fig. 6 - Curve of side friction resistance with penetration depth

According to Figure 6, it can be found that the variation of pile side friction with penetration depth is consistent with that of pile side soil pressure with penetration depth. With the increase of pile diameter, the frictional resistance of the pile side also increases gradually. This is because, with the increase of pile diameter, the effect of squeezing soil is more obvious, resulting in an increase of side friction. At the same penetration depth, the variation of lateral friction is the same as that of soil pressure at the pile side. With the increase of penetration depth, the lateral friction decreases gradually, and the obvious weakening phenomenon appears. This phenomenon is called "shear weakening" by Heerma[20], and "h/R" effect by Bondilph[21]. The variation law of side friction is consistent with that of earth pressure, which also shows that the essence of the degradation of side friction is the degradation of earth pressure.

Analysis of soil movement around pile

Taking a model pile with a diameter of 20 mm as an example, the movement of soil around the pile is analyzed when the pile passes through different soil layers during penetration.



（a）Penetration from silty clay layer to silt layer （b）Penetration from silty layer to silty clay layer

Fig. 7 - Changes of soil around pile

From Figure 7, it can be seen that when the pile penetrates into different soil layers, the form of soil breakage is different. Figure 7 (a) shows that the shear band between pile and soil is wider and filled with silty clay when the end of pile is penetrated from silty clay layer (yellow) to silty soil layer (red), but the width of shear band between pile and soil decreases with the increase of penetration depth. This is because: when the end of the pile is penetrated from soft soil to hard soil, punching failure occurs when the end of the pile penetrates into the soil, resulting in a wider shear band between the soil layer and the pile. As the pile continues to penetrate, the width of the shear band decreases with the increase of the lateral earth pressure of the pile in the hard soil layer.

Figure 7 (b) shows that when the end of the pile is penetrated from silt (red) to silty clay (blue), the shear band between pile and soil is narrower and there are fewer silt particles filled. It shows that when the end of the pile penetrates into the soft soil layer from the hard soil layer, the end of the pile penetrates into the soft soil, resulting in a narrow shear band between the soil layer and the pile.

DOI 10.14311/CEJ.2020.03.0033

Particle displacement analysis

In the process of pile driving, the change of contact force is essentially the expression of particle movement and redistribution. DEM software can monitor the displacement of soil particles in real time. The displacement distribution of particles in different soil layers was obtained by DEM. The direction of the black arrow indicates the direction of the particle displacement, and the length of the arrow indicates the size of the displacement.

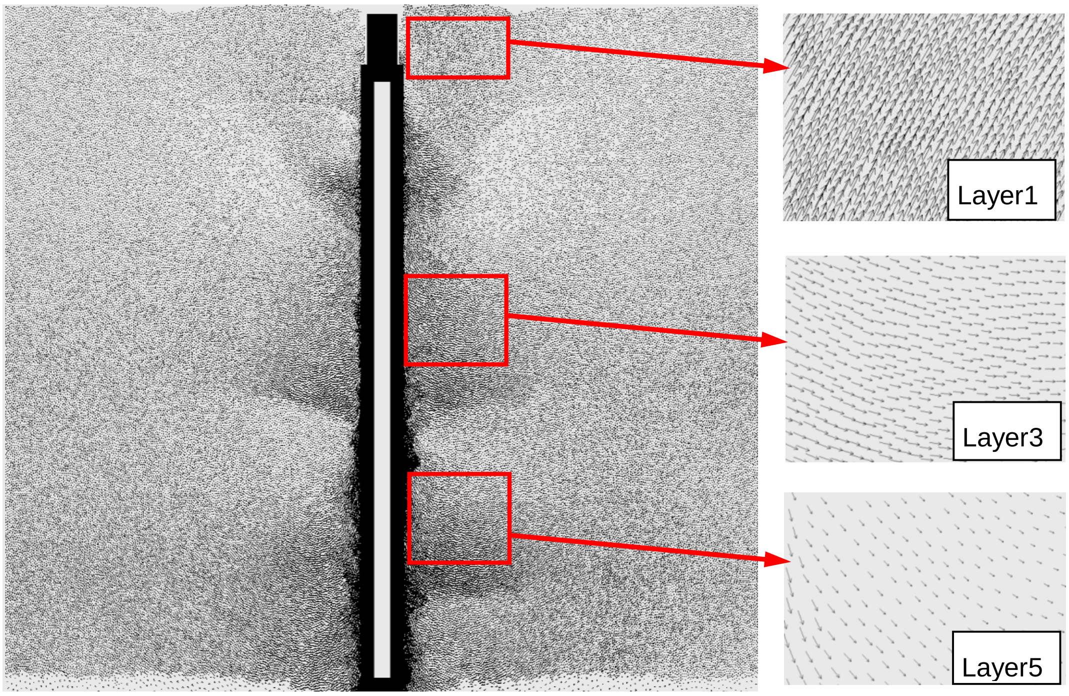


Fig. 8 - Particle Displacement Diagram after Pile Driving

From Figure 8, it can be seen that the displacement of soil around piles in different soil layers is quite different. In the process of penetration, the particles in the first soil layer move upward due to the compaction effect, and the macroscopical behavior is the uplift of the top soil during penetration. This is also one of the reasons why the friction resistance and radial pressure of pile side are smaller in the early stage of penetration. In the third soil layer, the horizontal displacement is the main one, because the third soil layer is silty clay layer, the contact stiffness and friction coefficient are small and the cohesion is large, so the horizontal displacement is easy to occur under the action of soil compaction. The fifth layer is silty soil with larger contact stiffness and friction coefficient. Compared with silty clay, the soil is harder and the effect of particle extrusion is stronger. Under the condition of pile penetration shear, the downward displacement occurs, which shows that the particles move downward obliquely.

Through Figure 8, it is found that the influence range of particle displacement in different soil layers is different after penetration. The influence range of particle displacement of silt layer is obviously smaller than that of silty clay layer, which indicates that the displacement of hard soil layer during penetration is smaller than that of soft soil layer, which corresponds to the conclusion that the sensitivity of soft soil is high, the structure is strong, and the strength of soil decreases more obviously after disturbance.

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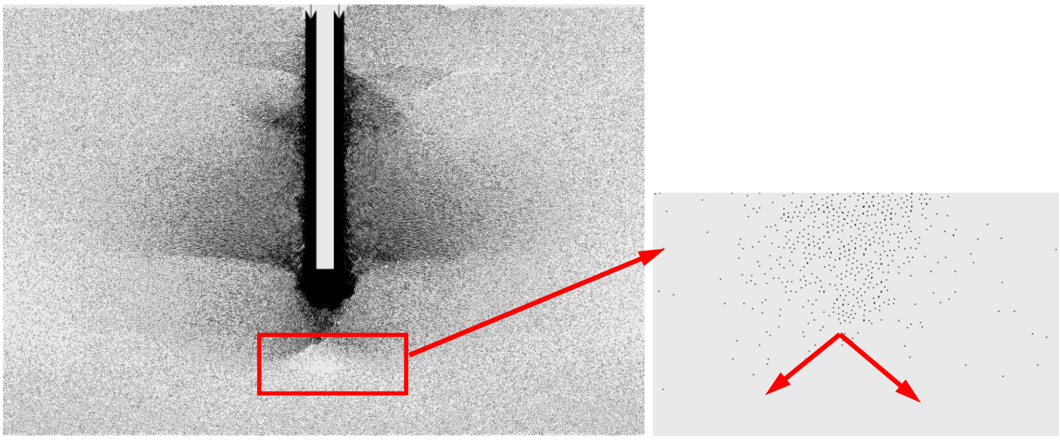


Fig. 9 - Pile tip particle displacement diagram during penetration

Pile diameter 20 mm penetration process is shown in Figure 11. By enlarging the red area at the end of the pile, it can be found that the displacement of the soil at the end of the pile presents a "triangular" distribution, indicating that the soil at the end of the pile is squeezed around under the action of the force at the end of the pile.

Analysis of contact force chain

Contact force chain refers to the average force between particles and the effective stress in soil. After the foundation model is generated and given the contact model, force chains will be generated between particles according to the position and displacement of particles. The thickness of black line in the force chain diagram represents the size of contact force, the direction of black line represents the direction of contact force, and the red force chain represents the tensile stress. In the process of pile penetration, the force chain will change.

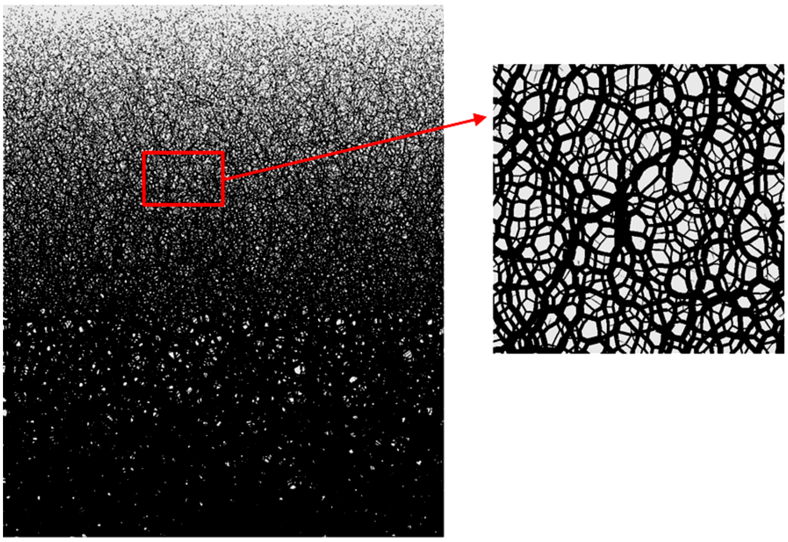
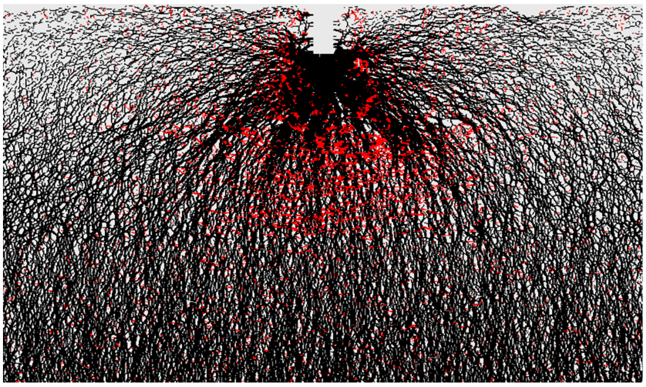
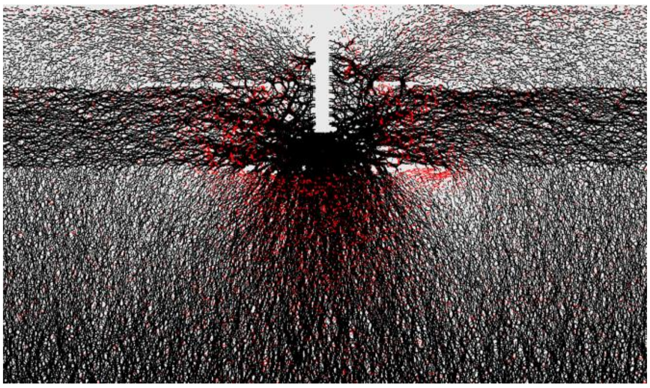


Fig. 10 - Force Chain Diagram after Soil Layer Generation

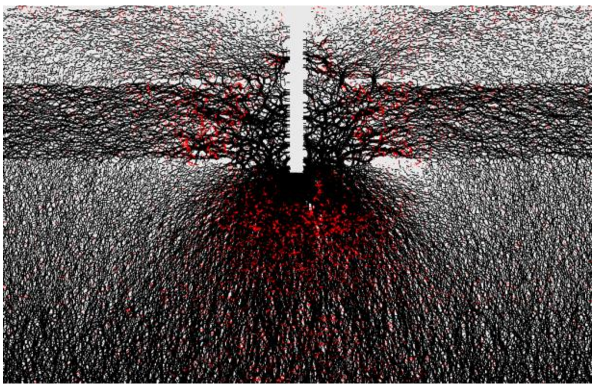
From the Figure 10, it can be seen that the contact force generated by deadweight increases gradually from top to bottom, and the transmission direction of the force chain is mainly vertical, there are also smaller horizontal and inclined bifurcations, showing a clear tree network.



(a) penetration 2 cm



(b) penetration 7 cm



(c) penetration 10 cm

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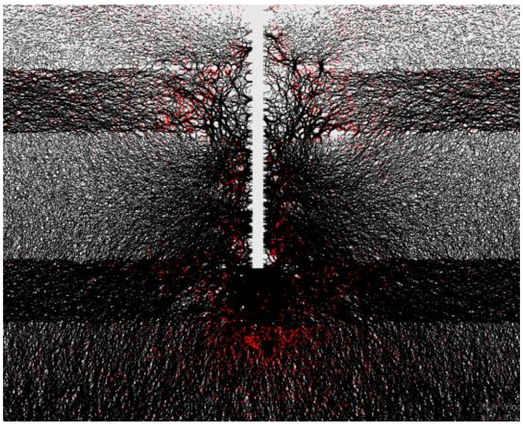


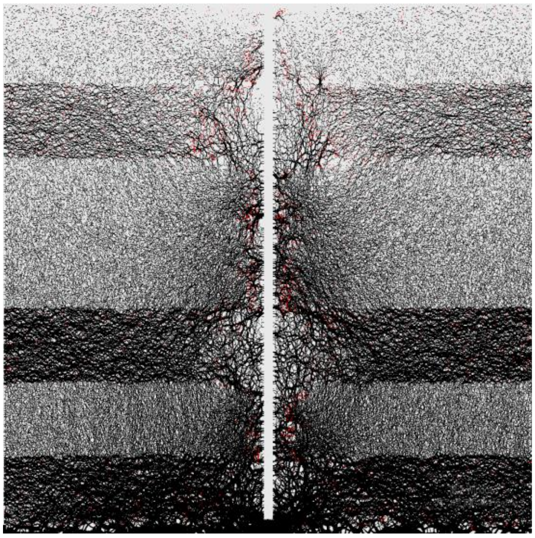
（d）penetration 20 cm

Fig. 11 - Force chain changes at different depths

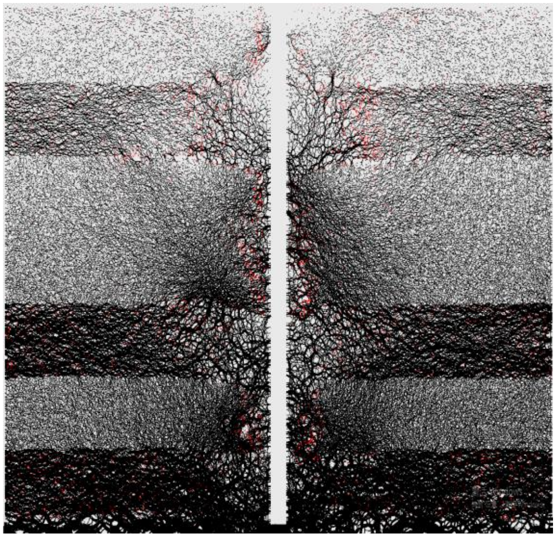
Figure 11 shows that in the initial stage of penetration, the force chain at the end of the pile is concentrated and radiated around, and the force chain at the side of the pile is sparse, indicating that the soil at the end of the pile bears most of the penetration force and the frictional resistance at the side of the pile is smaller at the initial stage of penetration. With the continuous penetration of the pile and the continuous extrusion of the soil, there is a large horizontal force chain near the pile side. With the increase of the distance between the soil and the pile side, the large horizontal force chain gradually changes into a force chain under self-weight.

The range of action of force chain in different soil layers is different, and the range of action of hard soil is larger. In silty clay layer, the tension and compression stress concentrates near the pile. With the increase of distance, the tension stress gradually disappears, and the compression stress gradually decreases to the contact force under self-weight.

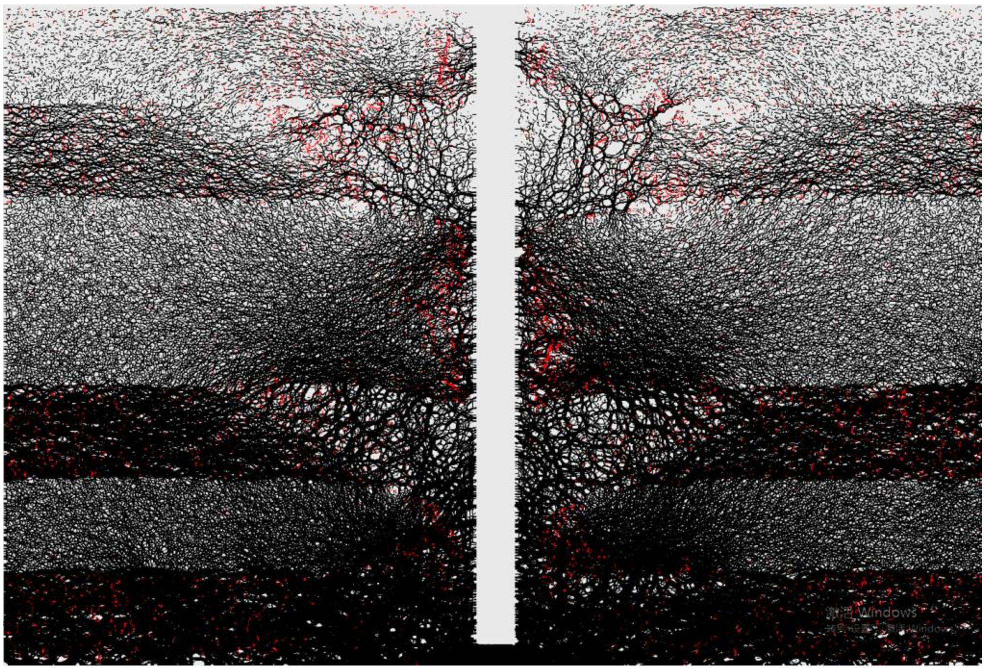
The contact force of silt layer is obviously greater than that of silty clay layer, and the stress of the soil beside the pile in silt layer also shows a horizontal direction, and the action range of tension and compression stress is larger.



（a）Pile diameter 10 mm



（b）Pile diameter 15 mm



（c）Pile diameter 20 mm

Fig. 12 - Variation of force chain under different pile diameters

From Figure 12, it can be found that with the increase of pile diameter, the compressive stress and tensile stress in the soil layer are gradually increasing, and the influence range caused by soil compaction effect is also gradually increasing. From the comparison of Figures 12 (a) (b) (c), it is found that with the increase of pile diameter, the transmission direction of the force chain becomes vertical and the force chain increases gradually. This is because the cohesion of silt layer is smaller and the contact stiffness is bigger, so horizontal displacement is not easy to occur; while the cohesion of silty clay layer is bigger and the contact stiffness is smaller. Under the extrusion force of pile body and soil, the particles at the interface of silt layer and silty clay layer tend to move in the direction of smaller contact stiffness, resulting in larger vertical compressive stress at the interface between silt layer and silty clay layer.

With the increase of pile diameter, the greater the extrusion force between pile and soil, the greater the movement displacement of soil particles, and the greater the compressive stress between particles at the interface.

CONCLUSION

(1) The penetration force increases with the increase of penetration depth and pile diameter. The increase of pile diameter is beneficial to overcome the influence of unfavorable strata.

(2) At the same penetration depth, with the continuous penetration of the pile body, the radial pressure gradually decreases, showing a significant degradation phenomenon. The reason for the degradation of lateral friction is essentially the degradation of the radial pressure.

(3) The distribution of contact force chain in different soil layers is similar, but the range of action is different. The contact force in silt layer is obviously larger than that in silty clay layer. The compressive stress of the soil at the end of the pile transfers radially with tensile stress. With the increase of pile diameter, the compressive stress and tensile stress in soil layer are gradually increasing, and the influence range of compressive stress and tensile stress is also gradually increasing.

(4) The displacement of the soil below the pile tip is triangular, and the soil at the pile tip is squeezed around under the action of the pile tip. The influence range of particle displacement in each soil layer is different, and the influence range of particle displacement in silt layer is obviously smaller than that in silty clay layer.

ACKNOWLEDGEMENTS

The work presented in this paper was financially jointly supported by the National Natural Science Foundation of China (Grant No. 51778312).

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