Analysis of the penetration mechanism of CPTU based on large deformation finite element

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Abstract: The Piezocone Penetration Test (CPTU) is a new in-situ testing technology developed in the 1980s. Compared with the traditional Cone Penetration Test (CPT), it has the advantages of high precision, large amount of data, good stability and wide application. Because of the short history of pore pressure static penetration (CPTU) technology, the CPTU develops slowly in China. By the large deformation, finite element simulation method is used to numerically simulate the CPTU penetration process in ABAQUS software; and the distribution and variation characteristics of soil stress, strain and pore pressure field at different penetration depths are studied. The results show that during the penetration of the cone, there is a stress concentration zone around the cone. The resistance of the cone is mainly the resistance below the cone tip. When the penetration is shallow, the soil is disturbed with the penetration. As the depth increases, the disturbance becomes smaller; according to the variation of the pore water pressure, the water permeable element can be placed at the junction of the conical head and the conical body.

1. introduction

With the rapid development of China's economy, construction and its scale have reached an unprecedented level. Therefore, determining geotechnical parameters accurately and efficiently has become a difficult problem in engineering construction. In situ testing technique[1-4], it does not need to disturb the original sample like indoor test and borehole sampling, and is widely used in engineering construction because of the need of no sampling, which is convenient and quick. However, the pore pressure static penetration probe (CPTU) technology [5-6] is the best in-situ testing, the most widely used modern test method. It can effectively determine the soil name, measure the soil profile, obtain the geotechnical parameters, and determine the type of foundation soil by relying on the sensor set at the tip of the probe. It is of great significance to carry out the CPTU penetration mechanism research. Many scholars are adopting the bearing capacity theory. The theory analyzes the pore pressure static penetration process. However, due to the excessive approximation of the theoretical analysis method, there are many limitations, and it is difficult to accurately analyze the penetration process.

Based on the finite element theory, this paper makes full use of the advantages of ABAQUS finite element software in geotechnical engineering to carry out numerical simulation. The purpose of this paper is to study the probe cone tip resistance and surrounding stress and strain and pore pressure field distribution during CPTU penetration, and analyze its mechanism.
2. Large deformation numerical simulation
In this paper, the ABAQUS software is used to simulate the penetration process of the probe in the process of clay penetration. During the penetration process of CPTU, the effect of the cone tip to the lateral squeezing is roughly equal, which is a typical axisymmetric geotechnical problem. To simplify the calculation, the probe penetration process is simplified to an axisymmetric problem. The soil material in the paper adopts the modified Cambridge model, and the soil is modeled with clay, which corresponds to the clay plastic model in ABAQUS. Because the elasticity and plasticity of ABAQUS are set separately, the Cambridge model must be used in combination with the porous elasticity. According to the application of CPTU in engineering, the soil with a depth of 10m and a radius of 5m with the cone tip as the axis is used to model the analysis area. In order to simulate the characteristics of the excess pore water pressure, physical forces are applied to the soil in the initial ground stress.

The CPTU penetration process specifies the downward displacement of the cone top to achieve the simulation. In addition, due to the large deformation of the soil during probe penetration, the CPTU component deformation is negligible, so the CPTU assembly is assumed to be absolutely rigid and will not deform. At the same time, the round head transition between the cone head and the cone body and the rigid guiding tube is convenient for convergence. The cone has the most common international standard of diameter 0.036m and cone angle 60 degrees.

The definition of contact problem in numerical simulation is an important factor affecting the success of the test. In this paper, the method of facing contact between the cone and the soil is set, and the two contact surfaces of soil and CPTU and auxiliary rigid tube are set respectively, of which CPTU is mainly controlling the surface; in order to avoid the soil penetration CPTU surface, the contact surface discrete method is set to point-to-surface discrete method. The main surface uses the smoothing default value of 0.2. The normal model of contact is hard contact and the tangential model is frictionless.

3. Simulation results and analysis
3.1. Characteristics of soil stress with CPTU penetration process
In order to analyze the soil stress characteristics during the penetration process, the stresses of the soil near the cone can be obtained by numerical simulation. Figure 1 shows the radial, axial, toroidal and shear stresses of the soil near the cone at 5 m.

Regardless of radial stress, axial stress, toroidal stress, and shear stress, there is an approximately annular stress concentration zone, but the position is different. The stress concentration zone of radial stress is located at the junction of the cone and the cone head, the stress concentration zone of the axial stress is located at the tip of the cone, and the stress concentration zone of the radial stress appears below the cone tip. But the shear stress on the vertical plane is a significant stress concentration zone appears below the cone tip, a stress concentration zone with opposite directions also appears above the cone tip, but the values and influence ranges are small. This is because the radial displacement of the soil at the tip of the cone is the largest during the penetration process. The soil above the cone tip has undergone a certain radial displacement due to the previous penetration, but the depth of the soil below is not penetrated, the radial displacement is relatively small. Therefore, the relative shearing displacement of the soil below the soil, the tip of the cone is larger than that of the upper part, so that the shear stress concentration is more strengthened and the range is larger.
The field variables at the penetration depths of 1m, 2m, 3m, 4m, and 5m are output, and each field variable is selected as a group for drawing, and Fig. 2 is obtained. The result shows that the maximum radial stress is greater than the maximum axial stress during the cone penetration process.

Figure 1. Penetration of 5m stress cloud.

Figure 2. Stress curve along the depth of the soil layer.
Overall, the cone penetration into the soil is a process of loading and unloading. As the cone penetration, the radial stress, vertical stress and toroidal stress increased, when the cone passes through the soil, the soil undergoes a rapid unloading process. However, it is worth noting that due to the penetration effect of the taper tip, when the penetration reaches a certain depth, the axial stress of the soil above is drastically reduced due to the generation of excess pore water pressure at the cone head, which is significantly lower than the effective weight under hydrostatic pressure.

During the penetration process, the maximum shear stress is at the tip of the cone, and as the penetration depth increased, the maximum shear stress increased. Among them, the normal shear stress corresponds to the soil below the cone tip, the negative shear stress corresponds to the soil above the cone tip, and the absolute value of the normal shear stress is greater than the negative shear stress. This also verifies the conclusion of the Gaotou Meng model test from the side: when the probe penetrates, the horizontal deformation of the soil layer at the tip of the cone is the largest, the soil below the cone tip is less disturbed, and a certain lateral extrusion occurs above, so that the soil below is more dislocated and the shear stress is larger.

3.2. Characteristics of soil strain with CPTU penetration process
Generally, in the static penetration test, during the penetration process of the cone tip, the soil near the cone head will be severely deformed. In order to analyze the soil strain during the CPTU penetration process, the strain field of the penetration 5m is drawn by numerical simulation. It can be seen from Fig. 3 that the radial displacement caused by the penetration of the cone is radially outward, and only a circle along the wall of the probe hole is relatively large, and rapidly decreases toward the periphery, which is represented by the radial extrusion of the cone. The radial displacement is small below the cone tip and relatively large within a certain range below the slope. The axial displacement is also limited to the periphery of the probe hole compared to the radial displacement, and the radial influence range is small. The outer contour of the plastic zone of the soil is arc-shaped, and the plastic strain is mainly concentrated around the probe hole and the tip of the cone, and also the vertical upper and lower plastic zones are basically the same.

Figure 4 shows the strain development law of the soil around the cone during the CPTU penetration process. When the cone head enters the soil and the penetration depth is shallow, the soil is disturbed horizontally very serious because the soil is in the exposure face, and the soil around the probe has a bulge. With the penetration of the cone, the radial displacement and axial displacement of the soil layer are the largest, but the displacement is mainly the horizontal displacement.
3.3. Characteristics of excess pore water pressure with CPTU penetration process

In order to analyze the change of super-void water pressure in the penetration process, Figure 5 shows the ultra-porous water pressure cloud map corresponding to the penetration of 1m, 3m and 5m. It is easy to see that the super-pore pressure field generated during the penetration process is the spherical. The super-porous water pressure is mainly concentrated near the tip end of the probe cone and rapidly decreases toward the periphery. As the cone tip penetrated, the super-pore pressure field continuously moves down, and the pore pressure of the soil quickly dissipates after the cone head left.

The curve of the excess pore pressure along the depth of the soil layer under different penetration depths was drawled. It is known from Figure 6 that during the CPTU penetration process, the maximum excess pore water pressure is located at the tip of the cone, and the maximum excess pore pressure increases with the penetration depth increase. However, due to the generation of excess pore water pressure accompanied by the dissipation of pore pressure, the pore pressure fluctuates along the depth, and the pore water pressure is less affected at the deeper point below the cone. According to the variation law of pore water pressure, the probe water permeable element can be set to the junction of the cone head and the cone body, where the pore pressure is sensitive and the stability is well.
4. Conclusion

(1) The radial stress is mainly compressive stress. During the penetration of the CPTU probe, the maximum radial stress generated is generated near the tip of the cone and decreases rapidly around the circumference, reflecting the compaction effect during the penetration of the probe. At the same depth, the radial pressure decreases rapidly from the center to the periphery. During the penetration process, the probe has a limited influence on soil disturbance. The soil below the cone tip is less affected, mainly controlled by the weight of the soil. And as the penetration depth increases, the radial stress also increases.

(2) The axial stress is mainly compressive stress, and the stress concentration area appears below the cone tip. It is reflected that the resistance of the probe during the penetration process is mainly the resistance below the cone tip, and the axial stress influence range is smaller than the radial stress.

(3) The radial displacement of the tip cone soil is the largest during the penetration process. The soil above the cone tip has undergone a certain radial displacement due to the previous penetration. The soil below the cone tip is not penetrated, and the displacement is relatively small. Therefore, the relative shearing displacement of the soil below the soil and the tip of the cone is larger than that of the upper part, so that the shear stress concentration is more strengthened and the range is larger.

(4) During the penetration process, the horizontal influence range of the plastic zone around the probe is about 1 probe radius, and the stress bubble is formed near the probe. The characteristics are in good agreement with the cavity expansion theory of Yu, et al.

(5) During the CPTU penetration process, the axial displacement of the soil layer where the cone head is located is the largest. When the probe penetrates shallowly, the soil around the probe has a bulging phenomenon. When the penetration depth is large, the influence becomes small, and the bearing capacity theory is verified.

(6) During the CPTU penetration process, an approximately spherical excess pore pressure field is generated at the tip of the cone, and the maximum excess pore water pressure is located at the tip of the cone and rapidly decreases toward the periphery. As the depth of penetration increased, the maximum excess pore pressure increased. However, as the excess pore water pressure is generated, the excess pore water pressure also begins to dissipate, so the excess pore water pressure fluctuates along the depth.

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