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Numerical Simulation of Failure Pattern of Overlying Soil during Vertical Jacking Construction

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***Abstract*—In order to clarify the failure characteristics and influencing factors of overlying soil during vertical jacking, using secondary development of discrete element program to simulate the construction process of vertical jacking, which reveals the failure mechanism, scope and development path of the overlying soil in the process of vertical jacking. The simulation results were compared with the test results and the influence of different factors on soil failure were discussed. The results show that the shear breakage of the overlying soil has nonlinear characteristics and the existing works assume that the breakage linearly distributes along a specific dip angle is insufficient. The failure range of the overlying soil is significantly larger than the empirical value, indicating that the failure range of the existing research is inaccurate. In vertical jacking, the overlying soil experiences the process of compressive shear, failure crack, fracture extension, breakage penetration, fracture expansion, formation of overlying soil column, soil redistribution , filling of cracks. The failure range of overlying soil decreases linearly with the increase of jacking speed and has a linear relation with the cohesion force and friction angle.**

Keywords—vertical jacking; overlying soil; failure characteristic; influencing factor; discrete element simulation

I. INTRODUCTION

Vertical jacking is a method to pierce through the overlying soil layer of vertical pipe by the hydraulic jacking equipment in the built tunnel to build functional wells such as water intake, ventilation or inspection, etc., which has been applied more and more in recent years due to its unique advantages [1]. Compared with conventional horizontal pipe jacking construction, vertical jacking construction technology is less mature and there are many problems in the implementation process, such as the understanding of failure pattern of overlying soil in vertical jacking construction. It is very critical for the successful implementation of vertical jacking to clarify the failure pattern of the overlying soil, including the failure mechanism, course and scope of the soil.

It is very difficult to observe the failure pattern of the overlying soil with vertical jacking method by experiment and the theoretical analysis is also extremely complicated. In contrast, particle flow simulation analysis can describe the microscopic and macroscopic mechanical behavior of the overlying soil during jacking and the failure mechanism, path and scope of the soil better, so it has been well developed[2]. Therefore, based on the secondary development of particle flow program, the numerical simulation of vertical jacking is carried out to study the failure mechanism, path and scope of the overlying soil during the vertical jacking process and the simulation results are compared with the test results. In addition, the influence of different overlying soil depth on the failure characteristics of the soil is discussed.

II. CALIBRATION OF MACRO AND MICRO PARAMETERS

The diameter of the vertical jacking construction pipe is 1.8m, the wall thickness is 0.2m, and the depth of the overlying soil is 8m, mainly cohesive soil. The soil of typical engineering sites was taken for indoor physical mechanics test and the main macroscopic mechanical indexes of the soil were obtained: density ρ=1.89g/cm^3, cohesion c=6.6kPa, friction angle φ=27.7°, and compression modulus Es=5.31MPa. The macroscopic parameters of soil cannot be directly used in particle flow calculation, so the corresponding microscopic parameters of soil layer should be calibrated by simulation test.

The test model shown in FIGURE Ⅰ was established with the test size of 20cm×10cm and the biaxial compression test was carried out to determine the shear strength index of the soil. In the biaxial compression test model, the upper and lower walls are used for loading. The fixed confining pressure is applied on the left and right walls to restrain the lateral deformation of particles. The walls are all set as smooth planes with no friction with soil particles. 100kPa, 200kPa and 300kPa confining pressures were applied respectively and the peak values of normal pressure and confining pressure difference were the failure points. According to the test results under different confining pressures, the shear strength envelope was drawn and the mesoscopic strength parameters were determined by comparing with the macro indexes of soil.

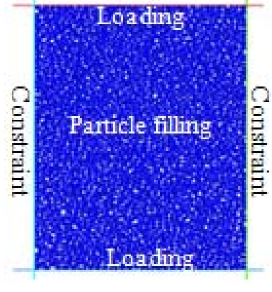


FIGURE I. TEST MODEL OF PLANE BIAXIAL COMPRESSION

The compression modulus of soil is the ratio of vertical stress increment to strain increment. Based on the model shown in FIGURE I , the simulation test of complete lateral compression is carried out. The two sides of the wall are fixed and set to a static state. The vertical displacement of the upper and lower walls is controlled to achieve the compression process. The vertical pressure was changed from 100kPa to 200kPa (the additional vertical stress was 100kPa) and the vertical additional stress-strain relationship curve was calculated, then the compression modulus was obtained.

The vertical jacking process of pipe is simplified appropriately. A two-dimensional plane calculation model is adopted, in which the model foundation is a single clay layer. In the model, particles were simulated by contact-bond model and the mesoscopic parameters of clay particles were calibrated by the above numerical simulation test (TABLE I). In addition, according to references [3-4], in the particle-particle contact bond model, the ratio of normal to tangential stiffness k is 2.5 while the ratio of normal to tangential bond strength is 1.

TABLE I. MESOSCOPIC PARAMETERS OF SOIL SAMPLES

Particle size of calibration model (mm)	**Ratio of normal to tangential stiffness**	**Contact modulus** *E*(N/m^2)	**friction coefficient** u	**Normal bond strength** (kPa)	**Tangential bond strength** (kPa)
2~4mm	2.5	7×10^6	0.7	9	9

III. NUMERICAL SIMULATION OF VERTICAL JACKING

A. Model Establishment

In the calculation model shown in FIGURE II, the horizontal length of the soil layer is 18m and the vertical height is 8m(jacking height). The calculation of the model boundary follows the principle that the ratio of the length of the short side to the maximum particle size is 80~120 [5]. In addition, according to the research results in literature [6], the elastic modulus and internal friction angle of two-dimensional model particle samples fluctuate very slightly with the change of particle size. Therefore, the same particle size ratio was adopted for the calculation model and the microscopic parameter calibration, but the particle size was enlarged to 4cm~8cm and the contact parameters were consistent with the calibration test parameters.

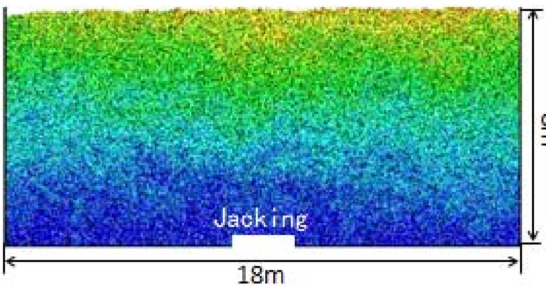
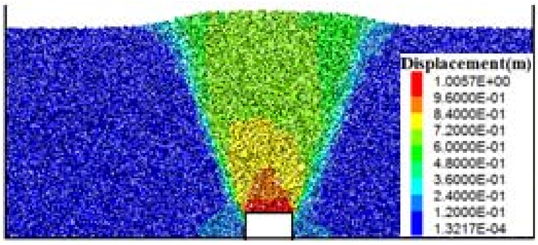


FIGURE II. CALCULATION MODEL OF PARTICLE FLOW

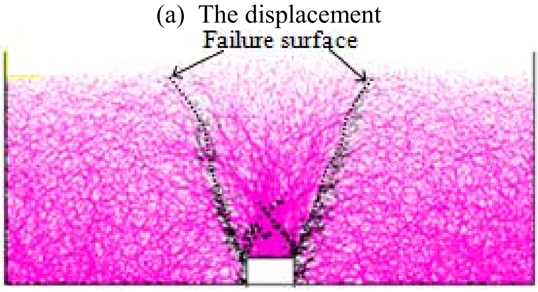
The boundary of the soil is the wall and the contact stiffness of the wall is the same as that of the soil particles. The friction coefficient is set at 0. In the model, simplified rectangular wall elements are used to simulate the pipe structure, with the length and width of 1.8m and 8m respectively. The stiffness of the jacking pipe wall unit should be much greater than that of the soil particles and the two are treated in series with two spring elements. The contact modulus between the wall and the particles of the jacking pipe section is 7×10^{6}Pa and the stiffness ratio k=2.5. The friction angle between the wall and the particles is 2/3 of the particles[7]. The corresponding friction coefficient u is 0.3. The uniform velocity of pipe jacking was set at 0.1m/s and the mechanical morphology of the overlying soil during the whole jacking process was recorded.

B. Verification of Model Rationality

In order to verify the rationality of the computational model of particle flow, a comparative analysis was conducted with the previous model test[8]. FIGURE III shows the cloud diagram of displacement and force chain when the pipe rises to 1. At this time, the failure surface of the overlying soil has been transfixed. The black force chain indicates that the bond has been broken and the particles have been relatively slippage. While the red force chain indicates bond contact.



(a) The displacement



(b) The distribution of force chain

FIGURE III. THE JACKING HEIGHT OF 1M CORRESPONDS TO THE DISPLACEMENT AND FORCE CHAIN

The particle flow in FIGURE III was extracted to calculate the distribution feature points of the sliding surface of the overlying soil and the comparison with the model test results was shown in FIGURE IV . FIGURE IV shows that the numerical calculation results are consistent with the failure pattern of overlying soil characterized by model test. At the same time, the top failure range calculated was about 2.97D (pipe diameter), 12.5% larger than the failure range of 2.6D in the model test, which was generally consistent. The difference was caused by the diversity between the soil structure calculated by particle flow and the actual soil. From the failure pattern and scope of the overlying soil, the particle flow calculation model is rational.

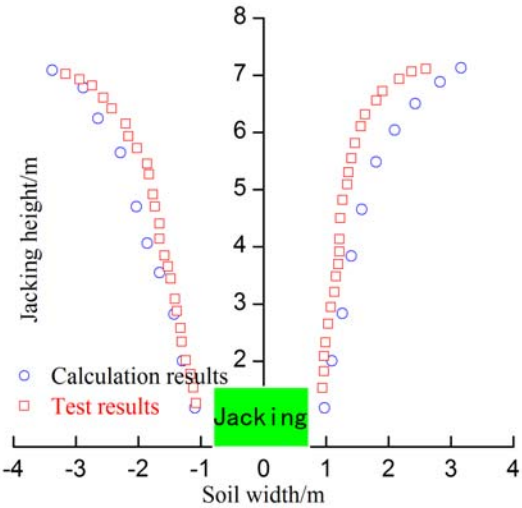
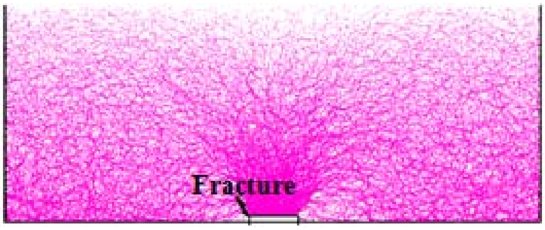
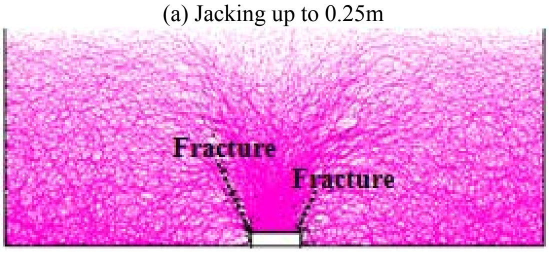


FIGURE IV. COMPARISON BETWEEN NUMERICAL CALCULATION AND EXPERIMENTAL RESULTS

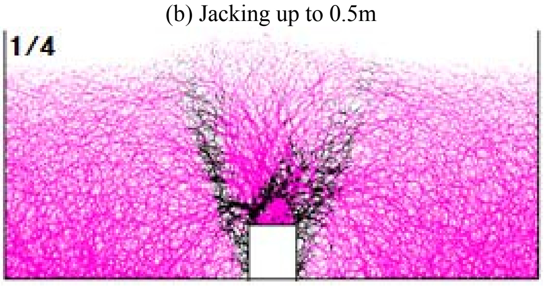
C. *Analysis of Failure Pattern of Soil*



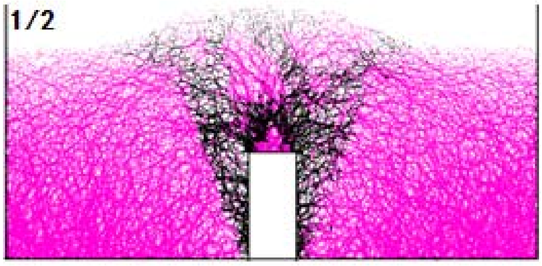
(a) Jacking up to 0.25m



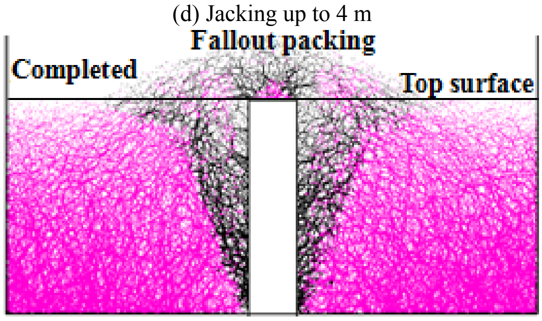
(b) Jacking up to 0.5m



(c) Jacking up to 2 m



(d) Jacking up to 4 m



(e) Jacking up to 8 m

FIGURE V. FORCE CHAIN OF THE OVERLYING SOIL CORRESPONDING TO DIFFERENT JACKING STAGES

FIGURE V shows the force chain distribution of the overlying soil at different jacking stages. FIGURE V combined with FIGURE III shows that when the pipe rises to 0.25m(1/32), partial shear failure occurs in the overlying soil at the top, resulting in cracks and upward extension and development along non-equivalent dip angle. When jacking to 1m (1/8), an obvious compression triangle is formed at the top. The shear breakage is extended and developed and the breakage of the overlying soil is transfixed. The cracks continue to expand, forming relatively independent soil column. Then the overlying soil is redistributed and the cracks on both sides of the pipe are gradually filled (FIGURE VI). Based on the above analysis, it can be judged that the overlying soil in the jacking construction experiences the process of compressive shear →partial failure crack and extension →fracture extension →breakage penetration → fracture expansion → formation of soil column → soil redistribution →filling of cracks. The top failure range was significantly larger than the empirical range 1.2~1.5D.

It is worth noting that the breakage development law of the overlying soil has typical nonlinear characteristics. Width b and covering depth h approximately satisfy the cubic function h=0.119b^3-0.137b^2-5.122b -4.069, which is not the regular linear distribution along a certain inclination angle assumed by existing research results[9]. It can be seen that the existing researches are inadequate in understanding the failure pattern and scope of overburden soil.

In the vertical jacking construction, the failure pattern of the overlying soil is mainly affected by the characteristics of the soil, including the depth of the overlying soil and physical mechanics index[8]. Based on the theory of shear strength of soil and combined with the analysis of literature[10], it can be seen that the overlying depth has the most significant influence on shear failure pattern. Therefore, different overlying depth was set to explore failure characteristics of overlying soil.

D. Analysis of Factors Affecting Soil Failure

Previous studies[8] have shown that the failure pattern of overlying soil induced by vertical jacking are similar under different conditions and the main differences are reflected in the failure range.

1) Effect of jacking speed

Based on the model shown in FIGURE II , jacking speeds of 0.1m/s, 0.3m/s, 0.6m/s and 1m/s were set to calculate the failure range of overlying soil (FIGURE VI). FIGURE VI shows that the failure range of the top of the overlying soil decreases linearly with the increase of jacking speed. The reason is that the compression zone of the pipe decreases with the jacking speed increases. The strain localization becomes more significant and the effect of the transmission to the two sides weakens.

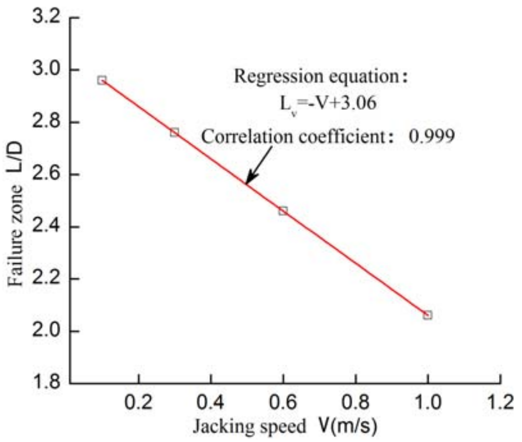


FIGURE VI. TOP FAILURE RANGE CORRESPONDING TO DIFFERENT JACKING SPEED

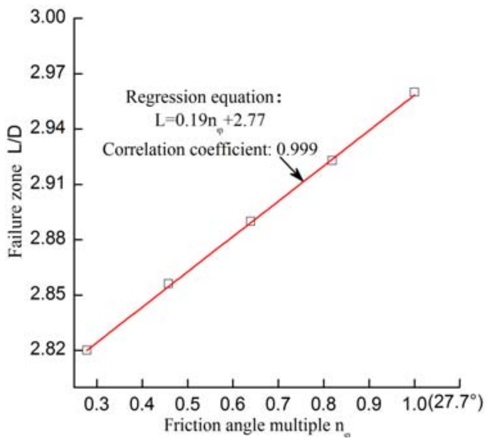


FIGURE VII. CALCULATION RESULTS OF DIFFERENT FRICTION ANGLES OF OVERLYING SOIL

2) Effect of friction angle

Based on the model shown in FIGURE II, the friction angles of 27.7°, 22.7°, 17.7°, 12.7° and 7.7° were taken respectively to calculate the top failure range. As shown in FIGURE VII , the failure range of the top of soil decreases linearly with the decrease of friction angle. Friction angle decreased by 72.2% and top failure range decreased by 4.73%.

3) Effect of Cohesive force

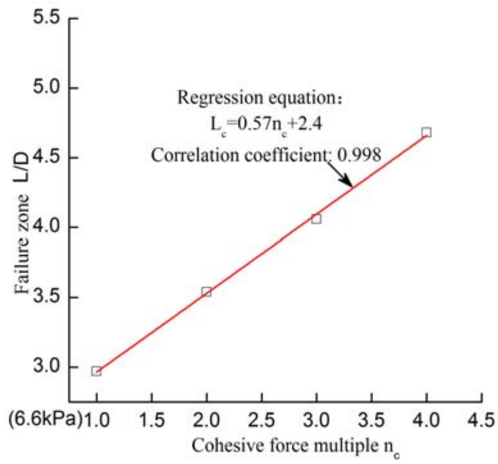


FIGURE VIII. CALCULATION RESULTS OF DIFFERENT COHESIVE FORCES OF OVERLYING SOIL

Based on the model shown in FIGURE II, the original macroscopic parameters of the basic model were set as 13.2kPa, 19.8kPa and 26.4kPa, which were 2-4 times of the cohesion of the basic model and the range of common cohesion of shallow overlying soil.

FIGURE VIII shows the failure range of the top of the overlying soil corresponding to different cohesive forces. The figure shows that the shear constraint between the overlying soil is strengthened due to the increase of the cohesive force of the overlying soil and the failure range of the overlying soil is increased. The two have a linear relation in the same direction. The cohesive force of soil doubled and the top failure range increased by 19.2%.

IV. CONCLUSION

- The breakage distribution of the overlying soil has nonlinear characteristics and satisfies the cubic function distribution. It is assumed that there are defects in the linear distribution of breakage along a particular dip angle.
- The failure range of the top of the overlying soil is 2.97D, which is significantly larger than the empirical range of 1.2D to 1.5D, indicating that the existing failure range is inaccurate.
- The overlying soil experiences the process of compressive shear, failure crack and extension, fracture extension, breakage penetration, fracture

expansion, formation of relatively independent soil column , soil redistribution, filling of cracks.

- The failure range of overlying soil decreases linearly with the increase of jacking speed and has a linear relation with the cohesion force and friction angle.

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