Progressive Deformation Failure Characteristics of Highway Tunnel Working Face in Sand Pebble Stratum

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Abstract The sand pebble stratum is typically unstable with discrete particles. The most important constituent elements are sand and pebbles. The surrounding rock of tunnels in the sand and pebble stratum has prominent engineering problems, such as being loose, easy to collapse, and unstable when exposed to water. Therefore, it is critical to ensure the safety of tunnel construction in this stratum. This paper studies the failure modes of surrounding rock on sand and pebble tunnel working face of different excavation footage, and the formation of subsidence law starting from the micro-mechanical and motion characteristics of particulate matter. This study is based on the Bai Heqiao tunnel of the Wudu expressway in Gansu Province. The results show that the instability failure of the surrounding rock mainly occurs in the upper part and sliding area in front of the tunnel working face. The sliding area is a curved body after the failure of the tunnel working face. The deformation and failure of the surrounding rock in the lower half of the tunnel working face are relatively small, and are gradually transferred from the vault to the surface, resulting in the subsidence of the surface and collapse. The deformation degree of the surrounding rock in the region closer to the tunnel vault is more obvious. After the formation is stabilized, the maximum subsidence deformation occurs above the tunnel vault. The final settlement amount of the stratum is also different with different footage. The smaller the excavation footage, the smaller the stratum settlement amount. Therefore, the appropriate excavation footage is selected as the principal safety control index during the excavation with the short-step method. The research results provide the necessary reference for the fine design and construction of tunnel engineering in the sand pebble stratum.

Keywords: Sand pebble stratum, Working face failure characteristics, Different footage, Highway tunnel

1. Introduction
Recently, with the comprehensive development of infrastructure and frequent exchanges between cities, the development of highway tunnels has accelerated [1]. Tunnel construction often crosses mountains and ridges and encounters complex stratum geological conditions. For example, in the Chengdu area of the 1st terrace of the Minjiang river system in the Western Sichuan Plain, the wide distribution of sand and pebble strata significantly affected the design and construction safety of underground transportation in Chengdu [2]. The pores in sandy pebble soil are filled with sand. The content of medium and fine sand accounts for 30%–50%, the particle size of pebbles are generally 2–8 cm, and the content of pebbles accounts for 50%–70%. The arrangement of coarse and fine particles is complicated (Fig. 1). The density, gradation, and water content of sandy pebble soil in different regions are different, and sandy pebble soil is also widely distributed in other parts of China [3].
The sand pebble soil structure is discrete, and the tunnel surrounding the rock has poor self-stability, strong water permeability, and has a typical particle discrete nature. The particle displacement in sand pebbles depends on each other, and the particles interact through contact points, which significantly differ from the engineering properties of sand and clay [4-5]. Therefore, based on the boundary element, finite element, finite difference, and other continuous medium mechanics theoretical methods, it is impossible to accurately simulate the mechanical and strength characteristics of sand and pebble surrounding rocks. Consequently, the destruction mechanism of the surrounding rock of the tunnel is unclear, and it can easily cause various construction difficulties and accidents [6].

Currently, many scholars have conducted relevant research on the deformation of the tunnel surrounding rock in different situations. Yuzhuo studied and numerically simulated the stress variation laws of the overlying soil induced by the bench method tunnel excavation [7]. Xu analyzed the self-stability of the vertical free surface at the side and the horizontal free surface at the bottom in the sand pebble formation and simulated the particle flow response characteristics of tunnel excavation and support process [8]. Mingming theoretically analyzed the causes of its formation and the mechanism of destruction, given the deformation characteristics of the surrounding rock of highway tunnels in sand and gravel strata [9]. Ruliang studied the stress-strain behavior of the surrounding rock and supporting structure in sandy cobble stratum with the premise of the densely-packed short pipe shed pre-support and three-bench reserved core soil method [10].

This paper studies the failure modes of surrounding rock on sand and pebble tunnel working face of different excavation footage, and the formation of subsidence law starting from the micro-mechanical and motion characteristics of particulate matter. This study is based on the Bai Heqiao tunnel of the Wudu expressway in Gansu Province, and provides the necessary reference for the fine design and construction of sand pebble stratum tunnel engineering.

2. Materials and Methods

Because of the large size of the model, when building the same model as the field grading, the PFC3D model particles reached 600,000 particles. Therefore, to shorten the calculation time, PFC2D is used for simulation. The radius of the tunnel model is set to 5.0 m, the buried depth to 15 m, and the size to 30 × 30 m. Moreover, only the ground surface of the model is the free surface, and the displacement constrain of the fixed wall around it restricts its deformation. The wall unit simulates the support after excavation, and the mechanical properties and deformation of the materials used are ignored. The simulated soil layer is medium-density sand and pebble soil. Table 1 shows the macro-mechanical parameters of the sample and meso-mechanical parameters of the model.
Table 1 Macro- and meso-mechanical parameters for the simulation of sand and pebble soil

| Compactness | Water content (%) | Laboratory test | Numerical simulation of meso-parameters |
|-------------|-------------------|-----------------|----------------------------------------|
| Medium      | 1.5               | 35.9            | 143.9                                  | 2.85E+07 | 0.24 | 0.28 | 3 | 9.50E+04 |

The model is excavated using the bench-tunneling construction method, which simulates the impact of different footage on the sand and pebble stratum. For the deformation and destruction process of the work face to be more convenient for observation and recording, the tunnel model is layered from bottom to top and distinguished by color. Fig. 2 (a) shows a part of the model. In the simulation process, the cross-section in the middle of the tunnel is used as the monitoring surface, and three monitoring points are set (Fig. 2 (b)).

![Fig. 2. PFC2D model of sand pebble tunnel: (a) Initial model (b) Model size and monitoring point layout](image)

During the excavation process, there will be changes in stress and displacement of the sand and pebble stratum. Because of the neglect of the mechanical properties and deformation of the supporting materials, the deformation of the surrounding rock manifests as the instability of the working face. The soil of the working face moves or squeezes and deforms toward excavation and simultaneously causes the obvious deformation of the strata in front of the working face (Fig. 3).

![Fig. 3. (a) Tunnel excavation form (b) Surrounding rock deformation](image)
3. Failure Mode of Surrounding Rocks on the Working Face of the Sandy Pebble Tunnel

3.1. Collapse process

The deformation and failure modes of the palm face caused by the benching-tunneling method in the sand and pebble stratum are studied by showing the instability and failure process of the particle model of the sand and pebble tunnel after excavation at different time-steps (Fig. 4).

![Fig. 4. Instability and failure process of sand pebble tunnel at (a) Excavation started (b) 4,000 time-steps (c) 8,000 time-steps (d) 12,000 time-steps (e) 16,000 time-steps (f) 20,000 time-steps](image)

Fig. 4 shows that when the sand pebble tunnel is excavated, the soil directly in front of the working face loses its stability and collapses along the opposite direction of the excavation. As the time-steps increase, the deformation of soil in front of the working face becomes increasingly larger. The deformation of the soil near the tunnel is also larger, deforming the soil in front of the working face more obviously. Its deformation and failure are gradually transferred from the vault to the surface, and eventually, the ground subsides, and the tunnel collapses.

3.2. Surrounding rock failure mode

During the excavation process, the change of contact force can reflect the change of stratum to a certain extent. The previous section analyzed the overall deformation of the working face without supporting pressure, from macro to micro. The contact force chain between the soil particles during the collapse of the working face is analyzed in the second section. Finally, the two are combined to study the deformation and failure modes of the working face of the sand and pebble tunnel.
Fig. 5. Evolution of the contact force chain between particles at (a) Excavation started (b) 4,000 time-steps (c) 8,000 time-steps (d) 12,000 time-steps (e) 16,000 time-steps (f) 20,000 time-steps during excavation.

Fig. 5 shows that in the initial stage of excavation, without support, no obvious stress relaxation of the soil in front of the working face exists, and the relaxation area is a curved surface. As the time-steps increase, the soil area of stress-change of the soil in front of the working face gradually expands to the upper right, and the area becomes increasingly larger, making the soil in front of the working face gradually unstable and eventually, destroys it.

In summary, in the sand and pebble stratum, the instability failure of the surrounding rock mainly occurs in the upper part and sliding area in front of the tunnel working face. The sliding area is a curved body after the failure of the tunnel working face, not a triangular wedge assumed in the analysis of sand, clay, and other related problems.

4. Effect of Excavation Footage on Deformation of Stratum

The model uses the benching-tunneling construction method to simulate tunnel excavation, and analyzes the deformation of monitoring points at different depths by controlling different footage. The deformation law of stratum of the monitoring surface is obtained, and the controlled excavation footage is studied.

4.1. Formation subsidence rule

Fig. 6 shows the settlement curves of monitoring points with different depths during excavation with footage at 0.5 m, 0.75 m, and 1.0 m, and the time-step distance is 5.0 m.
Fig. 6. The settlement curves of monitoring points with different depths during excavation with footage at (a) 0.5 m (b) 0.75 m (c) 1.0 m

Fig. 6 shows that when the location of the stratum does not reach the monitoring surface, the subsidence change of monitoring points is not obvious. When approaching the monitoring surface, the subsidence change of monitoring points starts undergoing rapid settlement. Behind the monitoring surface, the subsidence change of monitoring points gradually slows down, and at 0.5 D (tunnel diameter), the subsidence change of monitoring points becomes stable, which is close to the actual monitoring results.

When the excavation footage is 0.5 m, 0.75 m, and 1 m, the final settlement of monitoring points of the surface is 4.59 cm, 4.78 cm, and 6.01 cm, respectively. Therefore, the final surface settlement is the smallest when the excavation footage is 0.5 m. Therefore, the final settlement of the formation with different excavation footage is different. The smaller the excavation footage, the smaller the settlement of the formation, and the deeper the depth of the formation above the tunnel, the greater the final settlement.

4.2. Research on excavation footage control

During tunnel excavation, the stress redistribution of the surrounding rock and different excavation footage will affect construction safety. Therefore, it is critical to study and control the excavation footage. Fig. 7 shows the particle model and contact force chain diagram of different excavation footage when the tunnel excavation is complete and stable.
Fig. 7. Particle model when excavation footage is (a) 0.5 m (b) 0.75 m (c) 1.0 m; contact force chain diagram when excavation footage is (d) 0.5 m (e) 0.75 m (f) 1.0 m

Fig. 7 shows that the deformation of the soil in front of the working face with excavation footage of 0.5 m and 0.75 m is smaller than the excavation footage of 0.1 m. The larger the excavation footage, the greater the deformation of the soil in front of the working face, and the larger the stress relaxation area. Therefore, when using the benching-tunneling method to excavate the tunnel, appropriate excavation footage must be developed to ensure the safety of the construction, is more economical, and saves time.

5. Conclusion
Tunnel construction is challenging in sand and pebble stratum, and the surrounding rock failure mode is affected in numerous ways. By using PFC2D to simulate the formation deformation caused by tunnel excavation in sand pebble stratum and the evolution mechanism of the contact force chain, it reproduces the failure process of longitudinal working face excavation and analyzes the surrounding rock failure mode and rule of strata settlement at different excavation feet. Finally, the following main conclusions were obtained:

- The instability failure of the surrounding rock mainly occurs in the upper part and sliding area in front of the tunnel working face. The sliding area is a curved body after the failure of the tunnel working face.
- The deformation and failure of the surrounding rock in the lower half of the tunnel face are relatively small and are gradually transferred from the vault to the surface, resulting in the subsidence of the surface and collapse.
- The deformation degree of the surrounding rock in the region closer to the tunnel vault is more obvious. After the formation is stabilized, the maximum subsidence deformation occurs above the tunnel vault. The final settlement amount of the stratum is also different with different footage. The smaller the excavation footage, the smaller the stratum settlement amount. Therefore, the appropriate excavation footage is selected as the principal safety control index during the excavation with the short-step method.
- The research results provide the necessary reference for the fine design and construction of sand pebble stratum tunnel engineering.

6. References
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