Mechanical simulation of shield-machine empty-pushing through mine excavation section

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Abstract: During the empty-pushing process, pea gravel is generally used as a landfill to provide a reaction force to ensure that the shield-machine can pass through the risk area stably. The whole empty-pushing process involves the interaction and intercoupling between the pea gravel pile and the shield-machine. In this paper, the designs of shield-machine empty-pushing and shield-machine attitude were numerically analyzed and optimized based on the actual excavation process of Guangdong Rail Transit Line 21 in China. The conclusions are as follows: (1) during the tunneling process of the shield, the pea gravel pile underwent three stages: compaction, slipping, and balance. (2) As the height of the pea gravel landfill increased, the reaction force provided by the pea gravel gradually increased. (3) The filling height of pea gravel determined the force of the shield cutter-head and the thrust output of jacks. The stress distribution on the cutter-head was uneven, and the jack of various parts needed a different thrust output. When different shield-machines of various sizes were used for empty-pushing in several projects, the filling height of the pea gravel should be 60\%–80\% of the diameter of the shield-machine.

1. Introduction
With the development of urban rail transit, subway construction has become more common in China. The shield-machine is widely used in subway excavation due to its advantages, such as zero impact on traffic, fast construction speed, high precision, and suitability for weak geological conditions. The geological conditions in cities are mostly composite strata, and shield-machine excavation may encounter raised bedrocks \cite{1} and boulders (Figure 1), which will accelerate the wear of cutter, cause partial wear, chipping, etc. This event may also cause problems, such as the difficulty in controlling the tunneling attitude and ground collapse \cite{2}. In response to these situations, the related application of multiple construction methods has become a research hotspot in subway excavation.
In this case, the project can first use the mining method to excavate and fill the pea gravel in front of the shield-machine and finally the shield-machine empty-pushing through the area. During the empty-pushing process, the pea gravel was used as a landfill to provide a reaction force to ensure that the shield-machine can pass through the empty-push section stably. This combined construction method can simultaneously solve the problem of shield tunneling in the hard rock section and the problem of high construction risk in the soft rock section by the mining method. At present, the construction technology of shield-machine empty-pushing has formed a mature system\[^3\]. Scholars have studied the design and pre-fabrication of segments\[^4\], improved the equipment, and optimized the filler dosage\[^5\]. The cause of leakage has been analyzed, and treatment measures were proposed\[^6\]. The key technologies and quality control measures of shield arrival, advancement, and receiving phase have been applied in engineering\[^7\].

In practical engineering, large amounts of data, including the selection of pea gravel, the way of filling the pea gravel, the thrust output requirements of the shield-machine, the cutter-head force, the thrust control of jacks, and shield-machine tunneling attitude during the propulsion process, have been determined by experience without theoretical basis.

Combining with the practical engineering situation of Guangdong Rail Transit Line 21, the simulation research of shield-machine empty-pushing and that of tunneling attitude of shield-machine was carried out. The interaction process between the pea gravel pile and the shield-machine during the empty-pushing process was analyzed. The filling scheme of the pea gravel, power output scheme of the propulsion system under different filling methods, and the tunneling attitude of the shield-machine were determined.

2. Engineering Background

Combined with the project from Zhenlong Station to Zhongxin Station of Guangdong Rail Transit Line 21, the specific construction sections are as follows: right line, from YDK37+117 to YDK37+415 (298 m) and from YDK38+179 to YDK38+398 (219 m); left line, from ZDK37+102 to ZDK37+267 (165 m) and from ZDK38+166 to ZDK38+398 (232 m). The YDK and ZDK mean the excavation footage on the right and left side of the tunnel, respectively. Two problems will occur in the construction area: (1) raised bedrocks and (2) boulders.

The burial distribution and size of bedrocks and boulders are random. Drilling reveals that its lithology is granite, and the rock strength is relatively high. When the shield-machine excavates through the risk area, the cutter-head will be impacted by a large instantaneous load, which will greatly reduce the construction speed and cause destructive damage to the cutter-head and cutters. In addition, the soil pressure of the sealed cabin may be unbalanced, which will affect the attitude control of the shield-machine, and cause uneven cutting of the ground, which in turn causes the ground to settle or collapse.

To ensure the tunneling attitude and safe construction of the shield-machine, we conducted the project in numerous indoor experiments and field practices and finally adopted the following construction
plan: First, we blasted the area containing boulders and bedrocks and filled the blasting section with pea gravel. Finally, the shield-machine empty pushes through the blasting section and completes the lining support and grouting. During the tunneling process, the thrust and reaction force balance between the cutter-head and the pea gravel should be maintained to ensure that the jack thrust can maintain the tunneling attitude of the shield-machine. In addition, the thrust provided by the shield-machine during the propulsion process should not be less than 3000 kN to prevent water leakage of the tube segments and achieve the water-sealing effect. The total length of the shield-machine used in the project was 8968 mm, the total mass was 262 tons, and the diameter of the cutter-head was 6250 mm. Steel was the main material of the cutter-head and jack of the shield-machine, with an elastic modulus of 206 GPa and Poisson’s ratio of 0.3.

3. Simulation of Shield-Machine empty-pushing

3.1. Parameter of pea gravel
To provide sufficient reaction force for the shield-machine, we selected on-site a pea gravel with high density, good particle size distribution, and a rough surface. In consideration of the particle characteristics of the pea gravel, the traditional triaxial compression test and shear test cannot be used to obtain the internal friction angle of the material. In this study, the discrete element method (DEM) was used to simulate the uniaxial compression test of the specimen. Using spherical particles to simulate pea gravel, the pea gravel was filled in the cylinder to form a cylindrical specimen. The cylindrical model was simulated and set up. The sample was 5m in diameter and 10m in height, and the mesoscopic parameters of pea gravel were as follows:

| Number of particles | Particle maximum size (m) | Particle minimum size (m) | Particle normal stiffness (kN/m²) | Particle tangential stiffness (kN/m²) | Particle density (kg/m³) |
|---------------------|--------------------------|----------------------------|----------------------------------|--------------------------------------|--------------------------|
| 2458                | 0.1                      | 0.05                       | 2000                             | 1000                                 | 1800                     |

Given that only pressure and friction are present in the pea gravel particles, boundary conditions needed to be applied in the lateral direction to constrain its range. Therefore, wall elements were added on the left and right sides as the lateral boundaries. Wall elements were also added on the upper and lower sides as the loading and fixed plates, respectively. The speed of the loading plate was 0.1 cm/s to prevent the movement inertia caused by squeezing between the loading plate and the pea gravel, thus ensuring the stability of the entire specimen. Figure 2 shows the specimen after failure the simulation.

![Failure Surface]

**Figure 2.** Simulation of pea gravel specimen destruction.

According to the simulation results, the failure surface of the specimen is a group of conjugate failure surfaces, and the failure angle was about 60°. According to the Mohr–Coulomb strength criterion, the angle between the shear failure surface and the minimum principal plane of the specimen is related to the internal
friction angle of the rock as follows: when $\theta = \pi/4 + \varphi/2$, the internal friction angle $\varphi$ is $30^\circ$. The approximate range of the internal friction angle of common sand-gravel soil is $28^\circ$–$35^\circ$, and the simulation value of the internal friction angle of the pea gravel is reasonable.

3.2. Numerical simulation of shield-machine empty-pushing
Based on the parameters, a model of cutter-head and pea gravel landfill was established. The wall elements were used in the model to simulate the cutter-head with a diameter of 6.25 m. The diameter of the tunnel filled with pea gravel was 6.7 m. The internal friction angle of the pea gravel was $30^\circ$, and the friction angle between the pea gravel and the cutter-head was $12.8^\circ$. With the pile of pea gravel with a height of 3 m and a length of 6 m as an example, Figure 3(a) shows the initial state of the pile of pea gravel, and Figure 3(b) presents the pile of pea gravel that naturally slid down to a stable state without applying thrust to the cutter-head.

![Figure 3](image)

**Figure 3.** Model of cutter-head and pea gravel landfill.

In the simulation, a propulsion speed of 10 mm/s (the speed of the project) along the tunnel direction was applied to the cutter-head to enable the stable tunneling of the pea gravel pile. During the tunneling process, the pea gravel landfill underwent three stages: compaction, slipping, and balance (Figure 4). At the beginning of the empty-push, the pea gravel in the contact area with the cutter-head was gradually compacted. Subsequently, several particles at the upper edge of the pea gravel began to slip. With the gradual advancement of the cutter-head, the pea gravel reached a balance, and its shape stabilized. After stabilization, the filling angle of the pea gravel was about $30^\circ$. The thrust of the cutter-head simulated by the wall elements was monitored.

![Figure 4](image)

**Figure 4.** Simulation of shield-machine empty-pushing.

3.3. Analysis of the reaction force of pea gravel
Figure 5 shows the thrust of the cutter-head corresponding to the different filling heights of pea gravel.
Figure 5. Relationship between the landfill height and magnitude of the reaction force.

4. Simulation of Shield-Machine Tunneling Attitude

4.1. Analysis of shield-machine thrust
Combining with theoretical research and practical engineering analysis, the shield-machine was provided with a thrust by the jacks, and the resistance during the propulsion process included the following: (1) the friction $F_1$ between the shield-machine and bottom lining during propulsion; (2) the friction resistance $F_2$ between the shield tail brush and the pipe; (3) the traction resistance $F_3$ of the supporting trolley; (4) the friction resistance $F_4$ between the pea gravel; (5) the axial resistance $F_5$ of the shield supported by the pea gravel. The sum of $F_4$ and $F_5$ is the reaction force of pea gravel acting on the cutter-head, which was greatly affected by the height of the pea gravel pile.

The friction $F_1$ between the shield-machine and bottom lining during propulsion is shown as Equation (1), where $W_1$ is the gravity of the shield-machine, and $\mu_1$ is the friction coefficient between the shield-machine and bottom lining.

$$ F_1 = \mu_1 \times W_1 = 0.35 \times 2620 = 917kN $$

(1)

The friction resistance $F_2$ between the shield tail brush and the pipe is presented as Equation (2), where $W_2$ is the gravity of two segments, and $\mu_2$ is the friction coefficient between the shield tail brush and the pipe.

$$ F_2 = \mu_2 \times W_2 = 0.5 \times 400 = 200kN $$

(2)

The traction resistance $F_3$ of the supporting trolley is indicated by Equation (3), where $W_3$ is the gravity of the supporting trolley, and $\mu_3$ is the friction coefficient between the supporting trolley and bottom lining.

$$ F_3 = \mu_3 \times W_3 = 0.5 \times 1700 = 850kN $$

(3)

The sum of $F_1$, $F_2$, and $F_3$ is 1967 kN. Figure 6 shows the total thrust of the shield-machine corresponding to different filling heights of pea gravel in combination with previous simulation results. Compared with the shield thrust output of the practical project, the simulation results were consistent with the engineering excessive amounts of pea gravel, which will also cause the wasting of shield thrust.
Figure 6. Shield-machine simulation calculation thrust and practical engineering thrust.

4.2. Analysis of shield-machine thrust

A friction existed between the shield shell and bottom lining. The reaction force was provided by the pea gravel on the cutter-head, and the jack provided thrust. The pressure acting on the cutter-head increased as the depth of the landfill increased.

To better determine the force of the cutter-head and jacks under different working conditions, we simplified the key force transmission components of the shield-machine, namely, the cutter-head, jacks, and shield shell, into three parts to establish a model\(^{[10]}\) (Figure 7).

In the simulation, the interface module of numerical software FLAC3D was used to simulate the resistance between the shield-machine and tunnel lining. A fixed speed was applied to the jack position to simulate the propulsion of the shield-machine while monitoring the maximum stress distribution of the jack. Figure 7(a) presents the jack number.

Figure 7. Microstructure of a typical bedding plane.
The tunneling attitude simulation model of the shield-machine with the filling heights of pea gravel at 3, 4, and 5 m was established to analyze the force of the cutter-head and jacks at different filling heights (Figure 8). Figures 9 and 10 show the stress cloud chart of the shield-machine and jacks under the three conditions of the filling height, respectively.

Figure 8. Maximum-principal-stress cloud chart of the shield-machine under different landfill heights.

Figure 9. Maximum-principal-stress cloud chart of the jacks under different landfill heights.

By analyzing the force on the cutter-head, the following were obtained: (1) Most of the cutter-head was under pressure, and the maximum-principal-stress increased with the increase in the pea gravel filling height. For the area filled with no pea gravel, the stress was significantly reduced. When the unfilled area was large enough, tensile stress appeared in several areas of the cutter-head, which was not conducive to the stability of the cutter-head; (2) the stress distribution at the cutter-head was uneven. At the edge of the cutter-head, given the existence of the jack, the combined action of the pea gravel reaction force and the jack led to stress concentration in these areas; (3) the stress distribution and the level of stress concentration of the jacks are related to the height of pea gravel pile. Figure 10 shows the maximum stresses of each jack. When the shield-machine passed through the section, the analysis revealed the following: (1) As the height of the pile of pea gravel increased, the total thrust output of the jacks and their respective thrust output increased significantly; (2) different jacks have various thrust output; (3) when the pile gravel filling height was remarkably low, several upper jacks have no power output; (4) based on comprehensive considerations, the height of the pebble gravel pile should be 4–5 m.
Figure 10. Stress of jacks under different filling heights.

5. Conclusions
The simulation research of shield-machine empty-pushing and shield-machine attitude can provide several conclusions as follows.

(1) During the tunneling process of the shield, the pea gravel pile underwent three stages: compaction, slipping, and balance. The internal friction angle of pea gravel was about 30°.

(2) As the height of the pea gravel landfill increased, the reaction force provided by the pea gravel gradually increased.

(3) The filling height of pea gravel determined the force of shield-machine cutter-head and the thrust output of jacks. The stress distribution on the cutter-head was uneven, and the jack of different parts required various thrust outputs.

(4) When different shield-machines of varied sizes are used for empty-pushing in different projects, the filling height of pea gravel should be 60%–80% of the diameter of the shield-machine to ensure the shield-machine attitude, prevent water leakage of segments, and save thrust output.

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