Research Article

Experimental Analysis of Deformation Mechanics and Stability of a Shallow-Buried Large-Span Hard Rock Metro Station

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Based on a certain Qingdao metro station, a large-scale three-dimensional model test has been carried out to investigate the stability of the surrounding rock masses (hard rock) and a large-span metro station under different excavation methods and technologies. The model test includes an entire section excavation, an arch-cover excavation, and a primary support arch-cover excavation. Compared with the entire section excavation, the primary support arch-cover method can effectively control the vault settlement and clearance convergence deformation of the surrounding rock masses, reducing them by 15–30%. The deformation itself goes through three stages: slow, abrupt, and stable. The excavation of the “middle hole” creates a drastic change in the tunnel vault during the arch-cover excavation; however, the timely application of supports can effectively constrain the range of disturbance caused by the excavation and weaken the degree of load agglomeration of the surrounding rock masses.

1. Introduction

With the rapid development of the global economy, the utilization of underground space has gradually become an important way of solving major urban crises including population, resources, and environment and curing this “urban syndrome” by implementing sustainable development strategies all over the world [1]. Urban subways have gradually become the first choice for underground space development; what is more, domestic and foreign scholars have become concerned about the instability of the surrounding rocks [2–4] caused by subway tunnel excavations. Therefore, a means of reducing the impact of tunnel construction on the surrounding environment has become an important issue that needs urgent resolution.

Unlike deep mining tunnels [5–9], metro stations are usually engineered at relatively shallow depths. Therefore, the deformation mechanism is likely to be different. During tunnel construction, the surrounding rock and support systems are in an unstable state of adjustment for an extended period of time. When the stresses and load release processes intensify, dome collapses are likely to occur in the absence of reasonable construction and timely support [10–13]. Therefore, it has been a key engineering challenge to ensure the stability of tunnel construction based on different construction and support methods required for the different geological conditions surrounding a tunnel.

Due to their shallow depth, subway stations in most local cities such as Shanghai and Guangzhou are generally located in the soft rock stratum, and relatively conservative methods have been widely applied, such as two side-wall pilot tunnels, the center cross diagram (CRD) method, or the bench method. In most cases, one primary method has been selected and several other methods have been employed simultaneously to achieve stability in the surrounding rock mass, depending on the actual circumstances. However, a few cities such as Qingdao and Dalian have subway stations that lie in a stratum of slightly weathered and moderately weathered granite. The question that needs to be asked is, whether it is reasonable for construction methods such as the above to still be used for soft rock excavation. The arch-cover excavation method [14–17] is a new excavation
method for tunnel construction development based on conventional methods, such as cover excavation and open digging, the main point of which is to replace the side piles with a large arching scheme and to complete the construction of the main structure under the protection of the prior arching. The arch-cover method is applied mainly to the upper-soft-lower-hard strata. The support process for this method comprises a primary support and a second lining support; note that reserved core soil and small catheter grouting processes need to be conducted for poor surrounding rock conditions with high construction requirements. The primary support arch-cover excavation is proposed based on the arch-cover method, in consideration of the special geological features of the Qingdao area, eliminating the need for a new type of excavation-type construction method after the second liner. By contrast, the second lining would be carried out after the completion of the whole station; this is the primary difference between the conventional and primary support arch-cover excavation methods. The primary support method effectively reduces the risk of excavation construction and improves its efficiency. Compared with other shallow-buried excavation methods, it has several advantages that have been successfully harnessed on a number of tunneling projects, including fewer processes, less blasting time, smaller disturbances, simpler support, higher construction efficiency, and a shorter construction period. In general, the joint support method that includes a steel grid, steel arch, and bolt-shotcrete has been applied to a large-span station. The support process for this method contains an initial support and a secondary support; reserved core soil and small catheter grouting processes have to be conducted for poor surrounding rock conditions with higher construction requirements. More recently, Li et al. [18] have put forward primary support arch-cover excavation whose stress analysis has also been investigated. Choosing a reasonable construction technology and a proper support method is key to ensuring the rapid and safe construction of a large-span subway station.

Numerous studies [19–23] have been performed regarding the deformation of rock surrounding a tunnel to simulate its evolution process and behavior during the tunnel excavation process. The interaction between the surrounding rock and the support structure during the construction process has been studied, and the influence of lining operations on the load release process of the surrounding rock has been analyzed through an all-around simulation of the tunnel construction process by Galli et al. [24]. Zhu and He [25] defined the mirrored displacement release coefficient to reflect the release process of the “virtual support force” on the excavation face. In the past decades, a large-scale mechanical model test has become a new method for investigating the deformation and stress release of the surrounding rock in tunnel excavations. Systematic analyses of the stability of the surrounding rock masses for a super-large section of tunnel through a soft broken formation have been conducted by Li et al. [26, 27] through a large-scale three-dimensional (3D) geomechanical model test. The process of releasing the surrounding rock load during tunnel excavation has been studied by Zhao and Li [28], who pointed out the need for timely support. Presently, the research emphasis is focused on the deformation characteristics of the interval tunnel surrounding rocks and less on the deformation characteristics, the stability of the surrounding rock during excavation, and the applicability of the arch-cover method. Furthermore, the selection of the construction method for hard rock and large-span subway stations is relatively conservative.

In this study, the surrounding rock stability and safety during the entire section excavation, arch-cover excavation, and primary support arch-cover excavation through the hard rock and a large-span subway station are investigated. Moreover, the surrounding rock deformation mechanism is revealed, and the damage characteristics and instability criterion for the surrounding rock are discussed by comparing the stress and deformation response between two excavation methods. This is in support of a theoretical basis for a safe and rapid construction technology and the stability evaluation of similar tunnels.

1.1. Background. The Haichuan Road metro station, whose structure type is a large-span single arch double layer, was constructed using arch-cover excavation. The total length of the station is 198 m, the excavation span 19.2–22.1 m, the height 14.5–16.8 m, and the depth of the arch 13.3–16.9 m. It is located in the micro-weathering stratum with II-III rock levels. The stratum comprises soil, a coarse granite strong weathered zone, a coarse granite moderately weathered zone, and a coarse granite slightly weathered zone, as shown in Figure 1.

2. Materials and Methods

2.1. 3D Geomechanical Model. According to the geological conditions and research objects and abiding by the advice given for the test, the geometric dimensions of the physical model were determined to be $2,400 \times 2,400 \times 2,000$ mm (length $\times$ width $\times$ height) as shown in Figure 2, and the geometric similarity ratio $C_l$ was 1/50, which simulates the actual engineering size. Next, the sectional dimensions of the model station were calculated to be $400 \times 320$ mm (span $\times$ height) based on the geometric similarity ratio.

The upper-soft and lower-hard stratum occur mostly in the area of Qingdao at a depth of 15 m (the excavating depth of the station for the model), which represents the upper quaternary alluvium and the lower weathered granite. In order to better investigate the stability of the station, the overlying strata of the station were appropriately simplified in the model test. Loose sandy soil and slightly weathered granite were selected instead of the quaternary alluvium and weathered granite, and the thickness of both strata was determined by the rock span ratio and tunnel depth with different states of excavation in the model.

2.2. Similar Materials. The key parameters of this experiment were selected as the object of study, which needed to be strictly similar, and other parameters were somewhat based on these criteria.
The selection of similar materials is needed to track the main features for similarity between the in situ model and the actual material, as the physical and mechanical properties notably change with differences in material dosage. The material should also offer stable performance, low cost, and easy production. Therefore, loose coarse sand, iron powder, white cement, gypsum, and silicon lime powder, as shown in Figure 3, were chosen as similar materials that would meet the ratios of \( C_c = 1 \) and \( C_L = 50 \) [14].

The loose coarse sand and iron powder were selected to simulate the sandy soil with a material ratio of 9:1 and a density of 14.5 kN/m³. As the mechanical parameters of the sandy soil in the model were scaled by a similar ratio with a low value, the zero-cohesion of the sandy soil in the model was determined. The weathered rock was simulated by the loose coarse sand, iron powder, white cement, gypsum, and silicon lime powder in which river sand was used as the aggregate, the white cement as the cementing agent, and the gypsum and silicon lime as modifiers. Finally, the material ratio of the weathered rock was 725:72:43:36:72 (coarse sand: iron powder: silicon lime powder: gypsum: white cement) [14] as determined through repeated uniaxial compression tests as shown in Figure 4. What is more, a number of the completed similar blocks are shown in Figure 5. The physical and mechanical parameters of the prototype and model are listed in Table 1 [14].

2.3. Monitoring Arrangement of Model Test. All the processes for the entire section excavation without supports, the arch-cover excavation, and primary support excavation methods were simulated to reveal the mechanical deformation mechanism of the surrounding rocks and to determine a reasonable excavation method. The excavation methods were applied to different tunnels on the four sides of the model, in which one side was the reserved section of the...
overlying test. The variation and adjustment of the stress during the excavation were studied, the internal law for the space-time effect was revealed, and the mechanism for the spatiotemporal evolution of the surrounding rocks was obtained.

Three group monitoring sections were set up in each tunnel of the model, of which each group was divided into strain, stress, and displacement sections, as shown in Figure 6 [18]. Hence, the total number of sections was 36. A variety of miniature high-precision sensors, such as fiber grating sensors, a resistance strain gauge, an Earth pressure gauge, and multipoint displacement meters, were arranged to monitor the variation of stress and displacement of the surrounding rocks. Finally, a total of 168 monitoring points were set up with 24 fiber grating sensors, 60 resistance strain gauges, 24 Earth pressure gauges, and 60 multipoint displacement meters in the model.

2.4. Strain and Stress Test Equipment. An XL2101G static strain gauge measurement system was arranged for the embedding of strain transfer, as shown in Figure 7. An FY-TJ22 vibrating wire Earth pressure gauge was arranged to analyze the stress of the surrounding rock as the excavation process changed, as shown in Figure 8.

The strain brick and micro Earth pressure box were arranged as shown in Figure 9. The main aim was to monitor the change in displacement of the surrounding rock during the whole excavation process.

2.5. Displacement Monitoring System. The internal displacement of the model was measured using a grating multi-displacement measurement system, comprising a multipoint displacement meter, displacement sensor, and an original data acquisition component, as shown in Figure 10.

2.6. Model Excavation Test. The excavation tests were carried out after a 7-day drying period with the following stages. In this experiment model, there are four sides prepared for three excavation methods. After one hole is excavated, the model will stay still for one hour. Another hole will start after the model returns to steady state completely.

Stage I: The arch-cover excavation. The excavation footage was 0.6 m with six cycles, and the interval between the two excavations was 1 h.

Stage II: The primary support arch-cover excavation. The excavation footage was 0.6 m with six cycles, and the interval between the two excavations was 1 h.

Stage III: The entire section excavation without support. It was used to observe the instability and the failure of the tunnel.

The vibration of the stress and the displacement were monitored simultaneously in real-time using the grating displacement sensing system and the miniature Earth pressure gauge system. The test scene for the model excavation is shown in Figure 11.

2.7. Excavation Process of the Various Types of Excavation

2.7.1. Arch-Cover Excavation Method. As shown in Figure 12, the arch-cover excavation follows the procedure where the left and right holes of upper section were excavated (area 1), after which the middle hole was excavated (area 2), with the initial and secondary lining support being conducted next. Finally, the middle hole of the lower section was excavated (area 3), followed by the two sides (area 4).

2.7.2. Primary Support Arch-Cover Excavation Method. As shown in Figure 13, the primary support arch-cover excavation follows the procedure where the upper sides of areas 1–4 were excavated in turn, with the primary support being conducted on the arch section. Next, the lower sections of areas 5–7 were excavated.

2.7.3. Entire Section Excavation. As shown in Figure 14, the entire section was excavated.

2.8. Stress Analysis under Different Excavation Methods

2.8.1. Vertical Stress of the Surrounding Rocks. Under different excavation methods, the stress curves go through different stages, as shown in Figure 15.

For the arch-cover excavation, the stress was concentrated in the surrounding rocks when the left hole excavation is complete (step 6), after which the stress of the vault notably decreased. When the middle hole of the upper section was finished, the stress rose to a maximum and then dropped slightly with timely supports. The
stress reached a stable state after support when the model was completely excavated. Hence, it can be concluded that the excavation of the middle hole is the key stage of the destressing and violent deformation of the surrounding rocks, and that timely support can effectively improve the self-supporting ability of the surrounding rocks.

### Table 1: Physical-mechanical parameters of rock and similar material.

| Material type | $\gamma$ (kN·m$^{-3}$) | $E$ (GPa) | $\sigma_c$ (MPa) | $\sigma_t$ (MPa) | $\mu$ | $C$ (MPa) | $\Phi$ (°) |
|--------------|-----------------|---------|--------------|--------------|------|--------|--------|
| Prototype    | 24              | 10      | 30           | 4.5          | 0.25 | 15     | 38     |
| Model        | 24              | 0.2     | 0.6          | 0.09         | 0.25 | 0.3    | 38     |

For the primary support arch-cover excavation, the vibration of the stress could be divided into three stages with the tunnel face advancing, namely, the slow vibration, abrupt vibration, and stable vibration. When the distance between the tunnel face and the monitoring section was 0.5 times the span, the stress was not concentrated in the surrounding rock, while it notably rose and the concentrated stress was high when the tunnel face advanced through the monitoring section. The stress then tended to stabilize after passing through a distance of approximately 0.5 times the span.

For the entire section excavation, the surrounding rock masses maintained short-lived stability with an apparent stress release while passing through the monitoring section. This shows that the surrounding rock masses were unable to play their self-supporting role to achieve a self-stabilizing state and extrusion deformation, and therefore a roof fall emerged in the tunnel face. In this case, the sustainable excavation and excavation safety were seriously compromised.

Compared with arch-cover excavation, the primary support arch-cover excavation experienced three clearer stages of the surrounding rock. As long as timely support can be conducted, the primary support arch-cover excavation is recommended for station tunnel construction, the procedure of which is easier too.

### 2.9. Deformation of the Rock Masses

#### 2.9.1. Vault Settlement Change Analysis

The vibration curves of the vault settlement with the tunnel excavation were obtained, as shown in Figure 16.
For the arch-cover support excavation, the vault settlement curve is shown in Figure 16. The station surrounding rock deformation started when the left hole excavation was complete (step 6); the deformation rate significantly accelerated when the right hole excavation was complete (step 12); the vertical displacement of the tunnel entered a stage where the deformation abruptly changed when the middle hole excavation was complete (step 24); the deformation entered the stable stage when the roof supports were finished. It tended to be stable after excavation (step 30).

The deformation of the surrounding rock went through three stages during the tunnel excavation, namely, slow deformation, abrupt deformation, and stable deformation, with the continuous push of the arch-cover excavation and a disturbance depth of approximately 0.5 times the span. However, as a whole, the deformation of the tunnel was small and the maximum subsidence of the vault was only 13 mm. Compared with the entire section excavation, the primary support arch-cover excavation effectively controlled the settlement and convergence of the surrounding rock, reducing them by 20–35%. The disturbance depth was approximately 0.5 times the span.

For the primary support arch-cover excavation, the effect of the surrounding rocks was larger than that of the arch-cover excavation. Even though the deformation rate decreased to a certain extent due to the support, the deformation of the surrounding rocks still increased. The deformation of the surrounding rocks rose significantly during the tunnel face advancing through the monitoring section while it tended to stabilize after passing through the section. The disturbance depths were about 0.5 times the span. However, the station tunnel tended to stabilize eventually. Compared with entire section excavation, the primary support arch-cover excavation effectively controlled...
Figure 12: Excavation sequence sketch of the arch-cover method. (a) Initial excavation face. (b) Area 1 left excavated. (c) Area 1 right excavated. (d) Area 2 excavated. (e) Area 3 excavated. (f) Area 4 excavated.

Figure 13: Excavation sequence sketch of the primary support arch-cover method. (a) Initial excavation face. (b) Area 1 excavated. (c) Area 2 excavated. (d) Area 3 and 4 excavated. (e) Primary support conducted. (f) Area 5 excavated. (g) Area 6 excavated. (h) Area 6 excavated. (i) Side-wall primary support.
the settlement and convergence of the surrounding rock, reducing them by 15–30%.

For the entire section excavation, it was difficult to carry out a large-scale and continuous excavation. Further, if the surrounding rock masses could not reach a stable state, the closer the vault was, the faster the deformation occurred, and an overall collapse phenomenon occurred in the tunnel vault with sustained excavation. In this case, the safety and stability of the excavation could not be guaranteed.

Based on the above analysis, the vault settlement can be regarded as the criterion to evaluate the stability of the surrounding rock. Both the different excavations can be applied to station construction even though the vault values are larger compared with arch-cover excavation. The vault method experiences three important stages, and it is apparent that timely support needs to be conducted to ensure safe excavation.

2.9.2. Clearance Convergence Change Analysis. The vibration curves of the clearance convergence with the tunnel excavation were obtained, as shown in Figure 17.

It can be seen from Figure 17 that, during the entire excavation procedure, the clearance convergence did not reveal to us any apparent change process for both the different excavation methods. Moreover, the values were too small to affect excavation safety. However, for the entire section excavation, there was still an increasing trend even after the completion of the excavation. As such, safety could not be guaranteed.

2.9.3. Floor Heave Change Analysis. The vibration curves of the floor heave with the tunnel excavation were obtained, as shown in Figure 18.

It can be seen from Figure 18 that the floor heave values obtained from the monitoring equipment were small and can be ignored as they cannot affect the excavation safety for any of the three methods.

From the simulation results, it can be concluded that the deformation of the surrounding rock masses goes through three stages during station excavation, namely,
slow deformation, abrupt deformation, and stable deformation. The excavation of the middle hole has a powerful effect on the deformation of the tunnel vault; however, the timely application of supports can effectively constrain the disturbance range caused by the excavation and weaken the load agglomeration of the surrounding rocks in front of the tunnel face. This may improve the stability of the surrounding rocks around the face. The vault settlement can be regarded as an important criterion to evaluate the stability of the surrounding rock. As long as timely support can be provided, the primary support arch-cover excavation is highly recommended for hard rock metro station construction.

3. Results and Discussions

(1) From the results of the model test, the primary support arch-cover excavation can be applied to a hard rock and large-span subway station. The tunnel deformation and stress are within the safety range.

(2) From the experiment, three excavation methods were carried out and the excavation processes presented. However, it is difficult to completely reveal the actual process of every excavation method. Further study should be conducted.

(3) The model test was only targeted at hard rock of homogeneous stratum. However, some changes do happen at the tunnel face in an actual project, and, therefore, the means to achieve the requirements of the arch-cover excavation by pre-reinforcement through a fault, a broken belt, and other unfavorable geological conditions still needs further study.

(4) In the actual excavation process, blasting happens. Whether this will impact significantly on the results needs further research.

(5) In this paper, three excavation methods were compared. Whether there will be another more reasonable and safer construction excavation method in view of the current special stratum needs further study.

4. Conclusions

(1) All the processes of three different excavation methods were simulated utilizing a large-scale 3D geomechanical model test of a hard rock and large-span subway station. This model simulation was successfully applied to a metro station.

(2) Arch-cover excavation, entire section excavation, and primary support arch-cover excavation have all been simulated. Compared with entire section excavation, the primary support arch-cover excavation can effectively control the settlement and convergence of the surrounding rock by reducing them by 15–30%. The disturbance depth was approximately 0.5 times the span.

(3) From the simulation results, it can be concluded that the deformation of the surrounding rocks goes through three stages during tunnel excavation, namely, slow deformation, abrupt deformation, and stable deformation. Both arch-cover excavation and primary support arch-cover excavation can effectively ensure the stability and safety of the tunnel excavation.

(4) The excavation of the middle hole was a powerful factor in the deformation of the tunnel vault. However, the timely application of supports can effectively restrain the disturbance range caused by the excavation and weaken the load agglomeration of the surrounding rocks in front of the tunnel face, which might improve the stability of the rocks surrounding the face.
Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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