Experimental Study on Deformation Law of Soil Layer Induced by Undercut between Existing Twin Tunnels based on 3D Geomechanical Model

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Abstract, The underground excavation of subway station spaces between existing twin tunnels is vital for ensuring the normal flow of ground traffic during excavation, reducing costs, and protecting the environment. However, such excavation would induce the deviation of the existing tunnel segment due to the collapse upon soil layers. Based on model test theory, a large-scale geomechanical model test frame was conducted to investigate the soil layer deformation law. A high-precision multi-point extensometer and an earth pressure cell were embedded in the design position during the manufacture of the model stratum. All of the deformation and earth pressure data at each monitoring point were obtained during the whole test process, and these data were used to analyze the deformation law in three test phases: excavation and support of the station space, transverse tunnel excavation, and overload pressure exertion on the model top surface. Results showed that the deformation induced by the underground excavation space was small, and the excavation of the transverse tunnel and overload pressure on the top surface of the model were the main factors inducing the soil deformation. The maximum vertical displacement and horizontal displacement were 1.29 mm and 0.58 mm, respectively; as indicated by the geometric similarity ratio, the displacements of the corresponding points were 12.9 mm and 5.8 mm, respectively. The test also revealed that a pre-reinforced pile outside the shield tunnel could effectively limit the segment deviation and reduce the deformation of the outside soil mass. This method might be used in the excavation of underground station spaces under good geological conditions.

Key words Subway construction; Geomechanical model test; Measurement; Deformation

1. Introduction
A vital method of resolving the construction schedule conflicts that arise in the construction of shield tunnels and subway station spaces has been developed, and it can be used to construct subway stations between existing twin shield tunnels. This method avoids surface traffic jams with the use of open excavation and cover during construction [1]. It is also of great value for extending the application of subway shield engineering and ensuring construction safety, shortening construction periods, and reducing project costs [2,3]. Due to investment requirements, construction periods, and security
concerns, it is difficult to perform exploratory tests during the excavation of subway station spaces and shield tunnels \([4,5]\). In such cases, an effective research method involves reconstructing a large-scale three-dimensional (3D) physical model using artificial materials \([6,7]\). A high-fidelity model can truly reflect the spatial relation between a subway station space and the existing twin tunnels. In addition, it can be used to accurately simulate the impact of the construction process. Meguid et al. \([8,9]\) presented a geomechanical model that has been applied in simulating the excavation process of a metro tunnel below soft soil layers.

Usually, the use of a large-scale 3D geomechanical model to simulate a real underground project is complex \([10,11]\), and well-planned experimental studies are necessary to reproduce the stress and deformation characteristics of the prototype \([12,13]\). In the current research, the authors use a large-scale model test to study the feasibility of undercutting a subway station space between existing twin shield tunnels. The mechanics and deformation regulations of the soil layers surrounding the subway station space and shield tunnels were analyzed during the stratum excavation of the model. Moreover, the displacements of measurement points in the soil layer and the stresses of the secondary lining and support structure were obtained by the model test \([14,15]\). The overall mechanical characteristics and deformation trends of the existing twin tunnels and the stratum during excavation are described, and some useful references for the design and construction of subway station spaces between existing twin tunnels are given.

2. Model test frame system and reconstruction of initial stress field

2.1 Simulation area and laboratory condition

The actual underground project consists of a subway station space and twin shield tunnels. The outer diameter of each tunnel is 6 m, and the distance between the two central lines of the tunnels is 23 m. To eliminate boundary effects, we adjust the boundary conditions such that the length from the outside of the left tunnel to the left boundary of the prototype is \(3 \times 6 = 18\) m, and the same length is set for the right side. The height of the prototype is 27.8 m, and the length of the study area along the axis of the tunnel is defined as 18 m. Therefore, the size of the prototype is \(65 \times 18 \times 28.8\) m (length \(\times\) width \(\times\) height). Considering the size of the test frame, the geometric similarity scale of the model test is 1:10. Thus, the size of the 3D physical model box is \(6.5 \times 1.8 \times 2.78\) m (length \(\times\) width \(\times\) height), as shown in Fig. 1, and it is utilized to simulate the entire excavation process of the subway station space.

2.2 Model test frame system

The model test frame system consists of a test box, support system, and operating platforms. The test box is a space enclosed by four 5 mm-thick steel plates, and the internal sizes of the model box are \(6.5 \times 1.8 \times 2.78\) m (length \(\times\) width \(\times\) height), as shown in Fig. 1. The support system consists of four main vertical columns and dozens of I-shaped columns and beams. Four 400-mm I-shaped steels as vertical columns are set in the four corners of the test box and serve as the main support structure of the model test frame system. In addition, the heights of four 200-mm I-shaped steel columns are all 4.5 m, and the bottoms of the four 200-mm I-shaped steel columns are connected with anchor bolts and embedded in the concrete foundations together. The steel plates of the model are constrained by dozens of the I-shaped horizontal beams and vertical columns, as shown in Fig. 1.
In the simulation of the initial stress, the uniform vertical pressure loaded by the jacks is applied to the top surface of the model, and horizontal uniform pressure induced by the jacks is applied to the right lateral surface of the model [16]. Therefore, the initial stress field can be obtained by the self-weight of the soil mass and by changing the vertical and horizontal uniform pressures applied to the top surface and right lateral surface of the model, as shown in Fig. 2. The whole test frame system is rigid, and it can bear 100 t of vertical pressure and 80 t of horizontal pressure. The maximum value of the deformation of the main steel structures of the system is less than 3 mm, which satisfies the required measurement accuracy.

2.3 Loading methods and in-situ stress simulation

Initial in-situ stress is a type of natural stress existing in strata; it is generated by long-term geological structural evolution until a relative equilibrium state is reached [17,18]. The excavation of soil layers breaks the stress equilibrium and leads to deformation and damage of the underground engineering. In urban areas, subway tunnels are generally located about 20 m below the ground surface, where tectonic stress could be negligible compared with gravitational stress. In this study, the original stress is induced by the weight of the filling material and by pressures on the top surface and right lateral surface of the test frame. According to a similarity scale, the total thickness of the soil layers upon the subway station space in the model is defined as 2 m. Due to the limitations of the test box, only a 0.75
m-thick soil layer can be reconstructed in the geomechanical model. A uniform vertical pressure-loading device is developed to simulate the load boundary conditions of the real in-situ stress. The top loading system consists of eight screw jacks, as shown in Fig. 2, and the load is transmitted systematically to the soil layer of the model by the steel plate upon the top surface. The physical and mechanical parameters of the steel plate are shown in Table 1.

### Table 1. Physical and mechanical parameters of steel plate

| Material    | $\gamma$ (kN/m$^3$) | $E$ (Gpa) | Thickness (mm) |
|-------------|----------------------|-----------|----------------|
| Steel plate | 78                   | 210       | 12             |

The vertical pressures from the jacks are applied to the top surface of the model up to a maximum uniform pressure of 0.60 MPa. Meanwhile, 27 screw jacks are applied to the right lateral surface of the model, generating a horizontal pressure along the negative x-direction, as shown in Fig. 2(b). After the position of the screw jack is fixed horizontally, the rotary screw rod pushes the right lateral steel plate. The same number of revolutions ensures that the horizontal thrust generated by each jack is the same. Consequently, the horizontal thrust generated by the 27 jacks on the right lateral surface of the model is uniform.

### 3. Model construction and measurement

#### 3.1 Similarity scaling of the model

A 3D geomechanical model must satisfy a series of similarity requirements in terms of geometry, physical properties, boundary conditions, and initial states [19,20]. Based on the scaling criterion between the prototype and the model, similarity theory, and dimensional analysis, those of the similarity scales (such as material density, modulus of elasticity, and force) can be deduced from basic similarity scales [20,21]. Geomechanical model testing is a type of nonlinear destructive testing; therefore, the four similarity requirements for a destruction test should be met. These similarity requirements are as follows [22,23]:

- geometric shape and main geometrical structure of the prototype and model;
- deformation modulus, compressive and tensile strengths, and stress and strain;
- shear strength parameters of the prototype and model; and
- load condition, such as gravity and initial stress conditions.

Considering the experimental equipment, the geometric similarity constant and volume-weight similarity constant in this model experiment are determined as $k_L=10$ and $k_\gamma=1$, respectively. According to the similarity principle, the similarity constants of the other parameters can be deduced as follows:

$$
k_\sigma = k_E = k_c = k_\gamma \times k_L = 10$$

$$
k_F = k_\gamma \times k_L^3 = 1000$$

if $k_\gamma = 1$, then

$$
k_E = k_L$$

$$
k_F = k_L^3$$

where $k_\sigma$, $k_E$, $k_c$, and $k_F$ are the similarity constants of stress, elastic modulus, cohesive force, and concentrated force, respectively. It is difficult to ensure that all the mechanical parameters of similar materials satisfy the requirements of the similarity ratio. Generally, several main parameters of the model materials are considered, and the similarity ratio of the main parameters is determined.
according to the test requirements. The similarity ratio of the other parameters between the material of the model and the prototype can be deduced from the basic theory of the model test. For example, Li Zhongkui and Zhu Weishen [24, 25] stated that, in large-scale model tests, the mechanical and deformation characteristics of similar materials should maintain a high similarity to those of the prototype materials, which requires strict control of the similarity ratio of the main parameters. In this paper, on the basis of the research results of experts and scholars, the similarity ratios of material density, strain, and Poisson’s ratio are 1. The similarity ratios of the other parameters between the model material and the prototype material are derived from similarity theory, as shown in Table 2. The model is designed according to similarity theory, as shown in Table 3. The simulation scope is large enough to meet the requirement for a destructive test and can fully represent the actual engineering situation [26, 27].

Table 2. Physical and mechanical parameters of prototype materials

| Materials       | $\gamma$(kN/m$^3$) | $E$(Gpa) | Thickness(m) | $c$(kpa) | $\phi$(°) |
|-----------------|---------------------|----------|--------------|---------|----------|
| Miscellaneous fill | 16.5                | 0.008    | 2.5          | 5       | 25       |
| Silty clay      | 19.2                | 0.013    | 16.6         | 60      | 29       |
| Segment         | 25.0                | 34.5     | 0.3          | -       | -        |

3.2 Model construction
In the prototype, the distance between the central lines of the left and right tunnels was 23 m. The inner and outer diameters of the tunnels were 5.4 m and 6 m, respectively. Thus, the distance from the left boundary of the left tunnel to the right boundary of the right tunnel was 29 m. Evidently, the range of the excavation effects was strongly related to the construction method. Generally, at three times the outer diameter away from the outer boundary of the tunnel, the intact stress changed little; far away from the excavation boundary, the effect induced by the excavation can be neglected [28, 29]. Therefore, the length of the prototype was 65 m (3 × 6 + 29 + 3 × 6). Considering the actual engineering and the dimensions of the test frame, the width of the prototype was defined as 18 m along the axis of the tunnel, and the height of the prototype was 27.8 m. According to the similarity scale, the dimensions of the model were 6.5 × 1.8 × 2.78 m, as indicated in Fig. 1.

Table 3. Design of similarity model

| Items                  | Designs | Principles                           |
|------------------------|---------|--------------------------------------|
| Law of similarity      | $k_E = k_\gamma \cdot k_L, k_\sigma = k_c, k_F = k_\gamma \cdot k_L^3 = k_E \cdot k_L^2$ | Geometrical similarity                  |
|                        | If $k_\gamma = 1$ $k_E = k_L, k_F = k_L^3$ | Similarity of mechanical and deformation characteristics |
| Geometric similarity constant | 10      | Similarity of shear strength parameter of soil masses |
|                        |         | Similarity of load and boundary conditions |
|                        |         | Meeting the precision demand of the test |
|                        |         | Considering modeling workload and economic effects |
**Simulation scope**  
65 × 18 × 45 m (L × W × H)  

**Geological model**  
Steel pipe supporting the remaining part of the segment  
Presupporting arch-shaped soil layer  

**Model materials**  
Mixing barged-in fill, gypsum, adhesives, and additive according to certain proportions  

The model was made by filling and ramming similar materials according to the design scheme. During this process, a multi-point extensometer and a pressure cell were embedded in corresponding places, as shown in Fig. 7(b) and (c). The inner and outer diameters of the segment were 54 cm and 60 cm, respectively, and the segment had a thickness of 3 cm and a width of 12 cm along the x-axis direction. After all segments were manufactured, each segment ring was prefabricated, and the ring was reinforced by stressed steel bars. Meanwhile, 15 segments of each tunnel were longitudinally constrained along the model tunnel by the four 16-mm-diameter steel bars. The prestressed steel bar was affixed on both ends of the tunnel by anchor bolts, as shown in Fig. 3(b). Pre-grouting was applied to the upper layer of the actual shield segment to reduce the settlement of the ground surface during the excavation process. To simulate the pre-grouting layer, we added 10% cement material into the soil, and this mixture material was used to make an arch-shaped soil layer with a thickness of 20 cm, as shown in Fig. 4. The test results showed that the physical and mechanical parameters of the mixture satisfied the requirements of the similarity ratio. After completion of ramming of the last soil layer, a 3–5 cm-thick gravel layer was used to cover the top surface of the model to reduce water evaporation and keep the model material from hardening. The model needed to be static and excavation had to be on hold for 60 days from the end of construction to the beginning of excavation and data recording to ensure that the model could simulate the natural state of the prototype and provide accurate data. Six micrometer gauges were placed in predetermined locations to record the settlement variation of the model ground surface, as shown in Fig. 5. The records showed that the top surface no longer had noticeable variations after 60 days.
Figure 3. Model construction process (units: mm)

(a) Segment rings constrained by longitudinal inner and outer steel bars (b) Segments reinforced by prestressed reinforcement

Figure 4. Presupport arch-shaped soil (units: mm) Figure 5. Measurement of model top surface

3.3 Measurement items and instrument layout

The automatic monitoring systems of the displacement measurement systems were adopted in the model during the experimental period, which consisted of an automatic recording system and dozens of high-precision micro-multi-point extensometers, to obtain the data of the displacements of the soil layers and the linings. The micro-multi-point extensometers (Type DWG-K2000) were developed by the authors and the Engineering Monitoring Center of the China Institute of Water Resources and Hydropower Research. The maximum range of each micro-multi-point extensometer was 20 mm, and the precision of their displacement measurements reached 1/1000 mm. The abovementioned measuring apparatus was adopted in the model during excavation and support. As shown in Fig. 6(a), nine micro-multi-point extensometers were embedded in the soil layers along the vertical direction and six along the horizontal direction; these could be used to automatically record the variations in the displacement. The earth pressure cells were embedded in soil layers where the positions upon the top arches of the subway station space and twin tunnels, as shown in Fig. 6(b). Each micro-multi-point extensometer consisted of four fine steel bars and a steel casing pipe. One end of the fine steel bar was affixed to the measurement point, and the other end of the fine steel bar was connected with the data wire. The steel bar can slip freely inside of the steel casing pipe.

3.4 Arrangement of monitoring points

As indicated in Fig. 7(a) and (b), three measurement lines were established along the x-direction to measure the ground surface settlement of the model. Their locations were defined as follows: line 1, \(y = 0.48\) m; line 2, \(y = 0.90\) m; line 3, \(y = 1.32\) m. Each measurement line had seven monitoring points. The layout of the ground surface settlement monitoring points is presented in Fig. 7(a) and (b). There were \(3 \times 7 = 21\)
monitoring points for the ground surface settlement, and the numbers of ground surface settlement monitoring points on measurement lines 1, 2, and 3 are shown in Fig. 7(b) and Table 4. The displacement variations at these points were continuously recorded during excavation and support. The micro-multi-point extensometers were placed in vertical measurement sections along the x-direction at y = 0.48 m, 0.90 m, and 1.32 m, as shown in Fig. 7(b) and (c).

### Table 4. Monitoring point serial number of ground surface displacement on measuring line

| Measurement line number | y(m)  | Monitoring point numbers |
|-------------------------|-------|--------------------------|
| 1                       | 0.48  | 10 13 22 25 34 37 46     |
| 2                       | 0.90  | 11 16 23 28 35 40 47     |
Fig. 7(c) shows the locations and numbering of the monitoring points in the y = 0.90 m section. There were five measurement lines in each vertical section: three vertical lines with two displacement monitoring points and two horizontal lines with three displacement monitoring points. The locations of all the displacement monitoring points are shown in Fig. 7(a). As mentioned above, the multi-point extensometers were embedded in 36 points in the soil layers.

4. Excavation and support of transverse tunnels

4.1 Excavation and support

The excavation and support of subway station spaces and transverse tunnels in models are very complex. Different excavation sequences will cause varied mechanical responses and further lead to displacement variations in the soil mass surrounding subway station spaces and twin tunnels. In this study, after the sequence of excavation in Fig. 8(a) was completed, each transverse tunnel—a bilaterally symmetric soil mass with 24 cm thickness—was excavated firstly. Then, the soil mass (the width of two segments) in the middle was excavated. After the excavation of the soil mass in the transverse tunnel, each transverse tunnel was supported immediately. The support system consisted of the previous support and a secondary lining, and the previous support force was induced by a steel frame structure designed by the authors, as shown in Fig. 8(c). A secondary lining was created as permanent support, and the thicknesses of the linings of the top and floor of the transverse tunnels were 10.3 cm and 12.1 cm, respectively. For the subway station space of the model, the construction sequence of the secondary lining concrete was defined as follows: floor, sidewalls, and roof. The transverse tunnels connected the twin tunnels and subway station space separately. Before excavation of the soil mass in the transverse tunnel, the corresponding secondary lining of the subway station space must be cut off to form an enlarged excavation face.

(a) Excavation sequence of transverse tunnels (units: mm) (b) Reinforcement of bottom floor (c) Previous support of transverse tunnel

Figure 8. Excavation and support steps for transverse tunnels (units: mm)

After the secondary lining of the subway station space was cut off, the soil mass in the transverse tunnel was excavated and removed. Meanwhile, a temporary steel frame was installed to support the...
soil mass upon the transverse tunnel, as shown in Fig. 8(c). Finally, the corresponding part of the segment was cut off, and the steel pipe column was installed in the open position of the segment immediately. There were 30 25-mm-diameter steel pipe columns.

4.2 Analysis of monitoring results

The testing process was divided into three stages: the excavation of the subway station space model, the excavation and support of the cross channel, and the model top loading. From September 29, 2007 to October 24, 2007 (26 days), the excavation and support of the subway station space was completed. The second stage, which included excavation, support, cutting of segments, and setting up of steel pipes, lasted from October 26, 2007 to November 26, 2007 (32 days). From November 27, 2007 to December 8, 2007 (12 days), uniform pressure induced by jacks was applied to the top surface of the model. The displacement and ground surface settlement were measured from the beginning to the end of the model test.

In this study, data obtained by the multi-point extensometer were used to study the deformation regulations of the soil mass. Partial displacement monitoring data obtained from the beginning of the first stage to the end of the third stage are given in Table 5. Fig. 7(a) shows the number of three measurement lines, and Fig. 7(c) shows the positions and number of 15 monitoring points in the 0.90 m section. Points 28, 29, and 30 were embedded in different depth positions along the vertical line through the mid-vault of the subway station space of the model. Point 28 was the monitoring point for ground surface settlement, and points 29 and 30 were the displacement monitoring points for the soil interior. Points 40, 41, and 42 were embedded in different depth positions along the vertical line through the mid-vault of the right tunnel. All of the displacements at these points were recorded automatically and are shown in Table 5. Fig. 9(a) shows the displacement–time curves of points 28, 29, and 30, and Fig. 9(b) shows the corresponding curves of points 40, 41, and 42. All of the displacement–time curves can be divided into three sections corresponding to the three construction periods. As shown in Fig. 9(a) and (b), the displacement–time curves of the three measurement points were similar in variation trend. The first stage lasted 26 days (September 29 to October 24). The beginning of excavation of the subway station space model caused the rapid increase in displacement, and the curves then became gradually flat until October 24. The second stage lasted 34 days (October 24 to November 26).

The beginning of excavation of the soil mass in the transverse tunnel led to the fluctuating decrease in the displacement–time curves. The curves were flat until November 26, as shown in Fig. 9(a) and (b). However, in the second stage, the displacement–time curves of points 40, 41, and 42 decreased steeply during the cutting of the segments. The main reason was that all of the displacements at the monitoring points were induced by the deformation of the soil layers, and the cutting of segments had a strong impact overall lining structure, which led to the large deformation of the soil layers. During the construction and installation of the support and secondary lining, the whole model temporarily stabilized. Therefore, all of the curves gradually flattened until November 26. Several new support techniques were developed in the model test; for example, steel pipes were employed to support the open segments, and a unique steel frame was applied to support the soil mass in the transverse tunnel, as shown in Fig. 8(c). In addition, findings showed that optimizing the construction sequence and determining the support time rationally can distinctly reduce the displacements of measurement points.

| Table 5. Partial data of vertical displacement monitoring points |
|---------------------------------------------------------------|
| Serial number of monitoring points |
| Time | 28 | 29 | 30 | 40 | 41 | 42 |
|--------|----|----|----|----|----|----|
| 09.29  | -0.01 | -0.01 | -0.01 | 0.00 | 0.00 | 0.00 |
| Date (m/d) | Vertical Displacement (mm) |
|-----------|---------------------------|
| 9/29      |                           |
| 10/12     |                           |
| 10/24     |                           |
| 11/02     |                           |
| 11/06     |                           |
| 11/10     |                           |
| 11/14     |                           |
| 11/20     |                           |
| 11/24     |                           |
| 11/28     |                           |

(a) Points 28, 29, 30  (b) Points 40, 41, 42

**Figure 9.** Curves of the displacement vs. time for monitoring points

The third stage lasted 12 days (November 27 to December 8). The uniform vertical pressure induced by the screw jacks was transmitted to the top surface of the model through flexible rubber cushions inside of rigid thrusters. From 0 MPa to 0.23 MPa, the uniform vertical pressure was applied to the top surface of the model step by step. At the beginning of the third stage, the displacements of the

| Date (m/d) | Vertical Displacement (mm) |
|-----------|---------------------------|
| 12/02     |                           |
| 12/06     |                           |
| 12/08     |                           |
| 12/12     |                           |
| 12/16     |                           |
| 12/20     |                           |
| 12/22     |                           |
| 12/24     |                           |
| 12/26     |                           |
| 12/28     |                           |

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Figure 10. Curves of displacement–time and soil pressure–time in monitoring points. Points 28, 29, and 30 increased rapidly, and the curves decreased steeply, as indicated in Fig. 9(a). The curves then developed slowly in the later period of the third stage. In addition, the monitoring values of the horizontal displacement of monitoring points 4, 5, 6, and 52, 53, 54 during the three-stage test are shown in Table 6, and the change rule of the horizontal displacement of each point is shown in Fig. 10. All the displacements of measuring points 4, 5, and 6 were negative, and those of 52, 53, and 54 were all positive, which indicated that the soil outside the east and west sides of the tunnel produced deformation to both sides in the whole testing process. This was mainly caused by the excavation of the station space and the transverse tunnel, which resulted in the flattening of the segment and further compression of the lateral soil mass. The displacements of measuring points 52, 53, and 54 were very small, mainly because there was a row of reinforced concrete grouting files outside the east tunnel to restrain the lateral displacement of this part of the soil [30].

The pressure cells numbered ①, ②, and ③ were embedded in the soil layer on the top arches of the subway station space. As shown in Fig. 10 and Table 7, in the first stage of the station space excavation, the earth pressure–time relation curve of pressure cell ③ rose rapidly; in the second and third stages, the fluctuation trend continued to rise, and the maximum earth pressure reached 38.48 kPa. Meanwhile, in the first stage, the earth pressures of pressure cells ① and ② initially showed a fluctuating increase and then decreased; in the second and third stages, the maximum values were 27.94 kPa and 19.67 kPa, respectively.

**Table 6.** Partial data of horizontal displacement monitoring points (unit: mm)

| Time | Serial number of monitoring points |
|------|-----------------------------------|
| Time     | 4   | 5   | 6   | 52  | 53  | 54  |
|----------|-----|-----|-----|-----|-----|-----|
| 9/29     | -0.01 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| 10/9     | -0.02 | -0.02 | -0.01 | 0.02 | 0.01 | 0.01 |
| 10/19    | -0.03 | -0.02 | -0.02 | 0.03 | 0.02 | 0.01 |
| 10/29    | -0.04 | -0.03 | -0.02 | 0.04 | 0.02 | 0.02 |
| 11/8     | -0.16 | -0.12 | -0.05 | 0.05 | 0.03 | 0.02 |
| 11/18    | -0.40 | -0.30 | -0.11 | 0.18 | 0.15 | 0.11 |
| 11/28    | -0.52 | -0.38 | -0.20 | 0.23 | 0.19 | 0.14 |
| 12/8     | -0.58 | -0.43 | -0.27 | 0.25 | 0.21 | 0.17 |
| 12/13    | -0.58 | -0.43 | -0.27 | 0.25 | 0.21 | 0.17 |

**Table 7. Partial monitoring data from soil pressure cells (kPa)**

| Time     | Number of pressure cells |
|----------|--------------------------|
|          | 1 | 2 | 3 |
| 9/29     | 10.62 | 12.61 | 19.64 |
| 10/4     | 10.68 | 14.97 | 20.30 |
| 10/9     | 13.85 | 12.98 | 26.70 |
| 10/14    | 7.43  | 11.74 | 34.81 |
| 10/19    | 11.10 | 14.29 | 36.31 |
| 10/24    | 16.59 | 14.75 | 31.98 |
| 10/29    | 16.96 | 15.51 | 31.84 |
| 11/3     | 17.81 | 17.55 | 35.91 |
| 11/8     | 20.56 | 18.62 | 36.79 |
| 11/13    | 23.70 | 19.22 | 38.48 |
| 11/18    | 25.76 | 19.45 | 36.53 |
| 11/23    | 27.94 | 19.67 | 38.11 |

5. Conclusions
In this paper, a large-scale 3D geomechanical model test system was used to simulate the whole process of underground excavation between existing twin tunnels. The short-step excavation method was used to simulate the excavation effects of a subway station space, and partition excavation was used to cut the segment and excavate the transverse tunnel of the model. In addition, the jack reaction loading method was used to apply a uniform load on top of the model. The experimental results are as follows.

The vertical deformation of the stratum on the top arches of the subway station space was affected by the excavation of the soil mass, the transverse tunnel, and the overload pressure. There were differences in the three stages. In the beginning of each stage, the vertical displacement had different degrees of increase. In actual construction, the short-step or ultra-short-step method should be used in the beginning of the excavation of station space expansion. Small tools should be used for the excavation of transverse tunnels to break the segments as much as possible. In the beginning of overload pressure, the increment in control load was small and then increased gradually. The maximum vertical displacement of the model stratum was 1.29 mm, and that of the actual project is 1.29 cm.

Pre-reinforced piles are a key technical measure for effectively restraining the displacement of the existing tunnel segment and the horizontal deformation of the outer soil mass. The maximum horizontal displacements of monitoring points 4 and 52 were -0.58 cm and 0.25 cm, respectively. The simulation pile outside the right tunnel not only reduced the displacement of point 52, which was less than half the displacement of point 4, but also changed the displacement direction of the right side of the soil mass. The experimental study showed that an underground station space can be undercut in the stratum under good geological conditions as long as the construction method is suitable and the technology is reasonable.

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