

## Research Article

# Prediction on Ground Settlement Deformation and Influence of Urban Buildings in the Construction Process of Existing Tunnel Reconstruction

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Surface deformation is one of the key issues in urban tunnel construction control, regardless of the construction method. The study on ground settlement deformation and urban buildings in the construction process of existing tunnel reconstruction is not many at present; moreover, rebuilding projects for older tunnels have more complicated planting conditions and limited construction methods. In this study, the construction method and process characteristics of an existing structure are analyzed. In addition, the ground settlement deformations and building displacements during construction are monitored. The results reveal that the method of the Peck formula for predicting the ground settlement deformation and urban buildings of existing tunnel reconstruction is feasible and effective based on fitting curve by monitoring data. A finite element model is established. The results show that the simulation values of the ground deformation are consistent with the measured values. The differences between the simulated and measured values of the maximum ground surface sedimentation are 4.9% and 0.72% for single-sided excavation and bilateral excavation, respectively. The maximum building settlement is -9.6 mm in the single-sided excavation, the deformation rates remain within 0.1 mm/d, and the maximum width change of the building crack occurs during the demolition of the existing tunnel concrete in the single-sided excavation (with a value of 0.45 mm); subsequently, the building crack exhibits a decreasing trend, indicating that the crack is stable. The results can provide a reference for construction control for existing tunnels.

## 1. Introduction

Tunnel construction has a relatively large risk factor and a higher probability of accidents, especially in the complex environmental conditions of a city, where such accidents can be more harmful. Existing large-scale research studies have shown that the ground deformation caused by tunnel construction is a source of such accidents. Therefore, the core of safety control in urban underground engineering is the effective control of the ground deformation [1]. At present, the settlement and displacement in ground movements caused by the construction from urban underground engineering, especially in the construction processes for subway

engineering, have attracted the attention of many researchers worldwide [2, 3]; the ground settlement caused by the construction of urban shield tunnels is the most concentrated area of research [4]. The expansion of existing urban tunnels remains relatively rare, especially regarding the effect of tunnel expansion mode on the surface deformation and the impacts from adjacent buildings. Therefore, it is particularly important to study the influences of the surface and adjacent buildings on the construction of existing tunnels and underpasses.

As domestic research on the expansion of existing tunnels remains relatively limited and most of the research comprises engineering practice studies on construction

methods for mountain tunnel expansion projects, there are relatively few theoretical studies on construction control theory and the laws of the ground deformations caused by construction and lack of analysis of the changes in the process by finite element [5]. In addition to the cracks, man-made holes, water leakages, and other lining damage effects common in tunnels after years of use, there are often excessive human activities combined with restrictive requirements for urban underground pipeline networks and high-rise buildings above ground, making construction control especially important. Meanwhile, the sequence of pilot tunnel excavation has a significant effect on the development of the surface settlement trough [6–8]. The first line of a city subway is generally built by using a section of an existing underground human defense tunnel for renovation. To control the ground deformation at the construction site and ensure the safety of construction, the ground deformations and actions of surrounding buildings during the entire construction process are monitored and measured.

In this paper, the ground deformation characteristics of an existing tunnel renovation subway expansion construction by investigating the measured data of surface subsidence measurements on-site, considering the various factors affecting the ground settlements caused by subway construction, using Peck's formula for a surface settlement analysis, and conducting a numerical simulation of the structural deformations during construction for comparison with measured data are studied. Through the combination of the prediction method of Peck's formula, the finite element model and the actual engineering monitoring, a kind of assessment basis for determining the level of the surrounding rock, the stability and reliability of the surrounding rock, support and lining were provided in this paper. Furthermore, the study would help to identify a reasonable application time for the secondary lining and improve the construction plan and change support design parameters to ensure construction safety and quality. In addition, this paper also verifies that the Peck theory can be effectively used to predict ground settlement deformation.

## 2. Study on Surface Deformation Characteristics during the Construction of Expansion Excavation

*2.1. Existing Tunnel Expansion Methods and Processes.* This study considers an existing human defense tunnel built more than 30 years ago using the mining method of construction, and subject to the construction level at that time, that the circular construction joints are approximately 1.5 m. Behind its lining, there are many cavities, backfilled pieces of stone, sleepers, and so on. The concrete strength is approximately C30, the thickness of the arch is approximately 60 cm, the thickness of the side wall is 80 cm, the back arch is 120 cm, the tunnel width is 7.5 m, the height is 6.5 m, and the burial depth is 16–24 m. The lithology of this site is powder clay and sandy soil, and the topography of the surface site in the area shows relatively little undulation. The ground elevation is between 143.63 and 145.13 m, and the natural height

difference is small. The surrounding area is mainly used by commercial enterprises, and the proposed project site mainly comprises a road with enterprises, institutions, and residences on both sides. The road and underground pipelines on both sides are very dense, including those for water supply, telecommunications, electricity, heat, gas, and sewage, and certain pipes are crisscrossed. As restricted by the construction level at the time of construction, the structure has a relatively high number of construction joints; moreover, the concrete quality is discrete, and the concrete can easily be eroded by groundwater. To ensure safety and avoid large-scale damage to existing tunnels from accidents, in the jump trench excavation, existing structures should be used to cut out construction processes with less vibration to reduce the disturbance of the surrounding soil, e.g., a proposed PC80 excavator with a hydraulic hammer combined with a manual wind pick break.

Before construction, structural measurements were conducted, and a cross-sectional drawing was made every 5 m to map out the relationships between the existing tunnel and new tunnel; according to the results, the single-/double-sided expansion areas were determined. Following the principle of ensuring safety and minimal excavation, both single- and double-sided reconstruction and excavation methods were adopted, based on using the existing tunnel sidewalls for the initial support, laying waterproof slabs, and molding a 350 mm thick secondary lining.

For the single-sided expansion, in the laying of the overrun small conduit grouting support, the excavator broke the set range of the existing tunnel structure (by no more than 2 m). After removing the existing structural reinforcement and repairing the excavation and contact surfaces of the old and new concrete, the grating was erected, the locking anchor was laid, the temporary support was erected, and the shotcrete was added. After 20 m of continuous construction of the arch wall, the temporary support was gradually removed, along with the concrete of the existing tunnel elevation arch (not more than 2 m at a time). The initial support of the elevation arch parts was applied to form a closed ring. Finally, waterproofing, the concrete for the second lining of the elevation arch, and the concrete for the filling of the elevation arch were applied, and the concrete for the arch wall was constructed based on a formwork cart. The construction process is illustrated in Figure 1.

For the double-sided excavation, according to the measurement results, the breaking edge line was determined. Then, 120° of the arch was supported by overrunning the small conduit grouting, and the excavator broke the existing tunnel structure (no more than 1 m). After removing the existing structural reinforcement, the grating was erected, the locking anchor rods were laid, the temporary supports were erected, and the concrete was shot. After 20 m of continuous construction of the arch wall, the temporary support was gradually removed, the concrete of the existing tunnel elevation arch was broken (not more than 2 m at a time), and the initial support of the elevation arch was applied to form a closure. Finally, the waterproofing, concrete, and filling concrete of the second lining of the back arch were applied, and the concrete of the arch wall was constructed

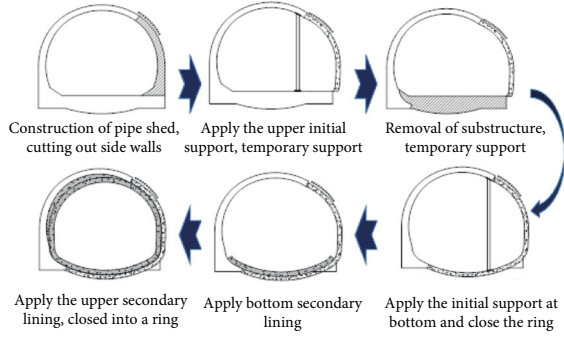


FIGURE 1: Construction process of single-sided excavation.

using a formwork cart. The construction process of this method is illustrated in Figure 2.

**2.2. Ground Deformation Monitoring Method.** The existing tunnel utilization section was SK7 + 642 to SK8 + 024.485 (between Qingbin Park Station and West Bridge Station); this section had a length of 382.485 m and comprised a single-hole double-line tunnel. The existing tunnel renovation construction took nearly one year and eight months, and the surface settlement continued to be monitored for 20 months. The data from a section with large changes were selected for analysis.

The construction area base point was buried in a stable area with an open view and good visibility outside the settlement influence range and was firm and reliable. The settlement measurement points were buried by drilling holes in the ground with percussion drills and then placing round-headed steel bars of 200–300 mm in length and 20–30 mm in diameter, with cross wires engraved on the ends and filled with cement mortar. The monitoring points were spaced 5 m apart longitudinally and 2.5 m to 5 m apart laterally. To investigate the impacts of the construction method adopted for the existing tunnel renovation, 45 points were placed on the ground within and adjacent to the existing tunnel. The surface settlement data were obtained for nine typical observation sections between SK7 + 905.266 and SK7 + 955.266. During the entire construction period, the cumulative settlement value of the ground surface was monitored. The maximum cumulative settlement value of the single-sided expansion excavation was on the expansion side, and its settlement value was -14.4 mm; this appeared when the initial support of the single-sided expansion was completed. The maximum cumulative settlement value of the double-sided expansion ground surface was on the centerline of the structure, and its settlement value was -23.5 mm, i.e., measurement point A3 in Figure 3; this appeared when the initial support of the double-sided expansion was completed. The minimum settlement value of the surface was -3.0. To maintain the structure in a safe and controllable state and ensure that the requirements for structural stability were met, and as combined with the relevant codes, regulations, and experience on similar projects, the control targets for the surface settlement and building settlement were determined before construction. The allowable displacement control value  $U$  [0] was 30 mm, the average rate of the

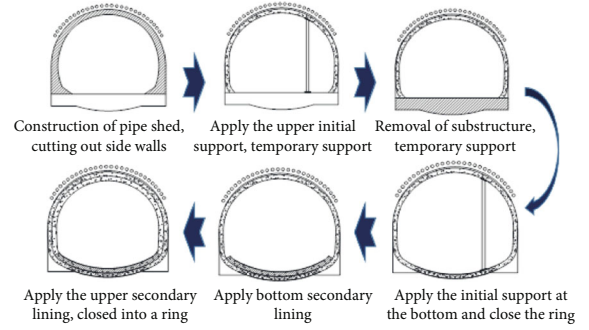


FIGURE 2: Construction process of bilateral excavation.

displacement control value was 2 mm/d, and the maximum rate of displacement control value was 5 mm/d. The alert value was considered as 80% of the control standard, and the monitoring frequency was strengthened when the alert value is reached or approached. The surface settlement values showed that none of them exceeded the alert value of -24 mm.

### 3. Results and Discussion

#### 3.1. Adaptation Analysis of Peck's Theory to Predict Surface Deformation

**3.1.1. Peck Theory Analysis.** The method proposed by Peck in 1969 is considered to be the simplest and most widely used empirical method for predicting the surface displacements owing to underpass tunnel excavation [9, 10]. Based on the experiences of O'Reilly and New in a London area [11], a natural ground settlement prediction model was synthesized, as follows:

$$s(x) = s_{\max} \exp \left[ \frac{-x^2}{2i^2} \right] = \left[ \frac{0.313 V_i D^2}{K z_0} \right] \exp \left[ \frac{-x^2}{2(K z_0)^2} \right], \quad (1)$$

where  $s(x)$  is the settlement of a ground point on the  $z$ -axis at a distance  $x$  from the tunnel axis on the cross-section (mm),  $x$  is the horizontal distance between the settlement point to be sought and the center line of the settlement curve (mm),  $s_{\max}$  is the ground settlement (mm),  $i$  is the reversal point distance (m),  $V_i$  is the formation volume loss rate,  $D$  is the diameter of the tunnel (m),  $z_0$  is the depth of the tunnel, and  $K$  is a width parameter for the settlement trough and mainly depends on the soil properties. According to experience, the softer silty clay can have values of 0.6–0.8.

Many domestic scholars have used the Peck formula to analyze and predict the effects of new underground projects [12–16], but there are relatively few studies on whether the ground deformation laws of underground reconstruction and expansion projects conform to Peck's empirical formula. This is especially true for the different expansion plans in urban underground projects; therefore, the impacts on the surface need to be further explored. In this study, the measured data and geological conditions of the existing tunnel reconstruction subway project in the city were investigated,

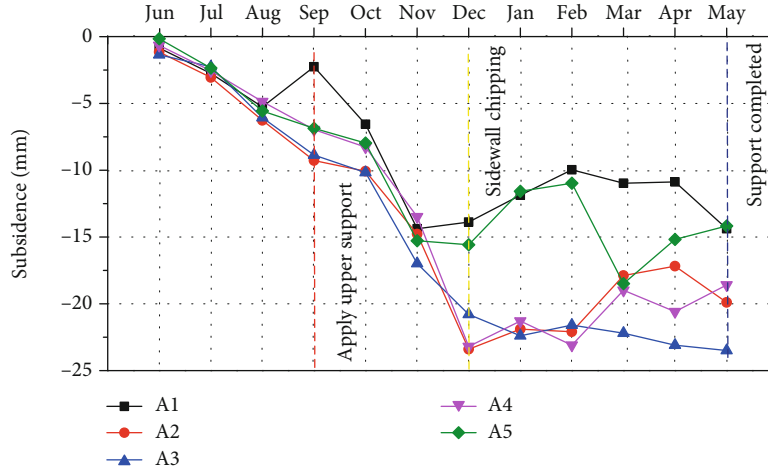


FIGURE 3: Surface subsidence change curve of "A" section.

and the calculation results were compared and analyzed using Peck's formula.

**3.1.2. Fitting of Peck's Formula Based on Measured Data.** Peck's formula uses a linear regression analysis; that is, after taking the logarithm, both sides of Equation (1) can be transformed to obtain an equation as follows:

$$\ln s(x) = \ln s_{\max} - \frac{x^2}{2i^2}. \quad (2)$$

From Equation (2), a linear relationship is suggested. Equation (2) is changed to Equation (3), as follows:

$$\ln s(x) = a + b \left( -\frac{x^2}{2} \right). \quad (3)$$

Here,  $a = \ln s_{\max}$ , and  $b = 1/i^2$ . The regression can be obtained from Equation (1), i.e.,  $s_{\max} = \exp(a)$ ,  $i = (b)^{(-0.5)}$ .

Table 1 lists the measured values of the surface deformation in section A during the monitoring interval.

Table 1 shows that  $a$  and  $b$  are equal to 3.1566 and 0.01454, respectively. The linear function after regression is determined as follows:

$$\ln s(x) = 3.1566 + 0.01454 \left( -\frac{x^2}{2} \right). \quad (4)$$

The regressed function is compared with the measured data. From Equation (1), it can obtain  $s_{\max} = \exp(a) = 23.4906$  and  $i = (b)^{(-0.5)} = 8.2931$ ; therefore, Peck's formula is as follows:

$$s(x) = 23.4906 \exp \left[ \frac{-x^2}{2 * (8.2931)^2} \right]. \quad (5)$$

Three sets of typical data were selected separately for the linear regression analysis, and the results are shown in Figure 4.

TABLE 1: Regression analysis of surface subsidence measured data.

Sample	1	2	3	4	5
Distance $x$ (m)	-8.5	-5.5	0	5	8
$s(x)$ (mm)	14.2	18.6	23.5	19.9	14.4
$-x^2/2$	-36.125	-15.125	0	-12.5	-32
$\ln s(x)$	2.653	2.923	3.157	2.991	2.667

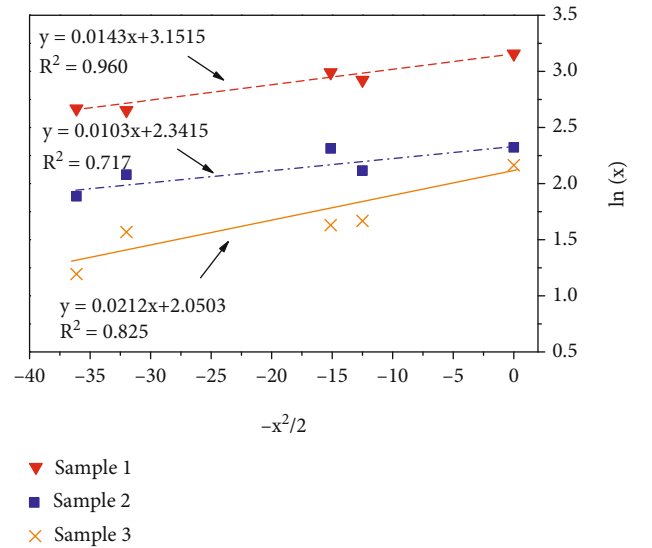


FIGURE 4: Linear regression function.

Figure 4 shows that the linear regression function fits well with the measured data and that the measured data are evenly distributed around the regression linear function. The correlation coefficients of samples 1, 2, and 3 are 0.960, 0.717, and 0.825, respectively. There is a high correlation between the regression parameters, which can better reflect the relationship between the converted Peck formula and the measured data and provide an accurate reference for the correction of the Peck formula. It can be seen that Peck's formula is applicable to the underground expansion

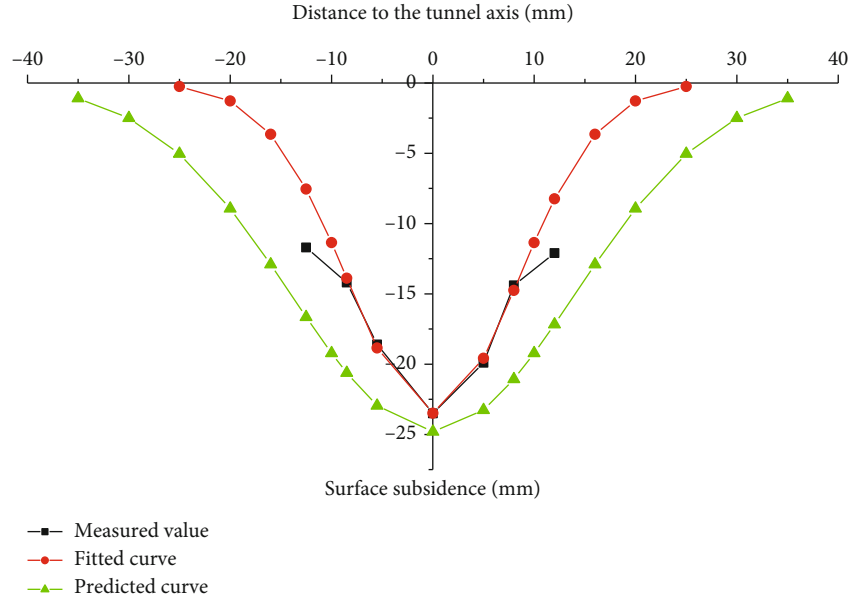


FIGURE 5: Comparison of settlement data, Peck’s fitting curve, and predicted curve.

TABLE 2: Material physical and mechanical parameters of calculation model.

Material	Density (kg/m <sup>3</sup> )	Elastic modulus $E$ (GPa)	Poisson’s ratio $\nu$	Internal friction angle $c$ (°)	Dilatancy angle (°)	Stress flow rates $k$
Surrounding rock	1900	0.095	0.35	25	15	1.0
Tube shed layer	2200	10.0	0.25	30	20	1.0
Primary lining	2300	23.0	0.2			
Secondary lining	2400	28.0	0.2			
Existing tunnel structure	2350	25.0	0.2			

projects, but the relevant parameter values need to be summarized and verified based on a large number of practices. For this project, Peck’s original prediction formula is used for the settlement analysis, and the value of each parameter is determined by combining the structural characteristics of the project, the geological and hydrological conditions in the area, and the experiences from similar projects. The value of  $V_i$  is 1.5%, whereas  $K$  is 0.7, and  $D$  is 8.6 m. The tunnel depth is approximately 20 m. The results are shown in Figure 5. As can be seen from Figure 5, the fitting and predicted values using Peck’s formula are consistent with the trends of the measured values, and the difference between the predicted maximum settlements and measured values is not large. This indicates that the relevant parameters as determined by Peck’s original formula for predicting this project are more reasonable and that the prediction method can be applied to the practices of urban original tunnel reconstruction and expansion projects.

3.2. Numerical Simulation of Surface Deformation during Construction [17]. Existing research shows that the selected parameters have a great significance to ground settlement owing to tunneling [18, 19]. To better understand the construction methods for controlling the structural safety of the tunnel, the finite element analysis software was used to

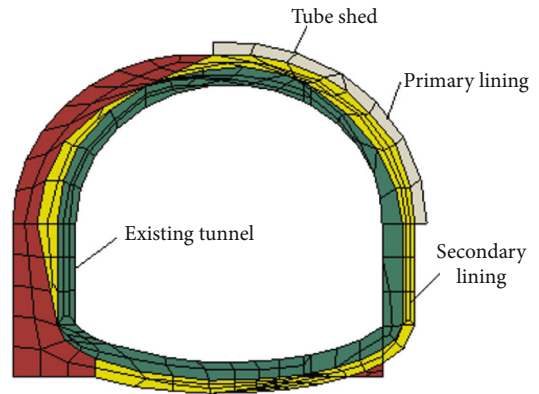


FIGURE 6: New cavern after single-sided excavation.

establish respective numerical models for the two modification construction methods of the tunnel (single-sided expansion and double-sided expansion), based on the geological and structural characteristics of the tunnel. The material physical mechanical parameters and hardening parameters of the computational models are shown in Table 2. The tunnel excavation and support were simulated based on unit passivation and activation, whereas the grouting reinforcement was achieved based on a simulation analysis of the

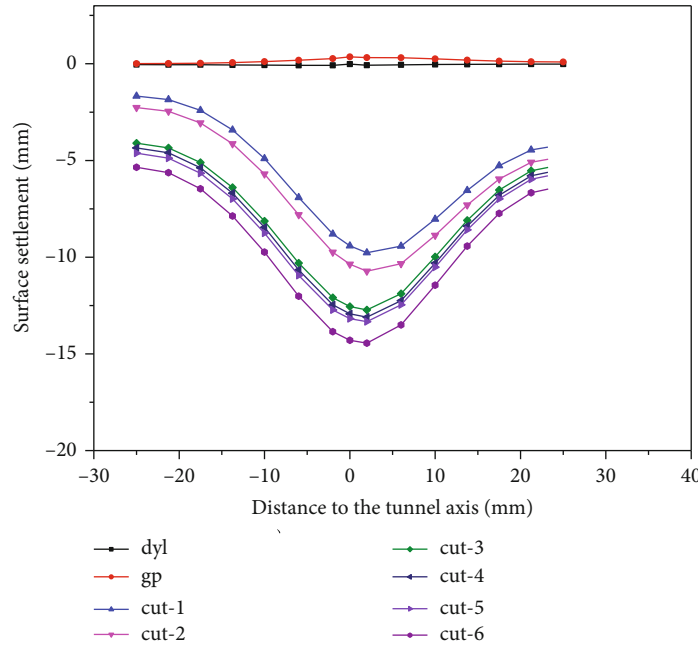


FIGURE 7: Surface subsidence change from single-sided excavation.

entire construction process, providing theoretical support for the selection of the reconstruction construction method for the concealed excavation interval.

A finite element simulation of each stage of the tunnel unilateral expansion process was performed to obtain the vertical displacement variations of the tunnel structure in each construction stage. As shown in Figures 6 and 7, the application of the pipe shed (simulation of the grouting process) changed the nature of the surrounding rock, with the soil above the pipe shed rising upward. After the tunnel excavation, the surface no longer rose, the upper soil settled downward, and the bottom soil rose upward and converged toward the tunnel interior. With the expansion process, a settlement trough was formed at the surface of the expansion side at the center of the tunnel. As shown in Figure 7, the ground surface began to settle after the removal of the original structure, and the maximum settlement value reached 15.10 mm after the completion of the new structure masonry. The surface deformation on the excavated side was large, and the maximum settlement value was on the excavated side. In Figure 7, dyl is the ground stress balance, gp is the applied pipe shed, and cut-1 to cut-6 correspond to the single-sided expansion construction divisions shown in Figure 1.

As shown in Figures 8 and 9, the application of the pipe shed (simulation of the grouting process) changed the nature of the surrounding rock, and the soil above the pipe shed was uplifted. After the top structure of the tunnel was removed, the stress in this part of the surrounding rock was released, the surface no longer bulged, and the upper soil settled downward. The maximum settlement value of the surface reached 20.13 mm and that of the vault reached 36.18 mm, exceeding the control limit and raising the danger of collapse. At this time, the soil at the bottom of the tunnel

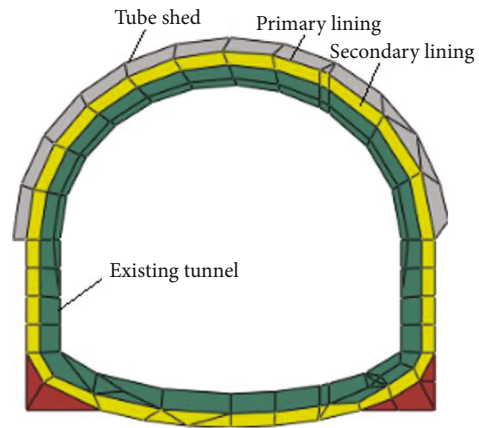


FIGURE 8: New cavern after bilateral excavation.

bulged upward and converged to the interior of the tunnel; the maximum bulge value of the vault bottom was 21.02 mm. With the expansion process, the surrounding rock stress was released, the tunnel converged inward, and the ground surface gradually formed a settlement trough on the expansion side of the tunnel center. The final settlement value of the ground surface reached 23.67 mm, and the maximum uplift value of the tunnel arch bottom was 34.21 mm. The new stability and equilibrium state were finally reached after the completion of the new lining structure. As shown in Figure 9, the deformation of the ground surface of the bilateral expansion excavation is symmetrically distributed along the center of the tunnel, with the maximum settlement value at the ground surface above the center of the line. In Figure 9, cut-1 to cut-6 correspond to the double-sided excavation construction divisions shown in Figure 2.

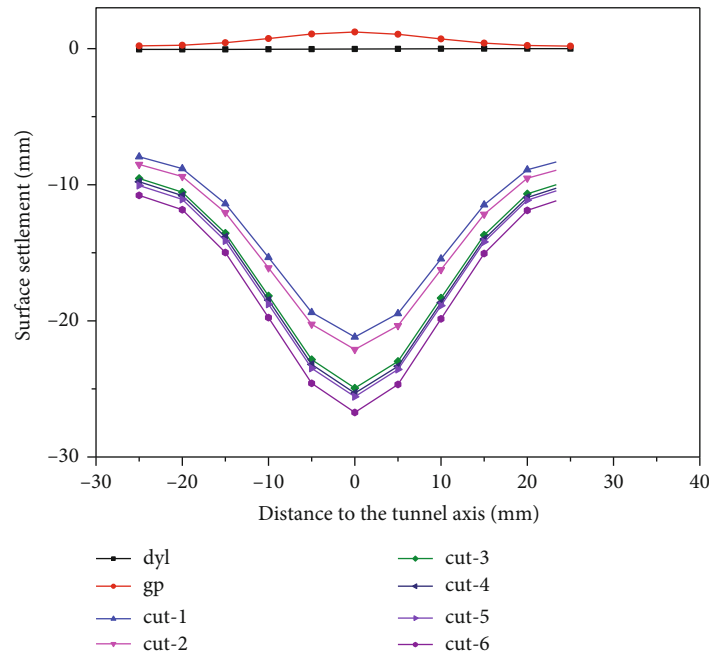


FIGURE 9: Surface subsidence change from bilateral excavation.

From comparing Figure 5 with both Figures 7 and 9, it can be seen that the trends and laws of the measured and numerical simulation value curves are consistent in different excavations, indicating that the structural model can be effectively used for construction control and can play a guiding role in the determination of the construction plan and control parameters.

**3.3. Monitoring Analysis of Buildings Adjacent to Work Sites during Construction.** Buildings within the longitudinal and lateral influences of the surface subsidence should be monitored for their building subsidence and tilt. By setting measurement points around the building, the safety of the building and the reliability of the adopted engineering protection measures can be determined. The arrangement of the building settlement and crack width monitoring points is shown in Figure 10. Among them, JCJ-1 to JCJ-5 are building settlement observation points, and FW-1, FW-2, and FW-3 are building crack observation points.

Five monitoring points were deployed for analyzing the building settlement, as shown in Figure 11. The settlement of the building began to increase during construction. At a later stage after the completion of the secondary lining, the structure tended to stabilize and did not settle, and a slight convergence was shown. The maximum settlement is at JCJ-2 with a point settlement value of -9.6 mm; for the unilateral expansion and removal of the existing tunnel concrete, the deformation rates are within 0.1 mm/d.

During the tunnel construction process, the safety of the building was determined based on the development of cracks in the building, so as to allow for appropriate engineering protection measures. Three existing cracks were selected on the existing building, and their crack widths

were observed during the whole construction process, as shown in Figure 12. The maximum crack width change value is 0.45 mm in crack FW-1 during the existing tunnel concrete was removed by the unilateral expansion and excavation. However, the later cracks show a slightly decreasing trend, indicating that the crack opening had stabilized.

## 4. Monitoring and Evaluation Methods

From the displacement monitoring data, the time-displacement and distance-displacement scatter diagrams, and a regression analysis of the measurement lines in a typical measurement section, the convergence measurement results can be used to determine the stability of the tunnel. If the convergence value is too large, the stability of the surrounding rock or soil should be improved. The disturbances from the excavation of the surrounding rock (soil) should be minimized, and the support should be strengthened if the tunnel monitoring measurement results appear abnormal. The support can be strengthened as follows: First, if the deformation rate suddenly increases and reveals signs of instability, the tunnel should be monitored by full-time observers to monitor the initial support, especially if accompanied by loud sounds and/or new cracks. Normal construction should be immediately suspended, the support should be strengthened, and, potentially, rescue measures should be taken. Second, the construction method or design parameters can be changed to enhance the initial support. If the displacement rate does not decrease significantly for a long time or the measured displacement value is close to the specified allowable value, the displacement may exceed the reserved deformation amount. In such cases, reinforcement

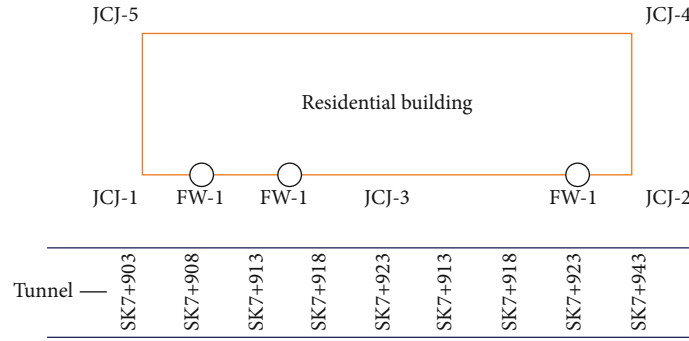


FIGURE 10: Schematic diagram of observation points for building settlement and cracks.

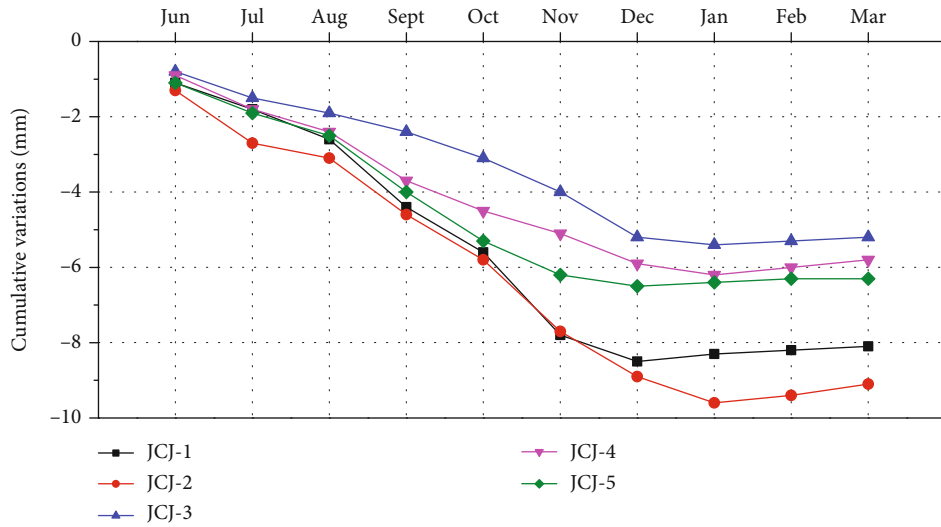


FIGURE 11: Cumulative variations of building settlement during construction.

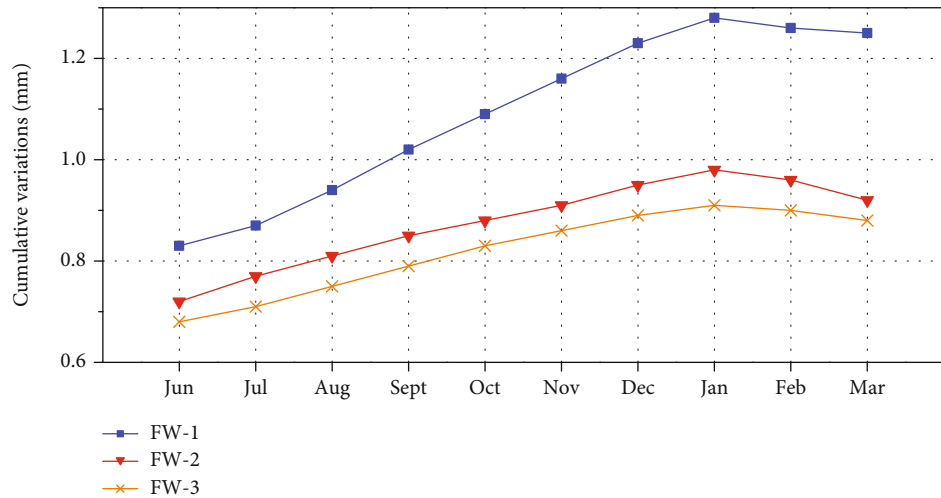


FIGURE 12: Cumulative variations of building crack widths during construction.

measures should be taken immediately. Third, when encountering one of these situations, the design parameters should be changed and the initial support should be appropriately reduced: those circumstances including confirmed that the surrounding rock category, engineering geology,

and hydrogeological conditions are significantly better than expected or there are specific engineering analogies; another situation is that the displacement converges and reaches the index for applying the secondary lining while the initial support is not fully completed.



## 5. Conclusion

In this study, the construction method and process characteristics of an existing structure are analyzed. In addition, the ground settlement deformations and building displacements during construction are monitored. Based on the discussion and analytical investigation, the following conclusions can be drawn:

The reconstruction and utilization of existing urban tunnels are important measures for resource reuse. However, the complex environmental conditions of existing tunnel structures and certain disease factors make it particularly important to determine the reconstruction method. The single- and double-sided reconstruction and expansion methods make full use of the remaining side walls of the existing tunnel for the initial support, and the use of slot-hopping excavation construction not only solves the boundary requirements for the line but also reduces the cost of tunnel excavation and shortens the construction period.

The existing tunnel single- and double-sided expansion methods have the same influences on the surface deformation, but their respective degrees of influence are different. The maximum accumulated settlement value is -14.4 mm during the single-sided expansion excavation and -23.5 mm during double-sided expansion excavation; the maximum value appears when the initial support of the single-sided expansion excavation is completed.

The case analysis shows that Peck's theory is applicable to the prediction of surface deformations during the expansion and reconstruction of existing tunnels, but it still requires a significant amount of practical analysis to obtain relevant prediction parameters. Based on the finite element simulation structure during the entire construction phase, it is shown that the simulation values of the surface deformations during the construction period are consistent with the actual measured values. The errors between the maximum settlement values and measured values of the single- and double-sided expansion excavations are 4.9% and 0.73%, respectively.

To ensure that the structure is in a safe and controllable state, the control value for the surface settlement is determined based on combining the requirements from the construction specification and the required structural stability; the allowable displacement control value  $U [0]$  is 30 mm, the average rate of the displacement control value is 2 mm/d, and the maximum rate of displacement control value is 5 mm/d. The ground deformation and building settlement during the entire construction phase are within the control targets.

The monitoring results for the building during the expansion period show that the maximum settlement value of the building settlement occurs during the single-sided expansion, at -9.6 mm, and that the deformation rate is within 0.1 mm/d. The maximum width change value of the building crack occurs when the concrete of the existing tunnel is demolished by the side expansion, at 0.45 mm. Nevertheless, the cracks tend to decrease slightly later, indicating that the cracks have stabilized.

## Data Availability

The data used to support the findings of this study were not available due to confidentiality.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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