Influence of Excavation of Loess Tunnel on Stability of Adjacent Existing Tunnels

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Abstract. This study investigates a project for new railway tunnels constructed adjacent to existing tunnels in the Loess Plateau region of Taiyuan, Shanxi Province, China. A comprehensive empirical evaluation method and three-dimensional Lagrangian numerical simulation were used to analyze the effects of newly built tunnels on the stability of existing tunnels. Research conclusions are listed as follows. Empirical evaluation method is used to study the construction of the newly built tunnel, which is located within the restricted range of the two existing tunnels and the caution range. When the newly built tunnel is within the restricted range of the existing tunnel, the smaller the distance between the two tunnels, the greater the influence on the deformation of the existing tunnel. When the newly built tunnel is located within the caution range of the existing tunnel, the tunnel contains maximum disturbance in the middle of the axis of the existing tunnel. The results provide a reference for future research on similar adjacent construction.

1. Introduction
Because of the rapid development of China's economy, the transportation demand of major cities is increasing, and the road network is continually improving. New structures often have to be built near existing structures. Improper construction can lead to large deformation, uneven settlement, or even collapse. Several construction accidents have occurred due to lack of understanding and attention to this type of project[1].

Many scholars worldwide have studied the construction of adjacent tunnels. Yang [2] studied the optimization of tunnel advance per round and blasting parameters under the construction condition of adjacent tunnels. Li [3] and Huang [4] studied the laws of deformation of existing tunnels caused by the excavation of adjacent newly built tunnels via numerical simulation, field monitoring, and centrifuge tests, respectively. Liang [5] proposed a simplified analytical method to explain the impact of above-crossing tunneling on existing tunnels. Yu [6] summarized the construction techniques and laws of deformation during the excavation of a twin tunnel above and under-crossing three tunnels. Fang [7] studied the case of two existing tunnel constructions adjacent to a twin tunnel. Furthermore, some scholars have analyzed the existing tunnel disturbance caused by blast-induced vibration [8].

The methods used in the above research mainly include theoretical methods, numerical simulations, and laboratory tests. The types of research are relatively simple. The project in this study is similar to many other projects, but possesses unique features. The tunnel excavation response of adjacent construction works was studied using a combination of empirical evaluation and three-dimensional numerical-simulation methods.
2. Project Overview
The proposed Tongchang exclusive energy tunnel in Shanxi is located in the Loess Plateau area on the west slope of the Lüliang Mountains. That area is characterized by undulating topography. The tunnel is 367 m long, and its maximum burial depth is approximately 38.2 m. Forty meters from the tunnel mouth is a twin tunnel, and the rest is a single tunnel. Both the Anjiazhuang Tunnel of the Xiaojiawa Coal Mine and the No. 2 open-cut tunnel of Anjiazhuang of Wadi Railway are located on the east and west sides, respectively, of the Tongchang exclusive energy tunnel. The Xiaojiawa Tunnel is designed as a single tunnel with a total length of 908.27 m and a maximum depth of 70.7 m. The total length of the No. 2 open-cut tunnel in Anjiazhuang is 100 m, and it was constructed by step-slope excavation. The geographical relationship of the three tunnels is illustrated in Fig. 1.

![Fig. 1. Location of the newly built tunnel and two existing tunnels](image)

According to the field investigation and exploration, the stratigraphic distribution of the tunnel area is relatively simple. The upper part is the Quaternary Upper Pleistocene (Q3dl+eol) slope aeolian sandy loess, and the lower part is the Tertiary Pliocene (N2) silty clay. No groundwater was found in the surveyed borehole.

The entrance of the newly built Tongchang exclusive energy tunnel is close to the Xiaojiawa tunnel, and the minimum distance is only 1.1 m. Therefore, a 35-m large pipe shed is used as tunnel support at the entrance of the Tongchang exclusive energy tunnel. The D12K0+600~D12K0+670 section is supported by a row of isolation piles in the middle of the spacing between the two lines. The lower part of the isolation pile is 5 m below the bottom of the inverted arch, and the upper part is 5 m above the vault. The isolation piles are completed before tunneling.

3. Empirical Evaluation Method
At the end of the 20th century, the Japan Railway Technical Research Institute presented different types of close-space construction and close-degree classification in the *Design and Guide for Close-spaced Tunnels* \(^9\) in response to issues about adjacent construction. According to the clear spacing between new and old tunnels, close degrees can be categorized into three ranges: the restricted range, caution range, and unrestricted range. The excavation of newly built tunnels has a different disturbance from paratactic and crossed tunnels, so their close-degree classification needs to be considered separately. The close-degree classification for paratactic and crossed newly built and existing tunnels should be distinguished, as shown in Figures 2 and 3.
According to the size of the newly built tunnel and its positional relationship to the existing tunnel, combined with the close-degree classification of the new and old paratactic tunnels, the affected area can be finally determined as shown in Table 1. The restricted range of the existing tunnel is 1D from the sidewall of the tunnel. The caution range is 1D~2.5D from the sidewall of the tunnel, and the rest is unrestricted.

| Mileage for the newly built tunnel section | Tunnel diameter (m) | Restricted range (m) | Caution range (m) |
|------------------------------------------|---------------------|----------------------|-------------------|
| D12K0+575~585                            | 11.56               | <11.56               | 11.56~28.90       |
| D12K0+585~605                            | 13.36               | <13.36               | 13.36~33.40       |
| D12K0+605~690                            | 10.25               | <10.25               | 10.25~25.63       |

Regarding the safety protection measures for tunnel stability, the newly built tunnel has a large diameter near the tunnel mouth and small distance from the existing tunnel, which has a significant influence on the tunnel on the right side. Therefore, measures must be taken with respect to the construction method. In addition, existing and new structures should be monitored and measurements should be managed.

4. Three-Dimensional Numerical Model
The numerical model for calculation was calculated and analyzed by the fast finite-difference software FLAC3D5.0. The computational grid model was built by Hypermesh and ANSYS software and imported into FLAC3D.
Consideration of the boundary effect and feedback from safety assessment obtained by the above empirical methods, enabled the selection of a range of D12K0+575–690 for the numerical calculation model. The network model was established to analyze the influence of the excavation of newly built tunnels on existing tunnels. The model has a total of 124,293 units and 26,464 nodes.

The outer boundary of the model only constrained the normal displacement of the boundary surface. The bottom of the model (z = 0 m) had fixed constraints, and the upper boundary surface was a free surface. The soil was simulated using four-node tetrahedral solid elements, and the Mohr–Coulomb constitutive model was used for calculating soil structure. The support structures, including the pipe shed and isolation piles, were simulated by pile elements.

5. Analysis of Calculated Results

Fig. 6 shows that the displacement of the newly built tunnel in the range of Y = 0–40 m is small. The final settlement of the vault is approximately 43 mm, and the maximum horizontal displacement is approximately 15 mm, both of which occur at the boundary of the model and can be considered to be caused by the boundary effect.

Figure 7 illustrates that when Y = 0~35 m, the displacement is quite large and the maximum horizontal and vertical displacements are approximately 0.29 and 0.10 mm, respectively. This is affected by the disturbance caused by the excavation of the newly built tunnel to the existing tunnel.

As shown in Fig. 8, the maximum horizontal displacement of the tunnel is approximately 0.18 mm, and the maximum vertical displacement is approximately 0.09 mm, which occurs at Y = 55 m along the longitudinal axis of the tunnel. The displacement of the Wari tunnel at Y = 115 m is approximately zero.

Fig. 6. Horizontal and vertical displacement of the newly built tunnel at vault
Therefore, according to the deformation law, when the existing tunnel and the newly built tunnel are relatively close, the maximum deformation of the existing tunnel occurs at the tunnel mouth with small clear spacing. When the existing tunnel is far from the newly built tunnel, the maximum deformation of the existing tunnel occurs in the middle of the tunnel. The deformation of the existing tunnel meets the requirements of the relevant regulations and specifications.

6. Conclusions

Empirical evaluation and numerical-simulation methods were adopted to study the influence of the excavation of newly built tunnels on the rock stability of surrounding existing tunnels based on the project of constructing new railway tunnels adjacent to existing tunnels in the Loess Plateau area of Taiyuan, Shanxi, China. The conclusions obtained are listed below.

(1) The construction location of the newly built tunnel is located within the restricted and caution ranges of the two existing tunnels. The boundary conditions of the three-dimensional calculation model were determined based on that. When these were combined with the numerical-simulation method, the laws of deformation of different existing tunnels caused by the excavation of newly built tunnels in different affected areas were obtained.

(2) When a newly built tunnel is within the restricted range of an existing tunnel, the closer the tunnel is, the greater impact it poses on the deformation of the existing tunnel. When the newly built tunnel is located within the caution range of the existing tunnel, the excavation of the tunnel has the largest disturbance on the middle of the axis of the existing tunnel.
Therefore, it is possible to refine the sensitive area of existing tunnels further by evaluating their affected areas, thereby strengthening the necessary monitoring and measurement of existing tunnels during the construction of new tunnels.

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