Finite element analysis-aided performance examination of the umbrella arch method for tunneling through weak zone

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ABSTRACT: The umbrella arch support is frequently used as the tunnel face support system in difficult ground conditions. The Dong'ao Tunnel of Taiwan, which traverses through two thrust faults and a series of well-developed fractured zones, provides an important database for developing an assessment approach based on numerical analyses. This study implements three-dimensional finite element analyses to evaluate and optimize the utilization of the umbrella arch method in the weak zones. Results show that the deformation of the excavation face at the vault can be reduced by approximately 40% with the installation of an umbrella arch system. Parametric analyses indicated that the spacing of the forepoling pipes dominates the ability to control the deformation, followed by pipe diameter and distribution angle. This study reveals that the finite element analyses can aid the performance examination and enable a more informed decision when the umbrella arch method is used for tunneling through a weak zone.

Keywords: 3D finite element analysis, umbrella arch method, design optimization, weak zone, Dongao Tunnel.

1 INTRODUCTION

Dong'ao Tunnel is a part of the Suhua Highway Improvement Project connecting Su'ao and Dong'ao, Taiwan. This project was launched in 2011 to provide an alternative route such that the disaster-prone sections of the original route in the mountain area can be avoided. The Dong'ao Tunnel, which was completed in 2016, is a two-way, twin-tube tunnel with a length of 3.32 km. During the construction, almost 200 disastrous events such as collapse and water inrush, which were due to geological difficulties, were recorded. The most serious collapse event occurred at Section NB4k+513.9 and caused the longest delay (678 hours) for the Dong'ao Tunnel project. In fact, the field investigation and geophysical surveys conducted in the preliminary design stages had indicated that the tunnel would traverse a weak zone at this section. We supposed that the hazard could be mitigated if the pre-support systems had been assessed during the design stage. In this study, the excavation at Section NB4k+513.9 for the Dong'ao Tunnel was simulated based on the finite element method (FEM). The primary goal of this study was to investigate the ability of the FEM analysis in facilitating the design of the umbrella arch method in the weak zone. The limitations of the FEM analysis on this topic are also discussed in this paper.

2 CASE STUDY: DONG'AO TUNNEL OF TAIWAN

2.1 Regional geological background

Figure 1a shows that the Dong'ao Tunnel encountered a series of strata that had experienced multi-phases of metamorphism, including the Dong'ao Schist, the Nansu'ao Formation and the Su'ao Formation. The lithology consists of metamorphic sandstone, metamorphosed diabase, slate, graphite schist, marble, quartz mica schist and amphibolite. The Xiaomaoshan Fault and the Houishan Fault are the main geological structures in the study area. Both faults are thrust faults with the strikes of west northwest–east southeast. The Xiaomaoshan Fault zone has a thickness of approximately 30 m and is composed of fractured slate (Lin, 2009; Lin et al., 2017). The thickness of the Houishan Fault zone is similar to the Xiaomaoshan Fault zone; however, the fault gouge and breccia are common in the Houishan Fault zone.

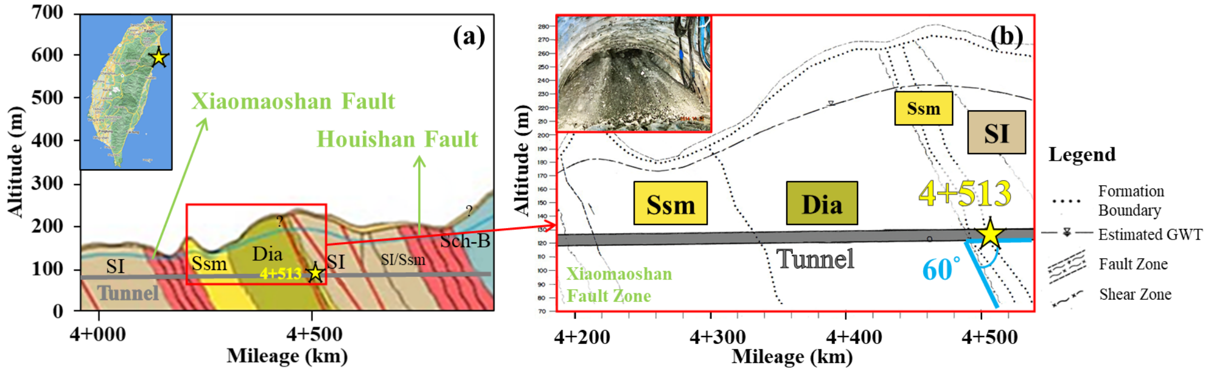

Figure 1. Geological profiles at (a) 1:50000 and (b) 1:1000 scales. The photo is the collapse hazard occurred at NB4k+513.9 in the Dong'ao Tunnel.

2.2 Engineering background

The 1:1,000 scale geological profile shows that Section NB4k+513.9 is located near a weak zone (Fig. 1b). The weak zone has a width of 10 m and contains a series of faults with an approximately 60-degree dip. Based on the Tunnel Seismic Prediction (TSP) tests conducted in the design stage, the average V_p and V_s values of the surrounding rocks are 3230 m/s and 1829 m/s, respectively. The geophysical surveys indicated that the rock mass at Sections NB4k+200 to NB4k+920 is composed of highly fractured metamorphic rocks. The photo in Fig. 1b shows a collapse event that occurred on November 23, 2014 at Section NB4k+513.9. Metamorphosed diabase and slate can be observed on the heading face. The Rock Quality Designation (RQD) value from the neighbor drill rock core is 15-20% at the excavation level. The on-site surveys revealed that the Rock Mass Rating (RMR) values on the excavation face is below 10. Thus, the rock mass near the Section NB4k+513.9 can be classified as Grade A-VI which is extremely poor rock according to the Taiwan Rock Classification System (PCCR-System) (Liu et al, 2007).

2.3 Supporting system

As the surrounding rock mass is extremely weak in the fault zone, a series of collapse and water inrush hazards occurred at the heading face near SectionNB4k+513.9. Fig.1b shows the typical deformation portents of continuous failure in the weak zone during the construction of the Dong'ao

Tunnel. The heading face was damaged seriously just several hours after the excavation. To support the heading face for the excavation, the umbrella arch method was adopted prior to the excavation. The design for the tunneling in the Grade A-VI rock mass is based on the suggestion of the PCCR-System of Taiwan. Details of the supporting method at Section NB4k+513.9 are discussed below.

3 THREE-DIMENSIONAL FINITE ELEMENT ANALYSIS

3.1 Model dimensions and geotechnical parameters

To study the effectiveness of the umbrella arch method for the Dong'ao Tunnel project in the weak zone, three-dimensional finite element analyses were carried out by using Rocscience RS3 program. The surrounding rock mass was modeled as a cube with an edge length of 60 m, and the heading face of the tunnel was simulated as a half circle for simplification (Fig. 2a). Hinge boundary condition was used at the model bottom, restraining the displacement and rotation in all directions. For the side boundaries, displacement was restricted in the orthogonal direction of the surfaces. Considering the critical response during tunnel excavation at the tunnel crown region, a finer mesh was used in this area to obtain more accurate results. Based on the 1:1,000 scale geological profile (Fig. 1b), the excavation would meet metamorphosed diabase, fault zone, and metamorphic sandstone in sequence. The fault zone dips with 60 degrees and has a width of 9 m. Hoek-Brown failure criterion was used for diabase and fault zone, and the Mohr-Coulomb criterion was chosen for metamorphic sandstone. The detailed geotechnical parameters are shown in Fig. 2a.

3.2 Simulation of excavation and tunnel support

The Dong'ao Tunnel was excavated by the NATM approach. Figure 2b shows the configuration of the primary support system, which consists of steel frames, lining shotcrete and grouted bolts. The mechanical parameters of the primary support system followed the default setting in the RS3 program. In addition, because of the weak zone condition, the umbrella arch method was applied prior as the forward supporting before the next excavation. The umbrella arch method consists of forepoling pipes and injected cement grout. As shown in Fig. 2c, forepoling pipes were embedded at the tunnel crown, and the effects of pipe diameter, spacing and distribution angle were studied through parametric analyses. We determined the equivalent Young's modulus for the injected cement grout for different pipe diameter conditions. Other material properties associated with the forepoling pipes and the primary supporting system are the default values in the RS3 program. The excavation process was simulated in a total of 4 rounds (Fig. 2c). The length for each round was 0.8 m.

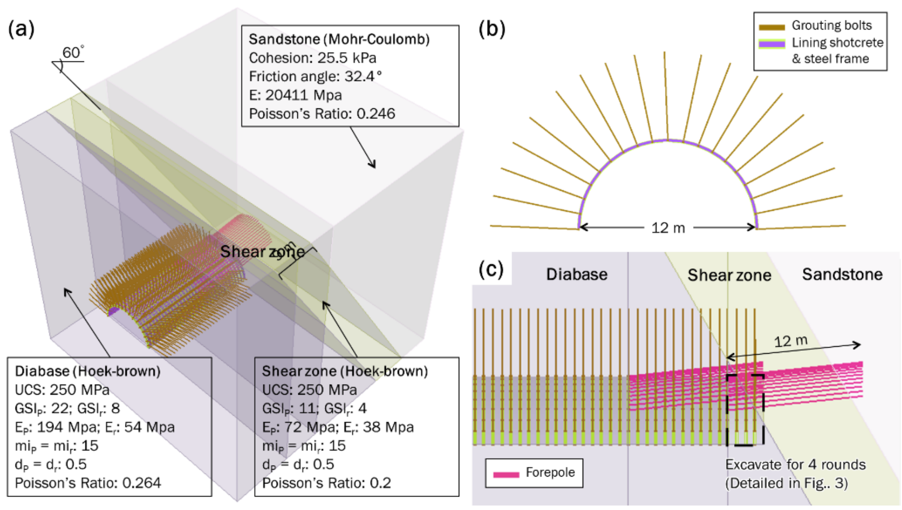

Figure 2. Geometry and geotechnical parameters and simulation process of the 3D FEM analysis.

4 RESULTS AND DISCUSSION

4.1 Effect of umbrella arch system and tunnel vault displacement

In this study, the threshold of ground settlement control for tunnel vault was set as 20 cm based on the requirement of detail design. Figure 3 shows the settlement during the first and fourth round of excavation in two different models: Model 1, which does not use umbrella arch support, and Model 2, which has an umbrella arch support. It can be observed that the settlement would exceed 20 cm during excavation round 4 in Model 1. However, if an umbrella arch support were installed (Model 2), the settlement at the same position (1.6 m) could be significantly reduced to 15.4 cm, which is about 23% less than the settlement control value (Figs. 3 & 4).

On the other hand, the advancing effect was also observed as the excavation round increased. This verified the reasonable location in the FEM analysis for monitoring tunnel vault displacement. As shown in Fig. 3, the settlement monitored along the forepole was much smaller after the first excavation round, indicating that the umbrella arch support is effective in reducing settlement. However, the data recorded at the top of the tunnel were found to be very similar between two models, which is not reasonable based on the experience. Although the rock mass below the forepole cannot detach as in reality in the FEM model, it is suggested that the monitoring location should be set along the forepole to accurately capture the tunnel vault displacement.

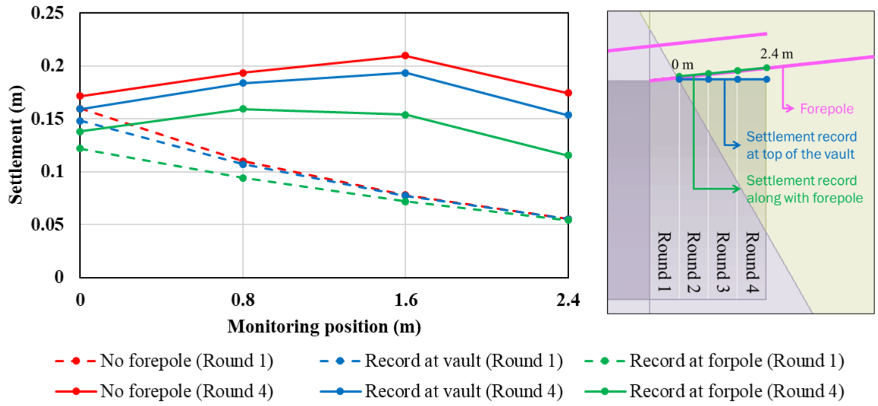

Figure 3. Comparison of the tunnel vault displacement for the model with/without umbrella arch support.

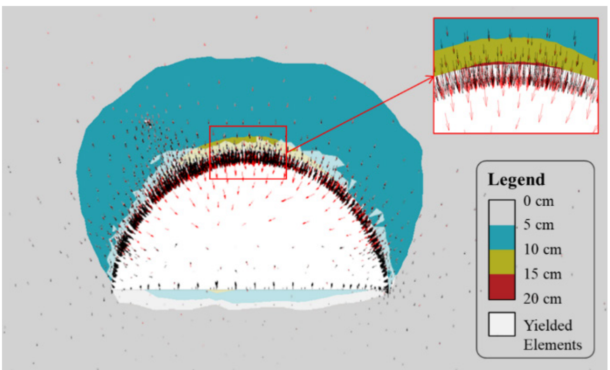

Figure 4. Cross-section of the tunnel face deformation at the round 4 excavation.

4.2 Parametric study

Three design parameters, including spacing, distribution angle and pipe diameter, were investigated to clarify the effectiveness of the umbrella arch support. Table 1 shows the parameter setting for the sensitivity analysis, which follow the suggested values for the Grade A-VI rock mass in detailed design report. All models with the umbrella arch support satisfy the threshold of ground settlement control. Figure 5 shows that the umbrella arch support could reduce the settlement by 39% to 42%. Decreasing the spacing between each forepole has the greatest effect on reducing the settlement of tunnel vault, following by expanding the distribution angle and increasing the diameter of the forepole.

In the simulations, an increase in the diameter of the forepole represents a higher amount of injected grout in the forepole. However, the reinforcement of the grout is much smaller compared to the kinematic movement of the failed rock mass due to the inherent small pipe diameter (Figs. 3 & 4). On the other hand, the parameters of spacing and distribution angle imply the forepole amount that will be installed as the pre-support system. The local arching that is formed by the overlap of forepoles contributes significantly on controlling the vault displacement. Thus, the selection of the proper range for the forepole arrangement is a critical factor when attempting the reduction of surface settlement. When the geological difficulty has been predicted in the preliminary survey, the effectiveness of umbrella arch support on the ground settlement control can be better assessed by using 3D FEM analysis.

Table 1. Parameters and simulation results of the sensitivity analysis.

Model No.		1	2	3	4	5	6	7	8	9
Spacing (m)		-	0.5	0.5	0.5	0.4	0.3	0.5	0.5	0.5
Distribution Angle (°)		-	120	120	120	120	120	100	140	160
Diameter (m)		-	0.10	0.12	0.14	0.10	0.10	0.10	0.10	0.10
Forepole amount		0	25	25	25	30	41	21	29	33
Settlement (m)	Round 1	0.160	0.122	0.120	0.120	0.118	0.116	0.120	0.122	0.117
	Round 2	0.168	0.134	0.132	0.131	0.129	0.128	0.132	0.133	0.128
	Round 3	0.171	0.137	0.135	0.135	0.133	0.131	0.136	0.137	0.131
	Round 4	0.172	0.138	0.136	0.136	0.134	0.132	0.137	0.137	0.132

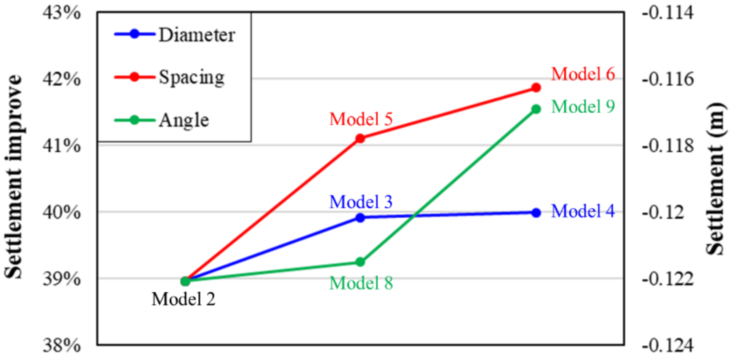

Figure 5. Results of the settlement improve based on the sensitivity analysis.

4.3 Current limitation and discussions

The sensitivity analysis proofs that the 3D FEM analysis has ability to provide scenario of tunnel vault deformation. However, the application of the FEM analysis on the umbrella arch support simulation shows two major limitations based on the Dong'ao Tunnel case study. In practice, the deformation monitoring system is usually installed on the surrounding rock mass after the advancing effect has occurred, Besides rock masses in weak zone may not be able to remain in place as excavation progresses, especially those around the vault. However, there were some countries start to installed the monitoring instrument from the very beginning or even installed inclinometer inside forepole pipes. The continuous-based FEM model is not capable of replicating the large deformation behavior such as collapse. Therefore, the monitoring location in the simulation needs to be calibrated to avoid the risk of misestimating values (Fig. 3). Another limitation needs to be considered is the joint network of the rock mass. Interlocking effect or kinematic release due to different joint networks can significantly influence the settlement of tunnel vault. In addition, an effective arrangement of the forepole is also dominated by the joint characteristics, including orientation and spacing. While the FEM analysis is currently unable to capture the kinematic movement of rock mass induced by the joint network, we argue that the continuum approach is feasible to the highly fractured rock mass in the weak zone, which had been graded a GIS value below 22 (Fig. 2). Considering the current limitation mentioned above, engineers need to be care on validation and interpretation of the simulation results by using FEM analysis.

5 CONCLUSIONS

The Dong'ao Tunnel project tunneled through a series of weak zone that bounded by Xiaomaoshan Fault zone and Houishan Fault zone in the period of 2013 to 2015. At the time, the umbrella arch method was used as the pre-support system and was able to overcome the geological difficulty during the excavation. However, the design of the umbrella arch method usually follows the suggestions associated with the PCCR-System of Taiwan, and its on-site application is based on experience. In this study, the major disastrous event that occurred at Section NB4k+513.9 was chosen to optimize the design of the umbrella arch support with the aid of FEM analyses. The results show that the umbrella arch method can reduce the settlement of the tunnel vault to 15.4 cm which is 23% less with respect to the settlement control requirement of 20 cm. The 3D FEM model also permits the evaluation of the variation of the tunnel face deformation due to advancing effect. The sensitivity analysis indicates that decreasing the forepole spacing is the most efficient way to control the settlement, followed by expanding the distribution angle and increasing the diameter of the forepole. The Dong'ao Tunnel project provides valuable data to calibrate a more robust FEM model for future design application. In the future, if the tunnel is expected to traverse the weak zone, the FEM analyses may be performed in the early design stage to examine the feasibility of the umbrella arch method. This can in turn avoid any delay in the construction due to collapse during excavation.

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