MODELING THE BEHAVIORS OF THE TUNNEL INTERSECTION AREAS ADJACENT TO THE VENTILATION SHAFTS IN THE HSUEHSHAN TUNNEL

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ABSTRACT

Seven tunnels, including 5 horizontal tunnels and 2 shafts, exist in each ventilation station of the Hsuehshan Tunnel. The behaviors of the tunnel intersection areas are complicated and their stability needed to be assessed carefully during construction. The three-dimensional numerical analysis program-FLAC3D was used to carry out feedback analysis using field monitoring data and to predict subsequent construction for ventilation station No.2. According to the results of the analysis, the tunnels are in stable condition judging from the tunnel closure and the loose zone of rock mass. The accuracy of the simulation was confirmed by the field observation during construction.

Keyword: tunnel intersection, 3-D numerical analysis, observation during construction

GENERAL

The number of long tunnels has been increasing in Taiwan in recent years. Shaft and cross-connection tunnels are usually used for long tunnel ventilation and emergency access. However, high stress concentrations and severe tunnel closures will be encountered during the construction of tunnels in poor rock conditions. Most of the empirical rock classification methods widely used in tunnel support design nowadays, do not consider the interactive effect between cross connecting tunnels. Therefore, reducing the rock mass rating and reinforcing support systems in tunnel intersection areas are commonly used practices. Actually, many factors, such as tunnel shape, intersecting angel, geological condition and construction sequence may influence the behavior of tunnel intersections. But the above empirical design philosophy is too simplified and impractical sometimes. As a consequence, deformation monitoring and back analysis are necessary to assess the safety of tunnel intersections during construction.

There are 3 sets of ventilation stations and shafts in the 12.9 km long Hsuehshan Tunnel. Among them, the

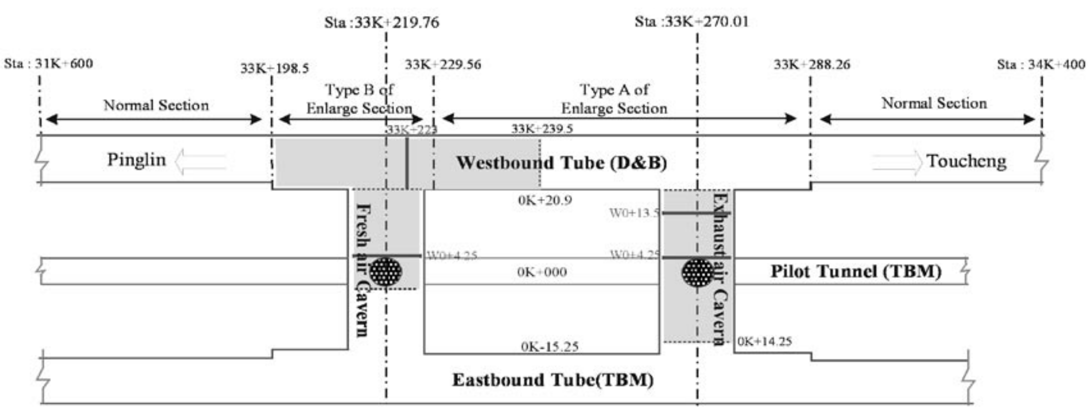

Fig.1 Construction Progress and Monitoring Layout in the Intersection Area between Shaft No.2 and Main Tunnel (2000.8.31)

Excavation Zone (Top Heading)
Monitoring Section

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238m deep fresh air shaft and the 249m deep exhaust air shaft for ventilation station No.2 are located at station 33k+220 and station 33k+270 of the westbound tube. Construction of ventilation station No.2 started from these two shafts and their connecting tunnels between the main tunnel and the shafts. Two additional advancing faces were launched in the westbound tube which headed toward Pinglin and Toucheng, respectively. The detailed construction procedures and the monitoring layout are shown in Fig.1.

Seven tunnels or shafts exist in the intersecting area, including a fresh air shaft, an exhaust air shaft, a fresh air cavern (cross connection tunnel), an exhaust air cavern (cross connection tunnel), the pilot tunnel, the westbound tube and the eastbound tube. Complex construction stages were designed for each tunnel, including top heading, several benches and inverts. The complicated tunnel geometry and construction procedures may cause an interactive effect when these tunnels are excavated. In the design stage, simplified analysis and assessments for tunnel stability had been performed based on limited geological information. Therefore, it was advisable to reassess the tunnel stability when the actual geological conditions were revealed when shaft No.2 and the caverns were excavated. This paper re-evaluates the parameters of rock mass by using the geological information revealed in the field and carrying out feedback analysis of the monitored tunnel deformation by using a 3-D numerical analysis. Prediction analyses were also conducted to assess the tunnel stability during the subsequent construction stages.

FIELD CONDITIONS

Geology

The rock formation encountered in shaft No.2 is the Tatungshan Formation of the Oligocene period. The rock revealed in the field is mainly composed of gray massive siltstone, locally intercalated with black Argillite. The rocks have been slightly metamorphosed. The average uniaxial compressive strength obtained from the laboratory test is about 430 kg/cm2 (see Fig.2). The bedding in the rock masses was not well developed, but there were three sets of major joints with attitudes at N15 E/70 N, N18 W/80 N and N45 E/68 S, respectively. The spacing of the joints is in the range of 6-20 cm and the joint lengths commonly exceed 3 m. The surfaces of the joints are partly filled with clay seams. The rock masses of the site have good

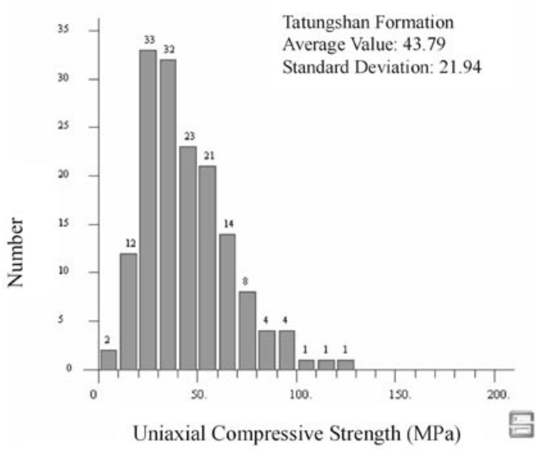


Fig.2 Laboratory Experiment Results of Uniaxial Compressive Strength of Rock Core of Tatungshan Formation

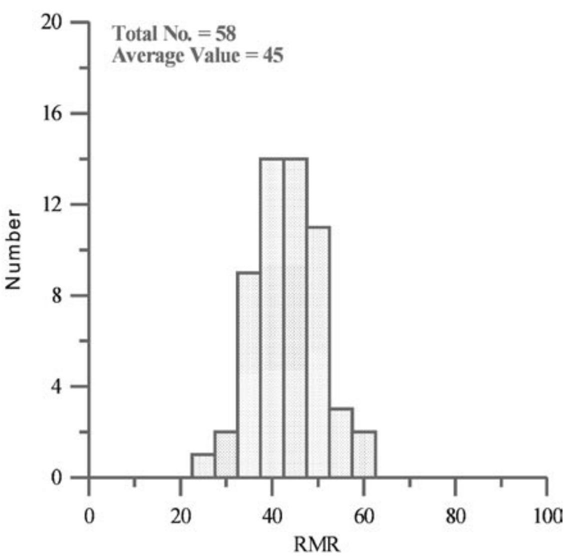


Fig.3 Statistical Results of RMR Ratings in the Intersecting Area

self-support capability even though several thin shear zones of clay existed. The RMR ratings of rock masses in the area are between 30 and 55 with an average value around 45 as shown in Fig.3.

Monitoring Data

Four monitoring sections were established at station 0k+4.25 in the fresh air cavern, station 0k+4.25 and station 0k+13.5 in the exhaust air cavern, and station 33k+223 of the westbound tube. The layout of these monitoring sections is illustrated in Fig.1 and the results are shown in Fig.4~Fig.7. The monitored crown settlements of the fresh air cavern were about 7 mm adjacent to the shaft and about 5 mm adjacent to the westbound tube. The

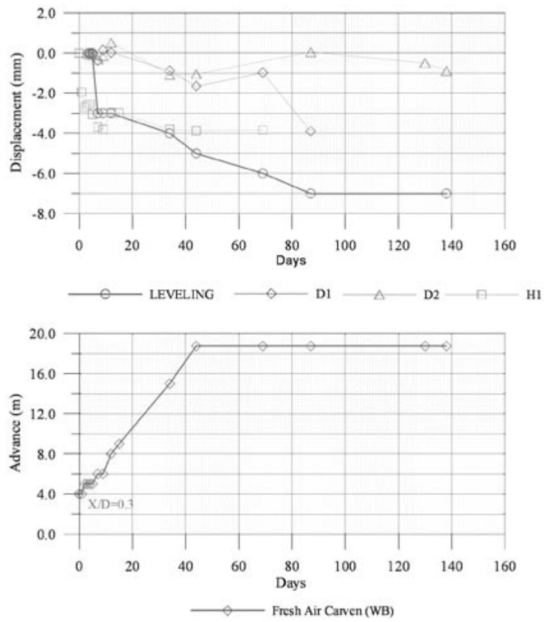


Fig.4 Monitored Data of Section 0k+4.25, Fresh Air Cavern

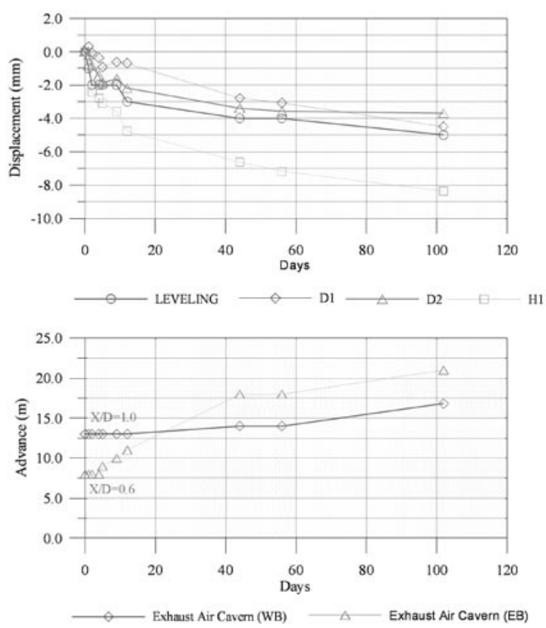


Fig. 5 Monitored Data of Section 0k+4.25, Exhaust Air Cavern

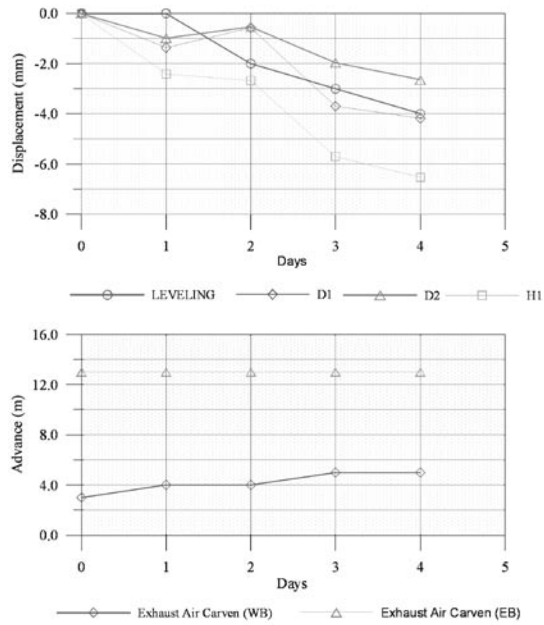


Fig. 6 Monitored Data of Section 0k+13.5, Exhaust Air Cavern

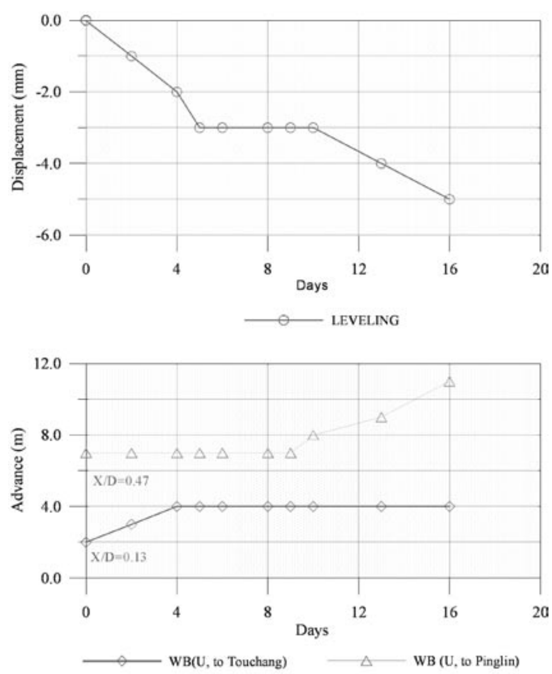


Fig. 7 Monitored Data of Section 33k+223, Westbound Tube

monitored crown settlement of the exhaust air cavern was about 5 mm adjacent to the shaft. Although these settlement measurements seem small (<1 cm), the measurement instruments in the exhaust air cavern were installed after the excavation of the top heading of the cavern had almost been completed. Similarly, the initial measurement of the fresh air cavern was not done until the advancing face of the cavern had passed through the monitoring section by a distance of 4 m (about 0.3 times the excavation span). Therefore, part of the tunnel closure had already occurred and could not be measured. Secondly, the crown settlement recorded in the intersection area between the westbound tube and the fresh air cavern was on the order of 5 mm. The construction work was still in progress and tunnel closure was occurring.

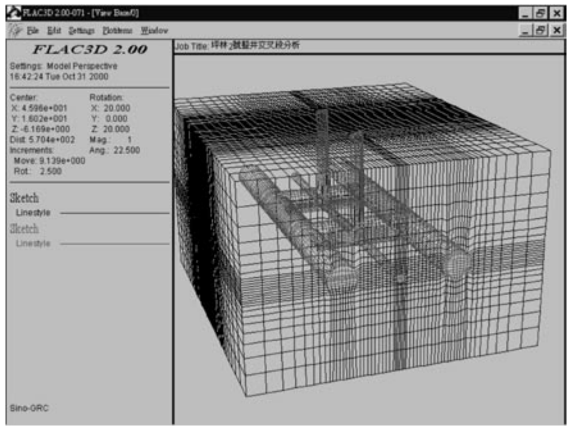


Fig.9: 3-D View of Numerical Analysis Domain

ANALYSIS METHODS AND PROCEDURES

The FLAC-3D computer program was used for the tunnel excavation simulation in the intersection areas. The domain of analysis was from station 33k+198 to station 33k+288 in the westbound main tube, and the length is around 90 m. The 3-D numerical meshes are shown in Fig.8 and Fig.9. Some of the assumptions and procedures about the analysis are summarized as follows:

(1) The behavior of rock masses at the site analyzed is regarded as an elasto-plastic.

(2) The overburden depth of the studied area is about 245 m. The vertical stresses are created by gravity, i.e. $\sigma V=\gamma H$, where γ is the density of rock mass and H is the overburden depth. The horizontal stresses are estimated from the results of in-situ hydrofracture tests in the project area. The ratio between maximum horizontal stress and vertical stress is 1.2, and 0.7 for minimum horizontal stress (Golder Associates, 1991). The direction of minimum horizontal stress is approximately parallel to the tunnel alignment.

(3) The generalized Hoek-Brown criterion (1994) was used to estimate the rock mass strength. The rock mass rating (RMR=45), intact core strength (44 MPa) and in situ stress conditions were used to estimate the failure envelope of the rock mass, and equivalent c,ϕ values in the Mohr-Coulomb criterion were obtained through regression analysis over an appropriate range of confining stress. The c value of 0.6 MPa and ϕ value of 48 were adopted in this simulation (see Fig.10).

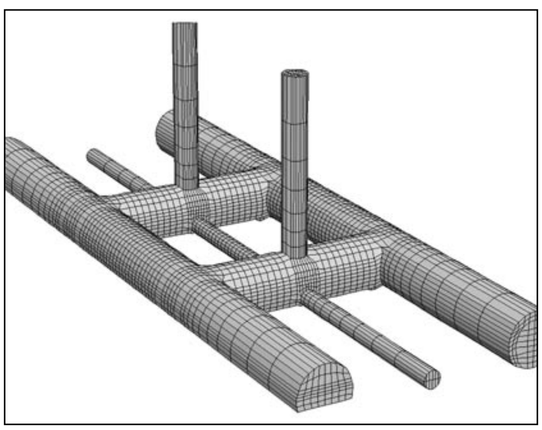


Fig.8: 3-D Numerical Mesh in the Intersection Area

Table 1 Tunnel Support Type and Materials in the Intersection Area

Tunnel	Support Type	Materials of Support System
Fresh Air Shaft	III	Shotcrete：15cm Rock bolt：25mmϕ，L=4.0 m，@1.5m×1.5m~2.0m
Exhaust Air Shaft	IV	Shotcrete：20cm Rock bolt：H100×100，@1.5m
Cavern (Top Heading)	V	Shotcrete：25cm Rock bolt：25mmϕ，L=6.0 m，@1.5m~1.0m Steel Rib：H150×150，@1.5m
Westbound Tube	V	Shotcrete：25cm Rock bolt：25mmϕ，L=6.0 m，@1.5m×1.0m~1.5m Steel Rib：H150×150，@1.5m

Table 2 Comparison between Analysis Results and Monitoring Data

Tunnel	Section	Date of Initial Measure.	Date of Final Measure.	Distance between Monitoring Sec. and Adv. Face (m)	Monitor. Data (mm)	Analyzed Displacement (mm)	* Total Displacement (mm)
Fresh Air Cavern	W0+4.25	2000/2/29	2000/7/16	4	7	8	17
Exhausted Air Cavern	W0+4.25	2000/5/21	2000/8/31	13	5	3	16
	W0+13.5	2000/5/16	2000/5/22	3	4	2.5	16
Westbound Tube	33K+223	2000/5/17	2000/6/2	2 (W) 7 (E)	5	5	26

(4) The deformation modulus was estimated by the results of the research report titled "Correlation Study on the Deformation Modulus and Rating of Rock Mass" (Sinotech, 1997), as shown in Fig.11. The deformation modulus of 3 GPa was adopted from the relationship between the rock mass modulus, the intact rock strength and the RMR rating, as proposed by the report. A similar value of deformation modulus of 3.41 GPa was also obtained from the result of a borehole deformation test conducted in the rocks of the Tatungshan Formation in the past.

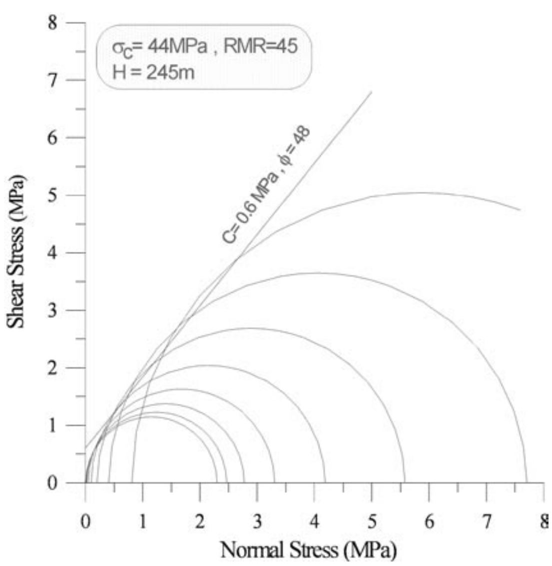


Fig.10 Empirical Estimation of Rock Mass Strength around the Tunnel

(5) The analysis simulates the actual procedures of the tunnel excavation and the support installation in the field. The support types and materials for each tunnel are listed in Table 1.

ANALYSIS RESULTS AND ASSESSMENTS

Based on the above-mentioned rock mass conditions and the tunnel construction progress, the numerical simulations were performed. The simulations were first conducted to calibrate the rock mass properties for best fitting the monitored data in the field, as shown in Table 2. The "comparison analysis displacements" shown in the table are the displacements from the analysis adjusted and subtracted by the lost displacements due to the timing of instrument installation for each monitoring section. According to the results of numerical analysis, the analyzed displacements in the fresh air cavern, the exhaust air cavern and the westbound tube are 8 mm, 3 mm and 5 mm, respectively, which are similar to the actual monitored data of 7 mm, 5 mm and 5 mm. Therefore, the numerical simulation is regarded as representative of the tunnel behavior in the intersecting area.

According to the results of the analysis, the tunnel deformation and the plastic or loose zone can be obtained for various excavation stages of the tunnels, as described as follows.

Fresh Air Shaft

The tunnel closure in fresh air shaft is quite small (about

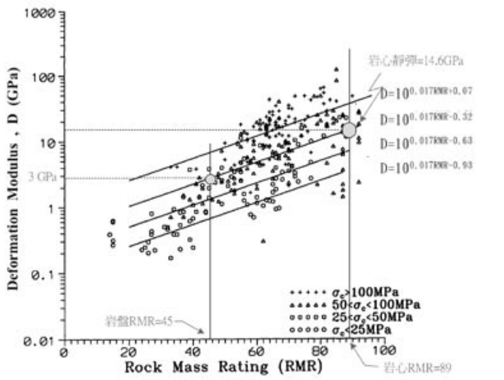


Fig.11 Empirical Estimation of Deformation Modulus of the Rock Mass

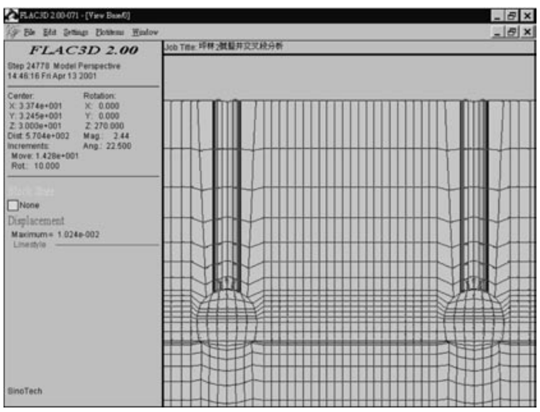


Fig.12 Vertical Cross Section Showing the Displacement Field and Loose Zone Distribution after Completion of Two Shafts

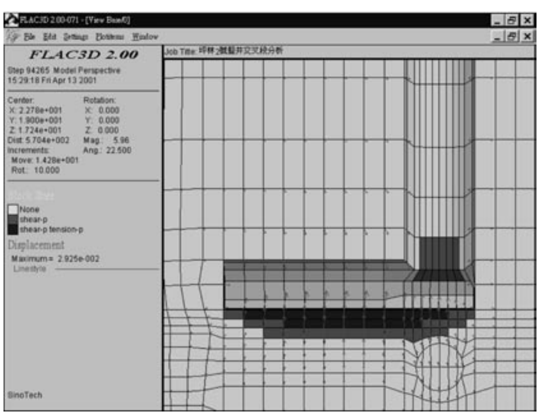


Fig.13 Vertical Cross Section Showing the Displacement Field and Loose Zone Distribution after the Top Heading of Fresh Air Cavern Driven

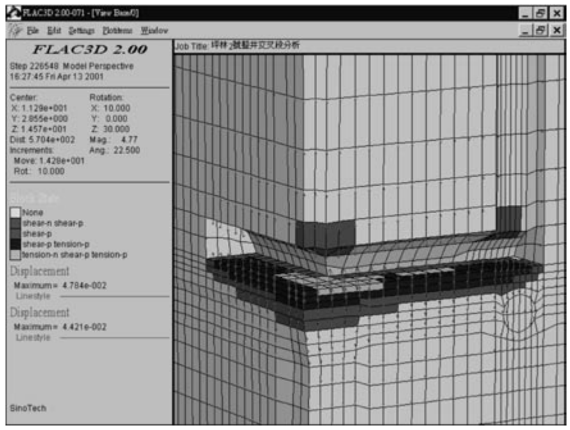


Fig.14 Vertical Cross Section Showing the Displacement Field and Loose Zone Distribution after the Top Heading of Westbound Tube Driven

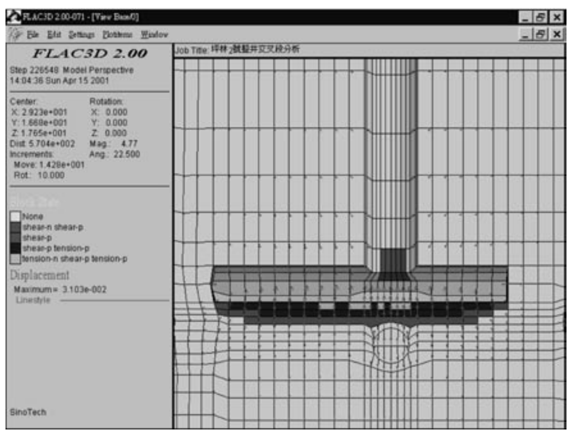


Fig.15 Vertical Cross Section Showing the Displacement Field and Loose Zone Distribution after the Top Heading of Exhaust Air Cavern Driven

9 mm) as the shaft was excavated down to the bottom at El.140 m. And the size of the loose zone surrounding the shaft is also small, as illustrated in Fig.12. While the top heading of the fresh air cavern was excavated, an additional tunnel closure of 2 mm was produced at the bottom of the fresh air shaft and a small increase in the loose zone was created, as shown in Fig.13. Besides, the excavation of the westbound tube seemed to have imposed very little effect on the rock deformation and the loose zone around the fresh air shaft.

Fresh Air Cavern

For the excavation of the top heading of the fresh air cavern, the roof settlement by itself was about 12 mm. A slightly larger settlement of 14 mm occurred near the shaft. Furthermore, the loose zone mainly occurred in the tunnel invert because no temporary support was installed. No significant loose zones developed in the tunnel roof or the sidewall area, as shown in Fig.13. After the excavation of the top heading of the westbound tube, a small additional roof settlement of 3 mm (total value of 17 mm) occurred at the intersection area of the cavern and the shaft, but a larger additional roof settlement (total value of 25 mm) occurred in the cavern near the westbound tube. A loose zone of 3 m was estimated in the tunnel roof, as depicted in Fig.14.

Westbound Tube

The roof settlement in the westbound tube caused by the excavation of the top heading was around 20 mm, but a larger settlement of 27 mm may have occurred closer to the cavern. The loose zone in the rock mass around the westbound tube mainly occurred in the crown area of the tunnel intersection. A loose zone also appeared in tunnel invert owing to no temporary support having been installed. The details of the above-mentioned tunnel deformation during the construction of the fresh air shaft, the cavern and the westbound tube are summarized in Table 3.

Exhaust Air Shaft

Table 4 displays the conditions of tunnel deformation for the excavation of the exhaust air shaft and the cavern. The final tunnel closure in the exhaust air shaft is about 9 mm with no apparent loose zone, which is similar to the condition of the fresh air shaft as shown in Fig.12. After the excavation of the top heading of the exhaust air cavern toward the west and east, the tunnel closure at the bottom of the shaft may have increased to 14 mm and a small loose zone of 1.5 m might have occurred, as illustrated in Fig.15.

Exhaust Air Cavern

The roof settlement in the exhaust air cavern caused by the excavation of the top heading was around 16 mm, and about an 18 mm settlement occurred in the neighborhood of the shaft. The main loose zone of rock mass around the exhaust air cavern also occurred in the invert, as shown in Fig.15.

From the results of the analysis and monitoring, the magnitudes of the tunnel displacements seem relatively small. The tunnel stability can be assessed by the empirical safety criterion shown in Fig.16 and Fig.17, which was originally proposed by Sakurai (1983) and applied to jointed rock masses in Taiwan by Chern et al. (1996). It was found that all the crown strains caused by the excavation of shafts, connection caverns and westbound tube fell below warning level II. According to the criterion and local experiences, the tunnel was in stable condition and the construction work could proceed.

The subsequent construction in the intersection area was also simulated. The procedures of construction were assumed as being (1) the top heading of unfinished, bench and invert of westbound tube, (2) the benches of the unfinished fresh air cavern and exhaust air cavern, (3) the full face of the pilot tunnel, and (4) the TBM driving of the eastbound tube. As the support works were installed in a timely manner, the crown settlement was about 3.5 cm at the intersection of the shaft and the cavern and about 4.5 cm at the intersection of the main tunnel and the cavern. Judging from the above empirical safety criterion as illustrated in Fig.16 and Fig.17, stable conditions can be expected for the subsequent construction. However, monitoring and field visual inspection shall be continued to ensure the behavior of tunnels during the progress of excavation.

CONCLUSIONS

1. In spite of the existence of well-developed joints in this region, the slightly metamorphosed rock masses showed good self-supporting ability. The strength/stress ratio (σcm/P0) of the site analyzed is on the order of 1.27, which may be classified as slightly squeezing ground (Chern et. al., 1996). Excessive tunnel convergence should not occur in such a situation. According to the results of the numerical analysis, the crown settlement at the intersection area between the shaft and the cavern is about 2 cm, and about 3 cm at the intersection area between the westbound tube and the cavern. Both of the crown movements fall below warning level II in the empirical safety criterion. From previous experiences, the tunnel shall be in stable condition with no excessive tunnel closure or severe stress relaxation problems.

Table 3 Analyzed Crown Settlement in the Intersecting Area between Fresh Air Shaft, Cavern and Westbound Tube (Unit：mm)

Location \ Construction progress	Excavation of Fresh Air Shaft	Excavation of Top Heading of Cavern	Excavation of Top Heading of Westbound Tube
bottom of fresh air shaft (A1)	9	11	11
cavern near shaft (A2)	–	14	17
cavern near Westbound tube (A3)	–	12	25
Westbound tube near cavern (A4)	–	–	27
Westbound tube (A5)	–	–	20

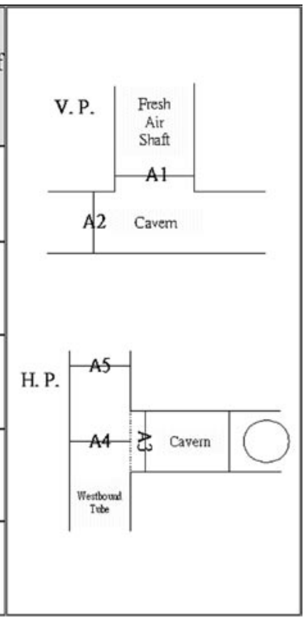
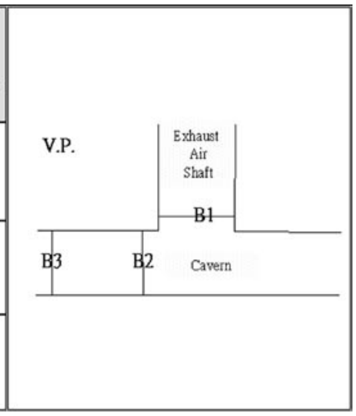


Table 4 Analyzed Crown Settlement in the Intersecting Area between Exhaust Air Shaft and Cavern (Unit：mm)

Location \ Construction Progress	Excavation of Exhaust Air Shaft	Excavation of Top Heading of Cavern
bottom of exhaust air shaft (B1)	9	14
cavern near shaft (B2)	–	18
cavern near Westbound tube (B3)	–	16



2. From the results of the numerical analysis, a loose zone of rock mass occurs mainly in the tunnel invert because no temporary invert support was installed. Except for that, only a small loose zone of 1.5~3 m occurred near the crown of the tunnel connection. Significant tunnel interaction effect was limited to the vicinity of the intersection area only. Rock mass around the shaft, as illustrated by the results of analysis, is disturbed by the excavation of the top heading of cavern, but less affected by the top heading of the westbound tube. The excavation of top heading of the westbound tube disturbs mainly the rock mass of the intersection area between the cavern and the westbound tube. Supplementary support work has been installed in the area, and the safety of the tunnel intersection area was achieved.
3. The results of subsequent construction simulations indicate that the maximum tunnel displacement in the intersection area would increase to about 4.5 cm. Tunnels shall be in stable condition according

Construction stage / Location	Back Analysis	Subsequent Excavation
Connection of fresh air shaft and cavern	○	●
Connection of fresh air cavern and Westbound tube	□	■

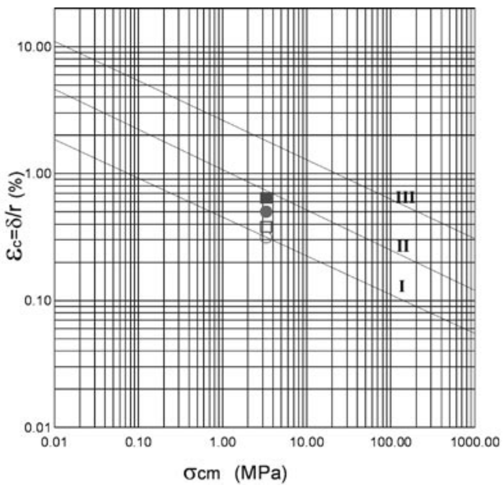


Fig.16 Tunnel Stability Assessment of Intersection Area between Fresh Air Shaft and Westbound Tube by the Empirical Safety Criterion

Construction stage / Location	Back Analysis	Subsequent Excavation
Connection of exhaust air shaft and cavern	○	●
Connection of exhaust air cavern and Westbound tube	□	■

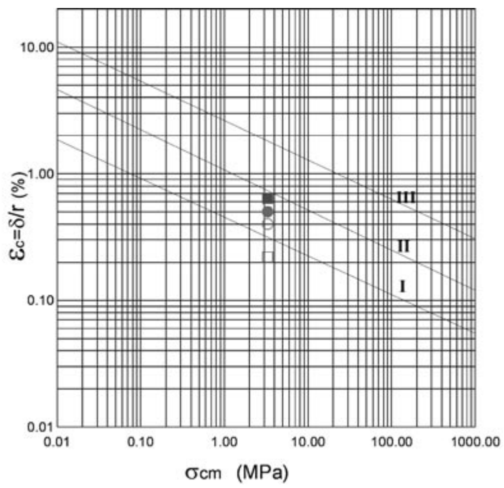


Fig.17 Tunnel Stability Assessment of Intersection Area between Exhaust Air Shaft and Westbound Tube by the Empirical Safety Criterion

to empirical tunnel safety management criterion. The whole construction work in the intersecting area has been completed now and the field behavior is consistent with the prediction. Obviously, deformation monitoring and back analysis are helpful and necessary for tunnel safety assessment in complicated tunnel intersection areas.

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