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An experience of tunnelling in mudstone area in southwestern Taiwan

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Abstract

Many tunnels will be constructed in southwestern Taiwan in the upcoming decade to meet the huge demands of transportation, energy and water infrastructure projects. Mudstone strata cover more than a 1000 km^2 area, consisting mainly of massive mudstone or alternation of mudstone and sandy layer, exhibiting unfavorable geological and hydrological characteristics, making it extremely difficult for tunnelling. This paper presents the lessons learned from three tunnelling projects in the 1990s in a mudstone area. In addition to discussing the rock behavior in the vicinity of tunnel and its failure patterns, the monitoring data during tunnelling are presented as well. Finally, the effective method of design and construction are recommended for tunnelling in mudstone area.
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Keywords: Tunnelling; Mudstone; Water deterioration; Southwestern Taiwan

1. Introduction

Poorly cemented mudstone covers more than a 1000 km^2 area in southwestern Taiwan. The engineering properties of this young sedimentary rock are highly sensitive to its water content and exhibit a wide range of strength and deformability. Moreover, more than 15 reservoirs located in southwestern Taiwan, the geological and hydrological conditions might cause adverse impact on civil works.

In the next decade the huge demands of transportation and the renovation of energy and water infrastructure system will be carried out in southwestern Taiwan. It is inevitable to construct numerous tunnels instead of cutting work to minimize the environmental impacts and residential resistance. Therefore, tunnelling in southwestern Taiwan is quite a challenging task due to the unfavorable engineering properties of mudstone.

This paper presents the experience from tunnelling projects in mudstone area over the past decade. In addition to discussing the geological and hydrological condition and the relevant tunnel behavior and failure patterns, the monitoring data are also accessed to establish the tunnelling concepts in mudstone area. Results from the experience can provide a valuable reference for the design and construction of tunnelling in mudstone area.

2. Engineering properties of mudstone in southwestern Taiwan

Fig. 1 illustrates the outcrops of mudstone formation in Chyai, Tainan, and Kaoshiung counties in southwestern Taiwan. The total thickness of these late Miocene to Pleistocene sedimentary rocks reaches several thousand meters. The stratigraphy is rather monotonic, consisting mainly of massive mudstone or alternation of mudstone and sandstone. Mudstone usually exhibits light alkalinity. Owing to the low resistance to weathering and unsuitability for plant growth, badland topographic expressions are commonly viewed in this area and are referred to as a ‘moon-world’. Fig. 2 illustrates a typical outcrop of mudstone slope taken from the northern portal of Chungliao Tunnel in southwestern Taiwan.

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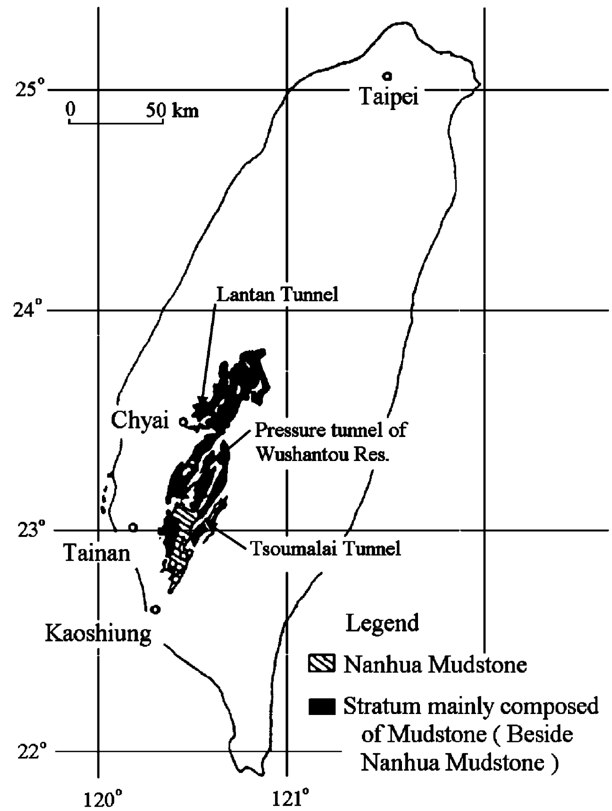


Fig. 1. The outcrops of mudstone in southwestern Taiwan and the location of tunnelling cases.

The engineering properties of mudstone are highly influenced by water. The uniaxial compressive strength of mudstone ranges from 0.2 to 8.5 MPa. Results obtained from a series of triaxial compression tests indicated that the cohesion varies from 0.06 to 0.24 MPa and the friction angle ranges from 10.6 to 55.0°, depending on its water content and weathered degree (Lee et al., 1994).

The permeability of mudstone ranges from 10^{-7} to 10^{-9} cm/s and can be considered as impermeable. Even in the rain season, the rainfall can only seep into approximately 40 cm below the ground surface. However, the sandstone layer sometime existed in mudstone strata may be an aquifer in mudstone area and the groundwater level might be risen.

The pronounced swelling and slaking properties are other characteristics of mudstone. The intact sample of mudstone exhibits a swelling pressure ranging from 0.14 to 0.35 MPa by preswelled method. The free swelling percentage is approximately 6–10%, and the slaking speed is approximately 10 $kg/m^2/h$ for the first hour immersed in water. The index of durability is approximately 9.4–97.3% (Tasi and Chang, 1994).

In a word, mudstone is sensitive to slaking and weathering, with a high erosion rate. In addition, the strength decreases with an increase of the water content. Moreover, there are many reservoirs located and streams crossed this area. The well groundwater supply system and the heavy rainfall in Taiwan deteriorate the engineering properties of mudstone, subsequently creating

Fig. 2. A typical outcrop of mudstone slope taken from the northern portal of Chungliao Tunnel in southwestern Taiwan.

Table 1
Basic information of tunnels in mudstone area

Tunnel	The pressure tunnel of Wushantou Reservoir	Lantan Tunnel	Tsoumalai Tunnel
Width × height (m^2)	4.9 × 5.1	16 × 12	12.3 × 9.8
Length (m)	408 (mined section)	1212 (NB) 1255 (SB)	333
Overburden (m)	19–44	40–70	10–45
Purpose	Water supply	Highway tunnel	Highway tunnel
Rock type	Alternation of mudstone and sandstone	Massive mudstone, alternation of mudstone and sandstone	Massive mudstone
Groundwater	None to water ingress	None to water ingress	None
Major support	Steel ribs and shotcrete	Bolts, lattice girder, steel fiber and shotcrete	Steel ribs and shotcrete
Excavated sequence	Full face excavation, top heading	Side pilots, top heading	Side pilot, top heading
State	Completed in 1996	Completed in 2001	Completed in 1998

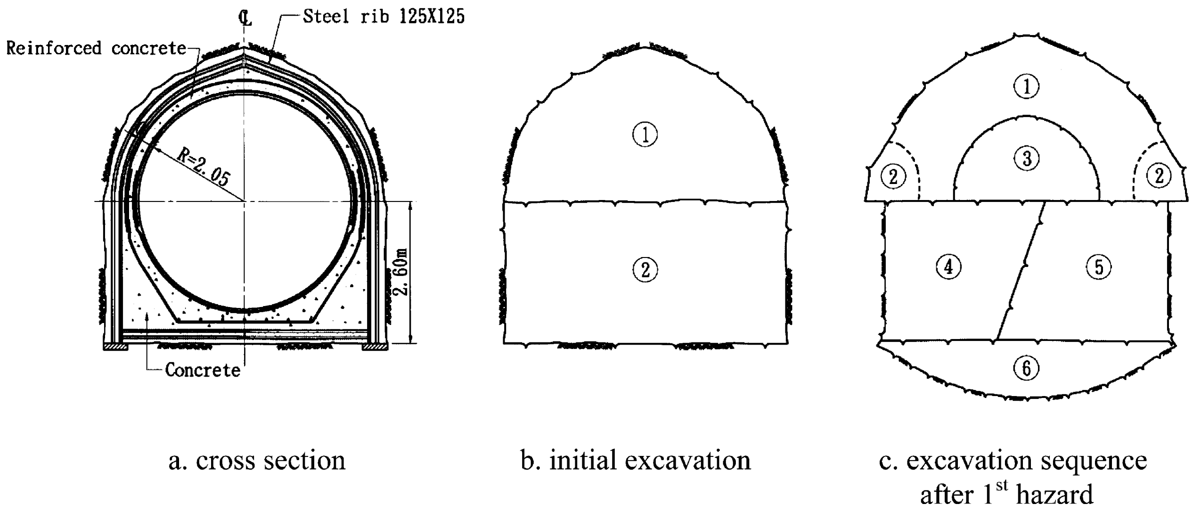


Fig. 3. Cross-section and excavation sequence of the pressure tunnel of Wushantou Reservoir.

unfavorable geological and hydrological conditions for tunnelling.

3. Case study in southwestern Taiwan

Three tunnels, i.e. the pressure tunnel of Wushantou Reservoir, Lantan Tunnel and Tsoumalai Tunnel, have been constructed in the mudstone area in southwestern Taiwan during the 1990s (United Geotech Inc., 1997; Wang et al., 1997, 1998). The locations of these tunnels are displayed in Fig. 1. Table 1 summarizes the basic information of these tunnels. Moreover, Figs. 3–5 illustrate their cross-section and excavating sequence.

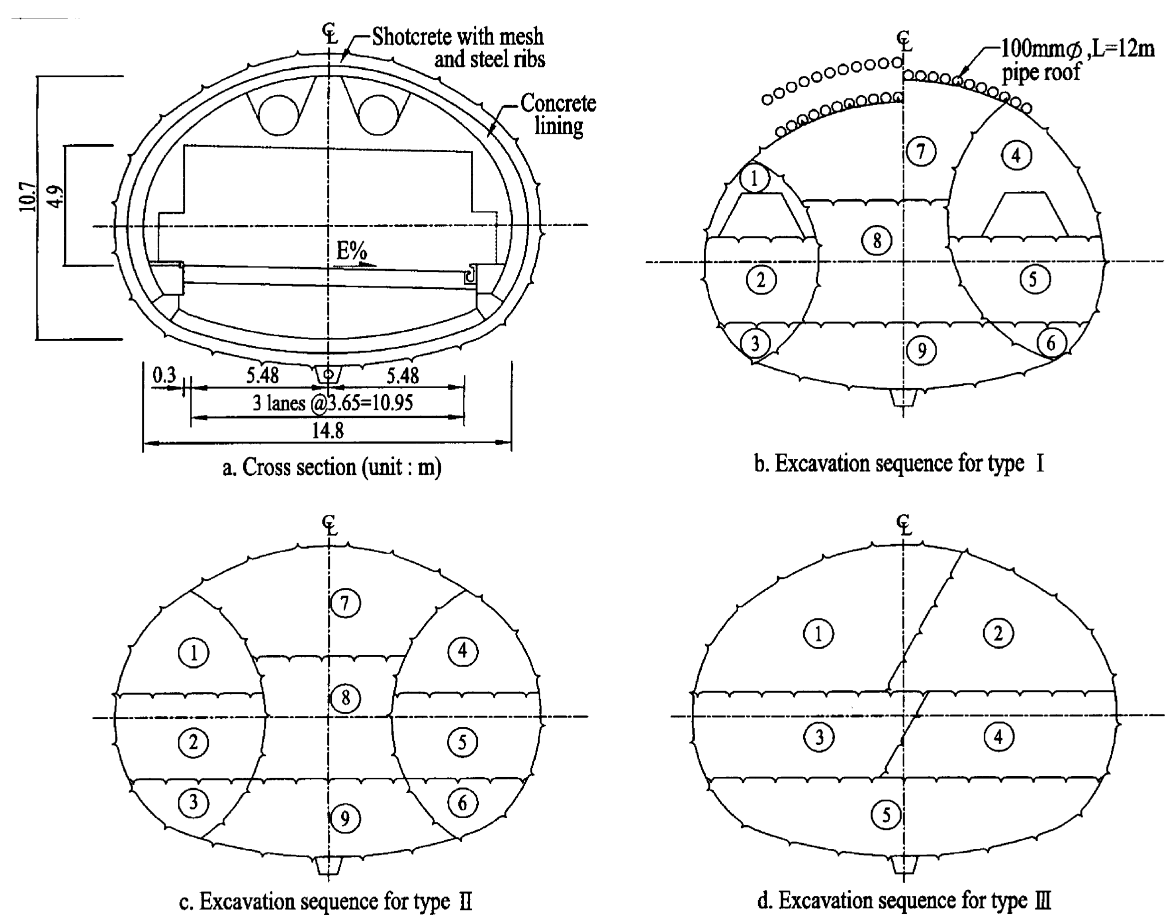


Fig. 4. Cross-section and excavation sequence of Lantan Tunnel.

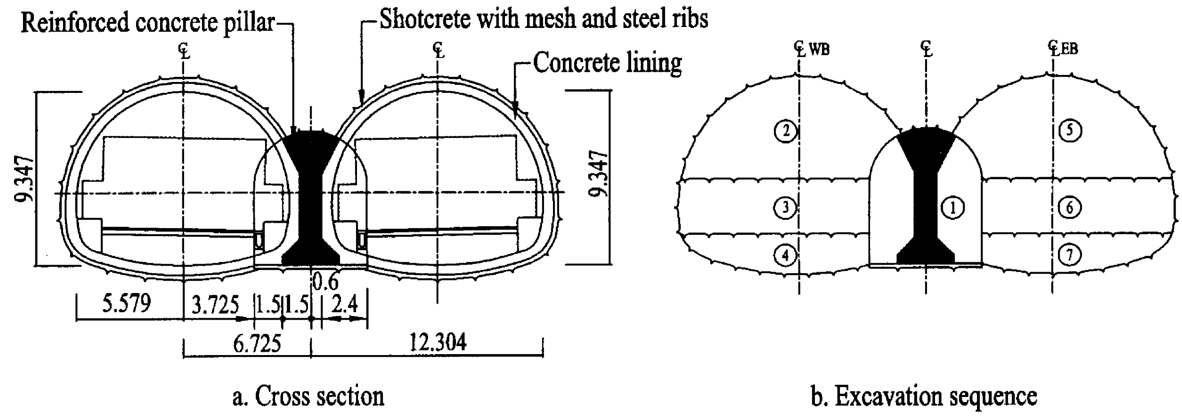


Fig. 5. Cross-section and excavation sequence of Tsoumalai Tunnel.

Fig. 6. The first collapse of the pressure tunnel of Wushantou Reservoir.

3.1. The pressure tunnel of Wushantou Reservoir

The pressure tunnel was constructed to renovate the water supply system of the Wushantou Reservoir. This tunnel passed through Liushuang Formation, which consists mainly of the alternation of mudstone and sandstone, and was driven against to the dip of the stratum. The high groundwater level in the dam-side section and the unfavorable attitude of bedding lead to an adverse condition for tunnelling.

At the beginning of tunnel construction the excavation and support scheme were determined by the geomechanics classification (Bieniawski, 1974). Rock mass rating (RMR) are evaluated based on six parameters, including the uniaxial compressive strength of the intact rock, drill core quality RQD, spacing, orientation and condition of joints, and ground water inflow. The site

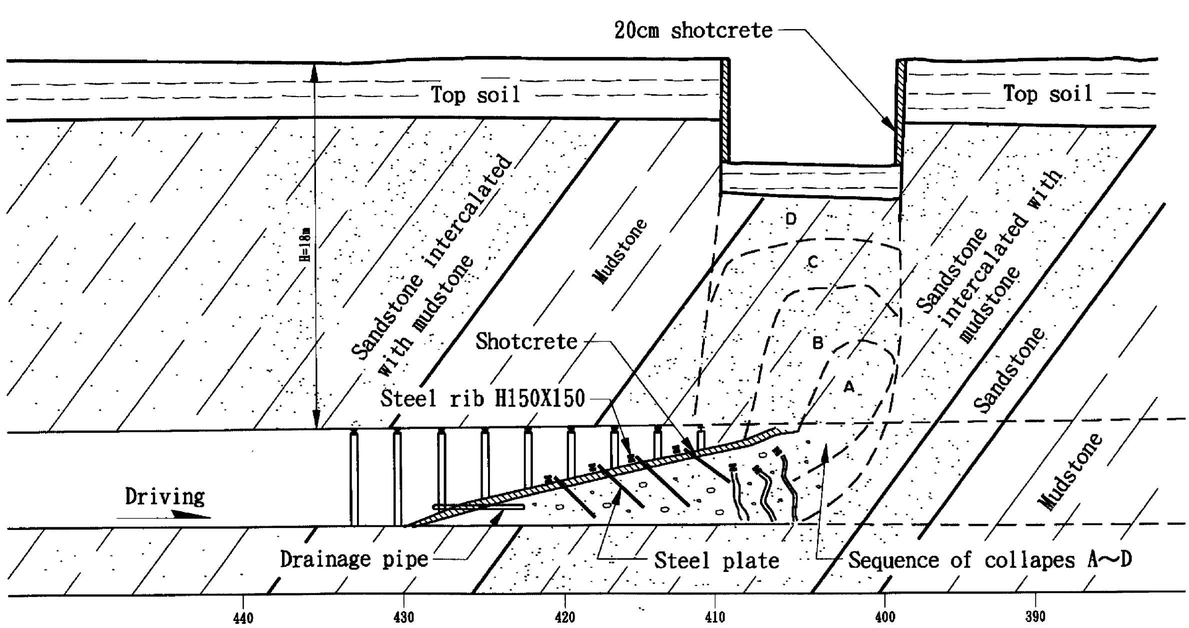


Fig. 7. Profile of the first hazard of the pressure tunnel of Wushantou Reservoir.

Fig. 8. Deteriorated mudstone beneath the working face of the pressure tunnel of Wushantou Reservoir.

experience revealed that this rating might not represent the engineering characteristic of surrounding rock properly due as poorly cemented rock and undeveloped discontinuities. The workability of the drilling tasks for grouting bolts was poor and the strength of bolts varied from 5.8 to 12.6 kN (the lowest designed requirement is 10 kN). Hence, the rock bolts were not used in this tunnel. In addition, steel ribs and shotcrete with mesh (i.e. the heaviest support type of preliminary design) became the main support element in this tunnel. The top heading and benching method were adopted to excavate the tunnel in the beginning of tunnelling.

Two major hazards occurred during tunnelling. At the Sta. 0k+424 tunnel ran into a mudstone layer, occasionally alternation of mudstone and sandstone was encountered. Notably, the minor water inflow significantly shortened the stand-up time and deteriorated rock squeezed into the tunnel form the excavation face. Drainage pipes were installed, forepolings by the 3 m long steel plates were adopted and tunnelling was continued. Until the Sta. 0k+406 tunnel ran into a 26 m thick formation composed of sandstone intercalated with mudstone. The sealing shotcrete with mesh were used to maintain the stability of excavation face; the forepolings by wooden and steel plate were also installed. Although these measurements could stabilize the tunnel, the instability occurred as soon as the excavating task started. Four cave-ins occurred in a week, finally induced a serious collapse approximately 1100 m^3 in volume, as shown in Fig. 6. This hazard also extended to the ground surface 18 m above the tunnel and caused a cavity with 11 m in diameter and 6 m in depth. Fig. 7 illustrates the geological profile of this hazard. Thereafter, the three stage excavations by heading–benching–invert with ring cut as shown in Fig. 3c were applied to overcome this unfavorable geological condition. The 3 m long steel plates for forepoling and wing ribs for strengthening of foundation were used to reduce the deformation. To strengthen the stiffness of the tunnel support as soon as possible, the invert was installed in four rounds (~3 m).

At Sta. 0k+275 tunnel had just passed through a mudstone layer and entered a weakly cemented sandstone. The heading stage had been completed in a mudstone layer. Drainage pipes covered by geosynthetics were installed because of the minor water inflow. However, the drainage measurements appeared to be ineffective and a serious mudflow occurred during the benching stage where tunnel just passed through the boundary of sandstone and mudstone. Huge water pressure destroyed the shotcrete sealing on excavation face and the sand grains were washed out. Piping phenomenon induced collapse of sandstone from the bottom of bench to the vault, subsequently causing continuous

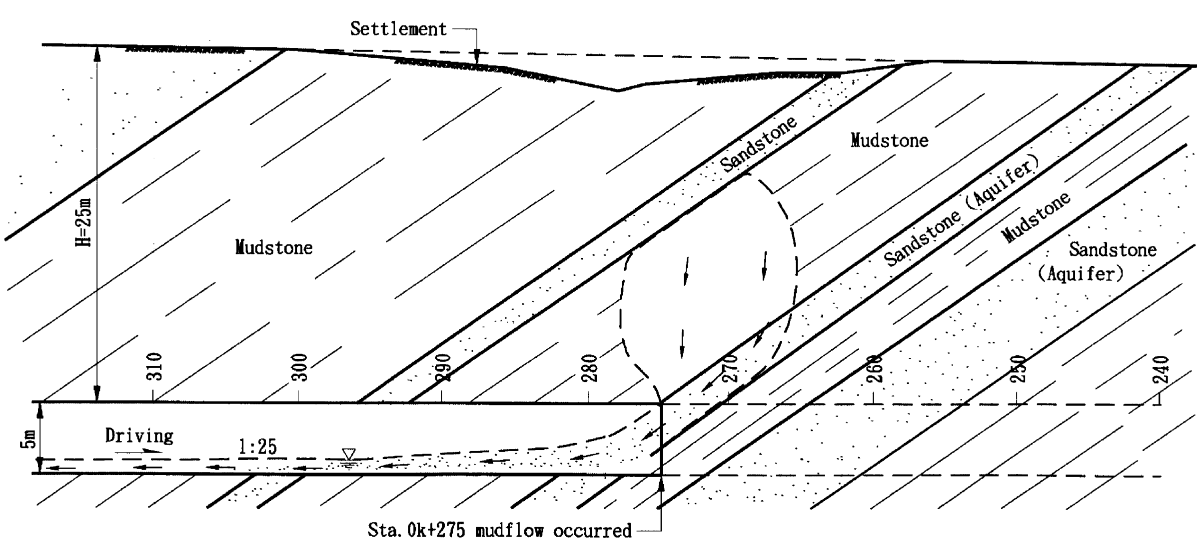


Fig. 9. Profile of the second hazard of the pressure tunnel of Wushantou Reservoir.

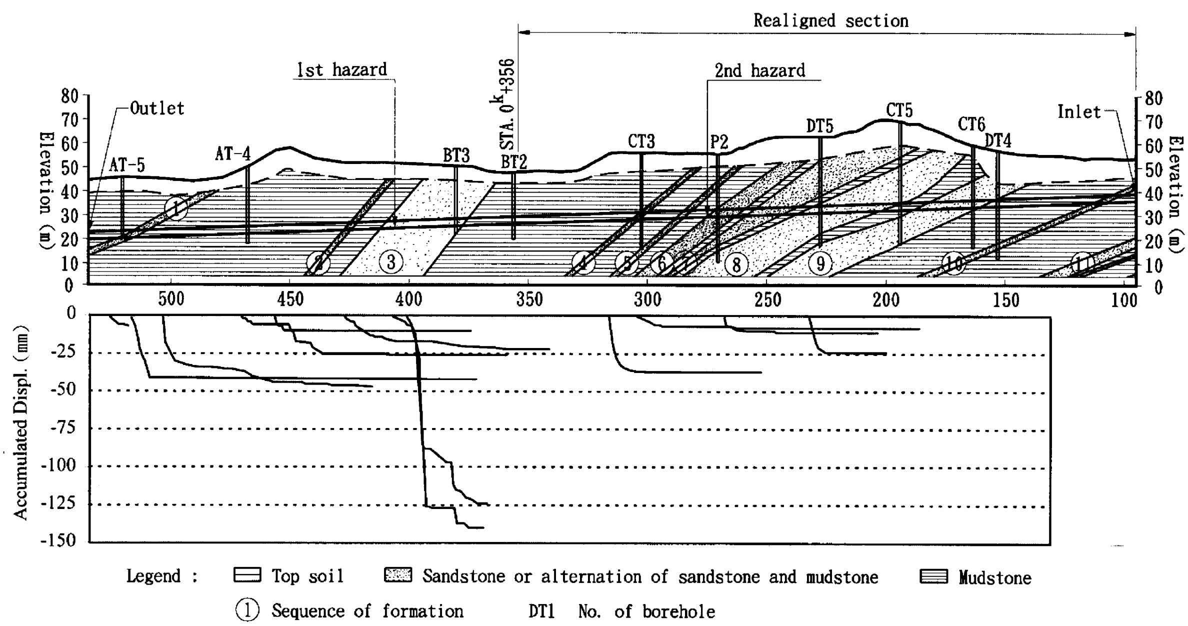


Fig. 10. The convergence monitoring result of the pressure tunnel of Wushantou Reservoir.

collapses of mudstone above sandstone. The collapsed mudstone slaked in a very short time. Fig. 8 illustrates the deteriorated mudstone beneath the working face a few hours before the collapse of the tunnel. In 6 h, the tunnel was flooded by mudflow approximately 125 m in length, as shown in Fig. 9. This hazard also caused severe settlement on ground surface 26 m above the tunnel. Nearly 3000 m^2 area was influenced and the maximum settlement reached 2.5 m. Finally, the tunnel was ended by realignment. A pumping project from

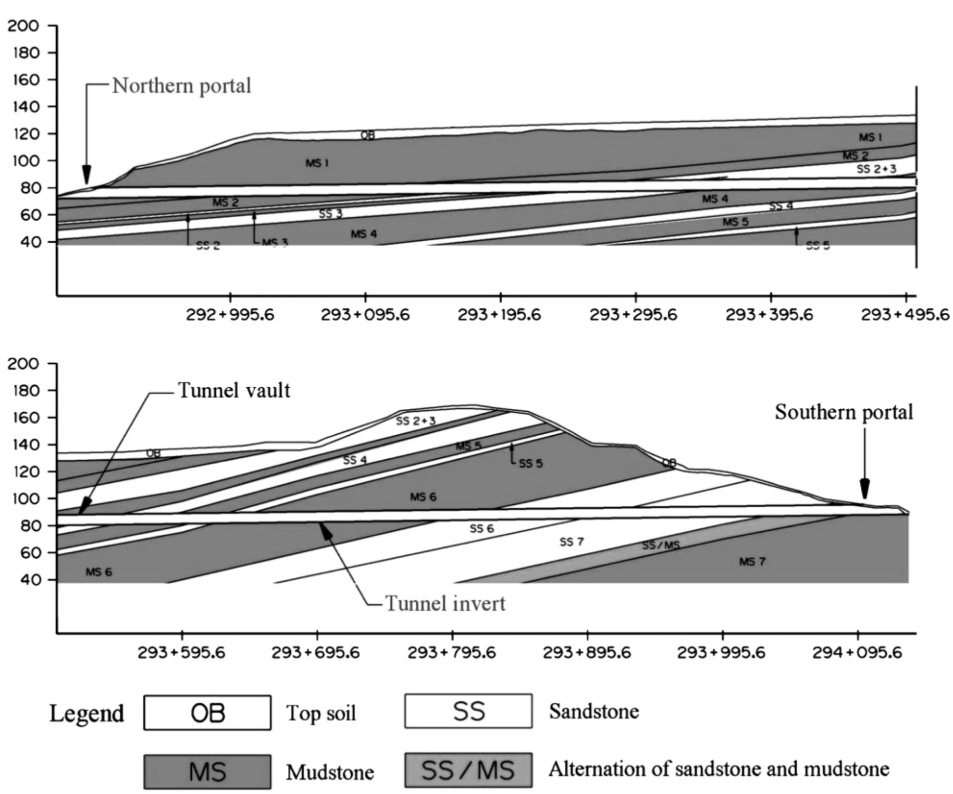


Fig. 11. The geological profile of Lantan Tunnel.

ground surface was applied to drop down the groundwater table before the reconstruction of tunnel.

The monitoring data reveal that the groundwater and the relative position of sandstone and mudstone heavily influence the convergence of tunnel. Fig. 10 demonstrates the convergence monitoring results of this tunnel. According to this figure, the convergence in sandstone layer and mudstone in the vicinity of sandstone are twice as great or higher than in middle section of mudstone.

3.2. Lantan Tunnel

Lantan Tunnel includes double tubes three-lane tunnels. The tunnels pass through Liushuang Formation composed of mudstone, containing poorly cemented sandstone and their alternation. The strike of the Pleistocene sedimentary rocks ranges from N5°–30°E, with dip 5–30° to west. The groundwater level is approximately 10–20 m higher than the vault of the tunnel. Although the mudstone can be sought as impermeable layer, the permeability of sandstone is high as 2.0×10^{-3} cm/s.

In the design stage of Lantan Tunnel, the characteristics of mudstone learned from the pressure tunnel of Wushantou Reservoir have been considered. Some tunnelling experiences with water inflow problem and their countermeasures e.g. the Pinglin tunnel (Tseng et al., 2001), have also been taken into account. A detailed survey by a large number of boreholes was also preformed to identify the thickness of mudstone and the relative position of mudstone and sandstone, as shown in Fig. 11. The groundwater level was surveyed as well. A pumping project from ground surface was performed to drop down the groundwater table before tunnelling. Three major excavation procedure and support classes are used according geological conditions. Table 2 presents the determination of the excavation procedure and the support type by the thickness of mudstone and its relative position with sandstone. Due as tunnelling behavior is highly affecting by the intercalated sandy layer, a nine stages excavation strategy shown in Fig. 12 was implemented in case of the thickness of mudstone less than 50 m. Similar excavation sequences with different forepoling methods were designed for alternation of sandstone and mudstone, and massive mudstone, respectively. The support strengths are also little different. Notably, the side pilots with 25–100 m drainage pipes were designed to drain the groundwater and reduce the settlement of tunnel.

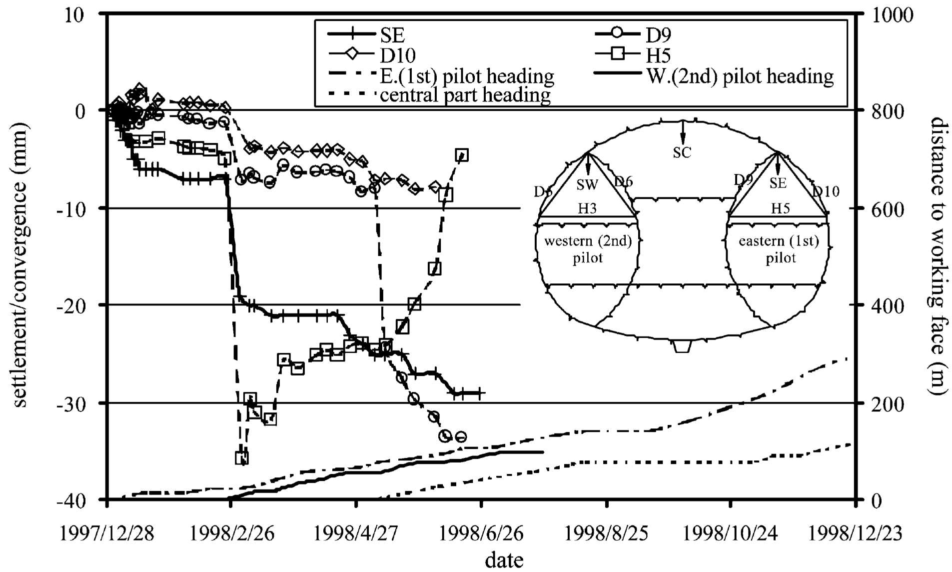
Fig. 12. The nine stages excavation process of Lantan Tunnel.

The construction of Lantan Tunnel began in 1997, and holed through in May 2000. Among the 1.254 km (northern bound) excavation of tunnel, approximately 1070 m are excavated and supported by Type I and Type II of Table 2. The tunnelling experience reveals that the pumping measurement form ground surface can lower down the groundwater level to certain level but reduce the saturation of mudstone. The side pilots with auxiliary drainage pipes play an important role to reduce the deterioration of mudstone caused by ground water, and then the stability of excavation face can be well maintained.

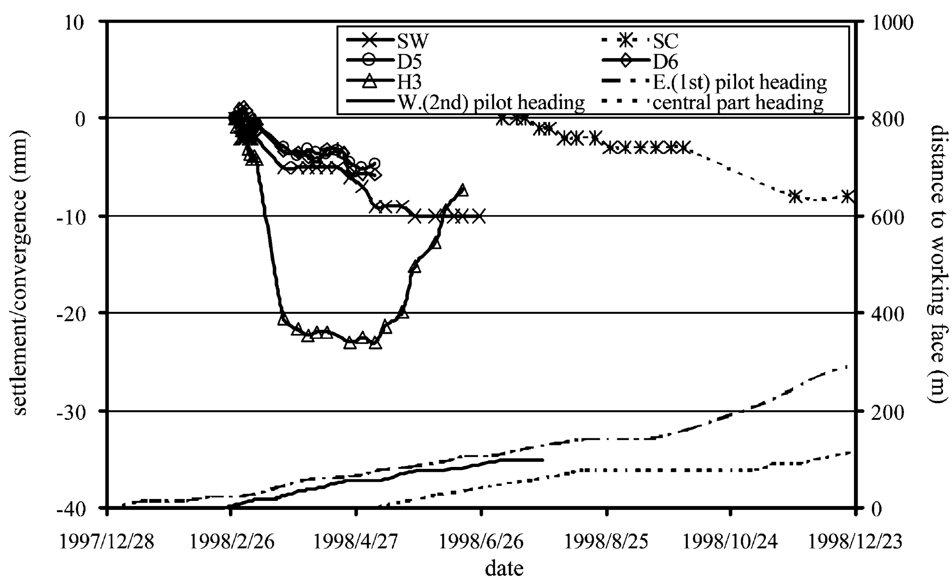
The monitoring data show that under different ground conditions the settlements are limited in 29 and 13 mm, and the horizontal convergence are limited in 36.0 and

Table 2
The determination of excavation and support of Lantan Tunnel

Excavation and support type	I	II	III
Advancing distance (m)	1.0–1.5	1.0–1.5	1.0–1.5
Applied rock type	Poorly cemented sandstone/sand, alternation of sandstone and mudstone, siltymudstone	Mudstone	Mudstone
Applied situation	General condition	The thickness of mudstone less than 50 m	The thickness of mudstone larger than 50 m
Excavation sequence	Side pilots	Side pilots	Top heading
Main support element	Steel fiber shotcrete, rock bolts and lattice girder	Steel fiber shotcrete, rock bolts and lattice girder	Steel fiber shotcrete, rock bolts and lattice girder
Auxiliary measurement	Pipe roof by large diameter steel pipe	Steel pipe	Steel pipe



(a) Settlement and convergence (both presented in negative) of eastern (first) pilot



(b) Settlement and convergence of western (second) pilot and central part

Fig. 13. An illustration of monitoring results, Sta. 293+852 of Lantan Tunnel.

96.8 mm (which are 0.6 and 1.8% compared with their width of excavation) for the first side pilot and for second one, respectively (Continental Engineering Corp. 2000). A typical monitoring result for nine stages excavation section is illustrated in Fig. 13. Settlement and convergence curve exhibit complex characteristics due to interaction of sequence excavation. The moment the adjacent pilot excavated, both of the horizontal convergence of the eastern (first) pilot and the western (second) pilot turned around into extensive tendency. However, the deformation of surrounding is rather limited for such a big tunnel in soft ground. It is believed that the excavation and support determination criteria may be appropriate.

Nevertheless, the average advancing rate during nine stages excavation is rather poor to be 27 m/month. The excavation procedure therefore was modified from nine stages to be seven. Finally, a single side pilot with five

Fig. 14. The five stages excavation process used in Lantan Tunnel.

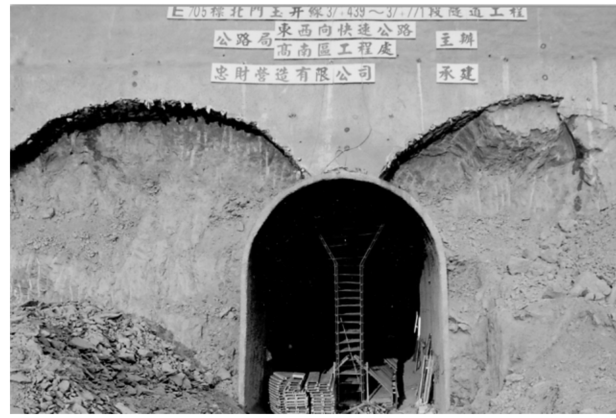


Fig. 16. Dry mudstone exposed in the portal of Tsoumalai Tunnel.

stages procedure was also adopted to drive the tunnel, as shown in Fig. 14. The advancing rate is rising to be approximately 60 m/month in average. Fig. 15 illustrates the modification of excavation sequence of this tunnel in some detail.

3.3. Tsoumalai Tunnel

Tsoumalai Tunnel consists of two double-lane highway tunnels. Owing to the space limitation, these two tunnels were designed to co-construct and resemble a pair of glasses (Fig. 5). This design enlarged the width of excavation and inevitably increased the rock pressure applied on the support. Therefore, a special excavation scheme shown in Fig. 5 was adopted to reduce the disturbance on the rock in the vicinity of the tunnel.

The tunnel underwent a massive mudstone layer. Fortunately, no groundwater problem occurred. During tunnelling, the mudstone exhibited excellent self-sustained capacity and stand-up time, as shown in Fig. 16 taken from portal. Forepoling and shotcrete sealing were not necessary in this tunnel. The monitoring data indicated that the convergence of this tunnel was limited in a few millimeters to 1 cm, and had stabilized in a couple rounds as the working face went ahead. The 333 m long tunnel was completed earlier than the expected construction period by 4 months.

4. Experience from mudstone tunnelling

4.1. The behavior of mudstone for tunnelling

Experience from these three tunnelling indicate that the groundwater conditions largely control the engineering properties of mudstone surrounding a tunnel. Moreover, its deterioration phenomenon may heavily influence the stability of tunnel. The influence of water content on the mudstone behavior for tunnelling can be well understood by comparison of Figs. 6, 8, 14 and 16.

Under a dry condition, the mudstone exhibits certain strength and moderate deformability. The mudstone is rather good to fair for tunnel excavation. The surrounding rock of tunnel exhibits the capacity of self-sustained and, usually, the stability of excavation face can be well maintained.

An increase of the water content causes the deterioration of mudstone to decrease its strength and increase its deformability. Although the excavation face may have a few hours stand-up time, the time dependent deformation occurs. The extra rock pressure may be

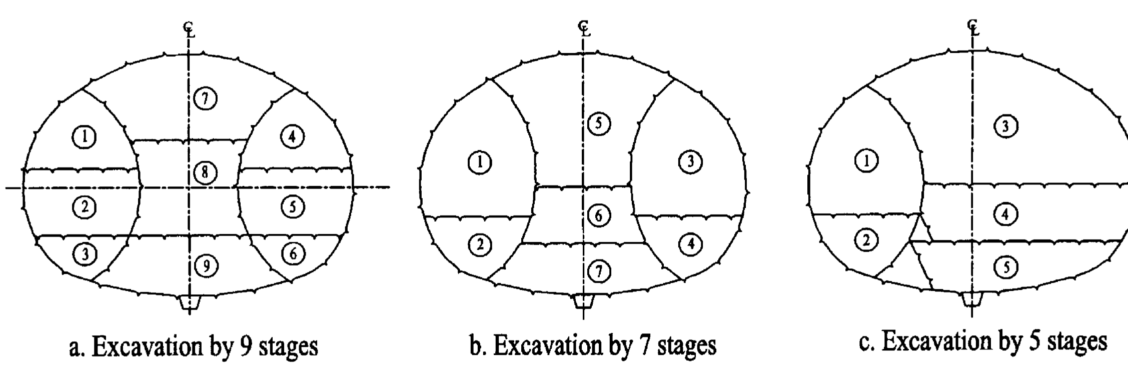


Fig. 15. The modification of excavation sequence of Lantan Tunnel.

induced due to the creep phenomenon. Under this circumstance, the deformation of tunnel should be controlled to minimize the zone of disturbance.

Under the circumstance that the aquifer exists, the mudstone may be thoroughly saturated, and the strength may loosen to residual level or even lower in case of large deformation occurred. Under this condition, the slaking phenomenon may occur after excavation and extra swelling pressure may apply on the support system of tunnel. Notably, piping phenomenon in aquifer and mudflow in mudstone should be prevented to avoid a serious hazard during tunnelling.

4.2. Technical comments for mudstone tunnelling

Determination of excavation and support should consider the possibility of deterioration of mudstone in site. Under the circumstance of mudstone tunnelling, the determination by the thickness of mudstone and its relative position to the nearby aquifer may be appropriate instead of the RMR or Q-value method which are widely used in Taiwan.

In mudstone area, if the groundwater level is higher than the vault of the tunnel, dewatering is one of the most important things in tunnelling. In order to drop down the groundwater, it is necessary to evaluate the effect of advanced drainage pipes, pumping well and drainage pilot regardless of whether inside or outside of the tunnel. Nevertheless, these auxiliary measurements may strongly release the water pressure in aquifer, but the water contained in mudstone is hardly reduced. Therefore, the forepoling with pipe roof by rebars, steel pipes, horizontal jet grouting or other measurements should be installed to protect the roof of the tunnel. In addition, shotcrete sealing or special excavation scheme such as ring cut should also be adopted to stabilize the excavation face. As the severe instability problem might cause the damages of tunnelling task, the ground improvement can also be performed.

To reduce the settlement of a tunnel, side pilot excavation method should be considered. The extra foundation such as wing ribs could be applied as well. Invert should be installed as soon as possible to strengthen the stiffness of the support. Under the condition of high swelling pressure, it is necessary to provided heavier support system.

Owing to the time dependent characteristic of mudstone in moisture condition, it is necessary to verify the effect of grouting bolts. Fig. 17 summarizes the results of pull out test of varies rock bolts used or tested in three tunnelling projects. The strengths of bolts installed by wash drilling method are significantly lower than which installed by dry-drilling. It is also clear that the strength exhibits high variation and reduces to 70–95% 1 month after installation compared to its initial strength (Liu et al., 1996; United Geotech Inc., 1997). Consequently, if rock bolts are determined to be one of the support elements, the designed strength should be reduced on the base of verification tests, and dry-drilling method should be adopted to avoid softening of the surrounding rock and collapsing of neighboring boreholes.

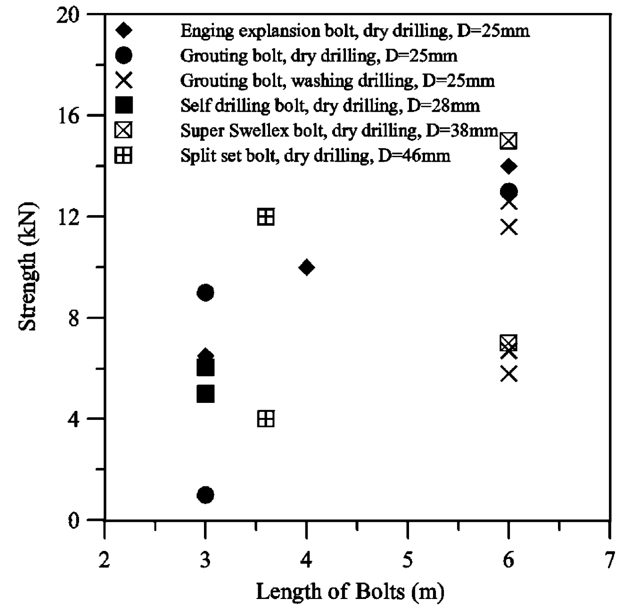


Fig. 17. The results of pull-out test of bolts installed in mudstone area.

In addition to the general monitoring item, some particular features require close attention: the groundwater level and groundwater pressure, the deformation of excavation face and the heave phenomenon. Among which, it is very hard to do monitoring task on the deformation of excavation face, the monitoring on the volume of muck in each tunnelling round may be easier to alert the occurrence of plastic flow.

5. Conclusions

Owing to the behavior of mudstone affected strongly by water, preventing the deterioration of mudstone makes tunnelling in mudstone area is an undaunting task. From the three tunnelling cases presented herein, related experience indicates that the excavation sequence and support system should depend on the characteristic of mudstone, and its thickness and relative position to aquifer may indicate about that. Under the advanced dewatering, forepoling and adequate support, the deformation of surrounding rock may be reduced and the construction can be successful in mudstone tunnelling.

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