Tunneling Issues Regarding the Rock Tunnel-shaft Intersection in Taiwan

Tai-Tien Wang[1], Tzu-Tung Lee[2], Shun-Min Lee[3], Kwei-Shr Li[4] and Cheng-Hsun Chen[5]
[1,2]*Institute of Mineral Resources Engineering, National Taipei University of Technology, Taipei, Taiwan*
[3,4,5]*CECI Engineering Consultants, Inc., Taipei, Taiwan*
E-mail: ttwang@ntut.edu.tw, taitienwang@gmail.com

ABSTRACT: The construction of an intersection between a shaft and a rock tunnel is a three-dimensional problem, and requires more complex excavation and support method than those used in conventional two-dimensional tunnel construction, and this fact affects both design and construction. Considering examples of rock tunnelling in Taiwan, this investigation reviews the construction of intersections between shafts and tunnels and related issues. First, cases of construction are collected and reviewed, and the excavation sequences are classified. Challenges to secure construction of the intersections of shafts and tunnels are investigated, including significant scale effects of rock masses on excavations with large cross sections, construction difficulties that are caused by the complicated arrangement of underground excavations, difficulties in controlling rock deformation near the intersections, and groundwater ingress. Strategies and countermeasures applied to overcome these difficulties are introduced with reference to recent projects, and their effectiveness is investigated. Finally, the state-of-the-art design and construction of intersections between shafts and tunnels in Taiwan are presented.

Keywords: Shaft, Rock tunnel, Intersection, Scale effect, Deformation control, Groundwater ingress mitigation.

1. INTRODUCTION

In the wake of advances in tunnelling machinery and equipment, excavation and support method, long tunnels are being increasingly built around the world for transportation and communication purposes in mountainous area. A shaft is required to ventilate long traffic tunnels to ensure their serviceability and, sometimes, to provide passageways to the working face for tunnel excavation to reduce construction time (Yan *et al*., 2009; Cheng *et al.*, 2010; Ji *et al*., 2013). Global climate change has increased the magnitude and frequency of extreme weather and earthquake events, resulting in sedimentation in reservoirs and a crisis of water supply world widely. A series of lifespan extension projects that involve the construction of tunnels to release sediment or bypass tunnels to existing reservoirs have been launched in Taiwan. These projects require the excavation of a shaft to accommodate hydraulic machinery, and space for their operation and maintenance (Mahmood, 1987; Chen and Liao, 2012; Lee *et al.*, 2016). The applications of shafts, with diverse functions, in underground engineering and the associated utilization of underground space, have become popular.

Intersections between shafts and rock tunnels are a mechanically three-dimensional problem. Excavation-induced rock deformation near the intersections differs from that caused by conventional tunnel construction, which can be considered as two-dimensional problems. Construction must be organized carefully. Effective excavation and support method are necessary to construct the required complicated underground structure. The size of the excavation-disturbed zone increases with the cross-section of the tunnel and/or shaft, affecting such engineering characteristics as the stability of excavation, rock deformation around the excavation, and groundwater flow adjacent to the excavation (Hofle, 2013; Moritz *et al*., 2013; Perras *et al.*, 2015; Sanada *et al*., 2015). Therefore, detailed geological and geotechnical information is typically required for the construction of an underground intersection as it is used to elucidate the excavation-induced stress and strain variation near the intersection, and to determine a preferable construction scheme.

The related literature includes revealing of the construction of intersections between shafts and rock tunnels and between adits and rock tunnels (Chen *et al*., 2005, Tsai *et al*., 2006, Venkatesh et al., 2007, Li *et al*., 2010, Wang, 2014,). In addition to practical case studies, numerical simulation is the most popular approach to investigating the deformation of rock near intersections. Hsiao (2010) adopted three-dimensional numerical simulations that considered the elastic-plastic behaviour of rock. Hsiao (2010) also generated a database of rock deformations near the intersection using various rock parameters, and then carried out a statistical analysis to identify the factors that affect rock deformation. He suggested that the angle of inclination between two tunnels (AI) and the ratio between the uniaxial compressive strength of the rock and the *in-situ* stress (strength ratio) dominate rock deformation near the intersection, and proposed a relationship between the incremental rock deformation in the crown part of a tunnel, the AI and the strength ratio. Wang *et al*. (2002) and Wang and Huang (2011) investigated the construction of the intersection between the New Quanin Tunnel and its north adit, where prolonged rock deformation of large magnitudes has been observed. They performed three-dimensional numerical simulations to study the influence of squeezed deformation on the construction of the intersection. Wang *et al*. (2002) compared their simulated results with monitored rock deformation over time, and suggested appropriate reinforcement measures and means of suppressing rock deformation.

This work concerns rock tunnelling in Taiwan, and reviews constructions of intersections between shafts and tunnels. First, the constructions of intersections are collected and reviewed, and the arrangements of the shafts and tunnels and their excavation sequences are classified. Challenges to the secure construction of these intersections are examined, including the significant scale effect of rock masses resulted from large cross-sections, difficulties in that arise from the complicated arrangement of underground excavation, the difficulty in controlling rock deformation near the intersections, and groundwater ingress mitigation. Strategies and countermeasures to overcome these difficulties are introduced with reference to recent representative projects, and their effectiveness is investigated. Finally, the-state-of-the-art design and construction of intersections between shafts and tunnels in Taiwan are elucidated.

2. CASES OF CONSTRUCTION OF INTERSECTIONS BETWEEN SHAFTS AND TUNNELS IN TAIWAN

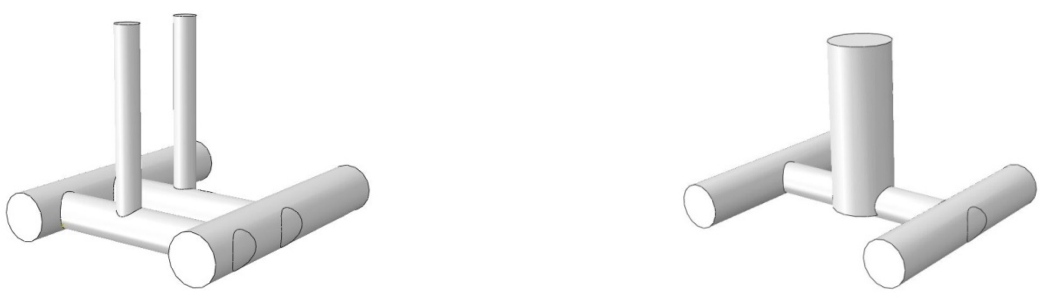
Table 1 summarizes representative cases of the construction of intersections between shafts and tunnels in Taiwan, in which the cross-section of the tunnel and/or connected shaft exceeds that of a single lane railway tunnel. The spatial arrangements of a shaft and a tunnel can be classified into two types according to whether the shaft is located right above the connected tunnel or beside the tunnel. Shafts above typically have the same cross-section as the tunnel, or one smaller than that of the tunnel, and the tunnel that is connected to the shaft is usually a ventilation room or a connected adit (Figure 1a). The No. 3 shaft of the Hsueh Shan Tunnel is typical. On the other hand, shafts in the latter have large cross-sections, typically equal to or larger than that of the connected tunnel. To prevent the excavation from producing a disturbed zone, the distance between the shaft and the main tunnel to which the shaft is connected is generally greater than the diameter of the tunnel and the shaft (Figure 1b). A railway tunnel is normally connected to a shaft of the latter type.

Excavation for intersections is classified into conventional setting excavation (Figure 2a) and raise boring method (Figure 2b). The conventional setting excavation is often called as the shaft sinking method in practice. The shaft is excavated from its top to its bottom round by round. When a shaft provides an additional working face for tunnel excavation, it has to be built by the shaft sinking method. Examples include the No. 2 and No. 3 Shafts of the Hsueh Shan Tunnel and the No. 42 shaft in the Xizhi section of Taiwan railway. The raise boring method separates the construction of a shaft into parts. First, a guide hole is bored from the surface down to the vault of the connected tunnel (at the bottom of the shaft). Second, the hole is broadened using a raise boring machine from the bottom of the shaft up to the surface. Finally, the shaft is excavated from the surface down to the vault of the connected tunnel again. Construction by the raise boring method appears complicated. However, the broadened hole enables the excavated rocks to be removed through the connected tunnel, which task is the single most time-consuming task in the shaft sinking method, and significantly reduces the impact of groundwater ingress on the excavation of a shaft. Therefore, raise boring method has become popular for use when the connected tunnel has been completed before the shaft is excavated. The No. 1 shaft of the Hsueh Shan Tunnel was built using the raise boring method.

Table 1 Representative cases for intersections of a rock tunnel and a shaft in Taiwan

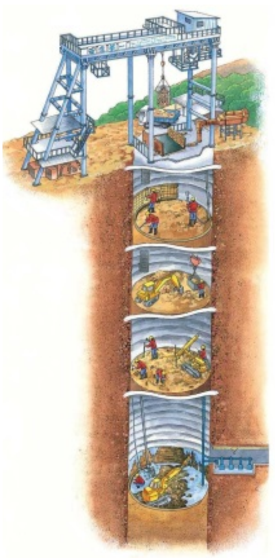
Case	Primary function	Lithology	Excavation method	Shaft (Diameter×Height) (m)	Tunnel diameter (m)
Xueshan tunnel No.01	Ventilation	SS/SH*	Raise boring	6×492	11.7**
Xueshan tunnel No.02	Ventilation	SS/SH*	Sinking	6.5×250	11.7**
Xueshan tunnel No.03	Ventilation	SS/SH*	Sinking	6×450	11.7**
Taiwan Railways Administration(TRA) Xizhi tunnel No.42	Ventilation	Mudstone	Sinking	23.9×24	34.4
Baguashan tunnel	Ventilation	Gravelstones	Sinking	10×240	6.5
Taiwan High Speed Rail (THSR) Linkou tunnel No.A	Escape	Gravelstones	Sinking	16×36	11.6
Taiwan High Speed Rail (THSR) Linkou tunnel No.B	Escape	Siltstone	Sinking	16×43	11.6
Mingtan hydroelectric plant	Gate	Sandstone	Sinking	14×150.2	7.5
Wanda hydroelectric plant	Gate	Schist	Raise boring	10×45.5	5
Zengwen desilting tunnel	Gate	SS/SH*	Modified raise boring	31.15×40	10
Nanhua desilting tunnel	Gate	SS/SH* Sandy shale	Sinking	25×65	10
Bihai hydroelectric plant	Gate	Gneiss	Sinking	5.4×78	2.7
Dawanping desilting tunnel	Gate	SS/SH*	N.A.	9×104	13
Dajia River hydroelectric plant	Gate	Slate	Raise boring	89.5(L)×17.5(W)×36	6.9

* SS/SH：Interbedding of sandstone and shale
** The diameter of the smaller connecting tunnel connecting the Xueshan tunnel No.1, No. 2 and No. 3 Shafts are 4.8 m.

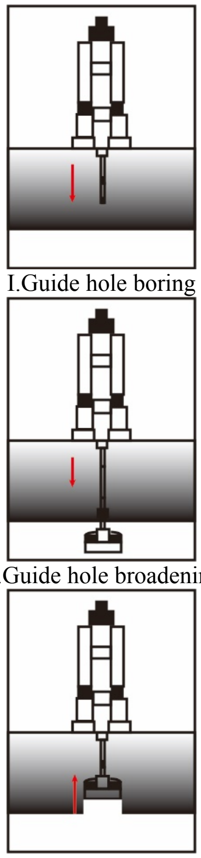


(a) Type I intersection between shaft and tunnel (b) Type II intersection between shaft and tunnel

Figure 1 Schematic diagram of Type I (a) and Type II (b) intersection between a shaft and a tunne



(a) Conventional setting excavation method (Tsai *et al*., 2006)



I.Guide hole boring

II.Guide hole broadening

III.Full face downward excavation

(b) Raise boring method

Figure 2 Typical excavation sequences for shaft construction. (Wang, 2014)

3. CHALLENGES AND STRATEGIES

Shafts have been designed and constructed in several rock tunnelling projects in Taiwan recently. Challenges in the construction of intersections between shafts and tunnels include the following; (1) rock masses may exhibit the scale effect owing to the construction of tunnels and shafts with large cross-sections, which refers to the fact that the stress-strain relationship of surrounding rock differs from that around tunnels and shafts with small cross-sections; (2) excavation-induced variations in the stress and strain of rock that surrounds the intersection are complicated, affecting their engineering characteristics and responses to subsequent excavation, making secure excavation difficult; (3) many curved surfaces, projection and corners are present near the intersections, so the monitoring and control of rocks that surround the intersection are difficult, and (4) the work underground that is required to mitigate groundwater ingress is difficult.

Many strategies have been proposed and applied to resolve the difficulties of constructing intersections between shafts and tunnels in Taiwan. The effectiveness of these countermeasures is studied using data that have been collected from the following practical projects.

3.1 Scale effect in rock masses and countermeasures

Hoek and Brown (1980a, 1980b) indicated that, for a specific rock site, a larger underground excavation is associated with more discontinuities in the rock masses in the excavation disturbed zone, worsening the engineering characteristics of those rock masses and causing difficulties in secure excavation. Such a variation in the engineering characteristics of rock masses affected by the size of rock engineering is the well-known scale effect. Discontinuum-based analysis methods, such as the key block theoretic analysis and the discontinuity deformation analysis were developed years ago. However, determining the spatial distribution and mechanical characteristics of discontinuities is difficult, limiting the range of the application of discontinuum-based analysis methods. Continuum-based analysis methods now dominate underground analysis and design.

In applying the continuum-based analysis method to the simulation of the underground excavation of rocks, relevant engineering parameters are determined by applying the equivalent continuum concept. The structure of a rock mass, which includes the spatial distribution and the attitude of its discontinuities, is captured using the equivalent geological strength index (GSI), and the effect of rock materials that form the major part of the rock mass is taken into account using the uniaxial compressive strength of the intact rock. The rock deformations collected during underground excavations are used to back-calculate the engineering parameters of the rock masses. However, most referenced underground excavations that have been used to determine the engineering parameters located in competent rocks and involved single or double lanes; few have involved large excavations diameters or underground intersections. When the cross-section of a tunnel is large, determination of the scale effect on engineering parameters is always a major issue for investigators of the site and in engineering design.

Wang (2003); Wang and Huang (2009) proposed a three-dimensional nonlinear constitutive model and an associated two-dimensional numerical implementation for rock masses with regularly distributed ubiquitous joint sets. The model combines the mechanical behavior of intact rock with the spatial configuration of joint sets and the mechanical behavior of joint plane into a rock mass by means of representative volume elements. They took into account the conventional pre- and post-peak deformation characteristics of intact rock, the pre-peak deformation of joints, including their closure, shear and dilatancy effects, and its post-peak deformation, which includes reduction of roughness. Their model captured the joint-induced anisotropy of strength and deformation of the rock mass, helped to determine possible failure modes and reasonably simulated the complete stress–strain relationship. Wang and Huang (2014) and Liu (2011) used the model that was proposed by Wang and Huang (2009) to investigate the joint-induced anisotropic deformation around a tunnel, and indicated that the characteristics of rock mass deformation, including the closure of joints, the reduction of roughness at post-peak deformation and shear-induced dilatancy, could be simulated using this model.

Wang (2014) utilized the nonlinear constitutive model of rock masses that was proposed by Wang and Huang (2009) to study the rock deformation, failure zone and normalized radial strain (defined as the radial component of deformation divided by the radius of the tunnel) of a tunnel that is excavated in regularly ubiquitous jointed rock masses with one, two and three joint sets. Table 2 lists the input parameters used in the numerical simulation. For illustrative propose, the mechanical parameters of various joint sets are resemble in this manuscript. Table 3 list the input support parameters in the numerical simulation, which are commonly used in Taiwan. Figure 3 plots simulated results of plastic zone area and radial strain of surrounding rock under various tunnel radii, among which a rock mass containing one, two and three joint sets are considered. The term A is defined as the ratio of plastic zone to the tunnel cross-sectional area and the radial strain ε as the ratio of the maximum displacement of surrounding rock to the tunnel radius. Both the plastic zone and radial strain induced by a tunnel excavation in a rock mass containing two joint sets exceed those in rock mass containing one joint set and three joint sets.

Figure 4 plots the anisotropic deformation that surrounds a tunnel in a rock mass with two joint sets. The displacement vectors increase rapidly with the tunnel radius, revealing the scale effect on

Table 2 Input parameters for numerical simulations

(a) Mechanical parameters of intact rock

Peak cohesion C_p (MPa)	12.2
Peak friction angle $\emptyset_p$ (°)	38.0
Bulk modulus K (GPa)	0.833
Poisson ratio ν	0.25
Uni-axial compressive strength σ_c (MPa)	50.0

(b) Mechanical parameters for joint sets

Initial normal stiffness k_{ni} (GPa/m)	20
Maximum closure u_n^m (m)	1.0×10^{-4}
Joint roughness coefficient *JRC*	10
Basic friction angle $\emptyset_b$ (°)	33
Uni-axial compressive strength of joint wall *JCS* (MPa)	50.0

(c) Parameters for spatial configuration of joint sets

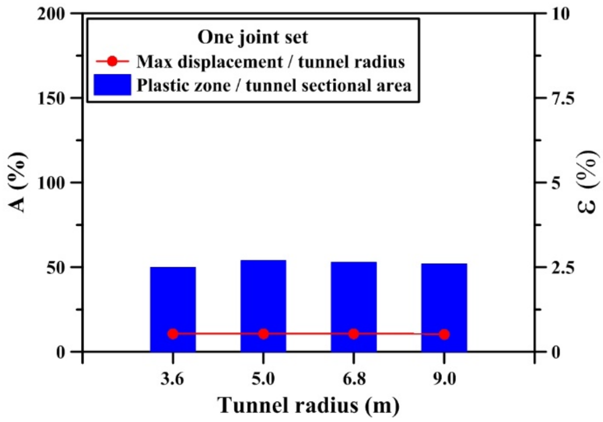
Joint set	Joint dip angles γ (°)	Joint spacing *S* (m)
Non	—	—
One	30	0.6
Two	30/-30	0.6/0.6
Three	30/90/-30	0.6/0.6/0.6

Table 3 Input support parameters for numerical simulations

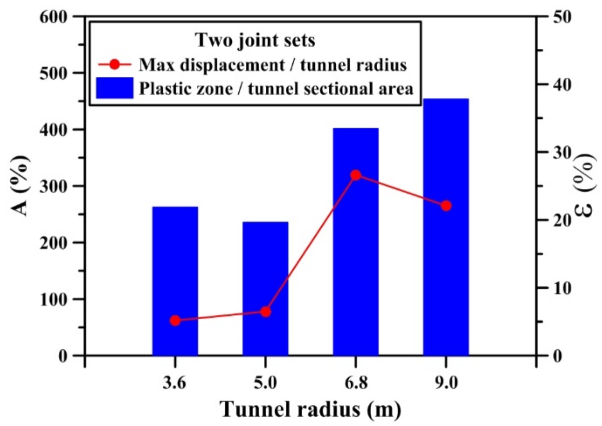
Shotcrete	Thickness t (m)	0.10
	Deformation modulus E (GPa)	10
	Area in unit tunnel length A (m^2)	0.10
	Moment of initial I (m^4)	8.33×10^{-5}
	Plastic moment M_p (kN-m)	5.25×10^{4}

deformation rock around a tunnel. Notably, the scale effect in the tunnel dependents on its radius. Figure 5 shows the simulated results concerning the sensitivity of the rock parameters to normalized tunnel displacement ε. The case with simulated strain more than 0.2 is indicated by a question mark for better presentation. While the compressive strength of the joint wall (*JCS*), the joint roughness coefficient (*JRC*) and friction angle of joint surface ($\emptyset_b$) increases, the ε decreases because the zone in which joint sliding failure occurs becomes smaller; while *JCS*, *JRC* and $\emptyset_b$ decreases, ε increases rapidly. As the deformation modulus (E_m) and cohesion (coh) of intact rock increases, ε increases. The significant difference between the strength and deformation characteristics of the intact rock and joint sets leads to the excavation-induced disturbance that is centered in the joint part of a rock mass, resulting large shear displacement in joints and increasing ε. The maximum closure (u_n^m) and initial normal stiffness (k_{ni}), which are the two parameters that describe the closure behavior of the joint surface, have a limited influence on the scale effect related rock deformation around a tunnel.

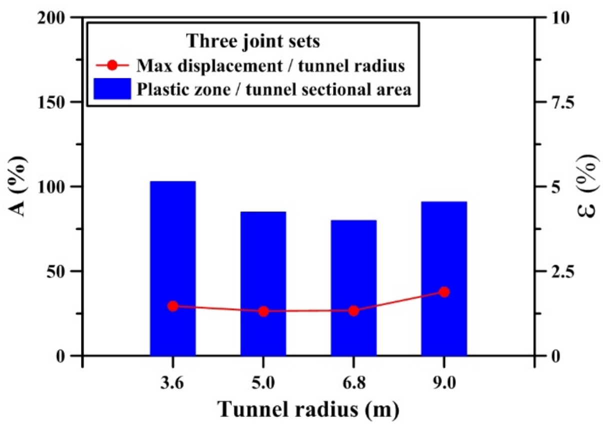
Wang (2014) suggested that, when the cross-section of a tunnel is large, the nonlinear constitutive model of the rock masses that was proposed by Wang and Huang (2009) can be utilized along with a detailed site investigation to investigate the influence of scale effect of a rock mass and the anisotropy in the strength and deformation that is induced by tunnel excavation. The three-dimensional rock deformation near the intersections of shafts and tunnels can be obtained by using the simulated two-dimensional rock deformations to back-calculate the equivalent engineering parameters using the equivalent continuum concept, and the scale effect of a rock mass can then be elucidated using these equivalent parameters by conventional three-dimensional numerical analyses. Figure 6 shows the influence of tunnel radius on ε, among which various mechanical parameters for joint sets are also considered, i.e., a 1.75 times of *JRC*, a 1.50 times of *JCS*, and a 1.20 times of $\emptyset_b$ (the values of *JRC*, *JCS* and $\emptyset_b$ are listed in Table 2). The value of ε increases significantly with the tunnel radius, especially above 6.8 m. The *JRC*, *JCS* and $\emptyset_b$ in Figure 6 and Table 2 were magnified by various factors to prevent numerical unstable caused by excessive rock deformations when the tunnel radius is large.



(a) One joint set

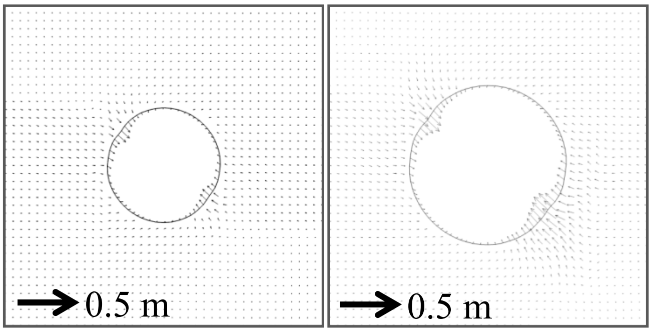


(b) Two joint sets

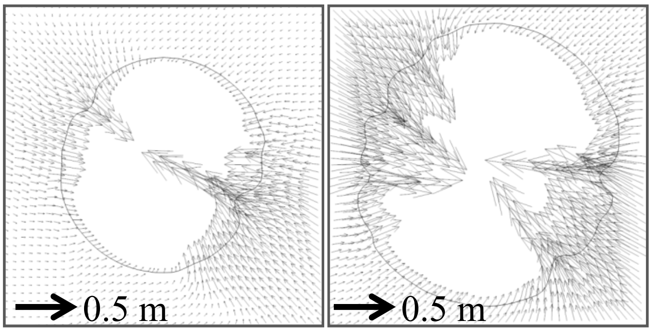


(c) Three joint sets

Figure 3 Simulated results of plastic zone area and radial strain of surrounding rock under various tunnel radii. The plastic zone is normalized by cross-sectional area of the tunnel, and the maximum radial strain is obtained by the maximum displacement dividing the tunnel radius. For a rock mass contains (a) one joint set, (b) two joint sets, and (c) three joint sets



(a) Tunnel radius=3.6 m (b) Tunnel radius=5 m



(c) Tunnel radius=6.8 m (d) Tunnel radius=9 m

Figure 4 Anisotropic deformation surrounding a tunnel in a rock mass with two joint sets

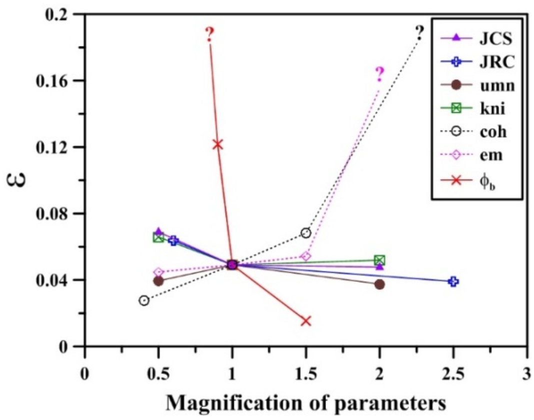


Figure 5 Simulated results for sensitivity of rock parameters. The question marks indicate that simulated strains of tunnel surrounding rock exceed 0.2

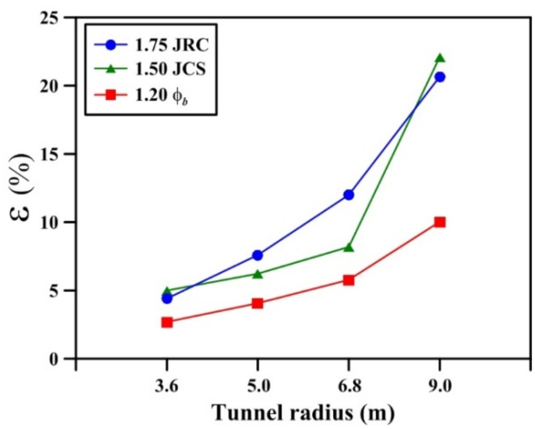
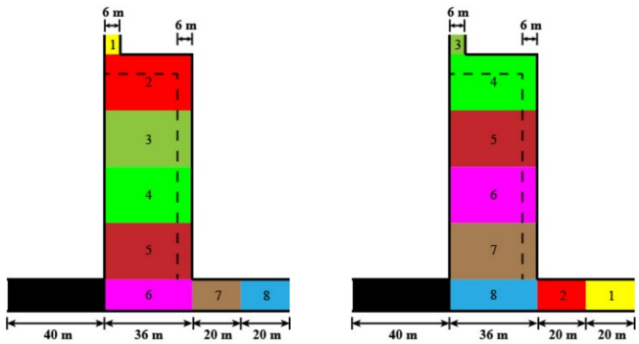


Figure 6 Influence of tunnel radius on ε

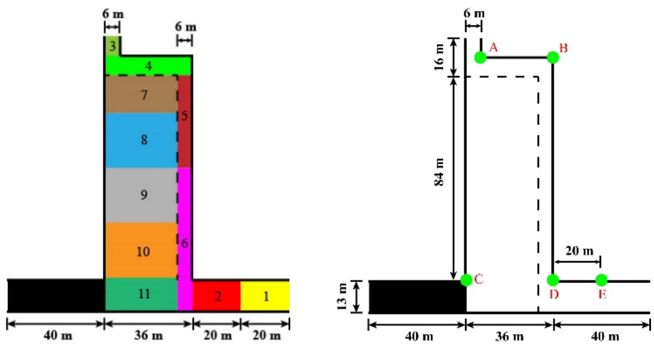
3.2 Excavation sequence for intersection between a shaft and a rock tunnel

The rock near the intersection between a shaft and a rock tunnel suffers from multiple disturbances that are caused by ordered excavation, and alters the stress and strain in the rock mass. The initial three-dimensional stress condition (that all three principal stresses are compressive) may become two-dimensional, or even uniaxial, such that the conventional two-dimensional tunnelling theorem and numerical simulation do not apply. The engineering characteristics of a rock mass depend on the stress-path. The order of excavation and support installation, and the time when the ground improvement is performed significantly influence the response of the rock that surrounds the intersection.

Three-dimensional numerical simulation is popularly utilized to investigate the variations of stress and strain of rock that surrounds an intersection that is excavated in a particular sequences. A proper understanding of the interaction between the excavation and the rock support, improves the effectiveness of the design and construction of the intersection between the shaft and a rock tunnel. Taking the intersections between the shaft and the tunnel in the Dawanping sediment sluicing tunnel in northern Taiwan and between the shaft and tunnel in the Tsengwen sediment sluicing tunnel in southern Taiwan as examples, Wang (2014) applied three-dimensional numerical simulation to investigate the rock deformation surrounds the intersection under different excavation schemes. The aforementioned scale effect has been also taken into account. Figure 7 shows three excavation schemes simulated and some representative corners where the variations of stress and strain of rock are monitored.



(a) Stages of excavation sequence I (b) Stages of excavation sequence II



(c) Stages of excavation sequence III (d) Monitoring locations in numerical simulations

Figure 7 Various excavation sequences and monitoring positions in numerical simulation

Figure 8 presents a typical numerical model. Figure 9 plots the variations of the maximum and minimum principal stresses under various excavation sequences. Through a three-dimensional numerical simulation, an appropriate excavation scheme can be determined by minimizing the difference between the maximum and minimum principal stresses during corresponding ordered excavation, and the time for installing the rock support, and even for improving the ground, can be elucidated accordingly.

3.3 Monitoring and necessary control of rock deformation around intersection

Monitoring the response of surrounding rock to an underground excavation is indispensable to the practical implementation of modern tunnelling theory and associated engineering techniques. Regardless of engineering geological conditions exposed on excavated rock surface is well interpreted or not, associated determination and installation of rock supports can be evaluated appropriately later on based on the monitoring results and timely reinforcement to modified and return feedback to subsequent construction. Conventionally rock deformation monitoring method that involves measuring the displacements of three to five points on tunnel wall can be used to estimate simple deformation mode for double-lane tunnels. The measured displacements are typically inward with various magnitudes. The deformation modes of the wall that surrounds a tunnel become increasingly complicated as its excavation radius increases, i.e., protruded displacements and limited displacement be observed in distinct locations, increasing the difficulty of monitoring and providing insufficient data to elucidate tunnel behavior. The deformations of the rock that surrounds an intersection between a shaft and a tunnel are multidirectional with significantly varying magnitudes. The conventional two-dimensional approach is used to monitor the convergence of tunnel walls at constant intervals, and typically fails to reveal such deformations. Recently developed approaches such as the photogrammetric method (Wang *et al*., 2009, 2010; Jaw *et al*., 2015) and ground-based LiDAR (Light Detection And Ranging) (Han *et al*., 2013a, b) can rapidly acquire both images and coordinates of tunnel walls with a precision of millimeters, possibly providing precious monitoring of tunnel construction with large cross-sections and intersections.

Wang *et al*. (2013) and Li (2013) proposed an advancing technique for rapidly evaluating engineering geological condition and support performance in working face that applies ground-based LiDAR to obtain precise point cloud data in the vicinity of tunnel faces right after an excavation round. The point clouds densely and precisely describe the excavated periphery, and can be used to evaluate the results of excavation. Through analyzing the point cloud data, the characteristics of various exposed joint sets on the excavating face, providing information on their attitudes, spacing, persistence and roughness coefficients (Yang *et al*., 2014). Accordingly, potential geological risks for subsequently excavation can be quick evaluated. Successively scanned point clouds can be superimposed to analyze the thickness of shotcrete, the locations of rockbolts and the displacements of tunnel walls, providing useful information for the evaluation of support performance and the need for reinforcement before the working face becomes far away. The results of the evaluation of excavation, support and potential geological risks provide early warning of engineering disasters and timely quantitative information that is required to implement auxiliary countermeasures such as fore-poling installation, favoring deformation control in working faces of a tunnel - especially near a three dimensional intersection.

Figure 10 illustrates an application of ground-based LiDAR on rock deformation monitoring around a sediment sluicing tunnel in southern Taiwan. Rock deformation near the three-dimensional intersection between the shaft and the main tunnel and the enlarged stilling pool section are precise monitored. The geological conditions, excavation and support performance in the working face, are also rapidly evaluated based on the methodology of Wang *et al.* (2013). The enlarged stilling pool section connects to outlet section that formed by two large tunnels, a central pillar-like rock between these two tunnels remains unexcavated and supported to enhance the stability of such a huge excavation. The crown part of northern tunnel was excavated first. Right after the crown of southern tunnel was excavated later on, LiDAR scan results indicated that the crown part moves to north with a horizontal displacement of several millimeters, and longitudinal cracks were also observed in the scanned image. Additional rock bolts and anchors are applied before the successive excavation, and the rock displacement surrounding the excavation is then suppressed. The results of ground-based LiDAR monitoring provides timely and precious rock displacement data during the successive excavations in the intersection and the enlarged stilling pool section, which significantly improves the control on rock deformation during construction.

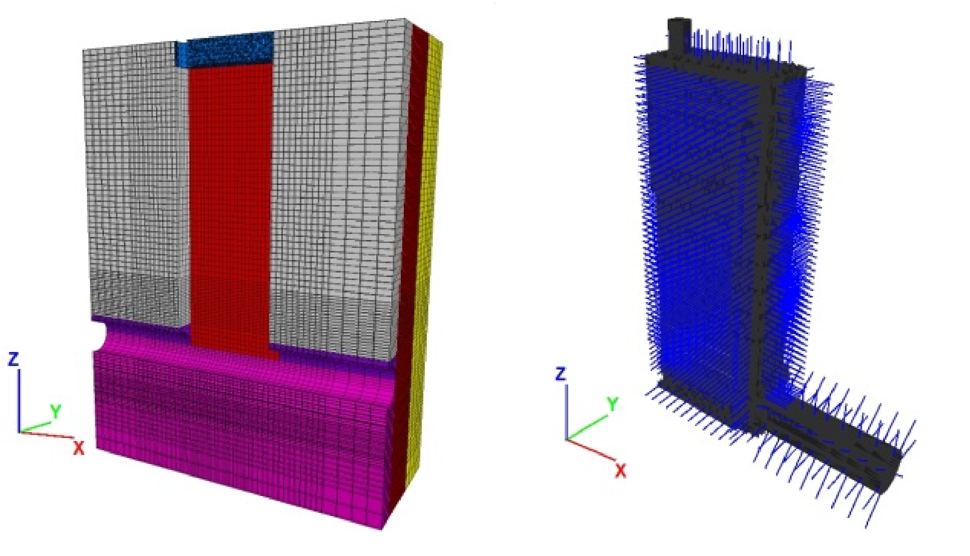
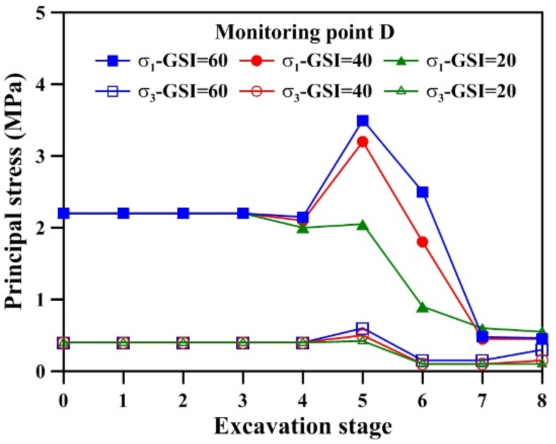


Figure 8 Representative numerical model



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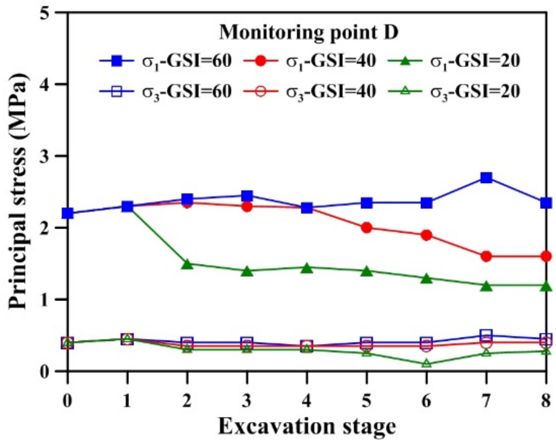

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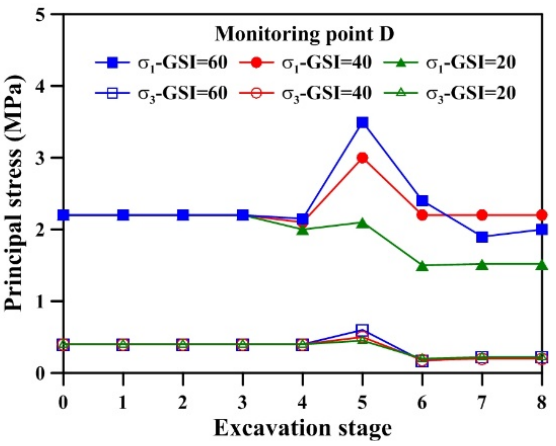

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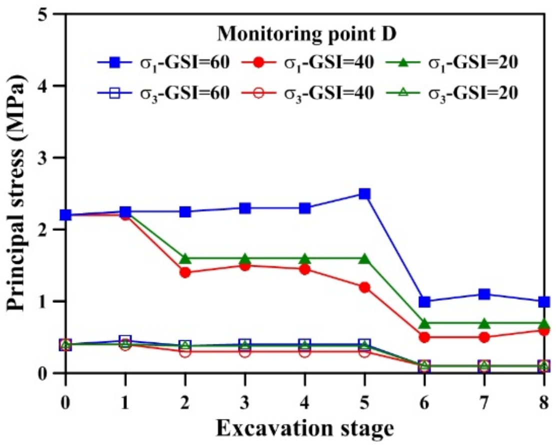

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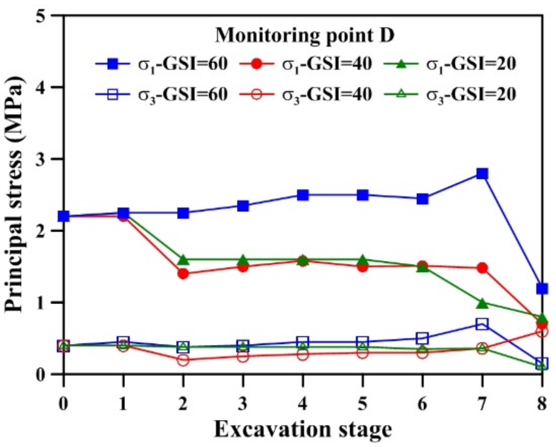
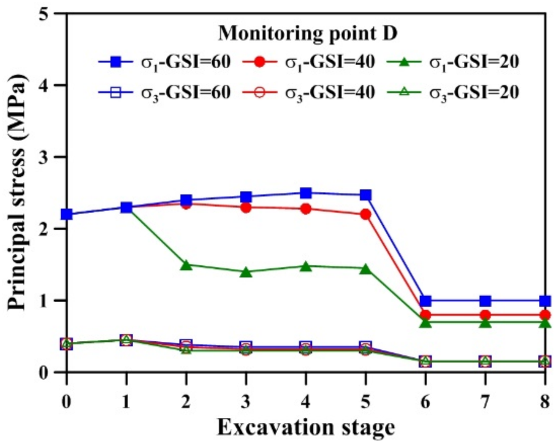
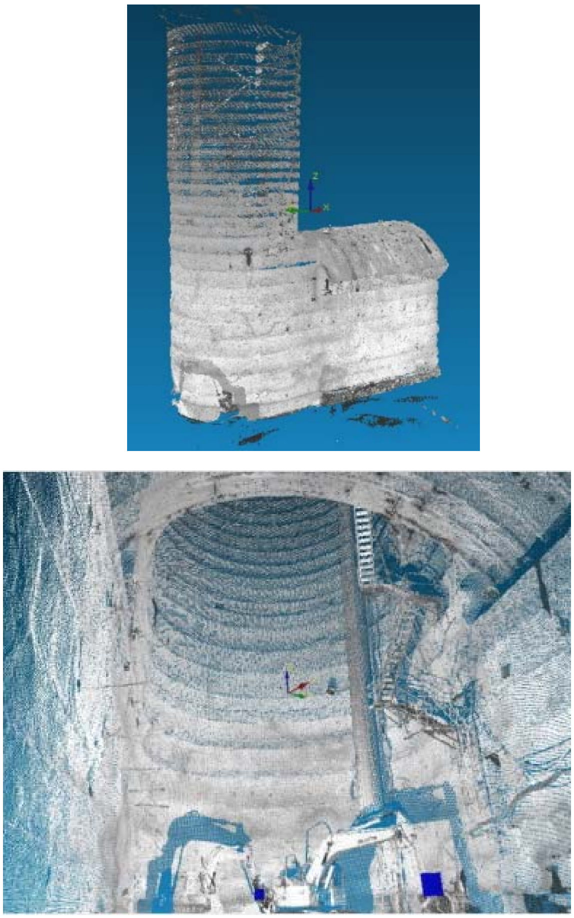


(c) Unsupported of II

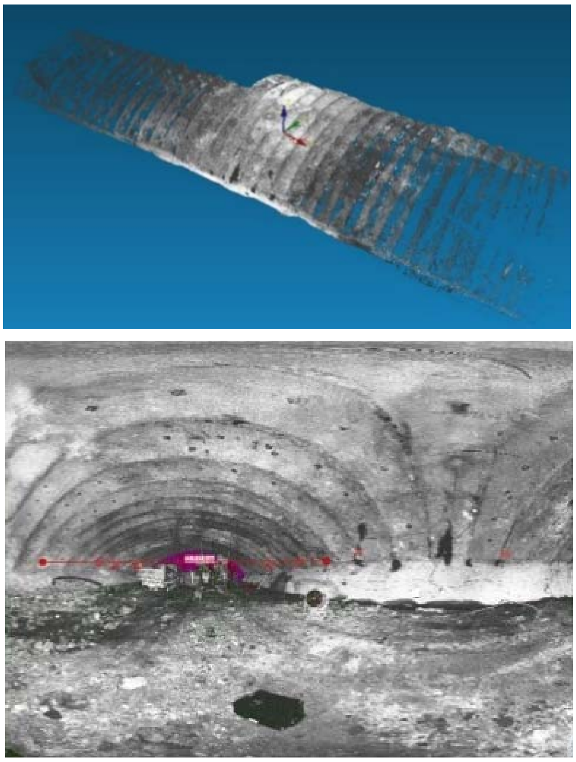


(f) Supported of III

Figure 9 Maximum and minimum principal stresses at monitoring locations for various excavation sequences under distinct geological strength indices



(a) Intersection between shaft and main tunnel



(b) Enlarged stilling pool section

Figure 10 Scanning results obtained using ground-based LiDAR

3.4 Mitigation of groundwater ingress for shaft construction using hydrogeological investigation approach

A shaft resembles a well for collecting groundwater. Construction difficulties that are caused by groundwater are consequential in the excavation of a shaft without appropriate measures to mitigate the inflow of groundwater. Such difficulties might worsen the construction of an intersection between a shaft and a tunnel, even stabilizing the surrounding rocks. Therefore, the mitigation of groundwater ingress in the beginning stage for a shaft excavation is essential for ensuring that its rate of construction is acceptable. Water-proof grouting and the installation of a pump pit are commonly conducted in conventional shaft construction. The former can be performed at the ground surface before the excavation of the shaft to reduce the permeability of the surrounding rocks, or during construction after the groundwater has flowed into the shaft. Groundwater inflow with a large water head can reduce the effectiveness of sealing grouting because seepage pressure that is caused by groundwater may leach out the grouting materials. The installation of a pump pit generally takes into account the influence of construction passageways. Therefore, selecting and planning an appropriate countermeasure that suits local circumstances to reduce the influence of groundwater are important in shaft excavation.

A hydrogeological investigation was conducted in the initial stage of excavation of the shaft of Caopu Tunnel, as part of the South Link Highway Improvement Project. A detailed geological surface survey, hydrogeological boring (Figure 11) and associated borehole televiewer scanning were used to investigate the locations of fractured zones into which the shaft run and possible spatial distributions of these fractured zones. Results concerning fracture distributions indicate the specific packed sections that are to undergo injection tests to determine the permeability of various fracture sets and potential preferential paths of groundwater flow. A near-field hydrogeological model is proposed based on aforementioned investigation results (Figure 12) (Zhan *et al*. 2013, Wang, 2014, Wang *et al*., 2015a, b). Based on the hydrogeological model, corresponding strategies for groundwater inflow mitigation are developed, including pumping wells installation in the ground, cement grouting from the ground and in the shaft. After the application of these measures, the discharge of water into the shaft is below the design value. The secure excavation of the shaft validates the hydrogeological investigation and associated mitigation measures.

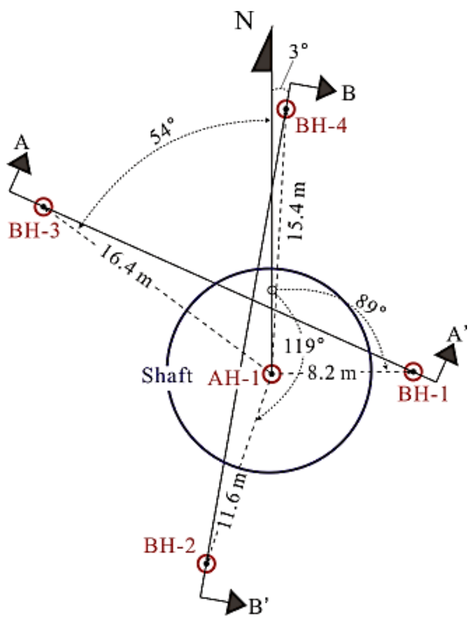


Figure 11 Layout of hydrogeological borehole for the shaft construction of Caopu Tunnel

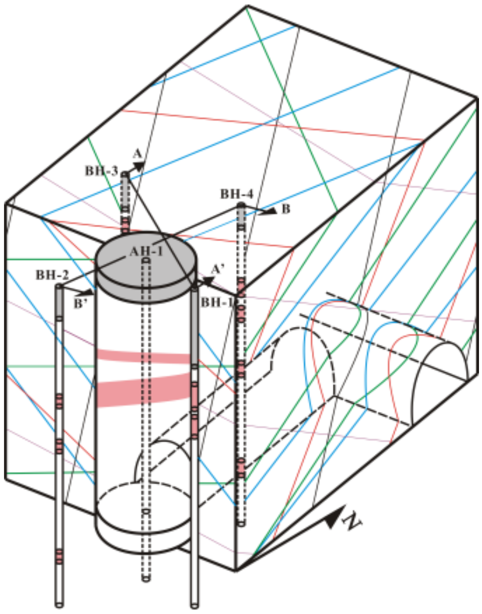


Figure 12 Hydrogeological model close to the shaft site of Caopu Tunnel

4. CONCLUSION

Taiwan is located in a collision belt of tectonic plates and suffers from extensive tectonic activities, so the engineering characteristics of rocks in Taiwan are generally inferior to those of competent rocks, found in other countries. Geotechnical engineering herein Taiwan invariably confront many challenges. The design and construction of an intersection between a shaft and a tunnel are typical. Tens of shafts and their intersections with connecting tunnels have been built in past decades, and engineers have learned much about geological investigations, geotechnical analysis, design and construction. This manuscript introduces four representative challenges, which are the significant scale effect of rock masses that arises from excavation with large cross-sections, difficulties of construction that are caused by complicated arrangement of underground excavation, difficulties in controlling rock deformation near the intersections and groundwater ingress. Construction practices have revealed that abovementioned strategies and countermeasures to overcome these difficulties are successful, and can be referred to similar projects.

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