Abstract: Since the construction of the first expressway in the 1970s, the total length of expressways in Taiwan has increased to over 1 000 km, of which 40 km are aligned with tunnels. These twin-tube tunnels, which have two or three lanes in each tube, are characterized by large cross-sections. Due to the complicated topography and heterogeneous geological conditions of Taiwan, tunnel construction has encountered many difficulties. Thus, many advanced excavation methods were developed during tunnel construction. To satisfy the concurrent requirements of safety, economy and efficiency, new construction methods and techniques should be developed or introduced. Moreover, environmental protection and ecological conservation must be paid increasing attention to the goal of substantial development.

Key words: expressway tunnel; expressway network; environmental protection; ecological conservation; sustainable development

1 Introduction

Expressway No.1, the first expressway in Taiwan, China, was opened for traffic in 1978, leading to rapid economic growth in Taiwan. The number of vehicles also increased dramatically in a short period of time. Subsequently, expressways No.3, 5 and 6 were constructed and opened for traffic within the following three decades. Expressway No.1 was constructed mainly in the western plain area. Thus it has only one twin-tube tunnel on its alignment. Expressway No.3 mostly passes through the western foothills area. Thus, the number and length of tunnels were significantly increased compared to those of expressway No.1. The Taipei-Ilan section of expressway No.5 penetrates the Hsuehshan range, resulting in almost one-third of its alignment going through tunnels. In the future, expressway projects will pass through the rugged terrain in the eastern and central regions of Taiwan. The heavy tunneling works in unfavorable geological conditions will present a great challenge to the tunnel construction.

More than thirty years have elapsed since the construction of the first expressway. Since then, geotechnical science and technology have progressed significantly, and engineers have also gained many experiences from the past tunneling works. Currently, the local inhabitants are demanding on a much higher standard of living. Besides the improvement of transportation quality, environmental protection and ecological conservation must be taken into account increasingly, thereby the goal of sustainable development should be achieved.

2 Topographic, geological and hydrologic features of Taiwan

The island of Taiwan lies about 150 km off the southeastern coast of Mainland China, separated by the Taiwan Strait. The longitudinal axis of the Taiwanese mainland extends roughly from north to south with a length of 385 km. The maximum width is 143 km. The island occupies a total area of around 36 000 km².

Taiwan is located in the suture zone of the Eurasian Continental Plate and the Philippine Sea Plate. Due to tectonic activity, the island is largely covered by mountains, with relatively fewer plain areas. Therefore, its geological conditions are very complicated. The central range, with a north-to-south axial length of
around 350 km, forms the backbone ridge of Taiwan. In this range, there are more than 25 mountains with a height of 3 km above the sea level. One significantly high range is distinguished to the west of the main backbone ridge of the central range, namely, the geologically distinct Hsuehshan range. The central range slopes extend westward into foothills and then into tablelands and coastal plains. The east of the central range is the coastal range. It is 140 km long and 10 km wide, with peak height ranging from 1 to 1.5 km above the sea level.

From west to east, Taiwan can be divided into seven major geological areas, as shown in Fig.1 [1]:

1. Penghu islands. The Penghu island group in the Taiwan Strait exposes extensive basalts from the Pleistocene age.
2. Coastal plain. Most of the coastal plain is Quaternary deposits composed of mudstone, siltstone, shale, sandstone and conglomerate.
3. Western foothills. This area is composed of Oligocene to Pleistocene clastic sediments. The rock formations are mainly alternations of sandstones and shale with locally interspersed limestone and tuff lenses.
4. Western central range belt. This is a broad Tertiary sub-metamorphic belt. It can be further subdivided into two lithotectonic belts, i.e. the western Hsuehshan range belt (IVa) and the eastern backbone ridge belt (IVb).
5. Eastern central range belt. This belt is underlain by a Pre-Tertiary metamorphic complex exposed largely on the eastern flank of the central range. This area is subdivided into the western Taroko belt (Va) and the eastern Yuli belt (Vb).
6. Taitung longitudinal valley. This valley has been recognized as a suture zone between the Eurasian Continental Plate and the Philippine Sea Plate. It separates the central range and coastal range.
7. Coastal range. This area is underlain by the Neogene sediments. The rocks are characterized by an abundance of volcanic derivatives, poorly sorted volcanioclastic sediments, turbiditic clastic rocks, and chaotic melange.

Taiwan has a subtropical oceanic climate. The average annual rainfall is up to 2500 mm. However, the variability of rainfall is significant in different terrains and during different seasons. Especially in the summer and autumn, intense precipitation often causes floods and landslides [2]. Thus, with respect to the issues of tunnel excavation, not only the unfavorable geology but also the abundant groundwater must be taken into account by geotechnical engineers.

3 Statistics of expressway tunnels

The constructed expressway length in Taiwan has reached 1000 km, and the additional length of expressway in the planning or design stage is around 420 km. The expressway network and the geological areas are shown in Fig.1. The 373 km-long expressway No.1 runs through the western plains and some hilly areas, and there is only one twin-tube tunnel at the northern end of its alignment. The 518 km-long expressway No.3 completed in 2004 passes through Taiwan from north to south. Most of the routes run through the western foothills, and there are 14 twin-tube tunnels, totaling 13.7 km in length (thus, the total length of two traffic ways is 27.4 km).

To balance the regional development of eastern and western Taiwan, the 55 km-long Taipei-Ilan section of expressway No.5 was opened for traffic in 2006. This was the first expressway penetrating the central range in Taiwan, and more than one-third of the route is in tunnels. In this project, there are five sets of tunnels totaling 20.1 km in length. Among these tunnels, the
12.9 km-long Hsuehshan tunnel is the longest one. The Hsuehshan tunnel is composed of two main tunnels and one pilot tunnel. At present, it is still the longest road tunnel in Taiwan.

The 38 km-long Nantou section of expressway No.6 starts in Wufong, Taichung County, and ends at Puli, Nantou County. There are three twin-tube tunnels totaling 4.3 km in length. This project was opened for traffic in 2009. According to the expressway network plan of Taiwan, this project will be extended eastward into Hualien County to connect with the expressway No.5 in the future.

The future expressways, such as the eastern expressways, the central island-cross expressways and the southern island-cross expressways, will all pass through the mountainous terrain. Therefore, a large amount of tunneling work is anticipated. According to the plan, there will be many twin-tube or three-tube tunnels to be constructed, totaling 128 km in length. The single length of some tunnels may exceed 10 km. The construction of these long tunnels associated with large overburden depth, geothermal conditions and high-pressure groundwater will present great challenges to the engineers. The statistics of Taiwan expressway tunnels are listed in Table 1.

### Table 1 Statistics of expressway tunnels in Taiwan.

<table>
<thead>
<tr>
<th>Project</th>
<th>Alignment length (km)</th>
<th>Number of tunnels</th>
<th>Tunnel alignment length (km)</th>
<th>Total tunnel length (km)</th>
<th>Tunnel length ratio (%)</th>
<th>Maximum tunnel length (km)</th>
<th>Maximum overburden depth (m)</th>
<th>Working stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expressway No.1</td>
<td>373</td>
<td>1</td>
<td>0.5</td>
<td>1.1</td>
<td>0.13</td>
<td>0.5</td>
<td>120</td>
<td>Operation</td>
</tr>
<tr>
<td>Expressway No.3</td>
<td>518</td>
<td>14</td>
<td>13.7</td>
<td>27.4</td>
<td>2.64</td>
<td>1.9</td>
<td>300</td>
<td>Operation</td>
</tr>
<tr>
<td>Taipei-Suao section of expressway No.5</td>
<td>55</td>
<td>5</td>
<td>20.1</td>
<td>53.2</td>
<td>36.55</td>
<td>12.9</td>
<td>750</td>
<td>Operation</td>
</tr>
<tr>
<td>Wufong-Puli section of expressway No.6</td>
<td>38</td>
<td>3</td>
<td>4.3</td>
<td>8.6</td>
<td>11.32</td>
<td>2.5</td>
<td>350</td>
<td>Operation</td>
</tr>
<tr>
<td>Puli-Hualien section of expressway No.6</td>
<td>90</td>
<td>22</td>
<td>47.4</td>
<td>116.2</td>
<td>52.67</td>
<td>15.1</td>
<td>1 600</td>
<td>Planning</td>
</tr>
<tr>
<td>Suao-Hualien section of expressway No.5</td>
<td>86</td>
<td>11</td>
<td>39.8</td>
<td>79.6</td>
<td>46.28</td>
<td>10.2</td>
<td>1 200</td>
<td>In design</td>
</tr>
<tr>
<td>Hualien-Taitung section of expressway No.5</td>
<td>173</td>
<td>3</td>
<td>8.2</td>
<td>16.5</td>
<td>4.74</td>
<td>4.0</td>
<td>500</td>
<td>Planning</td>
</tr>
<tr>
<td>Taitung-Pintung section of expressway No.5</td>
<td>55</td>
<td>5</td>
<td>23.7</td>
<td>66.7</td>
<td>43.15</td>
<td>12.9</td>
<td>1 700</td>
<td>Planning</td>
</tr>
<tr>
<td>Fongyen-Dakeng section of expressway No.4</td>
<td>15</td>
<td>7</td>
<td>8.5</td>
<td>16.9</td>
<td>56.67</td>
<td>2.1</td>
<td>250</td>
<td>Planning</td>
</tr>
</tbody>
</table>

Total 1 403 71 166.2 386.2 11.85

### 4 Design and construction of expressway tunnels

The development of rock mechanics and technology has led to new and more rapid design and construction concepts in the past decades. The issues of rock mass classification, tunnel analysis and design, tunnel excavation and support, monitoring and portal treatment are described in the following sections.

#### 4.1 Rock mass classifications

The conventional drill-and-blast (D&B) method was used in the tunnel construction of expressway No.1. The Terzaghi’s rock load classification method was used for rock tunnel excavation and support. The rock load was evaluated according to rock conditions, tunnel dimensions and water level [3]. However, this classification is not suitable for modern tunneling methods that adopt shotcrete and rock bolts.

Quantitative rock mass classifications such as the rock mass rating (RMR) system developed by the Bieniawski and Q system by Barton et al. have been widely used in tunneling works recently. In particular, the RMR system has been popularly used for tunneling...
in Taiwan. In general, the rock mass classifications of expressway tunnels in Taiwan are divided into six classes, i.e. classes I–VI, where a larger class number indicates weaker rock mass properties.

The geological and topographic features in Taiwan vary greatly. For example, the Lantan tunnel of expressway No.3 is located in southern Taiwan. Its stratum is the Liushuang formation, which is mainly composed of silt, mudstone and loosely consolidated sandstones. The geological condition of the Puli tunnel of expressway No.6 is mainly the Toukoshan formation, consisting of loosely consolidated gravels filled with sand and clay. The above-mentioned geological conditions are not suitably rated by the RMR or Q system. Instead, qualitative classifications evaluated from strata characteristics, compositions of geological materials and their sensitivity to water, are more suitable for tunneling in these weak and unconsolidated ground conditions.

Considering the complex ground conditions in Taiwan, several consulting engineering companies were tasked with developing the public construction commission rock mass classification (PCCR) system during 2000–2003. This system classifies all rocks in Taiwan into types A, B, C and D according to their mechanical properties and geological characteristics obtained in laboratory, field tests, past tunneling experiences and available literatures [4].

In general, rocks of type A are commonly hard and brittle. This type includes most of metamorphic rocks, volcanic rocks and high-strength sedimentary rocks. In accord with the International Society of Rock Mechanics (ISRM) grading, rocks of type A can be classified as the medium-extremely strong rocks (R3–R6 in ISRM grading) listed in Table 2 [5]. Rocks of type B commonly contain weak sediment, such as the rocks located in the western foothills. This type of rocks coincides with the weak rock (R2 in ISRM grading). Rocks of type C include poorly cemented rock whose uniaxial compressive strength is less than 5 MPa. Soils and rocks with mechanical behaviors governed by fine particles also belong to this type. Rocks of type D indicate those materials with a percentage of coarse grains exceeding 50%. Conglomerates and breccias belong to this type.

Rocks of types A and B are classified according to the RMR, whereas rocks of types C and D are qualitatively classified according to geological materials, degree of cementation and groundwater conditions. The geology of most tunnels in Taiwan should fall within the type A, whose criteria of classification are listed in Table 3 [6].

### Table 2: Field estimation of uniaxial compressive strengths [5].

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
<th>Uniaxial compressive strength (MPa)</th>
<th>Field estimation of strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>R6</td>
<td>Extremely strong</td>
<td>&gt;250</td>
<td>Rock material can only be chipped under repeated geological hammer blows</td>
</tr>
<tr>
<td>R5</td>
<td>Very strong</td>
<td>100–250</td>
<td>Requires many blows by a geological hammer to break intact rock specimen</td>
</tr>
<tr>
<td>R4</td>
<td>Strong</td>
<td>50–100</td>
<td>Specimen can be broken by at least a single blow of a geological hammer</td>
</tr>
<tr>
<td>R3</td>
<td>Medium strong</td>
<td>25–50</td>
<td>Specimen can be broken by a single blow of a geological hammer, knife may not scrape the surface</td>
</tr>
<tr>
<td>R2</td>
<td>Weak</td>
<td>5–25</td>
<td>Difficult to cut the material with a knife</td>
</tr>
<tr>
<td>R1</td>
<td>Very weak</td>
<td>1–5</td>
<td>Material can be crumbled under firm blows of geological hammer pick, and be shaped with a knife</td>
</tr>
<tr>
<td>R0</td>
<td>Extremely weak</td>
<td>0.25–1</td>
<td>Indented by thumbnail</td>
</tr>
</tbody>
</table>

### Table 3: Rock mass classifications and mechanical parameters of rocks of type A [6].

<table>
<thead>
<tr>
<th>Rock class</th>
<th>RMR</th>
<th>Strength parameters</th>
<th>In-situ modulus of deformation, $E_m$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$RMR$</td>
<td>Cohesion (MPa)</td>
<td>Internal friction angle ($^\circ$)</td>
</tr>
<tr>
<td>I</td>
<td>≥81</td>
<td>17.78</td>
<td>55</td>
</tr>
<tr>
<td>II</td>
<td>80–61</td>
<td>7.08</td>
<td>47</td>
</tr>
<tr>
<td>III</td>
<td>60–41</td>
<td>2.82</td>
<td>39</td>
</tr>
<tr>
<td>IV</td>
<td>40–21</td>
<td>1.12</td>
<td>31</td>
</tr>
<tr>
<td>V</td>
<td>20–11</td>
<td>0.45</td>
<td>23</td>
</tr>
<tr>
<td>VI</td>
<td>≤10</td>
<td>0.18</td>
<td>15</td>
</tr>
</tbody>
</table>

### 4.2 Analysis and design of expressway tunnels

The design methods currently available for assessing the stability of tunnels can be categorized as either analytical or empirical methods.

1. Analytical design methods. Analytical design methods utilize the analysis of stresses and deformations around openings. They mainly include such techniques as closed-form solutions and...
numerical analyses. Closed-form solutions are valuable in the conceptual understanding of excavation behaviors and calibration of numerical models. For design purposes, however, these models are restricted to simple geometrical and material modes. They are limited in practical tunnel design.

Computer-based numerical analyses (finite elements, finite difference, boundary element, etc.) have played an important role in recent decades. Numerical methods are available for irregular excavation shapes. Moreover, these methods can utilize more reasonable constitutive laws to account for different properties of rock masses. Programs such as FLAC, PLAXIS and PHASE³ are commonly used in Taiwan.

(2) Empirical design methods. Engineering rock mass classifications constitute a well-known empirical approach for assessing tunnel stability. In the planning and design stages of tunnel projects, the rock masses are evaluated and classified into several grades. The evaluation factors include geological properties (uniaxial compressive strength, rock mass structures, etc.), environments (topography, groundwater, etc.), and engineering characteristics (cross-sectional area, factor of safety, etc.). The excavation sequences and supports of tunnels are designed by referring to rock mass classifications and past experiences. In the construction stage, the stability can be evaluated from back analyses of monitoring results. Design adaptation with the aid of monitoring results during construction, which can verify the original design, is termed “ongoing design”.

Due to the complicated geological properties of a given tunneling site, the selection of appropriate model parameters and constitutive laws for ground materials is difficult. Therefore, the empirical design approaches associated with the numerical analyses are the main tunneling design concepts used in Taiwan. The design methods mentioned above should be verified by back analyses based on field monitoring data in the construction stage.

4.3 Evaluation of rock mass parameters

The evaluation of rock mass parameters is significant for tunnel design and analysis. In general, the parameters of a rock mass include its strength and deformability. Besides referring to previous tunneling projects, most of the geomechanical parameters are obtained from laboratory and field tests, as are the empirical estimations, which take into account the rock material and structural properties. Considering the complex geological features in Taiwan, several empirical correlations have been proposed by local consultants in recent years. For example, based on case histories and previous studies, Yu [7] suggested the following equation for estimating the deformation modulus of a rock mass:

$$E_m = 10^{(GSI-10)/40} \left(\frac{\sigma_u}{250}\right)^{1/2}$$

(1)

where $E_m$ is the deformation modulus of a rock mass (GPa); $\sigma_u$ is the uniaxial compressive strength of intact rock (MPa); and $GSI$ is the geological strength index introduced by Hoek [8], providing a system for estimating the reduction in rock mass strength under different geological conditions.

Many geotechnical programs have been written in terms of the Mohr-Coulomb failure criterion, in which the rock mass strengths are defined by the cohesion $c$ and the internal friction angle $\phi$. The parameters $c$, $\phi$ and $E_m$ suggested by the PCCR system for rocks of type A are listed in Table 3 [6]. However, the parameters listed in Table 3 are only for reference in preliminary design. Rational parameters should be evaluated by relevant tests and case studies, and verified by the back analysis of field monitoring data during construction.

The excavation behaviors of three-parallel-tube Hsuehshan tunnel were also investigated by Chen et al. [9] using the finite element program PLAXIS. The parameters adopted for rock masses of classes IV and VI are listed in Table 4. The values of $\gamma$ and $\nu$ in Table 4 represent the rock specific weight and Poisson’s ratio, respectively; and $\Sigma M$ is the factor related to rock mass stress release, which is taken to be less than 1.0 [10]. Figure 2 shows the displacement vector and extreme total displacement (ETD) of this tunneling work during each excavation stage. The above analyses assume that the rock overburden depth is 300 m, the class of rock mass is IV, and the ratio of horizontal to vertical stresses, $k$, is 1.0. The center-to-center distance between the main tunnels and the pilot tunnel is 30 m, and the groundwater was not considered in these analyses.

| Table 4 Parameters of rock masses of classes IV and VI in Hsuehshan tunnel [9].
|
|---|---|---|---|---|---|---|---|
| Rock class | $\gamma_{dry}$ (kN/m³) | $\gamma_{wet}$ (kN/m³) | $E_m$ (kPa) | $\nu$ | $c$ (kPa) | $\phi$ (°) | $\Sigma M$ |
| IV | 23 | 25 | 1.25×10⁶ | 0.28 | 340 | 24 | 0.75 |
| VI | 23 | 25 | 6.0×10⁶ | 0.3 | 220 | 19 | 0.65 |

In-situ stresses play an important role in tunnel design. Hydraulic fracturing stress measurements were conducted at the site of Hsuehshan tunnel in the primary design stage. In-situ stress ratios, $k_{ii} = \sigma_{ii}/\sigma_{ij}$, and
were estimated to be 1.1 and 0.6, respectively, where $\sigma_v$, $\sigma_h$ and $\sigma_k$ represent the vertical stress, the maximum and the minimum horizontal stresses, respectively. The general direction of $\sigma_h$ is N30°E, approximately perpendicular to the tunnel axis. The data were also considered to be consistent with the tensile stress regimes found in northeastern Taiwan [11].

According to monitoring data from around 180 tunneling cases located in the central and eastern regions in Taiwan, Kuang and Wang [12] also developed an equation representing the ratio of horizontal to vertical stresses as follows:

$$k = 2H^{-0.098}$$

(2)

where $H$ is the overburden depth (m). These measurements are plotted in Fig.3.

### 4.4 Tunnel excavation methods

The conventional D&B excavation with steel support sets was commonly used in Taiwan before the 1970s. This was commonly referred to the “American steel support method” (ASSM). From the 1970s onward, the new Austrian tunneling method (NATM) was dominant in tunneling works. Especially from the 1980s onward, more and more tunnels for highways, railways, mass-rapid-transportation and hydroelectric projects have been built by the NATM in the past three decades.

Most of the expressway tunnels in Taiwan up to now were excavated by D&B (NATM) in a modified horseshoe shape. These two-lane or three-lane tunnels were commonly excavated in three stages, i.e. top-heading, bench and invert stages, as depicted in Fig.4. In the poor-quality rock masses or unfavorable topographic conditions, more sophisticated methods, such as double-side-gallery (Fig.5), have been adopted in tunneling works to ensure stability.
roadheader instead of the D&B method.

For the sake of environmental protection and shortening the construction period, three tunnel boring machines (TBMs), two for the main tunnels and one for the pilot tunnel, were imported for the excavation of the Hsuehshan tunnel. However, due to the unfavorable geology and heavy groundwater, the TBMs did not perform well in the construction process. The TBM in the northbound tunnel was buried in a major collapse due to a large water inrush of 750 L/s, which caused a serious delay. To speed up the tunneling advances, some additional working faces were created through shaft No.2 in the construction stage [13].

4.5 Tunnel supports

The tunnel supports can be divided into two parts, i.e. primary supports and inner concrete lining. The primary supports mainly include shotcrete, wire mesh, rock bolts, steel ribs, forepolings, etc. At present, wet-mixed steel-fiber shotcrete spread by robotic machine is widely applied to tunneling works. Also, lattice girders are popularly used instead of H-type steel ribs. In poor geological zones, rock tendons or self-drilling rock bolts are installed instead of conventional grouted rock bolts. In general, the tunnel portal section has a shallow overburden with weathered rock conditions. Therefore, a pipe-roof formed by steel pipes with the diameter of 10 cm and the length of over 10 m is installed for the sake of stability.

In compliance with the fast excavation rate of TBMs, concrete-segment lining is commonly used as primary support. The concrete segments are precast and cured at the manufacture’s site. Therefore, their quality is easier to be controlled. The gap between the segments and the rock surface is usually filled with pea-gravel and cement grouting.

Aside from the primary supports, the expressway tunnel also has an inner concrete lining with an average thickness of 30–60 cm. In addition to increasing tunnel stability, the concrete linings also have advantages of facilities installation and ventilation. Between the primary support and inner lining, there exists a waterproofing layer composed of a membrane and a nontextile.

4.6 Geotechnical measurements for tunneling

Tunnel excavation is a process that disturbs the existing equilibrium of rock masses and creates induced stresses around the opening, so that the rock masses could deform. This phenomenon should be monitored by geotechnical measurements. The measurement items include convergence, leveling, extensometer, inclinometer, measuring anchor, pressure cell, strain gauge, and so on. Figure 6 illustrates the geotechnical measurement layout for tunneling. The convergence and leveling measurements are extensively performed in the field for disaster prevention. Extensometers are also deployed often because the plastic zones of surrounding rocks can be evaluated from these measurements. Inclinometers are usually installed at the portal section to monitor the stability and interaction of tunnel and slope.

Three-dimensional deformation measurements for tunneling have been performed for the tunnels of expressways No.3 and 5. From these measurements, the longitudinal deformations along the tunnel routes and their orientations can be monitored. Moreover, the geological conditions in front of the excavation face can be predicted by data analysis. However, due to the fact that some practical and theoretical issues remain under study, these measurements are not widely used in the tunneling field at present.

4.7 Tunnel portal treatments

To avoid a negative impact on the environment, the tunnel portal excavation is always in a condition...
of shallow overburden. Considering the stabilities of the slope and tunnel works, forepolings or pipe roofs are installed before the tunnel is dug, followed by the installation of steel arches and shotcrete. After the portal structure is formed, the tunnel excavation can then be commenced. The schematic drawing of a typical portal construction is shown in Fig. 7.

In irregular topography and unfavorable geological conditions, some countermeasures are considered for portal construction. For example, the Corinthian slab method was used in the construction of tunnels for expressway No. 3. In this construction method, the soil above the tunnel crown is firstly removed, followed by the placing of crown concrete. Its enlarged ends are then supported by micropiles. Consequently, the tunnel is excavated and supported cautiously under the protection of a crown slab. The schematic drawing of this construction is shown in Fig. 8.

Most of expressway tunnels are twin-tubed in Taiwan. Each tube has two or three lanes. Due to unfavorable geological condition, most of tunnels should be closed with invert. Therefore, the excavation area is always 100–160 m². In the excavation process of a tunnel with a large cross-section, some obstacles, such as cracking, buckling, cave-in, etc., are unavoidable if unfavorable geology or groundwater inflow is encountered.

To minimize the demolition of residential buildings, the Hsintien tunnel of expressway No. 3 passes through the toe of an 80 m-high slope. Thus the tunnel underwent severely unbalanced ground pressures. Moreover, owing to the fact that the ramp of a nearby interchange merged into the north portal of this tunnel, a unique four-lane cross-section with an excavation area of 230 m² was created [14]. During construction, tremendous deformations, shotcrete cracking and steel-rib bucking occurred, and the entire slope was on the brink of collapse. To ensure the stability of the slope and ensure that the tunnel could safely pass through the toe, the construction team was forced to adopt more conservative and sophisticated measures. The countermeasures included bored piles, additional rock anchors, ground improvement and backfilling at the toe of slope. Moreover, the excavation method was changed to the double-side-gallery method and the strength of concrete linings was also increased. A diagram indicating the countermeasures employed for this tunnel and adjacent slope is shown in Fig. 9 [14].

5.2 Tunnel intersection

For emergency treatment, evacuation and maintenance purposes, cross-connection tunnels are arranged at designed intervals for expressway tunnels. Taking the Hsuehshan tunnel as an example, the intervals of cross-connection tunnels for pedestrian and vehicle are 350 and 1,400 m, respectively. Due to their large cross-sections and stress concentrations in rock masses, disasters such as abnormal deformation and
cave-in are frequently encountered at the intersection areas. For instance, the intersection of Puli tunnel of expressway No.6 is composed of twin-tube, one vehicle cross-connection tunnel with a parking bay and a construction adit. During construction, shotcrete cracking and steel-rib buckling occurred. To control the tremendous and consecutive deformations (Fig.10), a temporary invert was utilized for the top-heading and consolidation grouting was applied in the vicinity of the intersection. With these mitigating measures, the tunnel deformation was gradually stabilized [15].

Fig.10 Settlement curve of crown at the intersection of Puli tunnel [15].

There are three sets of ventilation shafts in the 12.9 km-long Hsuehshan tunnel. Each intersection is composed of shafts, caverns, main tubes and pilot tunnel, totaling seven tunnels (shafts), as shown in Fig.11. During the excavation progress, the stability of these intersections was reassessed when the actual geological conditions were revealed. With the feedback of monitoring data and three-dimensional numerical analysis, the ratio of strength to stress \( \sigma_{\text{on}} / P_0 \) at the site of shaft No.2 was found to be approximately 1.27, revealing an incipient condition of slightly squeezing [16]. After partial changes of construction sequences, with the help of auxiliary supports, these three ventilation intersections were successfully completed.

5.3 Compound excavation method

In general, TBM excavation is not as flexible as the D&B method. During the construction of Hsuehshan tunnel, to avoid the trapping of the TBMs in the poor geological section, the strata more than 2 000 m in the southbound tube were excavated with the compound excavation method. The top-heading of the tunnel was excavated by the D&B method with primary supports like steel-ribs, shotcrete, rock bolts, etc. The side footings of the top-heading were grouted and reinforced by micropiles, as shown in Fig.12. After completion of top-heading, the remaining parts (bench and invert) were excavated by TBM. The full section was primarily supported by precast concrete segments. The gaps between the segments and the shotcrete surface in the top-heading were filled with lean concrete or shotcrete.

5.4 Grouting and groundwater treatment

The geology of the southern section of Hsuehshan tunnel is the Szenleng sandstone formation, which stretches for a length of 3.6 km. This formation primarily consists of slightly metamorphosed quartzitic sandstone and argillite, which generally behaves as a hard and brittle rock with high hydrological permeability. Therefore, many disasters such as severe groundwater inrush and cave-in were encountered in this section. To reduce groundwater inrush and consolidate the rock mass, a conical grouting method was applied to the Szenleng sandstone formation [17]. In this method, the drilling holes were installed in a three-ring arrangement, as shown in Fig.13. A mixture of cement and water glass was injected into the holes of external rings to form a water barrier. Grouting used in the inner rings is pure cement mortar for ground improvement. In general, the length of drilling and grouting is 30 m, while the following excavation length is 25 m. However, the length of grouting and excavation was adjusted according to groundwater inflow and geological conditions.

The 438 m deep intake ventilation shaft No.3 is also located in the Szenleng sandstone layer. To reduce water inflow during the sinking of this shaft, a clay-cement grouting method, developed by the Ukrainian company STG, was applied by the construction team. The grout consists of clay slurry, cement, water glass and some additives. This highly hydro-sealing integrated grouting method effectively reduced water inflow during shaft excavation.
5.5 Application of advanced construction methods and materials

The ASSM was the main construction method for the tunneling of the first expressway. Here, heavy steel arches and steel or wooden laggings were the main components of primary supports. From the second expressway, the NATM became the dominant construction method in tunneling works. The smooth cross-section design and semi-rigid primary support used in this method are favorable for the self-supporting status of surrounding rocks. In addition, the excavation sequence and tunnel supports can be adjusted according to the monitoring results during construction. In general, the concepts of the NATM are more flexible than those of the ASSM.

The 12.9 km-long Hsuehshan tunnel was the first expressway tunnel penetrating the central range of Taiwan. In consideration of construction period, costs, environmental constraints and technology improvement, three double-shield telescoping TBMs were imported for the excavation of the Hsuehshan tunnel. This was the first time that rock tunnels were cut by TBMs in Taiwan. The cutter-head diameters of the TBMs for the main and pilot tunnels were 11.8 and 4.8 m, respectively; the total lengths, including shield and back-up system, were 239 and 177 m, respectively.

There are three sets of ventilation shafts along the Hsuehshan tunnel. Each set includes intake and exhaust shafts with a distance of 50 m. The 6 m- or 6.5 m-diameter shafts are covered with depths from 250 to 512 m. The depths of intake and exhaust shafts of shaft No.1 both exceed 500 m. To accelerate the penetration rate, the raise-boring method was adopted for the excavation of shafts No.1. In this method, a 31 cm-diameter pilot hole was first drilled from the ground surface down to the bottom of the shaft. Subsequently, a reaming hole, with a diameter of 244 cm, was excavated from the bottom up to the ground surface. After the completion of the reaming hole, the shaft was enlarged by the conventional sinking method. The mucking material was dropped down to the pilot tunnel located at the bottom of the shaft and mucked out to the deposit sites outside the tunnel. Figure 14 illustrates the procedures of the raise-boring method. During the construction of shaft No.1, the deviations of the pilot holes at the bottoms of intake and exhaust shafts were only 14 and 72 cm, respectively [13]. In other words, the deviation rates were 0.03% and 0.14%, respectively, for intake and exhaust ventilation shafts.
Along with the rapid developments in technology and society, several advanced materials have been applied in the construction of expressway tunnels. For instance, the application of remote-controlled and wet-mixed shotcrete in the Penshan tunnel of expressway No.5 led to dramatic improvements in work efficiency and a good construction environment. During the construction of Lantang tunnel in expressway No.3, the wide use of steel-fiber shotcrete, lattice girders and self-drilling rock bolts for the primary supports not only greatly accelerated the process but also substantially reduced the construction risks.

5.6 Environmental protection and ecological conservation

The construction of expressway projects in Taiwan must obtain the permission of the Environmental Impact Assessment Review Committee. Due to the problems of groundwater inrush, air and water pollution, blasting vibration, mucking deposits, etc., tunneling construction always faces major issues of environmental protection.

To protect the tea plantations in the vicinity of Hsuehshan tunnel shaft No.1, the exhaust air was conducted through a 328 m-long horizontal adit to another valley. The northern section of Hsuehshan tunnel is located in a water-resources reservation area. Thus, the alignment gradient declines from the north portal to the south portal at a rate of −1.25%. The total volume of groundwater outflow for the two main tunnels and one pilot tunnel is about 50 000 m³ per day. After the treatment, the groundwater outflow is utilized for irrigation purposes or as a water supply for local residents [18].

The western portal of the Puli tunnel of expressway No.6 is located on a precipitous slope (Fig.15). To avoid local environmental damage due to the slope cut, the tunnel excavation progressed from east to west and was opened through at the western portal. The abutments of the adjacent bridge were also located inside the tunnel, thus reducing the impact on the surrounding environment to a minimum.

6 Perspective of expressway tunnels in Taiwan

In the future, as most of the planned expressways in Taiwan will pass through mountainous terrain, long tunnels will inevitably be constructed. These tunnels in craggy mountainous areas often have characteristics of great length, large overburden, high in-situ stresses, heavy groundwater inflows, geothermal issues, and so on. Therefore, finding a solution to these problems is one of the greatest challenges faced by the tunnelers. The perspectives of expressway tunnels in Taiwan are discussed in the following with respect to the areas of geology, technology, education and environment.

6.1 Advanced technologies for geological investigation

A thorough understanding of ground properties can effectively reduce the risks of tunnel construction. The geological conditions of future expressway projects will be more complicated than those of the existing projects. To overcome the difficulties in constructing long tunnels in mountainous terrain, the drilling technology of borehole with the depth more than 700 m in unfavorable ground should be developed. An in-situ stress database in mountainous zones should also be established as soon as possible. Moreover, the high-precision geophysical methods and advanced remote sensing and aerial photography interpretation...
must be further developed in the future.

6.2 Establishment of reasonable rock mass classifications

The RMR and Q systems are the most common rock mass classification methods used in Taiwan. Both methods originated in foreign countries, where tunneling cases and ground conditions are very different from those in Taiwan. In practice, they are not completely suitable for local tunneling works. The PCCR system was developed in Taiwan more recently, but has not yet been widely used in local projects. This classification method still requires further verification from ongoing tunneling works. The development of a rock mass classification method suitable for the local geological and topographic conditions is an essential task for geotechnical engineers.

6.3 Upgrading construction methods, techniques and materials

Tunneling work is a linear construction under the ground surface, and its working faces are thus limited. Therefore, the time and cost of tunneling are always higher than those of embankment and bridge constructions. The trend of future tunnels construction should be safer, faster, more economic and environmentally friendly. More automatic and efficient equipments, as well as intelligent lining systems, will be the main techniques applied in future tunneling works[19].

In recent years, the levels of mechanization and automation of TBMs have been improved significantly [19]. Considering their fast excavation velocities, environmental protection and shortage of labor, the TBM remains an optional excavation method for long tunnels in the future if the geological conditions can be fully understood.

6.4 Education and training

Both the academic and practical fields of tunnel engineering are important. It is necessary to create courses related to tunnel engineering and rock engineering in universities. Also, research and development (R&D) are required to provide engineering solutions and advanced techniques. Moreover, symposiums on the topics of tunneling should be held frequently for the interchange of information and ideas among schools, industries and officials. In addition, empirical design methods play a vital role in tunnel designing, and the experiences obtained from completed projects are valuable. Therefore, reutilization of retirees’ specialties would be beneficial for the transmission of tunneling experiences.

6.5 Enhancement of international interchange

In the initial stages of adoption of the NATM and TBM, local engineers and foreign experts worked in good cooperation. Some designs and specifications were accomplished with the help of foreign consultants. In the future, the construction of tunnels will face the problems of large overburden, geothermal issues, and difficulties in geological investigation. Therefore, we still need to cooperate with foreign consultants to ensure that the work is done well.

6.6 Environmental protection and sustainable development

Currently, with the increasing awareness of environmental protection and sustainable development, the elimination of air and water pollution and complete waste reuse are essential. The reuse of groundwater in the Hsuehshan tunnel and the minimum cut for the portal slope of the Puli tunnel are good examples of environmental protection. In addition, the ventilation and lighting system in the tunnel should be designed to make the best use of energy resources.

7 Conclusions

The accomplishments of the expressway system created the rapid economic growth in Taiwan, and the expressway tunnel experiences led Taiwan’s tunneling industry to a new milestone. Because the future expressway network will be extended to mountainous terrain with complicated topography and heterogeneous geology, tunnel workers will inevitably face greater challenges. In addition to passing on tunneling experiences, research and development of advanced techniques and materials are essential. Additionally, the interchanges of information among different fields and cooperation with foreign consultants should be enhanced. During tunnel construction, environmental protection and ecological conservation should also be taken into account more thoroughly so that the goal of sustainable development can thus be achieved.

Acknowledgements

The authors would like to express their gratitude to the staff of Sinotech Engineering Consultants Ltd. for their assistances with this work. The valuable comments from Professor K.J. Shou of National Chung
Hsing University, Taiwan, China are also appreciated.

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