Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 47 No. 2 June 2016 ISSN 0046-5828

Rock Tunneling Applied to Steady Water Resources Supply in Taiwan: Challenges and Examples

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ABSTRACT: Increasing soil erosion and slope collapse in some catchment area in Taiwan in the past decade has increased sedimentation rates of reservoirs and reduced their effective capacity, severely affecting the steady water supply. Among multiple measures that have been proposed for stabilizing the water supply, the construction of tunnels for trans-basin diversion and the release of sediment are the most effective and sustainable. Tunneling in a catchment area, even close to a dam, represents serious environmental and engineering risks. This manuscript presents two cases of rock tunneling applied to steady water resources supply. The background of these two projects, relevant geotechnical conditions and tunneling designs are presented. Challenges and some distinctive issues, such as the presence of a high-temperature ground, a combustible gas emission ground, and potential instability of rock wedges caused by large underground excavation, are discussed. Associated countermeasures are then presented, associated with a clever design of an elephant-trunk intake pipe to release turbid water from 15 m below tunnel entrance, and related design strategies applied for a huge underground stilling pool and outlet sections. State-of-the-art tunneling through rock and some innovative tunneling technologies are utilized in these two cases.

KEYWORDS: Sedimentation of reservoirs, Rock tunneling, Trans-basin diversion tunnel, Sediment-sluice tunnel

1. INTRODUCTION

Taiwan is located at the inclined convergent plate boundary between the Eurasian Plate and the Philippine Sea Plate. Vigorous geological activity causes frequent and strong earthquakes. The geological strata are generally young and highly variable, and the rock masses have poor engineering characteristics. The subtropical climate provides moist and rainy weather, including high precipitation and a high groundwater level. Additionally, extreme precipitation events, associated with the global climate change, are becoming more frequent. Such unfavorable environmental conditions cause the extensive erosion of surface soil and active slope movements, inhibiting the construction and subsequent maintenance of infrastructure.

Among the abundant infrastructure built in the past century are reservoirs that suffer from significant soil erosion and slope collapse in their catchment area. The sedimentation rates of reservoirs have increased dramatically in the past decade, reducing their effective capacity and lifespan. Most reservoirs in Taiwan have limited sediment-release facilities, such as sediment-sluice tunnels or sediment bypass tunnels. The steady supply of water is now a serious challenge in Taiwan, whose sustainable development depends on increasing the availability of water resources and the lifespans of reservoirs.

Multiple countermeasures have been proposed to support steady water supply, Of which, the construction of tunnels for trans-basin diversion and the release of sediment have been evaluated as probably the most effective and sustainable method in Taiwan. However, tunnel construction in a catchment area of a reservoir must overcome not only technical challenges (Wang and Lee, 2013), but also environmental problems, and to excavate a tunnel close to a constructed dam is very difficult. Nevertheless, numerous tunneling plans have been proposed for major reservoirs in Taiwan. Four such projects are under way - one in basic design stage and the other three in construction stage.

This study considers two tunneling projects and the challenge of tunneling through rock to maintain a steady water resources supply; the tunneling projects are the Trans-basin Diversion Tunnel (TDT) project and the Sediment-Sluice Tunnel (SST) project. Both are for the Tsengwen Reservoir, which has the highest capacity of any reservoir in Taiwan. Related challenges and countermeasures for sediment control are introduced. The project background, relevant geotechnical conditions and tunneling design are presented. Challenges and associated countermeasures with tunneling through rock are discussed. State-of-the-art rock tunneling and some innovative tunneling technologies are utilized in these two projects.

2. WATER RESOURCES IN TAIWAN

Although the annual precipitation in Taiwan is 2500 mm, most surface water runs away rapidly owing to steep terrain. Tens of reservoirs with a total capacity of over 2.8 billion cubic meters have been completed to store water. However, Taiwan is now facing problems concerning the steady supply of water because the effective capacities of its reservoirs are falling rapidly.

2.1 Challenges Related Reservoirs in Taiwan

The early, traditional design of reservoirs in Taiwan did not take sufficient account of issues related to sediment. Watershed management, including the conservation of water and soil in a catchment area, were the idealized design principle, associated with the capacity of a reservoir that typically provided as the space of sediment during its designed lifespan. However, actual sedimentation rates for most reservoirs have exceeded the magnitude that was estimated in the design stage, and especially so in the past two decades. Earthquakes and precipitation that is caused by typhoons of extraordinary magnitude, as well as overrunning cultivation in a catchment area, result in landslides in a catchment area, causing a high sediment rate (Chen and Liao, 2012). The rate of reduction of the effective capacity of reservoirs in Taiwan far exceeds 1%, which is the global average, according to Mahmood (1987).

Figure 1 presents the influences of the Typhoon Morakot on the Wanda Reservoir in central Taiwan. The Wanda reservoir typically contains clean water (Figure 1a). However, the strata in its catchment area include slate, phyllite, metasandstone and interbedded strata, which are vulnerable to high precipitation and strong earthquakes, therefore cause severe surface erosion and frequent landslides. The collapse of a slope upstream of the reservoir can silt up the dams. Debris, sediment and driftwood flow down with the water, and are then held back by the dam (Figure 1b). The intake trash racks or water gates sometimes become blocked, inhibiting from the operation of the reservoir.

Table 1 presents the sedimentation rates of reservoirs in Taiwan, of which 29 have a medium to large capacity. The total design capacity of these reservoirs is 2.807 billion cubic meters. However, the total capacity is now only 2.012 billion cubic meters, since debris and sediment, with a volume of over 795 million cubic meters, have silted up reservoirs. The sediment has depleted the dull capacity for most reservoirs in Taiwan.

Table 1 Reservoir capacity and sedimentation in Taiwan

Item	Reservoir	Weir	Artificial lake
Amount	29	27	39
Design capacity (million m^3)	2,807	39	26
Designed effective capacity (million m^3)	2,354	37	27
Total capacity of current situation (million m^3)	2,012	17	22
Statue of effective capacity (million m^3)	1,883	16	21
Sedimentation rate (%)	2,8.3	54.7	14.9

(a)Before typhoon (b)After typhoon

Figure 1 Sedimentation of Typhoon Morakot on Wanda Reservoir in central Taiwan

2.2 Sediment Management Strategies for Sustainable Use of Reservoirs

Multiple strategies have been proposed for managing sediment problem in a way that favors the sustainable use of reservoirs in Taiwan. Some strategies, such as increasing the conservation of soil and water in a catchment area and dredging the reservoir vary little among various reservoirs, whereas others are highly reservoir-dependent as the geological and environmental conditions of the reservoirs vary. Countermeasures for sediment management represent as a conceptual revolution in the design and operation of reservoirs in Taiwan. The measures that were proposed for the Tsengwen Reservoir after Typhoon Morakot are introduced below.

The volume of sediment that moves downward into the Tsengwen Reservoir from its upstream rivers is approximately 5.6 million m^3/year. In 2003, a master plan for sediment management in the reservoir, based on a two-stage strategy, was implemented. The first stage involved various countermeasures that are taken in the catchment area, and reservoir facilities, to reduce the volume of sediment to a volume of 2.36 million m^3/year. Two major measures that are taken in the catchment area, i.e., main river channeling and check dam dredging, are designed to reduce the volume of sediment by 0.38 million m^3/year. Dredging in reservoir area and mechanical desilting in the forecourt area are designed to reduce sediment volume by an additional 0.48 million m^3/year. With respect to the reservoir facilities, improving the permanent river outlet (PRO) reduces the volume of sediment by 0.46 millionm^3/year. A sediment sluicing tunnel is designed to reduce the sediment by 1.04 million m^3/year. This is thought to be one the most effective measures for managing sediment in the first stage (Chen and Liao, 2012). Figure 2 presents the proposed master plan for sediment management in the Tsengwen Reservoir.

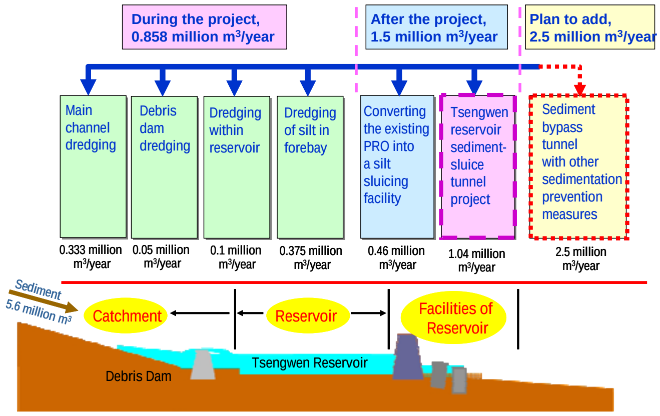


Figure 2 Master plan for sediment management at Tsengwen Reservoir

The conservation of soil and water in a catchment area is combined with the release of sediment as the optimal strategy for the sustainable management of a reservoir. Major reservoirs in Taiwan have been studied (Chen and Liao, 2012). It is found the reservoirs are suffered from severe sediment problems. Tunneling through rocks for sediment sluicing, bypassing, routing or flushing, has been proposed for some reservoirs. For example, two sediment sluicing tunnels are being constructed for the Tsengwen Reservoir and the Nanhua Reservoir, respectively. Two sediment bypass tunnels for the Shimen Reservoir are being planned and designed. Another project for the Baihe Reservoir is being constructed.

Increasing the discharge into reservoirs is also sometimes considered. Trans-basin tunnels have been used in Taiwan since the 1930s. In 2005, fifteen tunnels were constructed in the renovation of the Agondian Reservoir, and another tunnel was built for the Tsengwen Reservoir. The challenges of using rock tunnels to ensure the steady supply of water resources in Taiwan, and associated technical breakthrough, are introduced below with reference to two tunneling projects.

3. TRANS-BASIN DIVERSION TUNNEL

The Tsengwen Reservoir, located in southern Taiwan, is a versatile reservoir for the purposes of flood prevention, water supply and power generation. Water is supplied for daily use and irrigation in both Chiayi and Tainan County. The reservoir has a catchment area of 481 km^2 and a designed capacity of 713 million cubic meters. An extraordinary increase in water consumption during the 1990s provided a challenge for the steady supply of water to southern Taiwan. A series of innovative improvement projects have been performed since the late 1990s, including the joint distribution pipelines downstream of the reservoir and the construction of a new trans-basin tunnel; the former was completed in the early 2000s and the latter, called the Tsengwen Reservoir Trans-basin Diversion Tunnel (TDT) project, has been ongoing since 2005.

3.1 Project Background

The TDT project involves two tunnels with a total length of approximately 14.3 km. The east and the west tunnels, each with a diameter of 5.46 m, are respectively 9.6 and 4.3 km long. The maximum overburden of the east tunnel is roughly 1300 m. A river-crossing structure connects these two tunnels. Figure 3 presents the geological profile associated with the TDT project. Both tunnels go through Tertiary sedimentary rocks. Sandstone, shale, and their interbedded formations, with thicknesses ranging from a one decimeter to several meters, are the primary rock types. Additionally, synclines, anticlines, and several faults are present along the route of

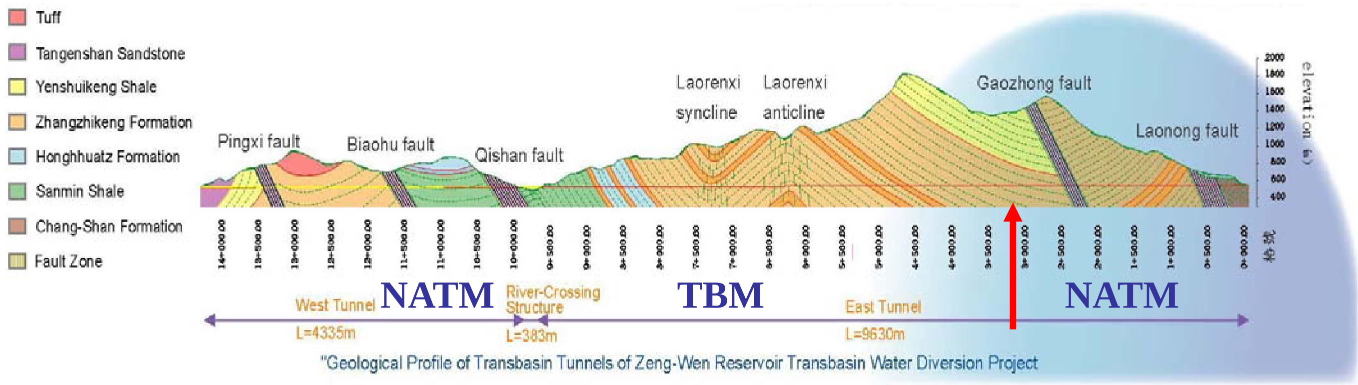


Figure 3 Geological profile along tunnels in TDT project

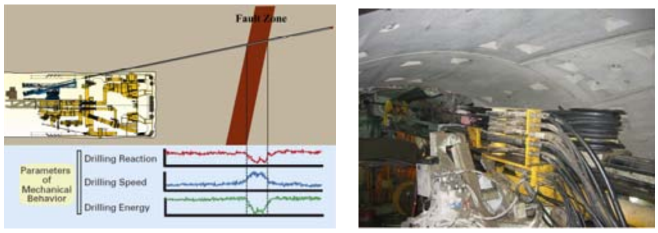
the tunnel. According to the results of a geological investigation, in the design stage, squeezing, the high-pressure inrush of groundwater, and the presence of high-temperature groundwater during excavation of the east tunnel are unfavorable geological conditions that were expected to be encountered, along with a hazardous gas in the west tunnel. Conventional drilling and blasting (D&B) tunneling method and TBM method are used in the construction of the eastern and western sections of the east tunnel, respectively. The D&B method is used for the west tunnel. Countermeasures for tunnel support and lining in a hot spring environment are studied to reduce tunneling risk under these unfavorable geological conditions.

3.2 Shotcrete and Concrete in a Hot Spring Environment: an Experimental Study

To determine the influence of hot spring water on the mechanical characteristics of tunnel supports that are made from Portland cement, the strength development and associated temporal variations of shotcrete and concrete specimens that were cast in situ and cured in water from a hot spring close to project site were studied as part of the TDT project. Experimental results revealed that weakly basic hot spring water with a curing temperature of 40°C does not adversely influence the strength development for shotcrete and concrete, but the hot spring curing environment may benefit early stage strength development and subsequent integrity. Chloride and sulfate ions in hot spring water do not significantly enhance the alkali-aggregate or alkali-carbonate reaction. Concrete specimens with high uniaxial compressive strength have high surface hardness, high electrical resistance and low permeability, indicating excellent short-term durability (Lee et al., 2013).

3.3 Application of Drilling Survey System

To investigate the geological conditions and reduce tunneling risks, the Drilling Survey System (DRISS, Figure 4) was applied to both D&B and TBM tunneling sections. The magnitudes of the uniaxial compressive strengths of the rock masses that were estimated using DRISS data match those obtained from the geological strength index and rock mass classifications. Two nonlinear relationships between drilling energy and the uniaxial compressive strength of rock mass with favorable coefficients of determination are obtained. The DRISS is then applied as a routine method of investigating the TBM section, and the tunnel seismic prediction method is applied in the D&B section with unfavorable geology condition. An extremely unfavorable tunneling section and several weakly unfavorable sections are thus accurately predicted (Lee and Wang, 2015).

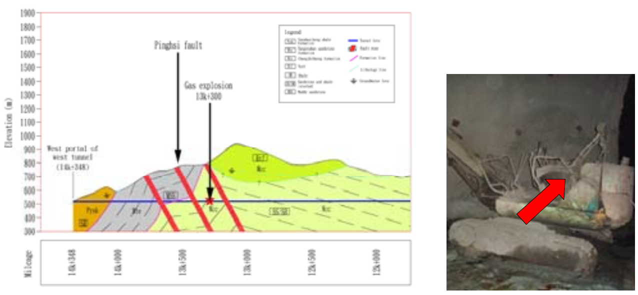


(a) Schematic diagram (b) Photo of DRISS

Figure 4 Drilling survey system (DRISS) utilized in TDT project

3.4 Gas Emission and Induced Explosion

A moderate to high probability of the emission of combustible gas was identified during design stage and both stationary and portable gas detectors were used during tunneling. Indeed, a gas-induced accident occurred in the west tunnel of the TDT project during tunneling (Figure 5). Excavation of the tunnel encountered a section in which gas was emitted and the concentration of methane, measured using a Gas Chromatography-Flame Ionization Detector (GC-FID), was 844,535 ppm; thus gas was responsible for a severe explosion that took the lives of two workers. Since other sections to be excavated were in areas of similar geological conditions, the TDT project was reviewed. A supplementary detailed geological investigation was then performed. Design modifications with a comprehensive program for mitigating combustible gas-related hazards were then implemented. Major measures included increasing the ventilation capacity of the tunnel from 1500 m^3/min to 1800 m^3/min, with air speed in excess of 0.5 m/s, the dense coverage by gas detectors (GC-FID) of sections with the potential emission of combustible gas, and the imposition of strict rules to prevent ignition (Lee and Wang, 2014).



(a)The cross-section of gas explosion location (b)Photo after gas explosion

Figure 5 Gas emission-induced hazards and geological profile near tunneling section

4. SEDIMENT-SLUICE TUNNEL

In 2009, Typhoon Morakot destroyed the intake section of the east tunnel of the TDT project and caused approximately 90 million cubic meters of sediment to enter the Tsengwen Reservoir. The TDT project was then suspended. The capacity of the Tsengwen Reservoir was reduced to 491 million cubic meters. Unfortunately, sediment is abundant in the upstream rivers, but the reservoir has no facility for releasing sediment. The spillways of the reservoir are located at high altitude, and so do not help to release the sediment. To ease the severe silting, the Tsengwen Reservoir Sediment-Sluice Tunnel (SST) Project was launched in 2013.

Figure 6 presents the layout of the SST project. The tunnel is located south of the earth dam of the reservoir, roughly parallel to the current No. 1 diversion tunnel. The maximum overburden of the tunnel is approximately 250 m. The stratum that the tunnel passes through is composed of sandstone, siltstone, mudstone, muddy sandstone, and interbedded sandstone and shale, with three transcurrent faults (NWF-1, NWF-2, and NWF-3). The construction of the diversion tunnel had suffered from water inrush and large deformation of the surrounding rock at the NWF-3 transcurrent fault. Apart from the section close to NWF-3, the rock mass provided fair to good conditions along the tunnel, with a shear zone of up to 1.5 m wide (Figure 6). Nevertheless, excavating a tunnel next to an operational earth dam is an extreme challenge. Design considerations associated with major geotechnical difficulties are presented below.

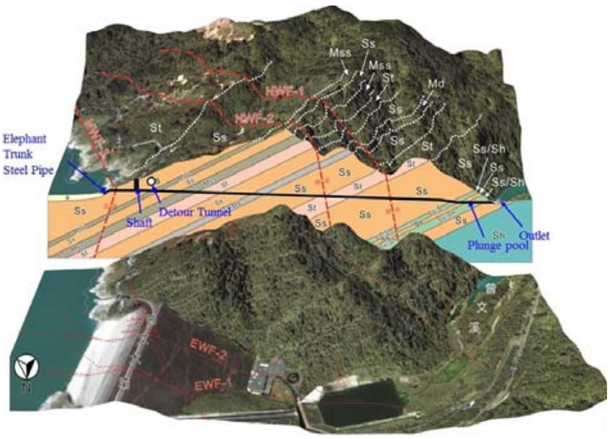


Figure 6 Geological profile in region of SST project

4.1 Tunnel Design

Most of the underground infrastructure in Taiwan is located in the west of the island, where the stratum are mainly composed of weak sedimentary rocks with weak diagenesis and undeveloped joints. The major concerns in conventional underground work, in both design and construction stages, are the excess deformation of surrounding rock and the failure of tunnel supports. Underground excavation is typically performed using continuum methods, which are based on the assumption that rock masses are homogeneous and isotropic. Such a design method insufficiently accounts for the influence of discontinuities. The mechanical parameters are usually reduced only when the discontinuity in a rock mass may affect the underground excavation. When the cross-section of a tunnel is large, the working face is commonly divided into sections and the rock is excavated using a stepped procedure. This method may reduce the likelihood of a huge structural failure, such as the falling or sliding of a large rock wedge, at the cost of a reduced excavation rate.

The construction of the No. 1 diversion tunnel in the 1970s revealed the geological profile along the SST tunnel. A geotechnical review of the geological conditions and engineering characteristics of the rock masses associated with the tunnel revealed key blocks that might have caused wedge failure during tunneling. The size of a key block that is formed by various sets of discontinuities increases with the width and height of the tunnel. The influence of potential key blocks were studied in detail during tunnel design.

First, a detailed geological investigation is performed and the geological profile is prepared accordingly. The dominant attitudes of various discontinuities are obtained by stereographic projection analysis. Wedge failure analysis is performed using Unwedge to identify possible locations and sizes of discontinuities associated with a potential key block (Figure 7). The excavation sequence and support system that is associated with the fore-poling that is required to prevent wedge failure can be determined by understanding the spatial distribution and mechanical characteristics of the discontinuities.

4.2 Design of Intake Section

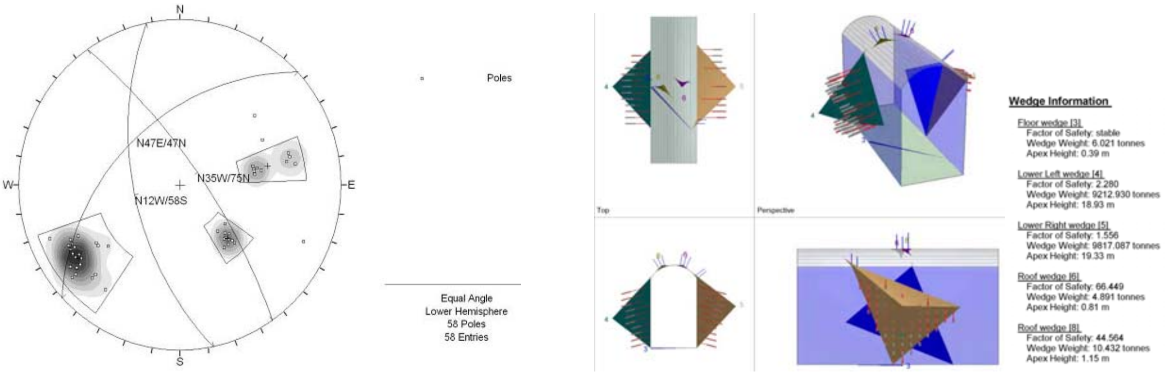
The impounded levels of the Tsengwen Reservoir vary by 60 m between EL. 170 m less and EL. 230 m, preventing the cofferdam, and inhibiting the usual construction of the tunnel entrance. Based on a numerical analysis and hydraulic model test, the optimal level for the center of the entrance of the SST tunnel is EL. 175 m. However, the feasible level of the constructed entrance of the SST tunnel is EL. 190 m. To release effectively the turbid water from 15 m below the tunnel entrance, an S-curve form steel pipe with a diameter of 10 m, called the elephant-trunk intake pipe, is designed and constructed (Huang et al., 2014). Figure 8a presents the longitudinal profile close to the intake section of the SST project. Hydraulic model test results verify the sediment sluicing effect by symphonic action when the sector gate is open and the water level exceeds EL. 230.

A shaft is designed as a chamber for the sector gate and the maintenance gate. The shaft is 10 m wide, 31 m long and more than 50 m high. As part of a secure construction procedure that minimizes the excavation-disturbed zone and prevents ingress of water from the reservoir, sealing grouting is applied in the zone between the shaft and the reservoir. A three-dimensional numerical simulation is performed using FLAC 3D to determine the locations where ground anchors and additional reinforcement are required (Figure 8b). Seismically induced stress increments in the lining during an earthquake are obtained by time-domain analysis. The design of the linings accounts for these potential dynamic stress increments.

4.3 Design of Stilling Pool and Outlet Sections

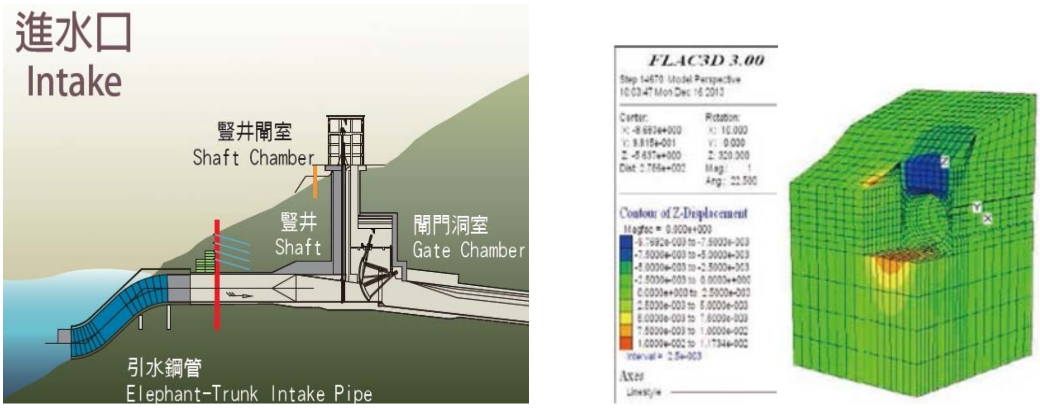
The maximum flow speed close to the outlet of the SST project is 30 m/s. However, the channel of the Tsengwen River close to the outlet is narrow. A stilling pool is required to reduce water erosion on the opposite river bank, and has to be excavated underground. A large double-arch underground stilling pool with a width of 24 m was first proposed. The outlet section obliquely intersects a slope. The overburden of this underground pool is shallow, and so is unfavorable for secure excavation of the pool. Therefore, alternative plans are proposed and a three-dimensional numerical simulation using the finite element software, Midas/GTS 2010, is performed to optimize the layout of the underground stilling pool and outlet sections. Finally, a twin-bore tunnel is proposed as the outlet section. Each of the constituent tunnels is 10 m wide and 30 m high. The maximum width of the underground stilling pool is reduced from 18 m to 10 m; its height is 32.5 m (Figure 9).

The results of the three-dimensional numerical analysis are used to design the support and lining of the stilling pool and outlet sections, and numerically obtained seismically induced stress increments in the lining are considered in the design of the lining.



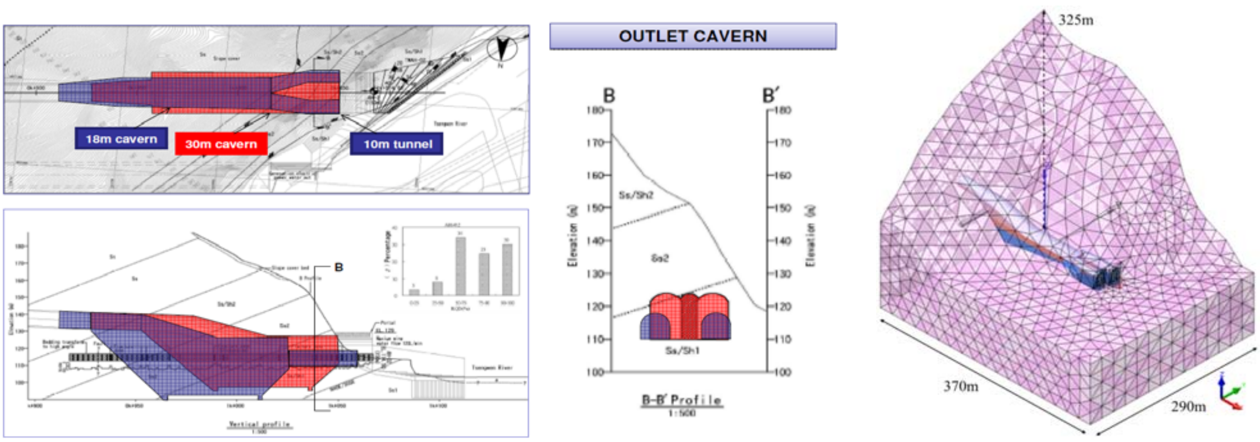
(a) Dips analysis (b) Unwedge analysis

Figure 7 Analysis of key blocks in SST project



(a) Longitudinal layout (b) FLAC 3D analysis

Figure 8 Intake section in SST project and mesh used for 3D numerical analysis



(a) Design change (b) Midas/GTS 3D analysis

Figure 9 Stilling pool and outlet sections of SST project and mesh used for 3D numerical analysis

5. CONCLUSION

Reservoirs are critical to ensuring steady water supply in most of the world. Sediment reduces the capacity of a reservoir. The effective conservation of water and soil in the catchment area of a reservoir and appropriate sediment management are important to the sustainable use of a reservoir. A rock tunnel provides the best means by which sediment can bypass and is effective for sluicing, and should be implemented in a new reservoir project. Problems related to sediment in existing reservoirs can be solved by constructing a sediment releasing tunnel. High environmental and engineering risks are associated with tunneling through rocks in a catchment area.

This manuscript presents the TDT and SST rock tunneling projects applied to steady water resources supply for the Tsengwen Reservoir, which has the highest capacity of reservoirs in Taiwan. The background of these two projects, relevant geotechnical conditions and tunneling designs are presented. Challenges and some distinctive issues, such as the presence of a high-temperature ground, a combustible gas emission ground, and potential instability of rock wedges caused by large underground excavation, are discussed with countermeasures, associated with a clever design of an elephant-trunk intake pipe to release turbid water from 15 m below tunnel entrance, and related design strategies applied for a huge underground stilling pool and outlet sections. State-of-the-art tunneling through rock and some innovative tunneling technologies are utilized in these two cases. The experience presented in this manuscript provides a reference for projects that engage similar environmental and geological conditions.

6. REFERENCES

Chen, H.K., and Liao, P.M. (2012) “Integrated Desiltation Strategies of Reservoir”, Water Resources Planning Institute, Water Resources Agency, MOEA.

Huang, S.W., Chang, S.H., Yan, C.Y., and Chen, F.S. (2014) “Plan and design of Tsengwen reservoir sediment-sluice tunnel project”, Journal of Professional Geotechnical Engineers, No. 8, pp. 38-49.

Lee, C.H., Wang, T.T., and Chen, H.J. (2013) “Experimental study of shotcrete and concrete strength development in a hot spring environment”, Tunneling and Underground Space Technology, Vol. 38, pp. 390-397.

Lee, C.H., and Wang, T.T. (2014) “Case Study on Gas Emission and induced Explosion during Tunneling in Taiwan”, 8th Asian Rock Mechanics Symposium, Sapporo, Japan, p. 359.

Lee, C.H., and Wang, T.T. (2015) “Application of Drilling Survey System for D&B and TBM Tunneling in Taiwan”, ISRM Congress 2015 Proceedings - Int’l Symposium on Rock Mechanics, Quebec, Canada (ISBN: 978-1-926872-25-4).

Mahmood, K. (1987) “Reservoir sedimentation. Impact, Extent and Mitigation”. World Bank Technical Paper, No. 71, 119 pp.

Wang, T.T. and C.H. Lee (2013) “Life cycle design considerations for hydraulic tunnels - lessons learned from inspection and maintenance cases”, Journal of Performance of Constructed Facilities, 27(6), 796-806.