Design of Temporary Construction Adit and Tunnel Plug for Nenggiri Hydroelectric Project

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ABSTRACT

The Nenggiri Hydroelectric Power Plant Project, located in the state of Kelantan, Malaysia, is among the largest renewable energy initiatives in the country. The main dam structure is 88.1m in height and can hold 1.239 billion m^3 of water. A twin main diversion tunnel (DT) is required to divert existing river flow to enable construction of the cofferdam and the main dam structures. The horseshoe-shaped temporary construction adit (TCA) with a 6m span and approximately 146m long, excavated using drill and blast method, aims to expedite construction progress by providing access at the middle of the proposed DT thus allowing additional excavation faces for the DTs. Key design approach involves NGI-Q System for initial tunnel support design, followed by the Convergence-Confinement Method to establish relationship between stress relaxation and advance length, forming the basis for subsequent temporary support design using finite element RS2 program. This paper presents an optimized design and construction approach for the TCA and the tunnel plug located at the TCA-DT junction. Innovative design was adopted that results in significant reduction of plug length compared to conventional design. Despite various major challenges the TCA and DTs were able to be completed one month ahead of schedule.

1 INTRODUCTION

1.1 Background and significance

Malaysia is a small open economy which is currently experiencing rapid urbanization and growing population, with population expected to grow from 32,700,000 to 40,000,000 people from 2022 to 2050, the energy demand is expected to rise by 2% annually until 2050 (Ministry of Economy, 2023). As of 2020, a large portion of Malaysia’s energy supply still rely heavily on fossil fuels such as natural gas, crude oil and petroleum products and coal. To achieve sustainable development, the government has taken proactive steps in driving the energy transition process to reshape its energy landscape towards renewable energy.

The Nenggiri Hydroelectric Project in Malaysia is a key initiative aimed at increasing renewable energy (RE) capacity, enhancing energy security, and promoting regional growth. It supports Malaysia's goal of achieving RE capacity mix target of 40% by 2035, and 70% by 2050. Beyond power generation, the project also helps with flood mitigation by managing rainwater during the monsoon season, and the re-regulating dam ensures a steady river flow. It will benefit the State of Kelantan by providing clean water and improving irrigation for agriculture.

The project includes essential components such as a roller-compacted concrete (RCC) dam, saddle dam, re-regulating dam, and a surface power station with two 150 MW generators that can transmit power to the main 275kV Switchyard. These generators will supply an average of 599.5 GWh annually. The dam, standing 88.1m high, can store 1.239 billion m^3 of water, supporting regional energy needs. A critical aspect of the project is the twin main diversion tunnels (DT), necessary to redirect river flow and facilitate the construction of the cofferdam, which enables subsequent works on the main dam structures. To optimize construction timelines, a Temporary Construction Adit (TCA) and temporary cross passage (TCP) was designed and implemented,

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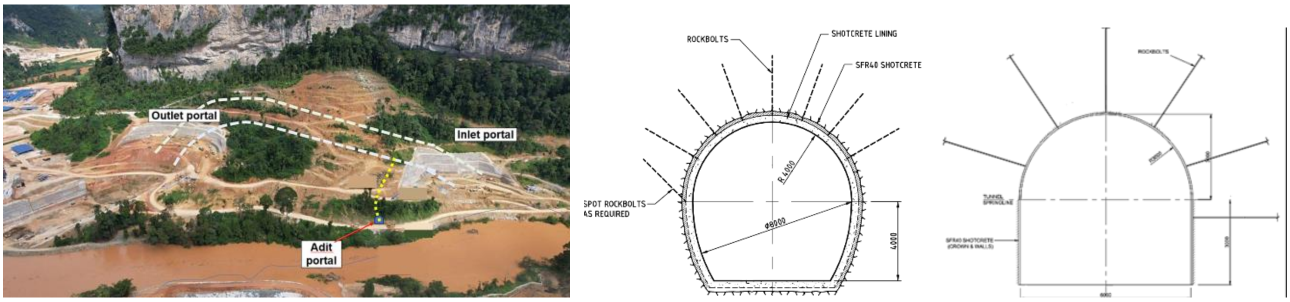
allowing access to the middle section of the tunnel alignment and enabling simultaneous excavation from both ends. Refer to Figure 1(a) which shows the project site layout plan.

This paper presents an optimized design and construction approach for the TCA, highlighting innovative solutions to address structural and site constraints, and evaluating the overall project outcomes and performance.

1.2 Project overview

The Nenggiri Hydroelectric Project (HEP) site is located within the Sungai Nenggiri catchment in Jajahan Gua Musang, approximately 30 km from Gua Musang town (Figure 2(a)). As mentioned in the background, the project requires the twin main diversion tunnels (DT) to facilitate the construction of the cofferdam and subsequent main dam structures. To optimize the construction schedule of the DTs, a TCA was added. The horseshoe-shaped TCA, approximately 145.9m in length and 6m in span, plays a crucial role in expediting the excavation of the diversion tunnels. By providing access to the middle section of the tunnel alignment, it enables simultaneous excavation from multiple headings, significantly reducing the overall construction timeline. Upon completion of the DTs, tunnel plugs were constructed to seal off the TCA prior to the commissioning of the DT for river diversion works. The typical sections of TCA and DT are shown in Figure 1(b) and 1(c).



(a) (b) (c)

Figure 1: (a) Site layout plan (b) Typical section DT (c) Typical section of TCA

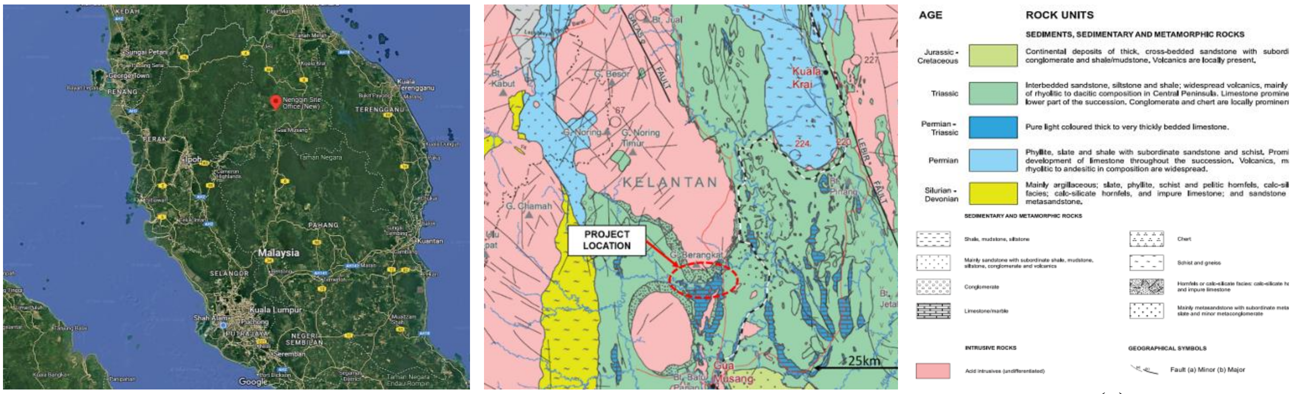
2 SITE CONDITIONS

2.1 Geology

According to the Geological Map of Peninsular Malaysia, 9th Edition, 2014 (Geological Map of Peninsular Malaysia, 2014), the project site is located on the Gua Musang Formation, which dates to the Middle Permian to Late Triassic period. This formation includes a range of geological materials, such as limestone, slate, phyllite, sandstone, minor conglomerates, and volcanic rocks like andesite and granite. The geological map of the site area, along with the corresponding legends, is provided in Figure 2(b) and 2(c). Limestone hills are prominently exposed in several locations within the Nenggiri area. The limestone here is characterized by low to high hills with very steep faces and pinnacles. The depositional environment of the site is a shallow marine shelf, with active volcanic activity, which has resulted in much of the local limestone being metamorphosed into marble. The nearest major fault, the Galas Fault, is located approximately 28 km to the north of the project site, and it is surrounded by minor fault zones.

2.2 Site investigation & laboratory testing

Two boreholes were drilled close to the alignment of the temporary adit tunnel. The borehole locations were selected based on site accessibility and to allow safe operation of the SI machinery. As the area is hilly with no proper berms or platforms during the early stage, the initial SI locations had to be shifted to location with safe access. The final borehole positions, as shown in Figure 5(a) were kept as close as possible to the TCA alignment to ensure the ground conditions were still representative. Standard Penetration Tests (SPT) were conducted at 1.5m intervals in all boreholes where soil was present to assess the soil profile and determine soil parameters using the SPT-N values. Rock coring was also performed to obtain rock samples as shown in Figure 3, and measure the Rock Quality Designation (RQD) and core recovery. One standpipe piezometer was installed at one of the boreholes to monitor the groundwater level.



(a) (b) (c)

Figure 2: (a) Site location (b) Geological map of the site area and the surroundings (c) Geological map legend

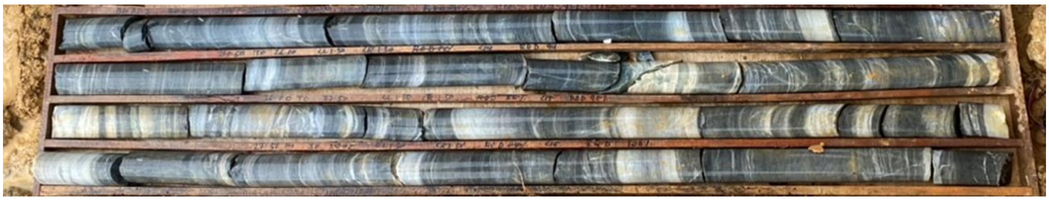


Figure 3: Rock samples from coring

Based on data from two boreholes, the site consists of a 3m thick hard sandy silt in one location, and in another, a 3m thick medium stiff silty sand overlying 2m of hard silty sand. The ground parameters were determined based on experience and engineering judgment. The elastic modulus for soft ground was calculated using local practices and SPT-N correlations, where E = 1N for SPT-N > 30, and E = 1.5N for 30 > SPT-N > 10. Unconfined Compression Tests were carried out on the rock core samples from the two boreholes. The results showed significant variation in strength, with up to a 50% difference in fracture load between samples. The rocks were identified as mixed rock types consisting of metasedimentary and meta-volcanic (metamorphic) rock types, with unconfined compressive strength (UCS) ranging from 30.4 to 168.4 MPa. The adopted parameters for the design are listed in Table 1.

Table 1: Design parameters for portal slope

Soil/Rock Type	Effective Cohesion, c' (kPa)	Effective Angle of Friction, φ'	Bulk Density, γ (kN/m^3)	Elastic Modulus (MPa)
Silty Sand, SM (Layer 1)	7	31	19	30
Sandy Silt, MS (Layer 2)	10	35	20	50
Moderately Weathered Rock (Layer 3)	10	38	20	-
Fresh to Slightly Weathered Rock (Layer 4)	15	45	24	-

The geotechnical design parameters for intact rock were determined by reviewing site-specific geotechnical information, including laboratory UCS test results on rock core samples. The modulus ratio (MR) was based on rock type using the MR recommendation table from "RS2" software by Rocscience, with a typical MR value of

400 adopted for design. The parameters for the intact metasedimentary and meta-volcanic rock, classified by weathering condition, are summarized in Table 2.

Table 2: Design parameters for rock tunnel

Rock Type	Bulk Density (kN/m^3)	Uniaxial Compressive Strength, UCS (MPa)	Elastic Modulus (GPa) (2)	Mi	Ko
Moderately Weathered	26	10(1)	3	9	1.5
Fresh to Slightly Weathered	26	50 – 80	20 – 32	9	3

Note 1: Estimated conservatively for moderately weathered metasedimentary and meta-volcanic rock.
Note 2: Calculated using the modulus ratio, MR, ratio between elastic modulus and UCS.

2.3 Geological Features from Face Mapping

During the excavation of the TCA, face mapping was carried out to determine the prescribed support system needed. Two main rock types were encountered, meta-sedimentary rock and meta-volcanic rock, both showing consistent geological features and engineering-relevance to tunnel design.

The meta-sedimentary rock was mostly good to very good quality, black to grey with white stripes, fine-grained, interbedded, and massive. The rock was strong, with UCS between 50 to 100 MPa, and appeared fresh to slightly weathered (Grade I to II). The meta-volcanic rock, found near the end of the tunnel, had similar strength and weathering grades but darker in color, fine-grained, and massive. Overall, the rock mass quality was suitable for tunnelling, with most sections requiring only 50 mm thick safety shotcrete with spot bolts as the support.

Several joint sets were observed during mapping. The joints were close to moderately spaced, with joint roughness observed as rough undulated and rough planar. Localized open apertures were also encountered, some of which contained quartz infilling. Weathering and infill were generally minimal. Some areas had intersecting joints, which created wedge-prone zones. Joint density was observed to be approximately 15 per cubic metre.

The rock mass quality was classified according to Q-System (NGI, 2015). Q-values ranged from 0.6 in weak zones to as high as 13 in strong sections. The average Q-value was about 7, with most values above 8, indicating generally good rock mass quality. Higher Q-values (10 to 13) were observed in fresh, massive rock, while lower values (0.6 to 1.0) were limited to localized sections near the portal and isolated weak zones.

3 DESIGN & ANALYSIS

3.1 Portal slope

The formation of portal slope involves strengthening of new soil cut slope using the soil nailing technique, the requirement of the design factor of safety is assessed by referring to the Hong Kong Geoguide 7: Guide to Soil Nail Design and Construction (GEO, 2023). In view of the portal slope is located inside construction site with controlled access and low heavy traffic volume, the consequence-to-life and economic consequence from a slope failure is categorized as category 3 and category C respectively, which a minimum factor of safety of greater than 1.0 is recommended considering 10 years return period rainfall.

The portal slope comprises 3 tiers, with 3 slope faces and 2 berms; the height and gradient of the bottom slope, middle slope and top slope is 9m (4V:1H), 6m (2V:1H) and 5m (2V:1H) respectively, as shown in Figure 4(a). Galvanized T25 steel bars were used for corrosion protection and shotcrete slope facing were proposed. Slope stability computation was carried out using limit equilibrium method following Morgenstern-Price method. With ground water level anticipated to be at 3m below the existing slope crest, a series of 12m long subsoil drain with 4.5m center-to-center spacing was proposed to be constructed on the second slope face to manage the ground water level. The design of portal slope has been optimized by incorporating various soil nail spacings and length for different slope face, the details and photo of designed portal slope are presented in Table 3 and Figure 4 respectively.

Table 3: Details of reinforced soil cut slope

Slope Details	Slope Height (m)	Slope Gradient (m)	Soil Nails Spacing (m)		Factor of Safety (Local)	Factor of Safety (Global)
			Vertical	Horizontal		
Bottom Slope	9	4V:1H	1.2	1.5	2.655	1.495
Middle Slope	6	2V:1H	1.5	1.5	2.669	
Top Slope	5	2V:1H	1.2	1.5	2.246	

(a) (b)

Figure 4: (a) Cross section of portal slope (b) Close-up view of portal slope

3.2 *Temporary construction adit (TCA)*

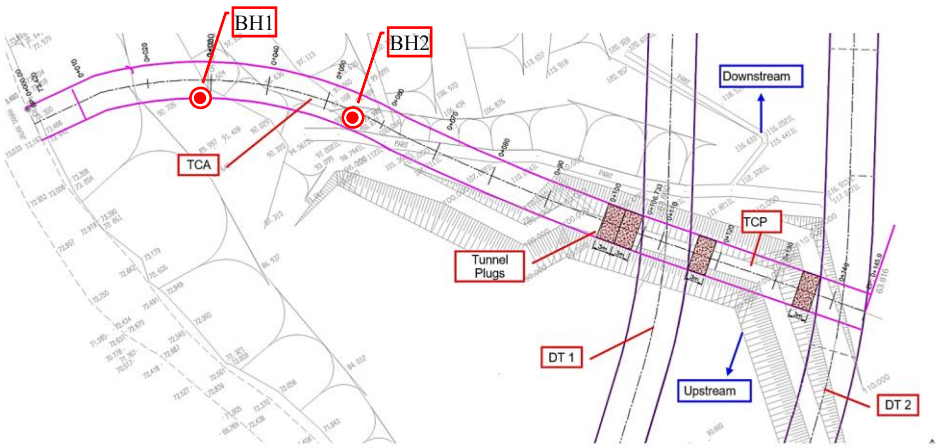


Figure 5(a): General layout plan

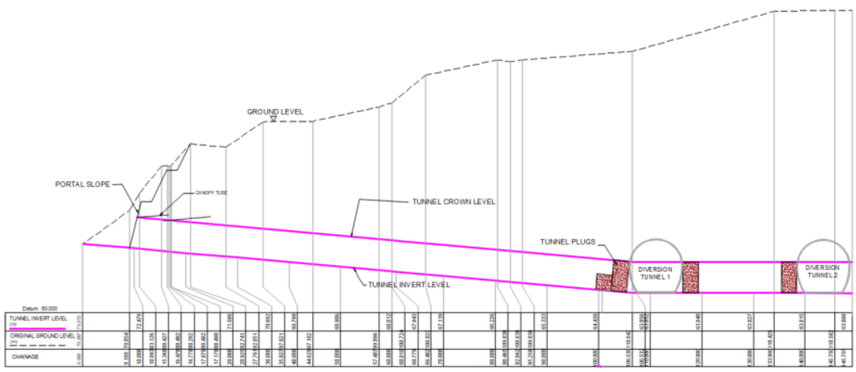
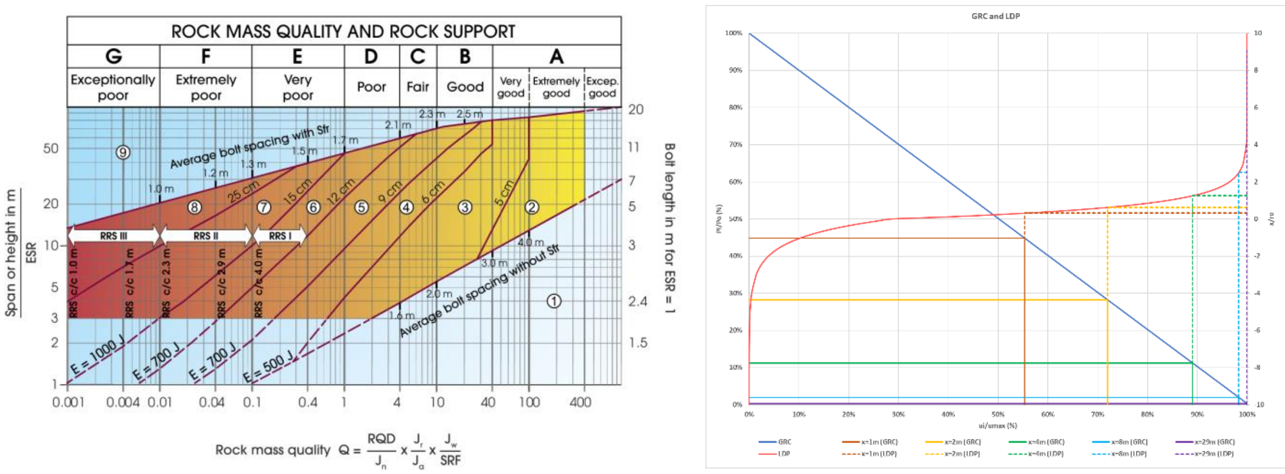


Figure 5(b): Vertical Profile of TCA

The design of temporary support systems for the construction adit adopted a multi-faceted approach, integrating empirical, numerical, and analytical techniques. Figure 5(a) and 5(b) illustrates the layout and profile of the TCA and its associated structures. The design steps of TCA, in general, follows that as described in Chin (2024) where empirical, analytical, and numerical design approaches are being adopted for the successful design and construction of TCA.

For empirical approach, the NGI Q-System (NGI, 2015) has been adopted to determine the temporary support requirements for the construction adit, as shown in Figure 6(a). Analytical approach is then deployed to assess the structural performance of the proposed supports such as steel ribs and canopy tubes. The designs are further validated by numerical modelling to assess the movements and the forces in the proposed support members.

In terms of numerical analysis, the Longitudinal Displacement Profile (LDP), established through Vlachopoulos and Diederichs' analytical method (Vlachopoulos & Diederichs, 2009), was used to determine the convergence behavior of an unsupported tunnel due to a specified tunnel advance length. The Ground Reaction Curve (GRC) analyzes the convergence behavior of an unsupported tunnel under progressive stress relaxation as excavation progresses, assessed through numerical analysis under varying ground conditions. By integrating these curves, as shown in Figure 6(b), the relationship between stress relaxation within the tunnel and tunnel advance length was determined. This general design approach adopted for TCA is being described in detail with example in Chin (2024).



(a) (b)

Figure 6: (a) Rock Support Design Chart (NGI, 2015) (b) Graph of LDP & GRC

Numerical analysis was carried out using RS2 finite element software, with the model adopted stratified ground conditions according to borehole logs. The Mohr-Coulomb model was applied to the soil and weak rock near the portal, while the Hoek-Brown failure criterion was adopted for the mixed metasedimentary and meta-volcanic rock. Parameters such as joint spacing, orientation, surface condition, and weathering were considered through the use of the Geological Strength Index (GSI), which was derived primarily based on the Q-value ranges assessed. These GSI values were then used to calculate the rock mass strength parameters for the Hoek-Brown model.

Joints were not explicitly modelled, but their influence was accounted for through the adjustment of rock mass properties using the GSI approach. The numerical analysis, combined with empirical design using the Q-System and analytical checks, provided a reliable and conservative basis for designing the temporary support system across the varying ground conditions encountered along the TCA (Chin, 2024). Design parameters adopted for the RS2 model are summarized in Table 4. The design of tunnel face support for soft and mixed ground conditions was conducted using Slope/W, a two-dimensional numerical analysis tool that calculates the factor of safety of slip surface considering the loading conditions, porewater pressure, and failure plane shapes.

For forepoling design, canopy tubes was installed above the tunnel crown in soft/mixed ground and/or low rock cover conditions as pre-excavation support measure. These tubes serve to stabilize the unsupported ground that will be exposed right after excavation but before installation of prescribed support, and provide load transfer ahead of the face in the longitudinal direction in conjunction with steel arches. Excavation round length was 1.5m, with temporary lining installed before next cycle excavation. The vertical stresses acting on the canopy tubes are assessed using silo theory John & Mattle (2002) as recommended by Geoguide 4: Guide to Cavern Engineering (GEO, 2008).

Table 4: Design parameters adopted in RS2

Soil / Rock Type	c' (kPa)	φ' (°)	γ (kN/m^3)	Elastic Modulus (MPa)	UCS (MPa)	GSI	mi	D
Sandy silt	10	34	20	50	-	-	-	-
Q = 0.1 - 1	-	-	-	182.7	10	20	9	0
Q = 1 - 40	-	-	-	4186.1	50	44	9	0

3.2.1 Typical tunnel section and portal section

The TCA is a horseshoe-shaped tunnel with 6m wide by 6m height were constructed, since the tunnel is a temporary structure, a factor of 5.0 is applied to the design Q-value obtained using Barton et al (1974). The primary support design includes three support classes for typical tunnel sections and two support classes for tunnel portals. The Q-ranges for typical tunnel sections were categorized as $0.1 \leq Q < 0.4$, $0.4 \leq Q < 1.0$, and $Q \geq 1.0$. The NGI Q-System is applicable when the rockhead cover exceeds 1 × span of the adit (i.e. rockhead at least 6m above tunnel crown), accounting for the relatively small tunnel size. However, for portal design, where ground condition is predominantly soil and highly fractured rock mass, the Q-System was not applicable due to insufficient anchoring of systematic dowels. Instead, finite element analysis using RS2 software was employed to assess ground stability and propose suitable support measures.

The adopted support system for typical tunnel section comprises steel fibers reinforced concrete (SFRC) with characteristic strength of 30MPa. T25 dowel bars ranging from 1.5 to 3.0m with spacing ranging from 1.5 to 1.8m grid were adopted to provide rock arching surrounding the tunnel opening. For tunnel portal area where soft mixed ground was encountered, temporary supports comprising steel ribs of 125 x 125 x 23.8kg UC at 1.0m spacing with 150mm thick SFRC were adopted. Canopy tubes of 114.3 x 5mm CHS with spacing ranging from 0.30m to 0.45m center-to-center and 3m overlap were proposed as pre-excavation support for soft mixed ground near the portal.

To ensure excavation stability, advance lengths were set based on ground conditions. In soft mixed ground and areas with shallow rock cover, the advance length was limited to 1m per round, while in hard rock conditions, an advance length of 3m per round was implemented. These selected advance lengths were further verified through numerical methods, incorporating longitudinal displacement profiles and ground reaction curves to ensure structural integrity during excavation.

3.2.2 Junction section at TCA and main diversion tunnels

The junction section design addresses the intersection between the TCA and Diversion Tunnels, following a staged excavation sequence to ensure stability. Excavation proceeds along the TCA alignment until reaching the boundary of Diversion Tunnel 2. Upon completion of the TCA and cross passage (CP) excavations, Diversion Tunnel 1 was excavated upstream towards the portal, while Diversion Tunnel 2 advanced downstream in the opposite direction along the tunnel alignment. The main Diversion Tunnels are 8m in width and 8m in height. To accommodate the transition from a smaller TCA to larger Diversion Tunnels, the excavation profile of Diversion Tunnel 1 from junction gradually expands from 6m to 8.6m, increasing by 0.5m per round until the final design profile is achieved. Support measures were installed incrementally at each excavation stage, following the prescribed junction support requirements. Once the design profile is reached, the remaining rock cover in the main diversion tunnel was removed to establish the final tunnel geometry. This sequential approach ensures controlled excavation and structural integrity throughout the process.

The overall design methodology for the junction follows the same approach as the TCA design, incorporating empirical, analytical and numerical techniques to ensure structural stability. The NGI Q-System (2015) is used to determine temporary support requirements, analytical methods further evaluate the structural performance of elements such as steel ribs and canopy tubes. while numerical modeling validates the proposed support system by assessing ground movements and forces in support members (Chin, 2024).

For the junction, numerical analysis focuses on critical sections, specifically at the TCA tunnel side and the Main Diversion Tunnel side. Due to the structural complexities at the intersection, an adjustment factor of 3 × Jn was applied to the design Q-value to determine the support requirements, extending one tunnel span from the junction to account for additional exposed rock wedges and 3D stress redistribution surrounding the junction openings. This comprehensive approach ensures that the support system effectively addresses the challenges associated with tunnel intersections.

Similar to typical tunnel section, the adopted support system for junction section comprises SFRC with characteristic strength of 30MPa, and T25 dowel bars ranging from 1.5 to 3.0m with spacing ranging from 1.0 to 1.8m grid were adopted as the rock bolt to stabilize the surrounding rock mass. For ground with Q-value less than 0.4 but greater than 0.1, steel ribs of 125 x 125 x 23.8kg UC with spacing ranging from 1.0 to 2.0m coupled with 150mm-thick SFRC were proposed. However, during actual construction, the ground condition was better than expected, predominantly Q-value greater than 1.0, with occasional localized weak zone with Q-value between 0.4 to 1.0, therefore no steel ribs were installed in the junction area.

3.3 Tunnel Concrete Plug

Constructed to expedite the excavation of the twin main DTs, both the TCA and CP were to be sealed upon the completion of and before utilizing the DTs for diversion of river water for the construction of the dam. It has been decided that instead of fully backfilling the entire TCA and CP, several concrete plugs will be installed at specific locations to seal off both TCA and CP from the main diversion tunnels (DT). A total of 3 tunnel plugs were planned and constructed. These plugs are located at (1) the opening of TCA – DT1 Junction, (2) DT1 – TCP Junction, and (3) TCP – DT2 Junction. Figure 5(a) and 5(b) show the location of the concrete plugs along TCA and CP.

The tunnel plugs design has adopted an innovative design approach, differing from the conventional friction-based design. The tunnel plugs are subject to maximum hydrostatic pressure of approximately 650kPa imposed by the water head at the upstream of the river, conventional friction-based design approach, which relies on frictional resistance between the concrete and rock, would result in up to 20m concrete plug length. The rock plug design adopted for this project included T40 galvanized rebar as shear anchorage at interface of the plug and surrounding rock mass, leveraging the strength of the rock mass in addition to the frictional force to withstand the design water pressure. Using concrete grade of G40 with characteristic strength of 40MPa, the design plug length is reduced from 20m to 3m, enabling massive saving in concrete volume and construction program, and subsequently reducing the carbon footprint.

The design procedures involve performing structural analysis of the concrete plug using SAP2000 program where the concrete plug was modelled as a plate subject to lateral hydrostatic pressure applied linearly and increasing with increasing depth. Boundary conditions of the plate element was modelled as pinned in the x- and y-axis along the periphery of the concrete plug, while pinned at x, y and z-axis along the invert as shown in Figure 7. This results in zero bending moment at the peripheral while maximum bending moment near center of the plug. The structural capacity of the concrete plug was assessed by means of plotting a M-N interaction capacity envelop and comparing against the state of stress (axial force and bending moment) of the plug. Instead of adding reinforcement bars for flexural capacity like a conventional slab design, the thickness of the plug is increased such that the entire section without rebar is structurally sufficient. The design bending moment has also considered the effect of twisting moment.

The anchorage design of tunnel plug consists of equally spaced T40 rebar distributed along the tunnel plug's periphery to transfer the hydrostatic load and anchor the plug to the surrounding rock mass. The sliding action of the plug under the hydrostatic pressure was designed to be counteracted by the shear capacity of T40 rebar. Friction resistance at the base of the plug, which is favourable, has been ignored in the design. The shear capacity, V_c, of rebar was calculated using Equation (1).

$$V_c = \frac{p_y \times A_v}{\sqrt{3}} \quad (1)$$

Where p_y = design yield strength of rebar = $\frac{1}{\gamma s} \times f_{yk}$, γs is partial factor for anchor rebar = 1.15, f_{yk} is characteristic yield strength of rebar = 500MPa, and A_v = shear area = 0.9A (for solid bars), where A is steel bar nominal cross sectional area.

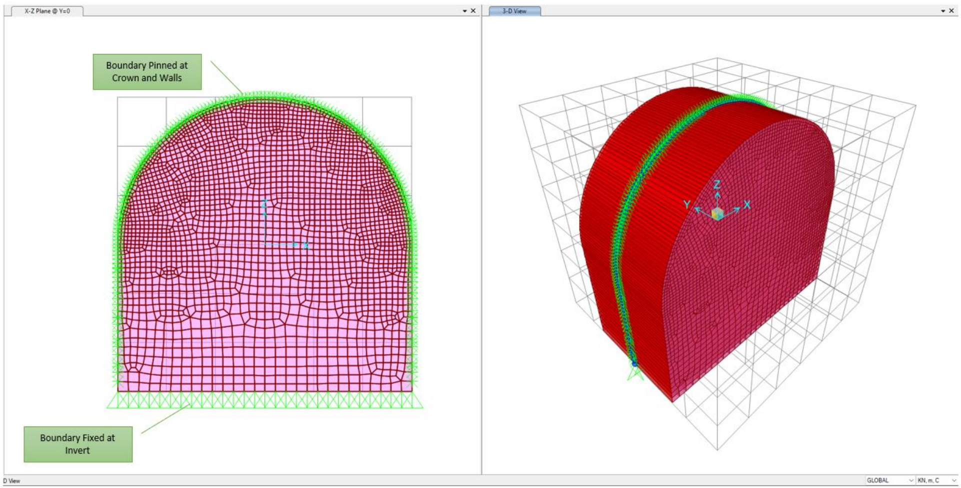


Figure 7: Model set-up for concrete plug in SAP2000

The required shear force was extracted directly from the structural model as boundary reaction force and compared against the shear capacity of rebar. The number of rebars required to resist the shear force is calculated accordingly. A load factor of 1.05 is applied to the maximum hydrostatic pressure for safe design. Load factors of 1.35 or 1.4 are usually adopted for hydrostatic pressure due to uncertainty, however it was considered overly conservative here because the maximum height of the dam is known, and it is physically impossible for the plug to consider hydrostatic pressure that is higher than the crest of the dam.

The required embedment depth of anchoring rebar was calculated according to EOTA, TR 029, Section 5.2.3 (EOTA, 2010) resistance to shear loads. Various failure mechanisms such as steel failure, concrete pry-out and concrete edge failure were assessed. Sufficient embedment depth is vital to ensure the full allowable shear capacity of rebars is mobilized.

The final design concluded with T40 rebar embedded minimum 900mm each side i.e. into rock and concrete plug, with in- and out-of-plane spacings of 0.70m and 0.75m respectively. The minimum achieved Factor of Safety for against steel failure, concrete pry-out and concrete edge failure is 1.1, 2.7 and 1.2 respectively. Figure 8 below shows the site photo of the drill hole for the T40 dowel bars.

(a) (b)

Figure 8: Site Arrangement of Rebar Along Tunnel Profile for Tunnel Plug (a) Left Side Wall, (b) Right Side Wall

4 INSTRUMENTATION & MONITORING

A comprehensive Instrumentation and Monitoring (I&M) system was implemented, consisting of three key components which are convergence monitoring, vibrating wire rock bolts, and vibrating wire shotcrete cells. These instruments were installed and monitored throughout the construction period. Leveraging the extensive experience of the contractor and the systematic installation of temporary support measures such as SFRC and rock bolts following each excavation cycle, the I&M and support system effectively mitigated any potential displacements and prevented any exceedance of alert thresholds (Yasir Ali, n.d.).

Figure 9 illustrates the three convergence monitoring points, which were assessed using optical prisms. Monitoring was conducted daily before the commencement of work and after the completion of each blast cycle at the TCA. The instrumentation data indicated no significant displacement, with measurements remaining well below the alert threshold throughout the monitoring period.

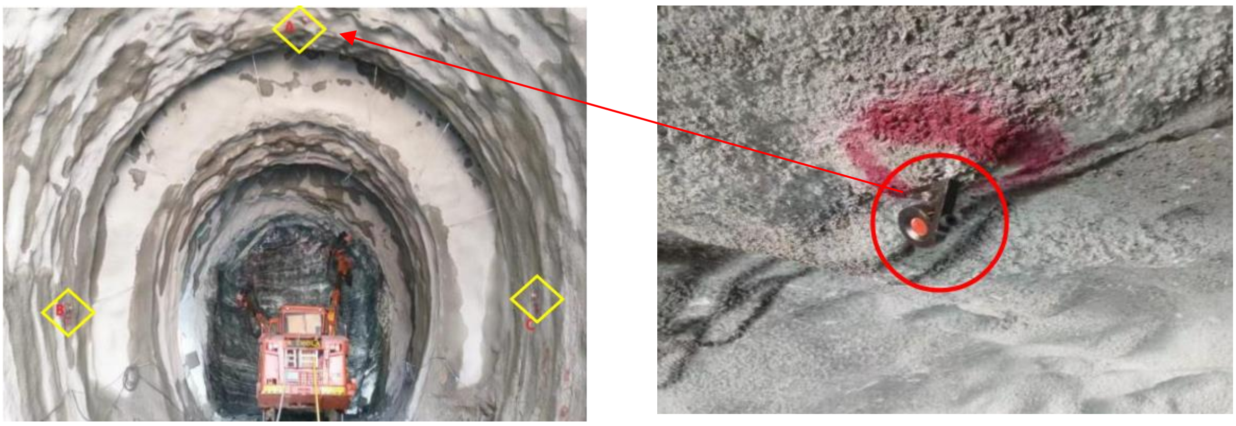


Figure 9: Instrumentation installed in TCA

5 CHALLENGES AND MITIGATION STRATEGIES IN TCA EXCAVATION

The excavation of the Temporary Construction Adit (TCA) at the Nenggiri Hydroelectric Power Project presented significant engineering and logistical challenges. The need for precise planning and innovative solutions was critical to ensuring safety and progress, particularly given the constraints posed by simultaneous excavation of twin diversion tunnels (DT1 and DT2).

5.1 Logistical challenges and traffic management

The excavation of DT1 and DT2 from a single access point via the TCA resulted in congestion and machinery movement constraints at ingress and egress. To mitigate delays and streamline excavation operations, a comprehensive traffic management plan was implemented to regulate machinery movement, ensuring smooth transitions between excavation, mucking, and support works. The main contractor Protext Construction (M) Sendirian Berhad developed detail excavation sequence to coordinate four active excavation faces concurrently, reducing idle time and maximizing efficiency. Additionally, an optimized haulage strategy was introduced, deploying designated pathways for muck disposal and material transport, which significantly enhanced overall workflow.

5.2 Tunnel gradient related challenges and stability measures

The TCA's steep vertical gradient (approximately 9 degrees) presented operational challenges such as increased risk of machinery skidding and water accumulation. To mitigate these potential risks, an efficient dewatering system was implemented to prevent water ponding and maintain continuous excavation progress. The invert was reinforced with BRC A6 mesh and G30 concrete to enhance durability, and groove lines were introduced at concrete surface to facilitate smoother vehicle maneuverability and improve safety. Additionally, a pump sump was strategically located at the TCA-DT junction, with a dedicated operator (bankman) on standby to manage water control operations, ensuring uninterrupted site functionality. As shown in Figure 10, the dry surface inside the tunnel demonstrates the effectiveness of the bund system in mitigating water entry.

Figure 10: Reinforced Invert of the TCA

5.3 Machinery safety & equipment optimization

Given the steep gradient and continuous heavy-duty operations, safety concerns, particularly the risk of brake failures, were proactively reviewed and addressed. To mitigate such risk, advanced construction machinery was deployed, including 10-wheel tipper trucks and brand-new equipment, ensuring reliability and adherence to safety protocols. These measures collectively minimized risks and enhanced productivity throughout the TCA excavation process.

6 SUSTAINABILITY CONSIDERATIONS IN DESIGN & CONSTRUCTION

Sustainability plays a key role in optimizing both environmental and economic performance throughout the design and construction of the portal slope, temporary construction adit, and associated tunnel systems. Efforts have been made to minimize resource consumption and reduce the carbon footprint.

For the portal slope, the design incorporated corrosion-resistant galvanized T25 steel bars and SFRC to enhance durability. This, alongside with optimized soil nail design spacing and groundwater management strategies, ensures long-term slope stability with reduced maintenance needs. The proposed subsoil drainage system, designed to control groundwater, was strategically placed to reduce the risk of slope failure due to water accumulation.

In tunnel construction, the design of concrete plugs at critical junctions was innovatively adapted to reduce material usage. By anchoring the plug to the surrounding rock mass instead of relying solely on friction at the interface of plug and surrounding rock, the required length of the concrete plug was reduced from 20m to 3m. This optimization significantly reduced concrete volume, reducing both material cost and the associated carbon emissions. Additionally, the use of higher-strength concrete (G40) further contributed to a more efficient, sustainable design.

The use of advanced structural program such as SAP2000 and finite element analysis ensured the most efficient and sustainable solutions for structural integrity, minimizing unnecessary material use and energy consumption during construction.

7 CONCLUSIONS

The Nenggiri Hydroelectric Project is a key step in Malaysia's shift towards renewable energy, showcasing innovative design and construction solutions. The project design, particularly portal slope, temporary construction adit (TCA), and tunnel plug, was optimized to address difficult site constraints, reduce construction time, while ensure safety and overall stability.

To stabilize the portal slope, soil nailing was used with calculated spacing, considering ground conditions, slope height, and gradient. This created a safe and stable structure with a high safety factor. The use of galvanized T25 steel and shotcrete facing further improved durability and long-term performance.

For the TCA, a combination of empirical, analytical, and numerical design approach was adopted. The design included the Q-System (NGI, 2015), analytical methods such as Longitudinal Displacement Profile (LDP) and Ground Reaction Curve (GRC) , and numerical modelling which resulted in a support system that fit the varying ground conditions of the project. Canopy tubes and steel arches provided essential support in soft and mixed ground during excavation. And finite element analysis using RS2 software helped assess tunnel stability and support measures for fractured rock, while validating the support system from empirical method, demonstrating the project's commitment to advanced design technologies.

These design choices reflect a comprehensive approach to geotechnical engineering, focusing on safety, efficiency, and resource optimization. The strategies not only support the project's timely completion but also contribute to Malaysia's energy goals and sustainable development. By integrating detailed planning, innovative engineering solutions, and advanced equipment, the project successfully overcame obstacles, setting a benchmark for managing complex excavation works in hydroelectric power projects.

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