Design of Reinforced Concrete Linings of NN2 Headrace Tunnel

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ABSTRACT

The design of the pressure tunnel is illustrated by the example of the headrace tunnel of Nam Ngum 2 Hydroelectric Power Project (NN2 HPP) in Lao PDR. The required length of steel liner is determined based on Austrian's confinement requirement criteria. The analysis and design of reinforced concrete lining is performed according to the geological conditions and specific loading conditions. The prediction of the water losses due to crack of the lining is performed to verify the acceptation of concrete lining. The slope stability analysis is carried out to ensure the stability of the rock cover and overburden above the headrace tunnel due to water leakage from the concrete lining. The analysis and design results show that the headrace tunnel is safe and meet the requirement for pressure tunnel.

1. INTRODUCTION

The Nam Ngum 2 Hydroelectric Power Project (NN2 HPP) is located approximately 90 km north of Vientiane in central Laos and approximately 35 km upstream of Nam Ngum 1 reservoir. A reservoir is impounded by a 182 m high Concrete Face Rockfill Dam (CFRD). The head of NN2 HPP is 165 m, and its installed capacity is 615 MW, with three Francis units. The connection between NN2 reservoir and the powerhouse consists of a intake structure, a 460 m long headrace tunnel, a manifold and three inclined penstocks as shown in Figure 1.

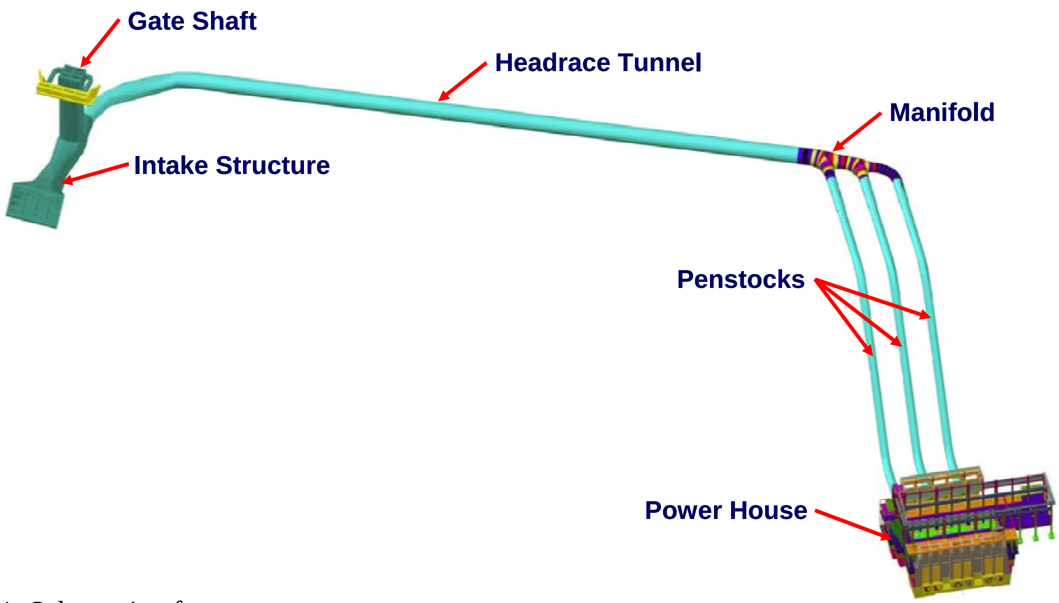


Figure 1. Schematic of power waterway system

The headrace tunnel with diameter of 10.7 m is located on the left bank of Nam Ngum River. The maximum water level in the reservoir will be EL. +375.00 masl and the minimum operation water level will be EL. +345.00 masl. The headrace tunnel will slope from an invert elevation of EL. +320.00 masl with 4.025% towards the steel lined manifold. According to the confinement requirement, it is agreed that the reinforced concrete lining will be employed between the gate shaft and the location that meet the confinement requirement, which is 60 m prior to reach the manifold. This paper describes some aspects of the design of headrace tunnel, which is lined with reinforced concrete over a distance of 400 m. The design of reinforced concrete lining shall fulfill the following functions;

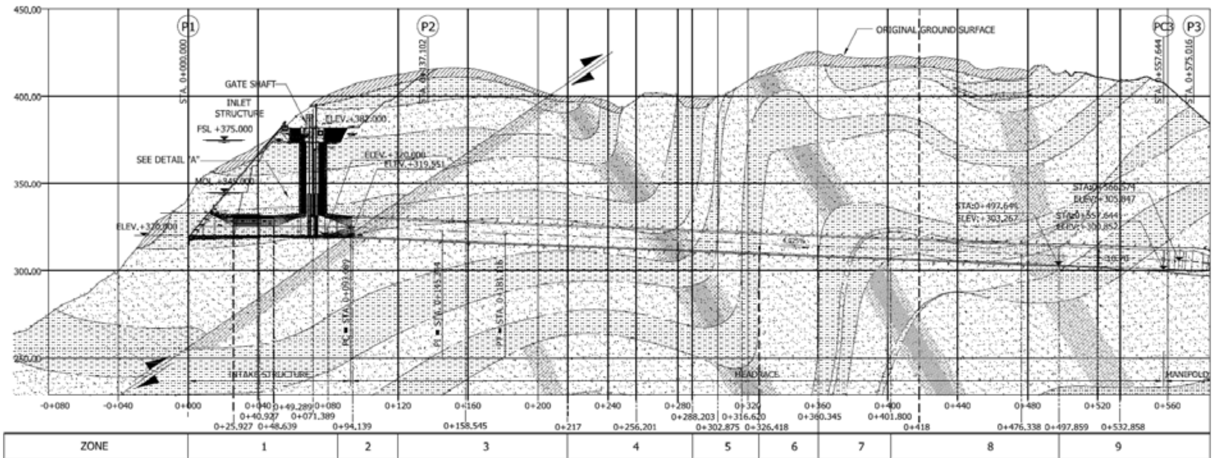
(1) Carry the external pressure exerted by the ground water and the rock,
(2) Limit seepage flows (reach and quantity),
(3) Reduce head losses,
(4) Prevent rock deterioration or erosion and washing out of joint fillings, and
(5) Ensure long-term stability under varying water pressures.

2. GEOLOGICAL CONDITIONS

The geological conditions for the headrace tunnel are defined as shown in Figure 2. The general geology and structural geology can be described as follows;

2.1 General Geology

The headrace tunnel is located in quartz–rich sandstone and siltstone of Khorat Group, Jurassic to Cretaceous ages. The quartz-rich sandstone forms a prominently and nearly vertical cliff. It is typically light grey in fresh and light to yellowish-brown when it is weathered. There is a medium bedded to massive, very fine to medium grain and hard to very hard. In addition, there is a few laminated grey siltstone located at intermediate. The siltstone (interbedded layer) is typically purple, thin bedded to massive, weak in general, locally medium hard when graded to sandy siltstone. It is highly weathered to decompose where exposed.



ZONE		1	2	3	4	5	6	7	8	9
UNIAXIAL COMPRESSIVE STRENGTH (MPa)		SI 0.5-1	SS 50-100 SI 15-25	SS 100-120 SI 20-30	SS 50-150 SI 20-30	SS 50-100 SI 15-25	SS 100-120	SI 20-30	SS 100-120 SI 15-25	SI 15-25
DRILL CORE QUALITY (RQD) (%)		SI 75-90	SS 25-50 SI 25-50	SS 75-90 SI 50-75		SS 25-50 SI 25-50	SS 75-90	SI 75-90	SS 50-75 SI 50-75	SI 50-75
SPACING OF DISCONTINUITIES (M)		SI 0.5-1	SS 0.2-2 SI 0.1-0.5	SS 0.6-2 SI 0.2-1		SS 0.2-0.6 SI 0.5-0.2	SS 0.2-0.6	SI 0.2-1	SS 0.2-2 SI 0.2-1	SI 0.2-1
CONDITIONS OF DISCONTINUITIES		SLIGHTLY ROUGH / SLICKENSIDE	SLICKENSIDE	SLICKENSIDED / SLIGHTLY ROUGH		SLICKENSIDE/SMOOTH			SLICKENSIDED / SLIGHTLY ROUGH	
GROUNDWATER		DAMP/WET		WET/DRIPPING			DAMP/DRY		WET/DRIPPING	
STRIKE AND DIP ORIENTATION DRIVE TO CHAMBER	DRIVE TO MANIFOLD	FAIR			FAVOURABLE	FAIR				UNFAVOURABLE
	DRIVE TO INLET	FAVOURABLE			UNFAVOURABLE	VERY FAVOURABLE				FAVOURABLE
ROCK MASS TYPE		RM3a	RM4a/4b	RM2a/RM2b	RM2a | RM3b	RM3a | RM2a | RM2b	RM1b/RM2a	RM3a	RM2b | RM3a	RM3a

Figure 2. Geological conditions along headrace tunnel

2.2 Structural Geology

The headrace tunnel is driven through S-form synclinal and anticlinal folds whose axis is approximately N80°E of trend and nearly perpendicular to the Nam Ngum river channel. The beginning of the headrace tunnel is driven in shear zone. Its plane is approximately N30°W of trend and approximately 35° of plunge to the northeast. The quartz-rich sandstone and siltstone located along the tunnel are intensely gentle to steeply joints and their trends are varies. The following length of the tunnel (120-130 m approximately) is driven through the low angle anticline, where the dips of bedding planes are between 0° to 30° to the north-northeast and 0° to 25° to south-southwest. The sandstone located in this location is closely to medium gentle to steep joints. At the middle length of the tunnel (70-80 m approximately) driven though the north limb of the S-form anticline, the dips of bedding plane are from 70° to 85° to the north-northeast. At the end of the headrace tunnel, it is driven in the syncline. The dips are between 0° to 30° to the south-southeast and 0° to 30° to the north-northeast. The strike of bedding plane ranges from east-west to N45°W. Their surfaces are typically cleaned. However, there are some iron-oxide stained, tight, slightly rough to rough, slight undulating and some slickenside surfaces. In addition, there is quartz-rich sandstone and prominent slickenside surface for siltstone. There are two joint sets that appear along the headrace tunnel. The first one is nearly vertical and another is gentle ranging from N45°E to N45°W of trend. The surfaces are typically cleaned or iron-oxide stained, slightly rough to smooth, slightly undulating. Furthermore, some joint surfaces are slickenside.

3. CONFINEMENT REQUIREMENTS

It is recognized that the rock cover would have to be of sufficient equivalent weight to sustain the internal pressure of an unlined tunnel. It is also recognized that soil, talus and colluvium deposits should be disregarded in terms of providing a contribution to the confinement, that is, a rock mass to sustain the internal pressure without hydraulic jacking. Hydraulic jacking does take place when the water pressure or thin grout pressure acting on a plane exceeds the normal stress across the plane, which can be a prevailing joint, bedding parting or impervious barrier.

An Austrian criterion is adopted as the confinement criteria for headrace tunnel. The minimal radius of rock zone for the static head can be defined as

$$R^{s}_{r\min} = \frac{F^{s}_{S}\gamma_w h_s}{k_0 \gamma_r} \tag{1}$$

where F^{s}_{S} is the safety factor for static head; γ_w is the unit weight of water; γ_r is the unit weight of rockmass; h_s is the static head; and k_0 is the minimum stress ratio.

According to hydrofracturing/hydraulic injection test results, it is found that the minimum horizontal principal stress is the minimum principal stress. The minimum stress ratio (horizontal stress/vertical stress) of 0.5 has been observed (k_0 =0.5). Since the static head at the connection between concrete lined and steel lined is 64 m, the required minimum radius of rock cover is 64 m approximately with the safety factor of 1.25.

4. TUNNEL ANALYSIS AND DESIGN

The headrace tunnel is mainly considered as the pressure tunnel. Therefore, the reinforced concrete lining are used to resist external and internal loads or to protect erodible and to limit the circumferential strains and cracks which develop under operating conditions. In order to design tunnel element economically, the tunnel element shall design with optimum reinforcement using proper analysis model.

4.1 Beam Spring Model

The beam spring model is a simple method that gives satisfactory results for this kind of analysis and design (Duddeck & Erdman, 1982; ITA, 1988; USACE, 1997). The tunnel is modeled with elastic bedded beam element. Whereas, the bedding to the rock is considered as non-tension spring, which can only have compression and tension is excluded. The beam spring model used in the analysis is shown in Figure 3.

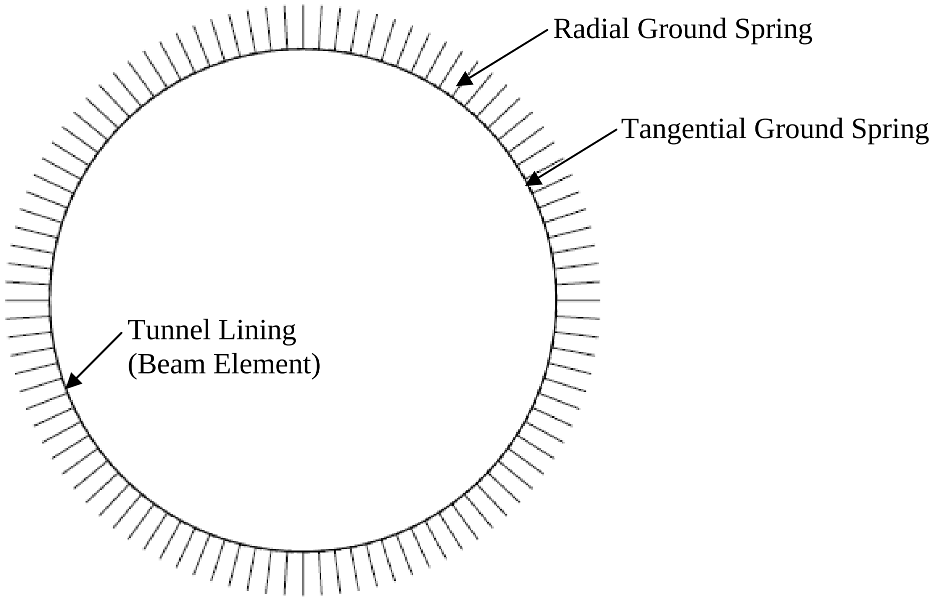


Figure 3. Beam spring model for tunnel analysis

Since the tunnel location is in sandstone and siltstone, the rock mass parameters used in the analyses are based on laboratory test results. The rock mass properties used in the analyses are generally determined based on Geological Strength Index, GSI (Marinos and Hoek 2000) as shown in Table 1. The spring constants for rock masses are determined based on the following equations;

For radial spring constant

$$k_{sr} = \frac{E_s}{r} \tag{2}$$

For tangential spring constant

$$k_{st} = k_{sr} \tan\left(\tfrac{2}{3}\phi\right) \tag{3}$$

Table 1. Rock mass properties

Rock Type	*UCS* (MPa)	γ (kN/m^3)	E_s (GPa)	c (MPa)	ϕ (°)
Sandstone	130	26	19.02	1.863	59.44
Siltstone	25	26	1.05	0.215	26.49

4.2 Loads on Tunnel

Loads acting on headrace tunnel are consisted of self-weight of lining, external water pressure, loosening rock load, internal water pressure, grouting pressure, etc. The headrace tunnel is designed for all appropriated load combination, using the proper factor of safety. The load acting on the tunnel is combination between external and internal water pressures, loosening rock load and grouting pressure, while the self-weight of tunnel lining is considered for all cases of analyses. Important loading combinations are specified for construction, operation and maintenance periods.

4.3 Tunnel Analysis

The commercial software DIANA (Displacement Method Analyzer) is employed for conducting analysis of headrace tunnel lining. The analysis is carried out using a beam spring model, which is simple model and the results can easily be interpreted.

The 72.5 cm thick of tunnel lining is considered all around tunnel lining. The general geometry of tunnel is shown in Figure 4. It notes that the temporary support is not considered in the analysis.

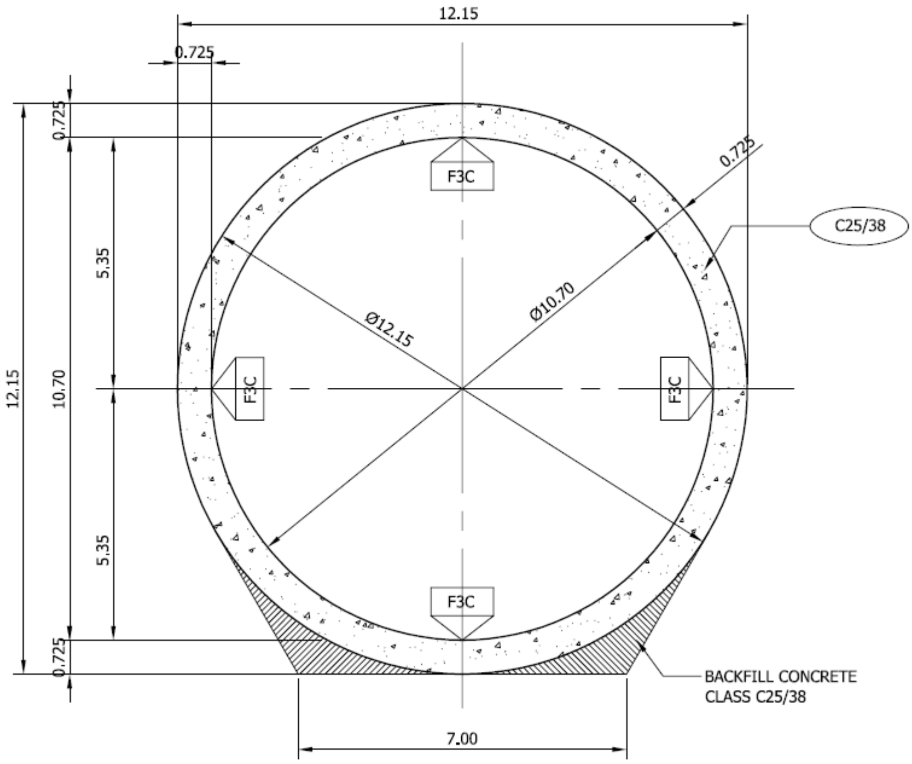


Figure 4. General geometry of headrace tunnel

The analysis results of distortion (δ), axial force (N), bending moment (M) and shear force (Q) for each load case and rock mass type are obtained. For an example, Figure 5 shows the analysis results of the loosening rock load consideration during construction period.

4.4 Tunnel Lining Design

Once the axial force and bending moment are obtained, the tunnel lining must be designed to achieve acceptable performance. Since the tunnel lining is subjected to combination of axial force and bending moment, the design is conveniently carried out using the capacity interaction curve, also called the

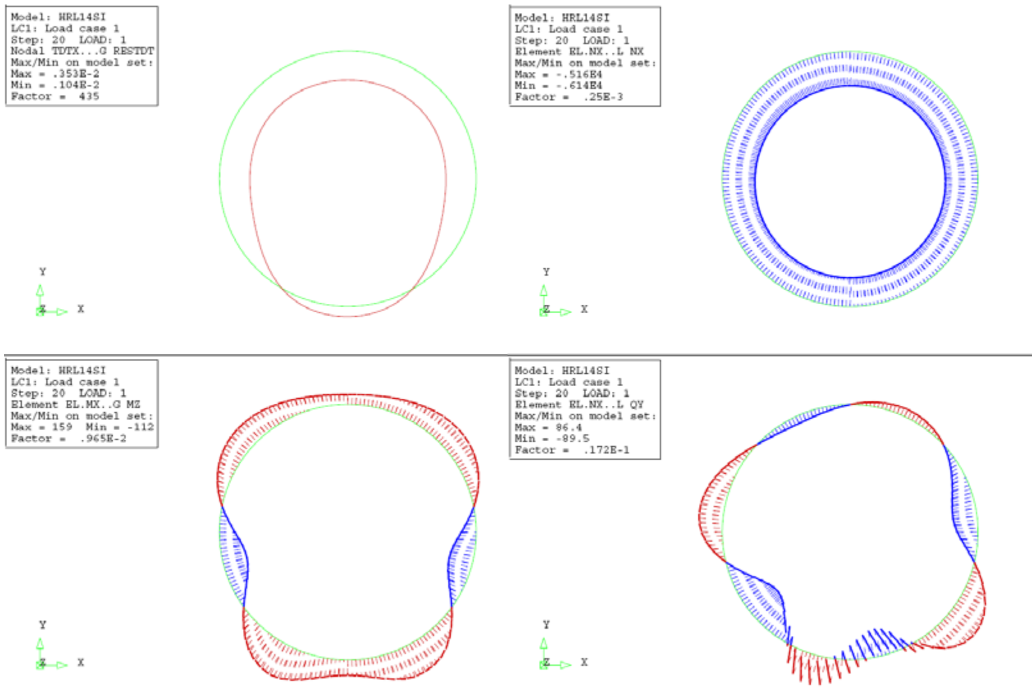


Figure 5. An example of analysis result, i.e., distortion (top left), axial force (top right), bending moment (bottom left) and shear force (bottom right)

thrust-moment (*N-M*) diagram. The ACI code (ACI 318) or European code (EN 1992) can be applied to design the tunnel lining.

The required reinforcement is mainly dependent on the geological conditions and internal pressure as shown in Figure 6.

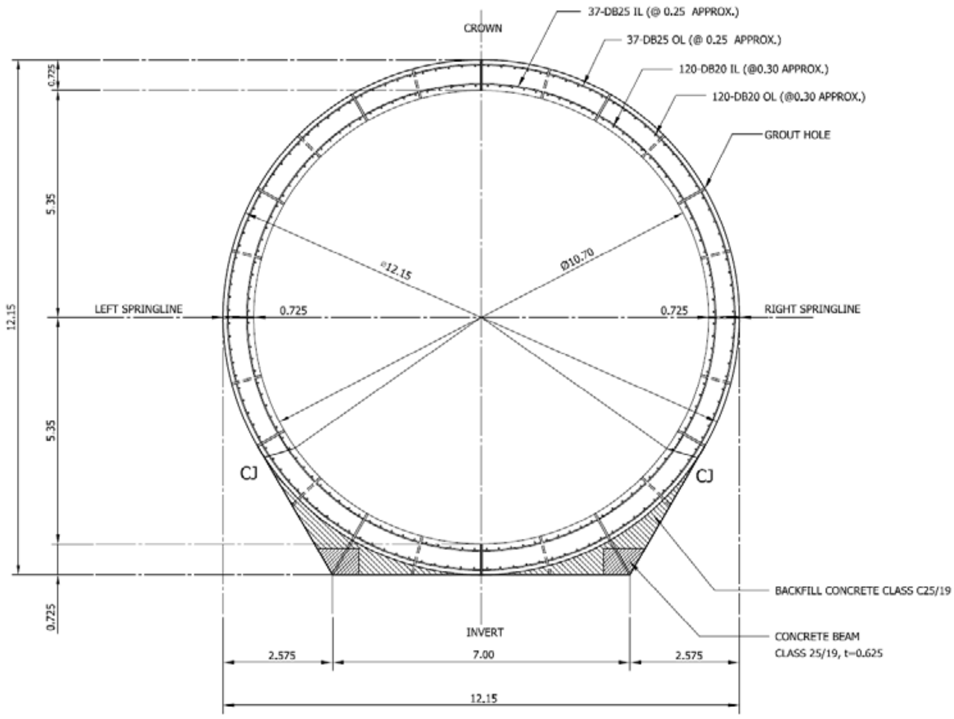


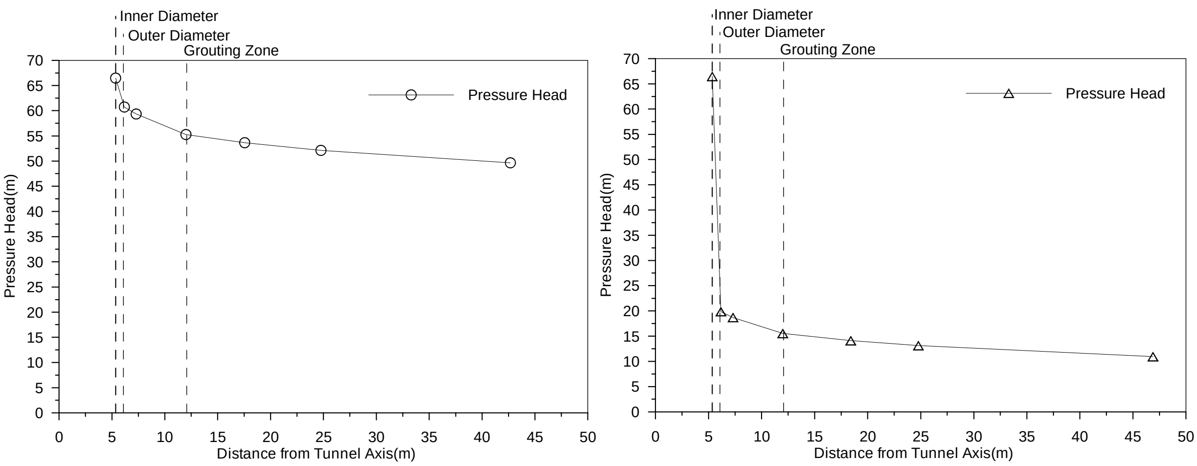
Figure 6. Detailed reinforcement for headrace tunnel

4.5 Seepage and Stability Analyses

Seepage analysis is conducted in order to predict the water losses through the lining taking account of the cracked concrete lining, grouted zone and surrounding rock mass. The seepage analysis is carried out at the critical section, connection between steel liner and reinforced concrete lining. The seepage analysis is conducted for both permeability of cracked concrete, i.e., k_c = 10^{-7} m/sec and k_c = 10^{-8} m/sec, in order to investigate the influence of lining permeability on water pressure in surrounding rock mass.

It is considered that after a certain transient state, which may be of long duration, a steady flow will take place, as shown in Figure 7. Even this steady flow is the result of a quite complex combination of hydraulics and rock mechanics phenomena. As shown in Figure 7, starting from the internal pressure in the tunnel, there is a pressure drop due to the more or less pervious lining. The eventually grouted zone around the tunnel is beneficial in reducing the permeability of the rock and producing an additional pressure drop. From this point on, the permeability of the rock mass defines the further drop in pressure. It is immediately cleared that the ratio of the permeability of the lining to that of the rock mass plays a determinant role in the distribution of the water pressures around tunnel.

The slope stability analysis is carried out to ensure the stability of the rock cover and overburden above the headrace tunnel due to water leakage from the concrete lining resulting from above seepage analysis.



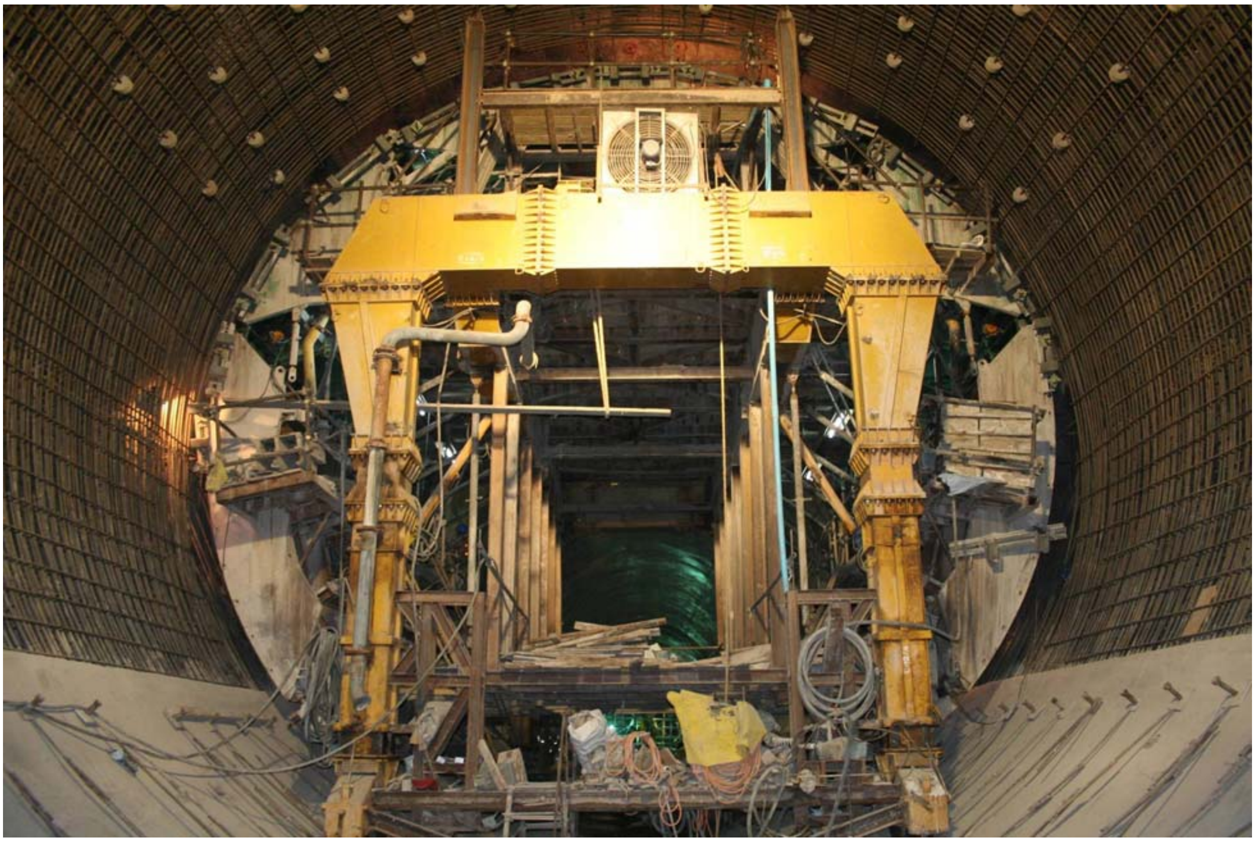
(a) For $k_c = 10^{-7}$ m/sec (b) For $k_c = 10^{-8}$ m/sec

Figure 7. Distribution of water pressure head around tunnel

5. CONCLUSIONS

As the analysis and design results, the thickness of reinforced concrete lining is determined by practical constructability considerations rather than structural requirement, the thickness of tunnel lining is resulted as 72.5 cm. The reinforced concrete lining are designed to resist external and internal loads, limit the seepage losses from the tunnel and protect the rock from deterioration or erosion. The reinforcements are generally required dependent on the geological conditions and internal pressure. Picture 1 shows a shutter assembly for supporting a concrete lining to be poured inside of the tunnel.

The radial consolidation grouting is required to induce favorable change of the stress distribution around the tunnel and to reduce the permeability of rock mass around the tunnel. The leakage is controlled within allowable limit by limiting the cracked width of concrete lining and consolidation grouting around the tunnel. The slope stability of the rock cover and overburden above the headrace tunnel is ensured by slope stability analysis.



Picture 1. Shutter assembly for supporting a concrete lining to be poured inside of the tunnel

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