Design and construction of the 5.5 km TBM excavated headrace tunnel of the Theun Hinboun Expansion Project, Lao PDR

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ABSTRACT

The Theun Hinboun Expansion Project (THXP) in Lao PDR aims to increase the installed capacity of the existing hydropower plant from 220 MW to 500 MW. Lombardi Eng. Ltd. was assigned by the Italian design-build contractor CMC di Ravenna to carry out the basic, detailed and construction design of the main underground waterways system between the water intake diverting from the Nam Theun River and the new power house. This included a 5.5 km single shield TBM excavated headrace tunnel which constitutes the main focus of the present paper. This tunnel represented in fact the first underground structure in Lao PDR excavated using a TBM. This tunnel is lined using precast reinforced concrete segments made of 1.6 m long rings, each constituted of 6 segments. The internal diameter of the lining is 6.90 m while the excavated diameter is 7.65 m. The segmental lining is erected in parallel to the excavation works and subsequently backfilled with pea gravel and grouted with cement based mix. In addition to their importance in providing good protection against wedge instabilities of the soft mudstone/sandstone/siltstone rock found along the tunnel axis, this lining system allowed a fast and easy completion of the tunnel providing also an adequate smooth surface avoiding thus major head loss. With a maximum overburden of 400 m and a minimum of 18 m, several initial hypotheses regarding the design of lining system were considered taking into consideration the internal and external water pressure combined with water hammer event. During the excavation works, special provisions were adopted at fault crossing by the TBM. With carefully considered procedures, the faults were successfully crossed with almost no delay. Fractured rock at these locations was adequately treated. This paper aims to provide a detailed description of the most relevant theoretical bases considered during the initial design of the headrace tunnel, and to give an overlook of the challenges endured and successful management procedures adopted during the excavation and the lining works.
1 THE FIRST TBM EXCAVATED TUNNEL IN LAOS

The first 220 MW hydropower plant of the Theun Hinboun Power Company (THPC) is located in both Bolikhamsay and Kammouane Provinces in Lao PDR with commercial operation started during the year 1998. After a decade of operation, THPC decided to expand the project to a new total capacity of 500 MW by regulating the water volume of the Nam Gnouang River, which is one of the tributaries to the existing project.

In 2008, the Italian construction company CMC di Ravenna won the design-build contract of the new expansion project and assigned Lombardi Eng. Ltd. to become its designer for the main waterways system consisting principally of a headrace tunnel, a penstock and a surge tunnel. Lombardi was equally charged to follow the construction of key structures on site.

This system conveys water from the upstream intake structure to the new powerhouse (Figure 1). The headrace tunnel represents the longest and most relevant and challenging scheme of the system. It is a 5.5 km long tunnel with a total capacity of 110 m$^3$/s and a 6.90 m internal diameter while the external excavation diameter is 7.65 m. This tunnel is lined using precast reinforced concrete segments. This lining answers to the design requirements related to the maximum allowable values of head loss in the waterways system.

A 30 m deep TBM dismantling shaft is foreseen around 200 m downstream of the water intake, to dismantle the TBM thus allowing a full independence of the excavation works with regards to the flood season. The upstream reach of the headrace tunnel between the dismantling shaft and the water intake is composed of an underground drill and blast tunnel and an open trench section excavated in the river bed, and partially steel lined.

Finally, it must be mentioned that the choice to excavate the headrace tunnel by TBM had lots of advantages related to environmental requirements. For this mechanically excavated tunnel, no adits will then be needed, and the construction of access roads to the adits in the middle of a dense forest is no longer necessary. Moreover, the access to the site was relatively easy since a new road n°8 crossing all the width of Lao and linking Thailand to Vietnam was recently constructed. This road passes through the construction site and the TBM erection yard could be foreseen only some kilometres far from the this road.

Several other parameters were taken initially into consideration that favoured the choice of a mechanized excavation such as the favourable and relatively homogenous geology, the short construction duration requirements, the cost effectiveness analysis, and finally the experience of the contractor in such special works.

Figure 1 General layout of the waterways system
2 GENERAL CONCEPT AND GEOLOGY OF THE HEADRACE TUNNEL

2.1 General concept of the headrace tunnel

The alignment of the new headrace tunnel ran almost parallel to the existing one. It has a constant slope of 1.14 %. It is excavated ascending from the downstream TBM assembling yard (Figure 2). The first 75 m section of the headrace tunnel used as a TBM launching tube was excavated by drill and blast method. This launching length was calculated as a function of the TBM requirements and the needed place for its back-up system. Additionally, a space was reserved in this tube for the storage of the continuous conveyor belt inside the tunnel used for mucking. Only the precast invert segment was placed in this section after building a concrete slab. This allowed the access of the TBM and the future train traffic during the excavation works.

The main section of the headrace tunnel is around 5.2 km long. It is excavated using a single shield TBM and precast reinforced concrete segmental lining was applied. Beyond the TBM dismantling shaft at the upstream portal of the headrace tunnel, two different sections were considered. The underground D/B section is lined with reinforced concrete, designed to absorb almost the entire internal water pressure due to insufficient rock overburden. The other section, connecting the headrace with the water intake, is built in the riverbed in open trench excavation. It is mainly constructed with reinforced concrete while the section with bends is steel lined.

Figure 2 Erection in the portal yard of the 7.65 m diameter single shield TBM
The first technical constraint considered during the initial conceptual stage of the project was related principally the headrace tunnel. This constraint is associated with the geology and topographical configuration of the tunnel. Being excavated in the vicinity of the existing headrace tunnel, the local geology of the new headrace tunnel is relatively well known based on the mapping carried out during the drill and blast excavation of the old tunnel.

After a thorough initial analysis of the existing data, it appeared that the geological layer in the area is formed by a sequence of mudstone, siltstone and sandstone pertaining to the Nam Xot Formation K1nx (Figure 3). The layer is normal to the tunnel axis and dips at a lower angle. Most of the rock mass is classified as fair to good quality. Some limited sections of the headrace are expected to cross faults where weak and extremely weathered rock might be found. Keeping in mind the prevalence of this soft rock normally subjected to swelling during excavation and eventual wedge breaking, two main initial considerations where decided:

- The TBM should be equipped with a shield to allow a safe erection of segmental lining
- The cutterhead should be equipped with overcutters allowing the machine to excavate 100 mm beyond the nominal tunnel diameter

![Figure 3 Geological profile along the headrace tunnel and the penstock](image)

### 3 DESIGN OF THE SEGMENTAL LINING SYSTEM

#### 3.1 Concept of the lining system

The segmental lining is assembled ring per ring under the protection of the TBM tail-shield. The boring diameter being bigger than the external lining diameter leads to the necessity to backfill the gap between the lining and excavation rock face applying in two steps. First the gap is filled with pea-gravel by air-injection. In a defined distance to the excavation face the gap filled with pea-gravel is grouted later with cement based slurry.

For the headrace tunnel of the THXP a segmental lining with trapezoidal/parallelogram segments and a special invert segment was designed. The lining consists of rings with a length of 1.60 m, assembled from 6 reinforced precast concrete segments. Since the invert segment is placed always on the same position, it was possible to foresee a central drainage
ditch and fixing bushes for the rails for the TBM backup system. The main geometrical characteristics are summarized in Table 1 while an overview of the lining system is illustrated in Figure 4.

<table>
<thead>
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<th>Characteristics</th>
<th>Invert</th>
<th>Lateral segments</th>
<th>Central keystone</th>
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<td><strong>Quantity</strong></td>
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<td>4</td>
<td>1</td>
</tr>
<tr>
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<td>7'460 mm</td>
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<tr>
<td><strong>Internal Diameter</strong></td>
<td>-</td>
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<td>6'900 mm</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
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<td>280 mm</td>
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<tr>
<td><strong>Angle</strong></td>
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<td>58°</td>
<td>64°</td>
</tr>
<tr>
<td><strong>Shape</strong></td>
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<td>Parallelogram</td>
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<tr>
<td><strong>Weight</strong></td>
<td>67.0 kN</td>
<td>39.0 kN</td>
<td>44.9 kN</td>
</tr>
</tbody>
</table>

Figure 4 Concept of tunnel lining consisting of precast concrete segments
Each segment is equipped with an elastomeric sealing gasket situated at the intrados of the contact zone of the joints. The position of the sealing gasket was chosen to allow the grouting of the joint in case it is not completely sealed.

To overcome the push-back forces of the rigid sealing gasket during the assembly of the ring, the connection between two consecutive rings is done by pins which provide a sufficient pull-out resistance that help keeping the joint closed. The longitudinal joints instead are temporarily fixed with screwed-in steel bolts that might be removed after completion of the grouting of the gap between segmental lining and rock mass to avoid an opening of the joints.

To avoid excessive deformation and to ease the assembling process the longitudinal joints are equipped with guiding rods. This makes it possible to design the joints with a flat and smooth contact surface without any further structural elements, such as shear keys or groove and tongue.

3.2 Structural design hypotheses and analyses

Precast concrete segments for tunnel linings are subject to several loading conditions during their lifetime for which they have to be designed for. Often it is not the final state or the operating stage of the tunnel that is the most relevant loading situation, but the several initial handling situations when the segments are not yet erected.

The life of a precast segment begins with its production, i.e. the pouring of the concrete into the formwork mould already containing the reinforcement cage. Little time after pouring and vapour-curing, the segments are ready for demoulding. At this stage the segments are prone to damages since the concrete has not yet reached its final strength. Handling has to be done consequently with great care.

After demoulding and curing of the segments, the segments are ready for stockpiling on the construction yard of the prefabrication plant. Only before transport to the tunnel the perimetral sealing gasket was installed to prevent loss of characteristics in case of prolonged sun exposure. In case of the Theun Hinboun Expansion Project stockpiling was done for complete rings, one segment above the other, separated by wooden interlayer.

Stockpiling is followed by the transport of the segments (Figure 5) in the tunnel to the TBM where the lining ring is assembled under the protection of the tail-shield by using the segment erector.

![Figure 5 Stockpiling packets for transport of the segments to the TBM erector](image)

After erection and before backfilling and grouting, the gap between lining and excavation border has not yet been completely backfilled. The segmental lining is then sensitive to ground loads. Due to the poor bedding during this stage, increased deformation of the lining has to be expected as a consequence of ground loads. Once the gap outside the segmental lining is completely backfilled and grouted, the lining is ready to resist to the loading conditions when the headrace tunnel operating.
Structural analysis of the segmental lining was carried out by means of a bedded frame model (Figure 6). The segments are modelled as a sequence of mono-dimensional beam elements. The interaction between the rock mass and lining is taken into account by nonlinear bedding springs that are active only when compressed.

The section forces due to the loading conditions depend highly on the assumed structural behaviour of the longitudinal joints between the single segments in the ring. In order to simulate the deformational behaviour of the lining as realistically as possible, the joints were modelled as concrete hinges whose rotation stiffness depends on the bending moment and the axial force acting in the joint. In the calculation model rotational hinges were introduced between the elements representing the single segments of the ring (Figure 6, grey dots). The rotational stiffness of these hinges was calculated independently for all the hinges of the ring and for all the loading conditions. The final equilibrium state for each loading condition is obtained by iteration of the joint stiffnesses.

![Figure 6 Calculation model – bedded frame structure with nonlinear bedding springs (triangles) and rotational hinges at the longitudinal joints (grey dots) (left); typical bending moments for asymmetrical loading (right)](image)

Janssen (1983) proposed a theoretical approach which gives the rotation stiffness of a flat concrete joint in relation to the acting section forces. The two cases “wide open joint” and “fully compressed joint” are to be differentiated. The latter applies if the resulting force is inside the core section of the joint. In this case the joints behavior can be considered similar to a “no hinge” condition, while in case of a “wide open joint” a sudden drop of rotation stiffness is noted (Figure 7).
Figure 7 Rotation stiffness of longitudinal joints according to Janssen (1983)

The rotational stiffness for the condition “fully compressed joint” according to Janssen (1983) is given by:

\[ c_D = \frac{E_0 \cdot b^2}{12} \text{[kNm/rad]} \]

For the condition “wide open joints” the rotational stiffness is defined by:

\[ c_D = \sqrt{\frac{N^3 \cdot b}{\alpha^3 \cdot 18 \cdot E_0}} \text{[kNm/rad]} \]

where:
- \( N \text{ [kN]} \): normal thrust force in joint
- \( b \text{ [m]} \): height of contact zone in joint
- \( E_0 \text{ [kN/m²]} \): elastic tangential modulus of concrete

The rotation of the joint for the “wide open joint” joint condition can be deduced from:

\[ \alpha = \frac{8 \cdot N}{9 \cdot (2 \cdot m - 1)^2 \cdot E_0 \cdot b} \text{[rad]} \]

where:
- \( m \text{ [-]} \): coefficient \( m = M / (N \cdot b) \)
- \( M \text{ [kNm]} \): bending moment in joint

From the geological investigations and especially from the documentation of the excavation works of the existing power plant in vicinity to the herewith presented project, the loading conditions related to the rock mass crossed by the TBM have been deduced.

As documented for the existing headrace tunnel, mainly loads due to gravitational instabilities of rock wedges and blocks had to be expected. Lateral over-breaks, instable rock blocks in the tunnel crown would be expected to collapse with a maximum block height of 3.5 m in poor rock.

Further geological loading conditions have been identified being possibly squeezing pressure especially in fault zones with very poor rock mass properties. Uniform radial squeezing pressure has been considered as well as asymmetrical radial pressure corresponding to sloping fault zones. It is thus crucial for structural safety to exactly analyze...
the deformational behavior of the segmental lining in such situations. Especially the bedding conditions are by far more disadvantageous in poor weak rocks than in good rocks. The rotation of the joints thus is likely to increase and stress concentrations in the joints have to be verified. The geometrical design of the segments has to respect the statical requirements.

The segmental lining is considered being a permeable lining system which, by consequence, is not designed to sustain neither internal nor external water pressure. If filling and emptying of the headrace tunnel is done with care and according to the general rules which propose a pressure head variation of approximately 1 m per hour, internal and external water pressure can equilibrate without significantly loading the lining. The grouted gap between lining and rock mass together with the sealing gasket avoids excessive leakage.

4 EXCAVATION WORKS OF THE HEADRACE TUNNEL

4.1 TBM characteristics and site management

The TBM was manufactured by Robbins and transported to site. Its main characteristics are as follows:

- Normal Diameter (new cutters) 7.65 m
- Overcut diameter 7.70 m with spaces/7.75 m with 2 cutters
- Rotation Bi-directional with muck pick-up in one direction
- Shield length 8.2 m
- Thrust cylinder 18
- Nominal shield thrust 36.6 MN
- Emergency shield thrust 42.0 MN
- Segment erection Rotating beam and mechanical gripping
- TBM muck conveyor hydraulic drive system

The Robbins TBM machine is completely shielded and is equipped with mechanical device to allow placement of the lining segments as the machine advances. A rotary cutterhead assembly is used on the machine and is constructed to allow the use of 53 17” (432 mm) disc cutter. Cutterhead rotation is controlled through variable frequency drives. Cutterhead thrust is furnished by eighteen main thrust cylinders, which are fitted with shoes to allow them to push off the tunnel segments. These cylinders have independent control to allow for steering movements. Further steering is provided by twelve articulation cylinders, mounted between the forward shield and the cutterhead support, capable of tilting the cutterhead and shield stabilization.

At each excavation cycle (1.6 m excavated length), the 6 segments belonging to a complete ring are transported to the erection hydraulic arm in the back-up system of the TBM and erected following a predefined procedure (Figure 8). When the ring is completely erected the connecting bolts are fixed.

In the back-up further activities allow the completion of the rings support: injection of the pea gravel between the rings and the tunnel walls and injection of grout starting at the base of the rings. The backfill is injected from the lifting central threaded holes already foreseen for each segment. The purpose of the backfilling is to develop an intimate and uniform contact with the rock mass and provide a coupling between the precast concrete liner and the surrounding ground in order to improve adequate load transfer during service (max. 9 bar) and limit any eventual deformation of the liner prior to and during load transfer. No contribution of the grouting on the tunnel waterproofing is required. The segment’s gaskets are designed to prevent grouting seepage only.
4.2 Some highlights on fault crossing

During the 9 months excavation the major fault (600 m before the end) was successfully crossed by the TBM with a delay of almost 5 days. This fault was characterised with very loose material made of mixture of sand, gravel and water. Mud was flowing through the cutterhead openings (Figure 9) into the segment erection work area.

The monitoring of the situation showed that the mudflow continued at the same rate even after 24 hours of the event. At the initial stage the excavation was fully stopped and probe drilling was carried out in order to define the width of the fault and characterise the invert quality. When probe drillings showed that the main section made out of sand was only situated at the tunnel vault and that the invert at this location included a well consolidated conglomerates, the excavation carefully started again with low torque and thrust and with close geological follow-up. The scope was to cross this weathered sections as fast as possible. The conglomerates found at the invert had enough bearing capacity to prevent tilting of the TBM head. Backfilling with pea gravel and contact grouting in this area was carried out at very early stages close to the TBM shield in order to stabilize and secure the section and avoid eventual collapse on the erected rings.

Consolidation grouting of this section was carried out in later stage (Figure 9). It was performed along this fault section at the entire lining perimeter. The scope of this grouting was mainly to complete the backfilling and consolidate the weathered rock and loose material in order to increase their resistance against compressive strength due to internal water pressure. It must be mentioned in this context that the segmental lining as foreseen do not withhold any internal pressure. This pressure, when the headrace tunnel is in service will be completely and integrally transmitted to the surrounding rock-mass. Therefore, the latter has to be capable of withstanding compressive strength without excessive deformation.

Two alternated grouting depth were considered (alternation between two consecutive rings): Primary grouting was realized at a depth of 8 m and secondary grouting at a depth of 4 m while adapting the grouting pressure to meet the hydraulic requirements due to the internal water pressure in the tunnel when in service.
5 CONCLUSION

The present paper provides relevant details about the construction of the headrace tunnel of the Theun Hinboun Expansion Project (THXP) in Lao PDR. This tunnel is the main structural element of the waterways system and is approximately 5.5 km long and was excavated by a single shield TBM and lined with a one-pass precast concrete segment lining.

Mechanical excavation by TBM needed an increased effort regarding the fabrication of the precast segmental lining implying high accuracy during design, production, and erection processes. A careful structural design of the lining system and the shield machine to meet all the project requirements and to provide a sufficient structural resistance for all the loading conditions to be expected during excavation and in operation was achieved.

The environmental requirements, the relatively homogeneous geology and the cost and time effectiveness were the decisive factors for the choice of the mechanized excavation by TBM. Consequently, fully mechanized excavation brought the advantages of high advancing rates combined with adequate prefabricated tunnel lining system which would meet the hydraulic requirements of limited head loss due to its relatively smooth surface. The careful preparation during the design and the technical equipments of the TBM allowed crossing of fault zones with almost no delay.

The construction of the headrace tunnel by the first TBM drive in Lao PDR was completed in timeframe of about 9 months without major problems. The choice of a TBM drive for the headrace tunnel of the Theun Hinboun Expansion Project proved to be the most appropriate and efficient excavation method.

REFERENCES