DSU Tbm for Vishnugad Pipalkoti

TBM Design Development for Large Diameter Rock Tunnels Under the high Covers of the Himalaya

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SELI Overseas Spa

INTRODUCTION

Double Shield TBMs were introduced in the market in the early seventies with three main targets:

• Increase the TBM performances in term of advance per day thanks to the ability to erect a segmental lining simultaneously with the excavation phase.

• Be able to advance through unstable and disturbed rocks under the protection of the shields

• Provide a finished tunnel by installing a precast lining as the TBM advance.

In 2003 SELI developed the design of the Double Shield Universal (DSU) TBM as an evolution of the original Double Shield TBM design.

This new TBM design was targeted to improve: the TBM capability to advance through squeezing/converging rock formations under high cover, the telescopic joint design (allowing by such to operate the machine in double shield mode in very weak rock), the capability of the TBM to investigate and treat the ground around and ahead of the tunnel face.

In the same lapse of time Single Shield TBMs, originally utilized for soft ground tunnelling, extended progressively their range of application to mix rocks and finally to hard rock tunnelling with increasing performances.

This also thanks to the substantial reduction in the installation time of the segmental lining ring that contributed to minimize the TBM stand by time between two consecutive boring strokes.

Today the choice between the two types of TBMs needs to be carefully evaluated project by project since one type of TBM may “prevail” in certain geologies and diameters and vice versa.

THE VISHNUGAD PIPALKOTI TUNNEL

The Vishnugad Pipalkoti Tunnel is part of the 444 MW Vishnugad Pipalkoti Hydro Electric Project (VPHEP) on Alaknanda river in Uttarakhand (India).

The Owner is the Indian electric company “Tehry Hydro Development Corporation” (THDC) and the World Bank finances the project.

The Headrace Tunnel total length is 13.4 Km and a section of about 12,3km will be excavated by TBM by SELI Overseas (Italy) in subcontract to HCC (India) the General Contractor for the project.

The TBM will be delivered ex workshop in March 2016 and it is foreseen to start boring in the second half of 2016.

Figure 1 below shows the location of the project and the following Table 1 summarizes the geometrical characteristics of the TBM tunnel.
Table 1- TBM Tunnel Geometrical Characteristics

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Length by TBM</strong></td>
<td>12.300.00 m</td>
</tr>
<tr>
<td><strong>Tunnel slope</strong></td>
<td>1 : 321; 1 : 131</td>
</tr>
<tr>
<td><strong>Tunnel cover</strong></td>
<td>Minimum: 50 m</td>
</tr>
<tr>
<td></td>
<td>Maximum: 825 m</td>
</tr>
<tr>
<td><strong>Typical section</strong></td>
<td>Precast lining 8,8 m ID</td>
</tr>
</tbody>
</table>

GEOLOGY
The TBM will excavate entirely in the Pipalkoti geological unit. This unit consists mainly of:

**Dolomitic Limestone** (with minor inter-beds slate) will be found for about 33,3% of the 12.300 m. This formation is characterized by the following distribution of classes and rock strengths:

- 44% in RMR class II and for 56% in Class III
- 51% very strong, 23% strong, 16% moderately strong and 3% weak

**Slate** (with occasional bands of dolomitic limestone) will be found for about 64,1% of the 12.300 m. This formation is characterized by the following distribution of classes and strengths:

- 74% in RMR class II and for 26% in Class III
- 21% very strong, 64% strong, 15% moderately strong

Along the tunnel are foreseen several critical geological sections, namely:

**Thrust zones** – 150m long thrust zone in dolomitic limestone (Tapon thrust) under shallow cover

**Shear zones** – n.5 shear zones with max individual length of 50m and cumulative length of 200m

**Fault zones** - n.3 fault zones with max individual length of 30m and cumulative length of 70m

These zones, although limited in the total length (320 m, 2,6% of the tunnel), will represent the most critical sections by presenting weaker properties and being associated with local groundwater inflows.

In the following page Table 2, Figure 2 and Figure 3 summarize the foreseen geological data and the tunnel profile.
### Table 2 – Tunnel geological data

<table>
<thead>
<tr>
<th>PPALKOTTI FORMATIONS</th>
<th>LIMESTONES</th>
<th>SLATES</th>
<th>THRUST ZONES</th>
<th>FAULT ZONES</th>
<th>SHEAR ZONES</th>
<th>TOTAL METERS</th>
<th>TOTAL %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m</td>
<td>4098</td>
<td>7882</td>
<td>50</td>
<td>70</td>
<td>200</td>
<td>12300</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>33.32%</td>
<td>64.08%</td>
<td>0.41%</td>
<td>0.57%</td>
<td>1.63%</td>
<td>100.00%</td>
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<tr>
<td></td>
<td>I</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>1801</td>
<td>5836</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7637</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>2297</td>
<td>2046</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>IV</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>70</td>
<td>200</td>
<td>320</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>2.60%</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>UCS</th>
<th>strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25-1.0</td>
<td>EXTR. WEAK</td>
</tr>
<tr>
<td>1.0-5.0</td>
<td>VERY WEAK</td>
</tr>
<tr>
<td>5.0-25.0</td>
<td>WEAK</td>
</tr>
<tr>
<td>75-50</td>
<td>MOD. STRONG</td>
</tr>
<tr>
<td>50-100</td>
<td>STRONG</td>
</tr>
<tr>
<td>100-200</td>
<td>VERY STRONG</td>
</tr>
<tr>
<td>250</td>
<td>EXTR. STRONG</td>
</tr>
</tbody>
</table>

**Figure 2 - Geological profile – 1/2**

**Figure 3 - Geological profile – 2/2**
From all the above it can be resumed that the TBM will have to bore:

- For about 96.4% of the tunnel, in good geological conditions in hard rock with variable strength
- For the remaining 3.6% of the tunnel, in weak rock to extremely weak rock conditions that could affect the TBM advance. The need to minimize disruptions when crossing these critical conditions has been considered in the selection of the TBM type, its design and characteristics.

**DOUBLE SHIELD VS SINGLE SHIELD TBMS**

The choice of the most appropriate TBM type was made considering two major aspects:

- Advance rate capacity in the foreseen geological formations and conditions along the tunnel
- Capability to overcome critical conditions and minimize disruptions to the TBM advance

Two types of TBMs were considered, Single Shield TBM and Double Shield Universal TBM.

**Advance Rate Capability in The Foreseen Geology of the Project**

Table 3 below summarizes the foreseen average penetration rates of a 10 m diameter TBM in the main categories of rock to be excavated along the Vishnugad Pipalkoti tunnel.

Considering these penetration rates and the different advancing cycles of the two types of TBMs:

- Single Shield, alternating the boring phase with the segmental lining erection phase
- Double Shield, erecting the segmental lining simultaneously with the boring phase

Estimated advance rates for the 2 different TBM types in the foreseen formations of the project are given in Table 4.

<table>
<thead>
<tr>
<th>Table 3- Foreseen TBM penetration rates for the different rock strength</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TBM DATA</strong></td>
</tr>
<tr>
<td>TBM Diam.</td>
</tr>
<tr>
<td>M</td>
</tr>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4 – Calculated advance rates for the two TBM types</th>
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<tbody>
<tr>
<td><strong>DOUBLE SHIELD ADVANCE RATES</strong></td>
</tr>
<tr>
<td><strong>TBM DIAM.</strong></td>
</tr>
<tr>
<td>m</td>
</tr>
<tr>
<td>10</td>
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</tbody>
</table>
To better “appreciate” the performances of the two types of TBM in terms of advance rate, Figure 4 shows the graph of the advance rates of the two types of TBMs at different levels of penetration.

In the same graph it is highlighted in light blue the foreseen range of penetration rates along the tunnel. In this range of penetration rates the Double Shield TBM performs from 46% to 63% better that the Single Shield TBM.

Therefore, as far as the “Advance rate” capability in the geology of the tunnel, the Double Shield TBM performs substantially better than the Single Shield TBM.

**Figure 4- Advance rates at different level of penetration**

**Capability to Overcome Critical Geological Conditions**

Double Shield TBMs have some advantages in respect of Single Shield TBM when boring under very critical rock conditions, namely:

- Better behavior under squeezing rocks especially if the conicity of the shields is enhanced by a proper design
- Better capacity to deal with unstable ground at the face thanks to the possibility to pull back the cutter-head in combination with face treatment works
- Better steering control in mixed face conditions and very weak ground

Considering the higher advance rate capacity and the ability to better face very critical geological conditions, the Double Shield TBM type has been selected.

**SEGMENTAL LINING DESIGN**

The design of the segmental lining has been developed taking in to consideration:

- The geological conditions
- The hydraulic requirements in terms of roughness of the lining when in operation
- The TBM requirements.

The lining that has been finally selected is characterized by:

- 35 cm thickness to bear the estimated ground loads and TBM thrust loads
- n°6 segments per ring, for a fast installation of the ring
- 1.5 long ring, to keep the length of the TBM down to a minimum and at the same time be able to follow with accuracy the curves on the tunnel alignment
- Non-bolted joints, to avoid the presences of “pockets” in the inner surface and thus minimize the water flow friction losses when the tunnel will be in operation
- Connectors and guiding bars in the joints, to secure a precise assembly of the rings with minimal steps.

Figures 5 and 6 below shows the schematic typical cross and longitudinal section drawing of the segmental lining to be utilized in the project.

**Figure 5 – Precast lining typical cross section schematic drawing**

**Figure 6 – Segmental lining longitudinal section drawing**

As indicated in figure 6 above, pea-gravel will be injected as primary filling of the gap between segmental lining and excavation profile.

A second phase cement mix grouting will be systematically performed at low pressure and, were required by the combination of weak rock properties and tunnel cover, consolidation drilling and high pressure grouting will be executed.
This backfill system, although more costly and complex to be executed, has been preferred to the bi-component grout system due to the much better final results in terms of quality and strength of the filling, been this of extreme importance in an hydraulic tunnel to be operated under pressure.

**TBM MAIN FEATURES**

The design of the Vishnugad Pipalkoti TBM is an evolution of the Double Shield Universal design developed for the Kishanganga tunnel and has been performed jointly by SELI Overseas with Terratec and Mitsubishi, the same team that designed the first 10 m diameter Double Shield Universal TBM successfully utilized to bore the Abdalajis tunnel project in Spain back in 2003 (e.g., Gutter and Romualdi 2003).

The main features that have been introduced/enhanced in the design of the Vishnugad TBMs are:

**Extreme Overcutting Capacity**

Figure 7 below illustrates the mechanism of the tunnel convergence.

![Figure 7 – Tunnel convergence mechanism](image)

A substantial portion of the total convergence (the pre-convergence) occurs in front of the cutter-head and it is therefore “bored” by the TBM. Most of the residual portion of the total convergence develops in the first 2 diameters from the face, with a small portion occurring with the time along the tunnel. The amount of convergence depends from the tunnel diameter, the rock characteristics and it is physically limited by the clearance between the TBM shields and the excavation profile (overcutting).

Taking into account the above parameters and the TBM design data and specifications (overcutting, shields length and conicity, thrust) it is possible to verify the capacity of a given TBM to advance in the most critical foreseen conditions of the tunnel. For the Vishnugad TBM the outcomes of the above computations have been compared with the experiences of the Kishanganga and Abdalajis TBMs. As a result of this exercise the total overcutting has been increased from 30 up to 36 cm in the standard configuration.

The increase of the standard overcutting will:

- Grant the required 9,7 meter minimum tunnel diameter even under squeezing conditions
- Avoid the shields to be trapped by the unstable and squeezing ground in all foreseen critical conditions along the tunnel.

Figures 8 and 9 below shows the tunnel and TBM typical diameters and overcutting provision.
The TBM has the possibility to further increase the overcutting, if and where required by special unforeseen conditions, of additional 100 mm on diameter, with a total maximum over-cutting to 46 cm.

**Figure 8 – TBM Overcutting in standard configuration**

**Figure 9 – TBM general layout drawing**

**High Thrust, Power and Torque**

A total thrust of 83.600 KN will allow the TBM to advance the shields even in the most difficult foreseen ground conditions conserving the capability to apply the maximum excavation thrust at the face.

A cutter-head power of 4.200 KW and more importantly a maximum torque of 20.725 KNm, will provide the TBM a torque capacity similar or even higher than that of an EPB TBM of similar diameter. This will allow the TBM to rotate the cutter-head against unstable faces, minimizing the problem that was experienced with the Kishanganga machine.

**Extended Ground Treatment Capacity**

The TBM is equipped to treat the ground ahead in multiple ways:

- Through the gripper shield- With n*18 grout holes and/or pipes at 8-9° inclination
This unprecedented ground treatment capacity will allow a combination of grouting, piles and drainage patterns to be tailored to the different critical situations that are foreseen to be encountered along the tunnel.

Muck flow control-
A “flood door” system has been installed on the bulkhead of the TBM. This system regulates the flow of the muck & water to the conveyor and eventually seals out the excavation chamber, simulating a quasi-EPB advance mode. It will be utilized when boring in special ground conditions to limit the face instability and prevent the flooding of the TBM and of the tunnel.

COMPARISON WITH THE KISHANGANGA AND ABDALAJIS TBMS
The Kishanganga tunnel (e.g. Ariza, Mullerova, Palmer, Swannel, De Biase, 2015) has been the most successful TBM rock tunnel project in India and in general one of the main achievements of tunnelling technologies of recent years. The main reason for this success was the innovative design of the TBM for the specific project and application.

The key features of this TBM were:
• Large over-cutting in standard configuration; 30 cm on diameter
• Additional over-cutting for extreme conditions; additional 10 cm on diameter
• Conical shield design
• Extremely high torque (EPB like) of the cutterhead drive
• Extremely high main and auxiliary thrust
• Extended capacity for treating the ground at the face through the shield and through the cutterhead

Thanks to the above features in the Kishanganga tunnel the TBM never got stuck by the converging ground, even in the worse geological conditions and under high cover. However the Kishanganga TBM encountered problems in the heavily fractured quartzite formations that were collapsing at the face with blocks and raveling ground pressing against the cutterhead. The design of Vishnugad Pipalkoti TBM takes into account these operating experiences in Kishanganga and makes at the same time reference to the Abdalajis TBM design, a 10 m diameter DSU TBMs that was successfully utilized to bore the Abdalajis Tunnel in Spain in the early 2000s.

The Vishnugad Pipalkoti TBM has higher thrust and torque capacity, larger overcutting and more shields conicity in respect of both Abdalajis and Kishanganga TBMs. These improved features, together with: a more advanced ground pre-treatment system, the flood door system and other small but important detail design improvements will allow the TBM to better face the foreseen critical geological conditions along the tunnel.

CONCLUSIONS

For the geologies and diameter of the Vishnugad- Pipalkoti tunnel the Double Shield Universal type of TBM type was selected as preferred to the Single Shield TBM type.

To further enhance the capability of the TBM to overcome critical geological conditions, the design features and specifications of the Kishanganga and Abdalajis DSU TBMs have been improved in several aspects, introducing new features.

This TBM represents therefore the last step in the innovation process in rock TBM design that started back in 1972, when the first Double Shield TBM was invented, and has continued for almost 43 years with subsequent improvements and application experiences all around the world and in the very different geological conditions.

REFERENCES
