Pandoh Highway Tunnels in Indian Himalaya - a rock mechanical challenge in design and construction

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ABSTRACT: The National Highway NH-21 in the Indian State of Himachal Pradesh is developed into a 4-lane divided dual carriageway. The road section between Chandigarh and Manali with a length of approximately 21 km is located in topographically very difficult terrain where the Beas River formed a deep and narrow canyon with high and steep rock slopes. The paper describes the challenges in the design and the construction of the EPC Contract for six tunnels with a total single bore length of approximately 20 km. This includes geological design, NATM excavation design and detailed structural design for the rock tunnels in different tectonic formations. The variable rock mass conditions in combination with the short lateral distance to the very steep canyon slopes resulted in demanding rock mass behaviour and various difficulties to be solved during excavations.

Keywords: NATM, tunnel, design, construction.

1 THE PROJECT

The National Highway NH-21 is located in north-western India and connects the cities Chandigarh and Manali in the State of Himachal Pradesh. The northern part of the highway, the section between Pandoh and Kullu, is in a topographically very difficult area where the Beas River formed a deep and narrow canyon with high and steep rocky slopes. The existing 2-lane highway of this 21 km long section has to be widened to a 4-lane divided dual carriageway which requires many tunnels, bridges, cuts and other structures in this particular section.

The National Highways Authority of India (NHAI) has awarded Shapoorji Pallonji as concessionaire who has appointed Afcons Infrastructure Ltd. as EPC contractor (engineering, procurement, and construction). The detailed design for the entire 21 km long highway section was done by the Joint Venture of SMEC India (SMEC) and 3G Gruppe Geotechnik Graz ZT GmbH Austria (3G) on behalf of the EPC contractor.

SMEC took responsibility for the alignment, open road, and bridge designs while 3G was responsible for the tunnel design of the 6 highway tunnels with lengths of 0.6 to 3 km. The 4 double tube tunnels and the 2 single tube tunnels have 3 lanes (2 carriageways and 1 emergency lane) and a total single bore length of approx. 20 km.

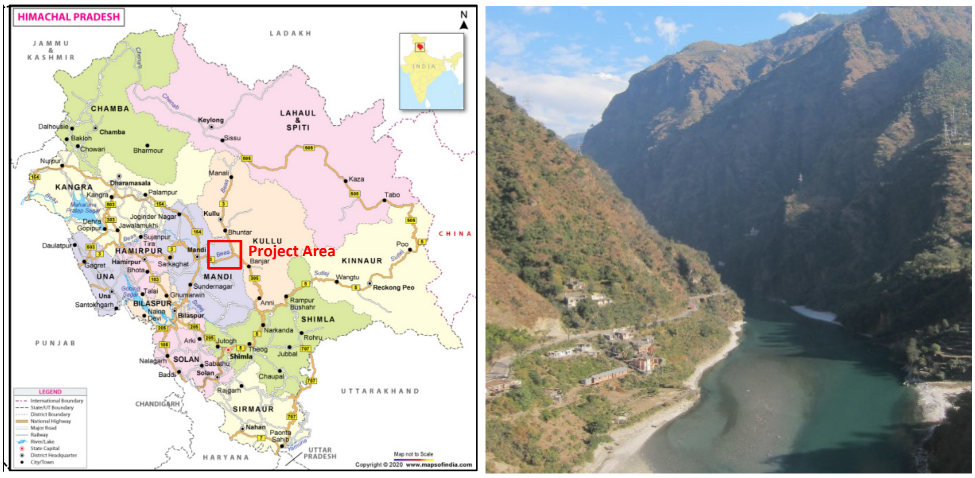

Figure 1. Location (left) and view (right) of the project area with steep slopes and existing 2 lane highway.

The scope of the NATM tunnel design is included

- Geological and hydrogeological design including subsurface investigation program for tunnels.
- Design of excavation and support of tunnels and portals.
- Final layout design of tunnels including inner lining design and final layout of portals.

2 GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

The project area is located between Pandoh and Aut north of the river Beas. Geologically the main part of the project area is situated in the Haimanta Formation of the Tethyan Himalayan Sequence (Precambrian to Cambrian age) belonging to the Greater Himalayans. The easternmost part of the project area is situated in the Bajaura Nappe (Lower crystalline nappe) and in the Shali Formation of the tectonic window of the Lesser Himalayas. The Main Central Thrust (MCT) forms the tectonic boundary between the Haimantas in the west and the Bajaura Nappe in the east. The MCT is a main tectonic element in the Himalayas. It intersects the project area in the eastern part perpendicular to the alignment.

Bedrock types of the Haimanta Formation dominate the main part of the project area and comprise an alternating sequence consisting of meta-sediments (meta-siltstones to meta-sandstones), shales, slates, various types of phyllites, quartzites, and schists. The easternmost part of the project area (Shali Formation) consists of dolomites, limestones, quartzites, phyllites, and shales. Fault rock may occur anywhere.

Tectonically the project area describes a flat syncline where the foliation planes of the rock mass in the western part generally dips towards east, whereas foliation in eastern part dips towards west. In the central part horizontal stratification is prevailing. The axis of the syncline is dipping very flat towards NNW. Two to three steeply dipping to vertical joint sets can be observed. They run predominantly (sub-) parallel respectively perpendicular to the tunnel axis. The easternmost part of the project area proceeds along the western limb of a steep fold (anticline) within mainly carbonaceous rock east of a major thrust fault.

3 TUNNEL DESIGN PRINCIPLES

The tunnel design includes the entire design process, from geological data acquisition via geotechnical design to structural design. It was organised in a way that the entire design process was done within one design team. Due to such organisation, the design of the underground structure could be executed without interface and consequently without loss of information from the ground investigation to the structural design.

The contractor was an integrative and important part of the design process of considering the available tunnelling equipment and material as well as bringing the experience from previous tunnel construction contracts in the difficult tectonic Himalayan region such as the 8 km long Rohtang tunnel. This also allowed quick response during the construction process in case of unpredicted ground conditions or design changes requested by the EPC contractor related to construction optimization.

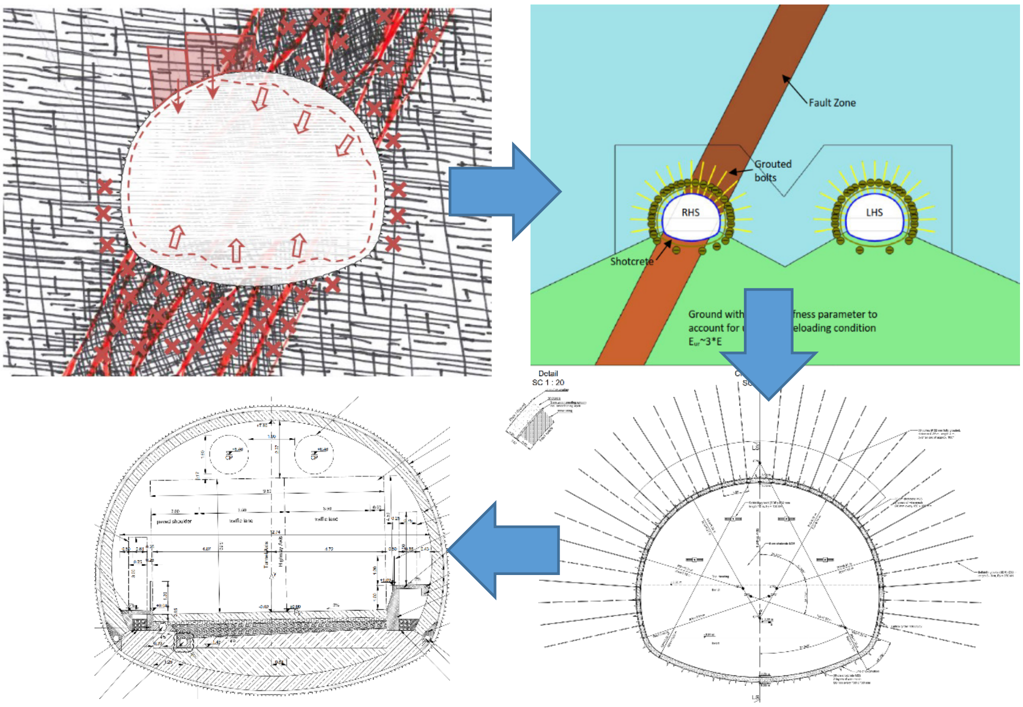

Figure 2. Design process from the ground to the structure.

4 TUNNEL LAYOUT

The typical cross section of the tunnel was defined in the concession contract based on the local national guideline of IRC:SP:91. In the early design stage the project team tried to optimise this typical cross-section by designing only two traffic lanes without emergency lane and by lowering the elevated footpath. The reduction of the tunnel excavation cross section and especially the reduction of the tunnel width would be beneficial for tunnelling in the tectonic rock mass. But due to the contractual constraints the optimization was not possible, and the tunnels had to be constructed with the largest diameter ever applied in Indian Himalaya for such structures (Figure 3).

The tunnel is in general designed as per Western European standards with uni-directional traffic, umbrella waterproofing, separated drainage for groundwater and carriageway water, concrete pavement etc. Compared to a typical Western European tunnel cross section, the following two general design requirements specified in the contract documents stand out.

- The typical tunnel cross-section consists of two driving lanes with each 3.5 m in width and an additional emergency lane, the so-called paved shoulder, with an additional width of 2.0 m. Due to the left-hand traffic this emergency lane is situated on the left-hand side. The width of the tunnels is approx. 13 m and is almost comparable to a three-lane tunnel.
- On the right-hand side an elevated footpath approx. 1 m above the highway elevation was specified in the contract documents. This elevated footpath is also specified in the local national guideline of IRC:SP:91.

Every approx. 350 m both tunnel tubes are connected with cross passages. According to the local national guideline IRC:SP:91 cross passages inside tunnels shall be designed with an angle of 30° to the tunnel axis. These inclined cross passages could be optimised to be constructed perpendicular to the tunnel axis as per international design practice.

The final lining of the tunnel was designed as plain concrete lining. Due to restraints in the contractual documents reinforced concrete had to be applied. Consequently, the typical lining thickness was optimized to thicknesses of 25 cm to 30 cm for economic reasons.

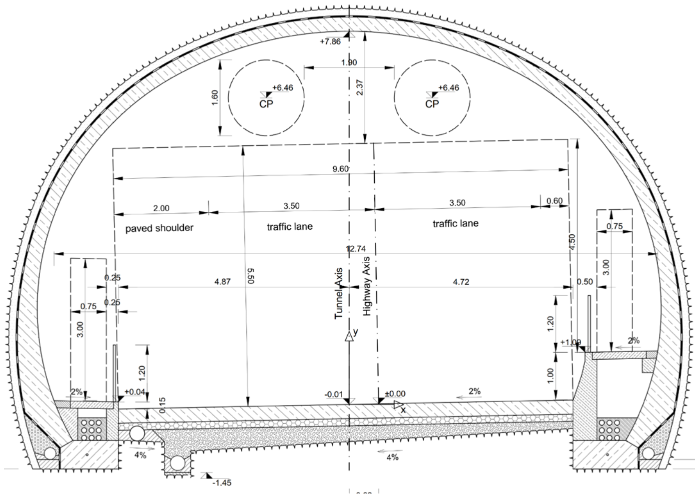

Figure 3. Typical tunnel cross section, largest road tunnel in Indian Himalaya

5 ROCK MECHANICAL CHALLENGES

5.1 Optimization of the alignment

The concession contract was based on a preliminary alignment study with only minor consideration of the geotechnical ground conditions. During the detailed design the highway alignment, especially for the tunnels, was optimized to reduce construction efforts e.g., to avoid construction of high cut slopes of up to 80 m in unfavourable ground conditions. This resulted in the re-location of some tunnel portals during the detailed design phase. Intensive technical discussions between the client, concessionaire, EPC contractor and designer were required prior to the re-location of the portals, since the land acquisition has been already finished based on the preliminary alignment study of the tender design.

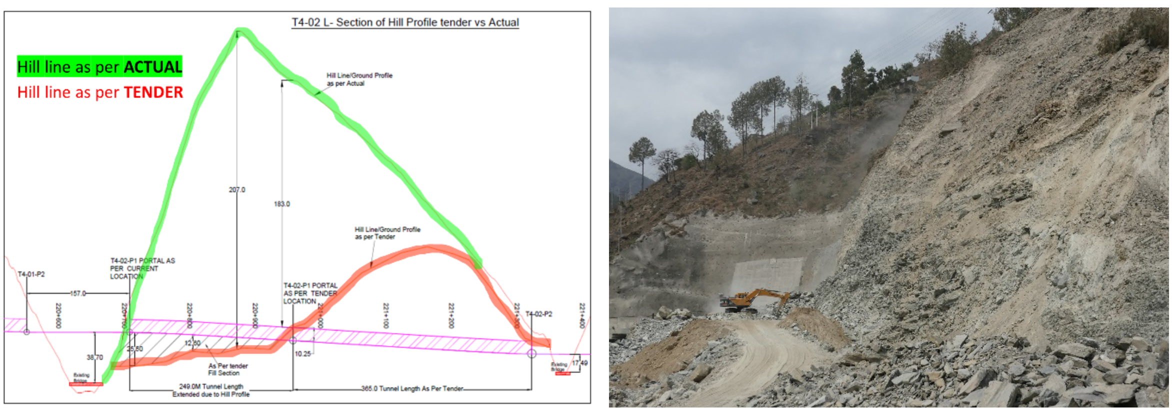

Figure 4. Difference in topography between tender documents an actual condition of tunnel T4-02 (left) and reduced cut slope at eastern portal of tunnel T2-01 (right).

Finally, the re-location of the portals was jointly agreed and the additional land was acquired, resulting in an optimized alignment and tunnel design. The western portal of tunnel T4-01 was shifted approx. 600 m west while the western portal of tunnel T4-02 was shifted 250 m west (Figure 4). Both portals of the tunnel T2-01 were shifted approx. 300 m east. These significant relocations of the tunnel portals were necessary due to very unfavourable topographical and geotechnical conditions in the area of the original portals and the cut slopes of the adjacent highway.

5.2 Challenges during Construction

A significant challenge during the tunnel construction was the low confinement pressure in combination with fractured rock mass. In tunnel sections close to steep natural canyon slopes with orientation approximately parallel to the tunnel alignment loose rock mass conditions with significant potential for gravitational overbreak were often observed. Due to low confinement a natural arch around the tunnel could hardly develop and significant support measures were required to stabilise the high vertical loads. In some sections significant rock fall events are common due to the stress release of rock slopes. Figure 5 shows a canyon section where the portal and consequently the alignment of the tunnel T4-04 is close to the natural slope which are well known for rock fall.

Figure 5. Steep natural canyon slopes parallel to tunnel T4-04 (left) with rock fall (right, from YouTube).

This primary stress condition resulted in vertical displacements and partly overstressing of the tunnel lining in tunnel sections with fractured but generally good rock mass conditions. In these sections a stiff tunnel lining had to be constructed to carry the vertical loads. In some sections, heavy steel arches had to be installed additionally to the typical tunnel lining to stabilise the utilized tunnel roof support. The vertical displacements in combination with the additional support resulted in an under profile which was compensated by lowering of the alignment in these sections. In some unfavourable portal locations this mechanism was even worse due to the shallow overburden in combination with weathered rock mass. This led to significant potential for overbreak which required a short excavation round length in combination with spiling and partial face excavation.

Figure 6. Tunnel T4-03 Western Portal (left) and overbreak in the top heading (right).

At the eastern portal of tunnel T4-02 a large slope instability along a fractured zone in the portal area of tunnel T4-02-P2 resulted in damages of the already constructed tunnel inner lining. One tunnel block, approx. 50 m inside the tunnel, was damaged by the differential displacements along the obvious intersecting sliding plane. At the moment the tunnel and the slope are being observed intensively and the design of slope support measures as well as the inner lining rehabilitation design is under preparation.

5.3 Bridge in Tunnel

In some areas, the natural hill slopes are steeply dipping with inclinations of up to 80°. In these cases, the area in front of the portal was too narrow to locate the typical foundations for bridges (see Figure 7). Consequently, the bridge footing and the tunnel in the portal area were designed in a way to locate the bridge footing inside the tunnel. The tunnel cross section was increased at the invert and sidewall. The inner lining was rigidly connected with the bridge footing. The interactive design process between the contractor as well as the tunnel and bridge designers, resulted in a technically sound, economic and efficient construction solution for the bridge footings.


Figure 7. The steep natural slope at the western portal of tunnel T4-02.

6 SUMMARY

The upgrade of the National Highway NH-21 from an existing 2-lane to a bi-directional 4 lane highway is a very challenging construction project. Due to the difficult topographical conditions many bridges and tunnels were necessary. The design of the 6 highway tunnels with a total single bore length of approx. 20 km was done for an EPC contractor covering all related scopes including geological data acquisition, geotechnical and structural design. The numerous design challenges like alignment optimisation or difficult topographical and geotechnical conditions were solved technically sound with a focus on constructive, safe and economic solutions for the EPC contractor. During the construction of the highway section, which is almost finished and open to traffic, many rock mechanical challenges had to be faced.

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