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PLANNING AND METHODOLOGY ADOPTED TO DEAL WITH ADVERSE GEOLOGICAL PROBLEMS ENCOUNTERED DURING HRTS EXCAVATION OF TEESTA VI HYDROELECTRIC PROJECT (500MW), SIKKIM, INDIA.

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Abstract

Tunnelling and Underground excavations in the Himalayan mountains is a formidable task in itself. The challenges in such a condition are further amplified if a project which was under execution by one agency due to financial issues came to complete halt. Further after a considerable time lapse, these partially constructed projects under ageing conditions are taken over by other agencies towards its completion. Teesta VI HEP, is one of such projects, which was partially constructed by M/s. Lanco Teesta Hydropower Limited (LTHPL), promoted by the Lanco Group but could not be completed due to financial crunch by scheduled completion time of May 2012 and the construction works were in standstill position since Dec 2012. Subsequently, acquisition of M/s LTHPL and execution of balance works of Teesta IV HEP was entrusted to NHPC by NCLT bench in Oct 2019. After taking over the partially constructed project by NHPC, excavation activities of the tunnel for balance stretches were resumed during June 2021 under challenging global pandemic period. This paper elaborated on the various geological challenges faced by NHPC during resumption and fresh HRTs excavations. Methodology, geological studies/ monitoring protocols followed to achieve the project's goal has been described in detail. As the execution of the tunnels were typically planned with precise deadlines to achieve the project excavation schedule, so this paper also expounded various measures taken during Re-strengthening of tunnel support, restoration of collapsed tunnel areas, precaution taken at low cover zone and adverse geology during excavation of tunnels.

Key words

Re-investigation, Re-strengthening, Restoration, Reassessment, Rehabilitation, Pipe roofing, Fore poling.

1 Introduction

The Himalayan mountains are the youngest mountain range and exhibit active plate tectonics that result in high stresses leading to common occurrences of folding, faulting, and shearing in the rock mass (KC Diwakar et al. 2022). These challenges further intensify in the Sikkim Himalayan range, due to its complicated geological settings and presence of highly deformed and fragile rock strata. That's why surface as well as underground excavation in the Sikkim region has become a much more challenging, time consuming, costly affair for project authorities. Very often geological problems pose significant obstacles that go beyond the expertise and scope of the developers. Not addressing these geological issues timely, results in a massive setback for the developer, as the project may be delayed or even abandoned in worst cases during any stage of the project's construction lifetime. In Sikkim state itself, many hydropower projects had been stalled for various reasons with delays ranging from few years to

even a decade.
Similarly, Teesta VI HEP located on River Teesta is such a project which remained undeveloped for about 9 years without any progress at the project site. NHPC- *A Govt of India enterprise* has taken up the task of completion of this project during the year 2019. The project is located on river Teesta in the Himalayan state of Sikkim in India. It is a Run of River (RoR) scheme with a Barrage located about 3 Km downstream of Teesta - V Powerhouse at Sirwani upstream of Singtam town. It envisages construction of 26.5m high barrage which shall facilitate diversion of river water by means of 02 Nos. of HRTs each of ±13.7Km long to an underground powerhouse located near Pamphok village to generate 500MW. Each pressurised headrace tunnel is modified horse shoe shape, with 9.8m finished dia of about 78 square metres cross-sectional area. The Head Race Tunnel will be concrete lined for its entire length. The minimum rock pillar thickness between wall to wall is ±30m between both the HRTs.

This paper highlights the primary geological adversities that concerned NHPC during restoration works and during excavation of balance span of HRTs. The Authors have drawn special attention to how adverse geological conditions encountered during tunnelling excavation have been dealt with in a professional way to achieve the project excavation schedule.

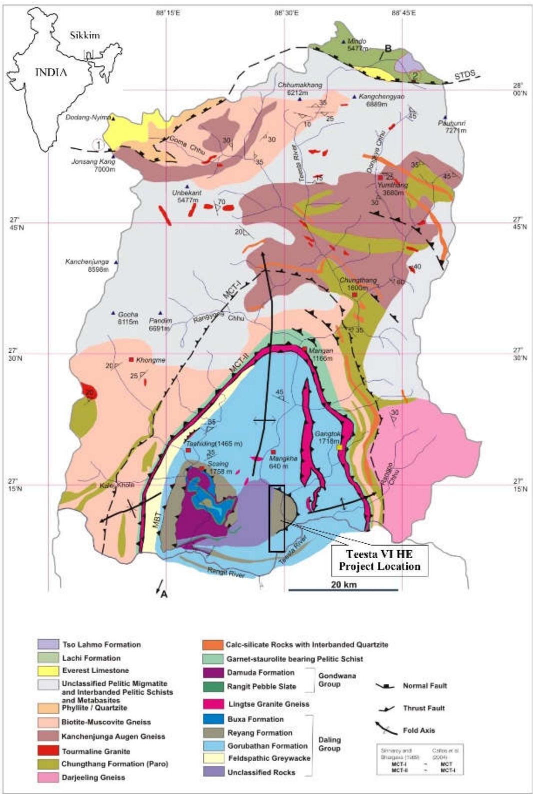

Figure 1. Geology and Stratigraphy of Teesta Basin in Sikkim, India (modified after Acharya, 1989; Ray, 1989; Neogi et al., 2000; GSI, 2001; Catlos et al., 2002, 2004).

2 Geological and Topographical seting of the Project

The Project area falls in the Lesser Himalayas consisting of low grade meta-sedimentary rocks belonging to Gorubathan formation of Daling Group. The Lesser Himalayan orographic tract in Sikkim area is found on both the sides of river Teesta and encircled by Main Central Thrust (MCT). Due to this thrust the Daling Group of rock mass underwent intense folding and faulting in the form of several anticlinal and synclinal deformational structures. In general, the distribution of the Daling Group of rocks shows a broad sweep in a north-south antiformal axis plunging gently due north resulting in divergent dips varying in directions from NW in western sector to NE in eastern sector through almost north in the central part. In the eastern and western sectors, broad warps with easterly and westerly axial plunges respectively are also responsible for local variation in attitude.

The rock types exposed in the project area are mainly interbedded sequences of Quartzite, Phyllite with their variants. Quartzite is usually coarse grained, medium strong to strong and highly jointed in nature except in HRT intake area, where it was completely crushed due to its vicinity to the regional anticlinal fold axis. Whereas, Phyllites show a complete wide range of compositional, strength variations, weathering grades, and deformation magnitude. The Phyllitic rock mass found in the project area displays variation in composition with Quartzitic, Chloritic, Sericitic, Carbonaceous and Slaty in nature along with layers of Quartzite bands in between. As the composition of Phyllite varies considerably and so are the strength and other geotechnical parameters. The ridges, which stand out along the HRTs alignment are predominantly of competent lithounit, while the phyllite rich portion make out gently sloping landforms. It is the natural landforms on the surface which determine geological conditions at the tunnel grade.

As per seismic zoning map of India, the project area falls within Seismic Zone-IV and has records of seismicity in adjacent areas. As per Seismotectonic atlas, GSI (2000), two major tectonic features viz. MBT & MCT are located about ±36Km South and ±15 Km East of the project location respectively.

Topographicaly both the HRTs are running almost North to South on Right bank of River Teesta. The tunnel alignments span having rugged topography with low to high mountains with altitude varying from EL: ±360M to EL: ±1300M, with 05 Nos. of prominent deep cut perennial streams. The maximum superincumbent cover over the tunnel is to the order of 900m while it is 55m-60m in the nala reaches.

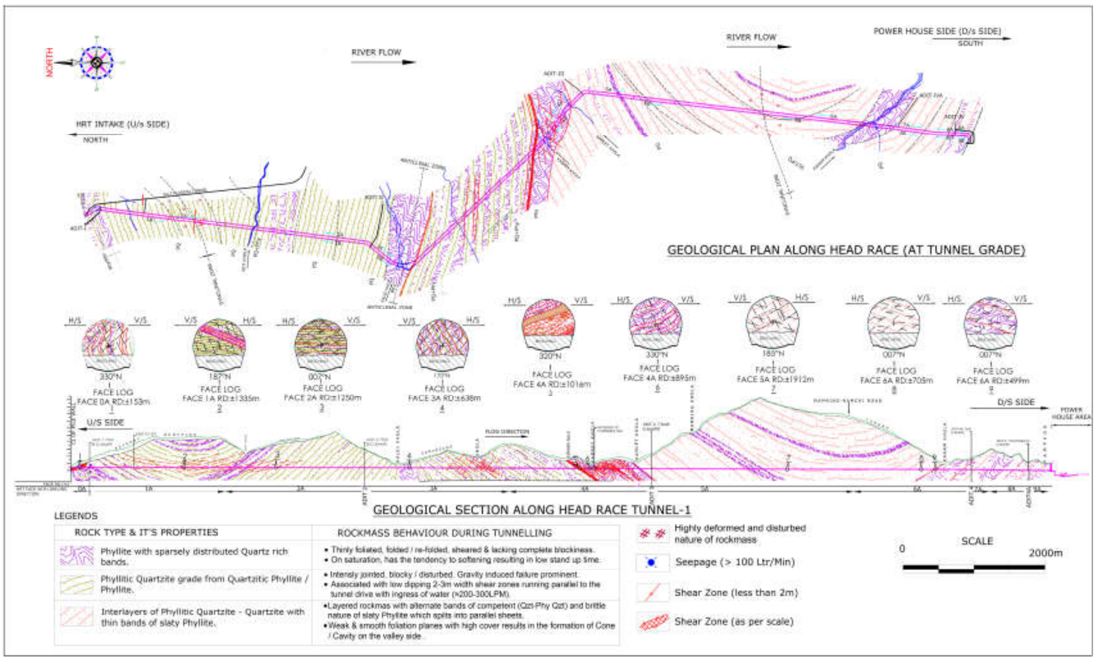

Figure 2. Geological Plan & section along Head race Tunnel (HRT) at Tunnel Grade of Teesta VI H.E. Project.

3 Hindrances faced prior to start of fresh excavation

Heading excavation of approx.10.8Km out of total 27.5Km, Benching excavation of ±4.27Km and Overt Lining of ±1.55Km was completed by the previous developer. To facilitate construction of the HRTs five numbers of Adits had already been constructed.

However, due to a long hiatus of the project, the primary support that had been provided by previous developer had developed with age various defects that had distorted the tunnel cross section and were vulnerable to failure. This vulnerable span of the tunnel was thoroughly investigated and identified. The major hindrances/challenges faced by the NHPC were as follows.

- Project had witnessed lots of urbanisation above the tunnel alignment which was once covered with dense forest. Now, the tunnel alignments span mostly traversing below private properties, public roads, NH, pharmaceutical companies, high power transmission towers, etc. Human activities have impacted slope stability and increased the risk of landslides mainly during the rainy season.
- Without any dewatering arrangement, Adit-1, 2 & 3 were flooded with seepage water and further access to HRTs were blocked.
- HRT Faces 0A and 0B from Adit-1 were in collapsed state due to encounterance of crushed quartzite in the form of sugar cube and bands of sheared Phyllite.
- HRT Faces 1A & 1B from Adit-1and Faces 2A & 2B from Adit-2 were in fairly good condition except some areas where Ribs and LGs were either twisted, deteriorated or cracked, wire mesh and shotcrete were detached and rock mass at crown areas were exposed.
- A big cavity was formed at 400m inside Adit-2 during restoration works due to prolonged exposure of rock mass to saturation conditions.
- HRT Faces 3A & 3B from Adit-2 and passing below Kalej Khola were in completely collapsed state. Furthermore, a surface cave-in was observed on the surface above face-3A.
- The already excavated tunnel behind HRT Face 4A and 4B from Adit-3 were collapsed due to encounterance of highly weathered and sheared Phyllite. Further, the reported incidence of a surface cave-in had compelled fear among the local public. Also, downstream Faces 5A & 5B of HRTs from this Adit had encountered a maximum number of collapses/cavities formations at various locations especially where Steel rib support was not provided.
- From Adit-4A two faces Face 7A & 7B were already excavated and partial lining work was also completed. But the upstream faces 6A and 6B were partially excavated and Face 6A was in a collapsed state 100m behind the Face.

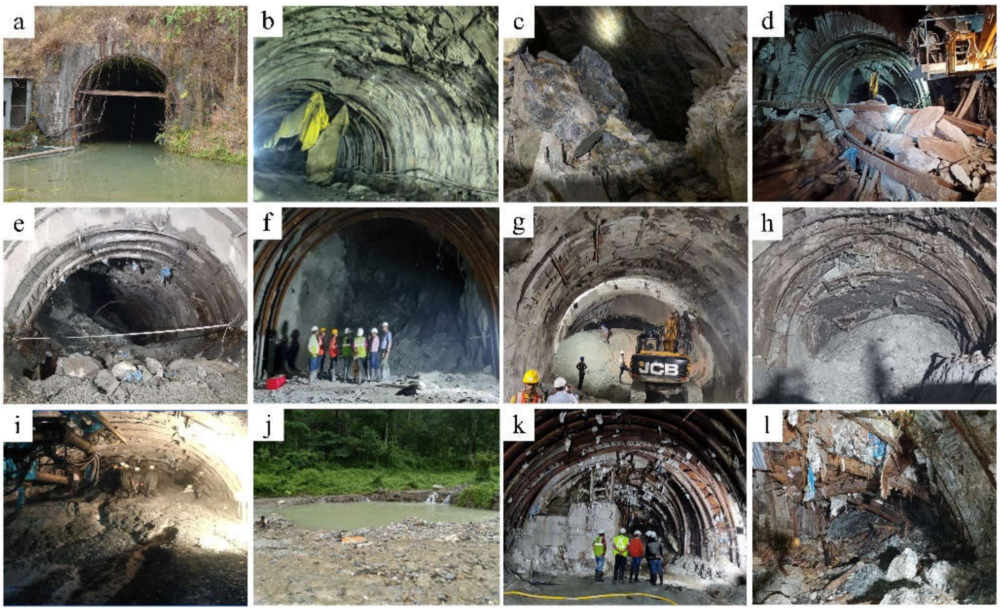

Figure 3. Showing Photographs of Hindrances faced during resumption of Underground works. (a) Water accumulation at Tunnels. (b) Twisting and Buckling in Lattice girder. (c) & (d) Rockfall and cavity formation in allready excavated tunnel portion (e), (f), (g) & (h) huge cavities and collapsed tunnel area in allready excavated tunnel portion. (i) & (j) Collapsed tunnel face and surface cave-in above the tunnel at Kalej Khola (k) & (i) Collapsed tunnel below Kamlet Khola.

3 Challenges & Mitigation Measures

During fresh excavation carried out by NHPC, several adverse problems have been encountered due to adverse geological conditions. These difficulties have been dealt with utmost care and giving attention to geological details. The various challenges faced along with mitigation measures taken while tackling these hindrances are as follows.

3.1 Archived Geological data acquisition

The acquisition of progressive geological data gathered by the previous developer during the course of tunnelling works was the first & most challenging task faced by NHPC. Most of the geological drawings were non digital or paper documents had deteriorated with time. Beside this, some of the geological data related to underground excavation was either missing or partial. So, the organisation of archived geological logs, reports, Lab test reports etc were done and studied for understanding the geological conditions of the area.

Figure 4. Showing Photographs of Confirmatory Surface Geological and Geophysical studies. (a) Geological survey along HRT alignment. (b) Assessing rock strength using Schmidt Hammer. (c) Drilling activity (d) Topographical survey (e) Resistivity Imaging. (f) Cross hole P-wave Tomography.

3.2 Reassessment of geological condition

COVID-19 paved the way towards subsequent nationwide lockdowns which had restricted NHPC to carry out additional geological exploration in time. Despite this restriction, confirmatory surface geological mapping, exploratory drill holes and geophysical survey along the vulnerable nala stretches was carried out particularly along the HRT alignment with much difficulties. The surface geological mapping was done along the road cut, nala sections, few sporadic rock exposures with the help of mobile based GPS & also through geodetic instruments at low cover / nala stretch to understand regional geological set up, litho contact & their engineering characteristics that might adversely affect the excavation works of tunnels. Geophysical investigations like Resistivity Imaging & Seismic Tomography surveys carried out at site specific locations for assessment of subsurface geological conditions. These geophysical techniques successfully delineated the geological conditions at Intake area and vulnerable nala stretches. Most of the collapsed face, cave in location at low cover zone, nala stretch was successfully dealt with utmost care and giving attention to geological details gathered through additional exploration, mapping and geophysical studies. Reassessment of geological conditions has helped in tackling many geological problems that were anticipated initially. Along with these geological and geophisical survey Pre conditional survey prior to the restart of the tunnelling works was also done for the existing buildings above the tunnel alignment. Structural integrity of the individual buildings, owner name etc was recorded during inspection.

3.3 Water accumulation / dewatering of tunnels

Seepage water accumulation at HRT tunnels and Adits had greatly influenced the stability of the tunnel support system and with time weakened making it vulnerable to collapse. Structural instability, corrosion of steel structures, chipping out of shotcrete, loosening of rock reinforcement etc were few of the major safety concerns during restoration works. To address this issue, a comprehensive drainage system and effective dewatering arrangements were established before resuming excavation activities. In low cover nala stretch, attempts were made to channelize / divert the surface water away from the vicinity of the tunnel alignments to avoid percolation down onto the collapsed or active work area at tunnel grade.

3.4 Re-strengthening of tunnel support measures

During construction by the previous developer, primary support in the form of shotcrete, rock bolts, dominantly Lattice Girder etc. were provided in HRTs / Adits that had the initial support for the opening. Consequently, many stretches of the already excavated HRTs by previous developer had developed with age various defects like chipping out of shotcrete, distressing in rock bolts, buckling of LG / Ribs, distortion of the tunnel cross section which has been associated with huge cavity / cone formation. Accordingly, more than 300 working days have been consumed for additional restoration and strengthening measures for most of the already excavated portion of the HRTs to avoid threat of further instability which has facilitated advancement in excavation from established faces. The additional protection measures included application of Steel Fibre Reinforced Shotcrete (SFRS) and anchored rock bolts and replacement of buckled LG/Steel ribs with new ones. Bracing support through MS beam / plate along with additional Rock bolts/ Self-Drilling Anchor (SDA) were provided which was completely embedded with fibre shotcrete. Afterward, extensive grouting activities were carried out on potentially vulnerable zones for consolidating the poor rock mass behind the rib supports.

Figure 5. Showing Photographs of rectification works and additional support measures (a) restoration work under progress, skin to skin ribs were embedded under SFRS (b) Rectified tunnel (c) Fore poling to stabilise the crown of the Tunnel. (d) & (e) Pipe roofing created an umbrella-like structure above the crown to prevent collapses. (f) Multisegmental excavation.

3.5 Rehabilitation of collapsed tunnel Face

Prior to the fresh excavation, most of the tunnel face was in collapsed conditions as these were excavated either in lower Class III or in Class IV & V rockmass. The restoration of these collapsed faces had hindered the start of underground activities of the project to a greater extent. Additional drawings and directives were issued to deal with these collapsed faces. Before the start of the activities, it was ensured that adequate resources viz, manpower, machineries and materials were readily available at site.

Specialised manpower were deployed for specialised works like pipe roofing, grouting activities etc. Pipe roofing was carried out with 21 m long, 89mm dia pipes @ 15-20 degree with an overlap of 10m length.

3.6 Restoration works

Vulnerable stretches of tunnel span that were excavated by the previous developer were identified and monitoring of these areas was done with instruments. Additional rectification works were carried out before restarting of the fresh heading excavation where the tunnel's structural integrity was uncertain. Beside this, some of the tunnel section excavated by the previous developer was in the undercut section and not as per design specification. To achieve the specified tunnel section, it was required to strip rock mass by removing already erected ribs /LGs to accommodate Gantry. This has necessitated strengthening of in-situ rock mass, cautious excavation by non-explosive method, additional support measures, systematic instrumentation programme etc.

4 Geological challenges encountered during fresh excavation

After re-strengthening and restoration of the collapsed tunnel faces, balanced underground excavation work was carried out by using suitable Drill Blast methodology or by Mechanical means of excavation as per the condition of rock mass. During progressive excavation of balance works, project had encountered several hindrances due to adverse geology conditions as given below:

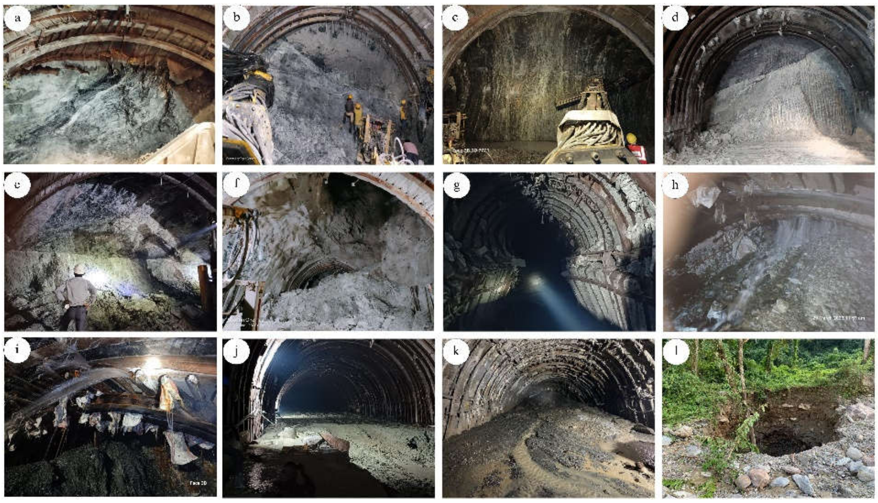

Figure 6. Showing Photographs of Geological hindrances faced during fresh excavation (a) Shear seams Parallel to foliation plane. (b) Shear zone at the hinge of synclinal fold. (c) vertical Shear seams at the hinge of Anticlinal fold. (d) & (e) Shear zones manifested along Fault planes. (f) Cone formation due to subparellel folaition plane (g) Squeezing in the tunnel. (h) & (i) Flowing water condition. (j) Tunnel filled with slush (k) &(l) Collapsed tunnel face & Surface Cave-in above the tunnel face.

4.1 High overburden and low rock cover zone:

The HRT intake is located in high overburden cover to the tune of 50m which mainly consists of highly saturated, unconsolidated and heterogeneous in nature. During excavation by the previous developer, local instability problems were reported at the surface due to the unconsolidated overburden mass. Although instability problems were observed at the surface, it also posed an immediate threat of instability at the tunnel during the excavation works of HRTs. The rock mass at tunnel grade in this zone was highly weathered and crushed Quartzite in the form of sugar cube along with bands of sheared and deformed Phyllite. Due to these adverse geological conditions, tunnelling activities at the intake area was a very challenging and difficult task. Knowing the geological conditions, the tunnelling in this span was done through non explosive means by providing a sequence of pipe roofs along with multi-segmental methodology. This area was further closely monitored by providing suitable monitoring instruments such as Load cell, MPBX, SPBX, Convergence metre and survey targets.

4.2 Sequence of Anticline & Syncline Structures

In the project area, Teesta River is flowing along a major antiformal structure and the effect of this has rendered the rock mass to be fractured, highly jointed with intermittent shear seams/zones particularly between Intake to Adit III. Thus, the closer the tunnel alignment nearer to the river, the more the adverse nature of rock mass has been encountered. In addition, sequence of anticline & syncline folds, passes throughout the HRTs alignment, causing the rock mass to be extremely deformed and under stressed condition. Beside this, the same litho-units are encountered repeatedly having variable physical and mechanical properties worsen the tunnelling in this area. Overall, the synclinal & anticlinal zones displayed increased jointing leading to more fracturization, intrafolial folds, shear zones, minor faults and other associated structures which are also variably-oriented. Overall, the weak rock masses produced by such regional tectonic features are present throughout the whole tunnel length. It is generally observed that the competency of the rock mass changed dramatically in a few metres and in such cases; frequent removal of rock support, particularly steel ribs proved to be dangerous if temporarily a better quality of the rock mass appeared for the shooter stretch of the tunnel.

4.3 Shear Seams/Zone

These geological features are associated with multiple shear seams of varying thickness from few cm to tens of metres had continuously hampered the tunnelling activities to a greater extent. The rock mass along these shear seams/zones are strongly deformed, crushed, cohesionless and showing substantial heterogeneity. Encountering these shear zones during tunnelling results in the form of face instability/collapse, excessive over break, cavity/chimney formation, running ground condition, mud inrush, squeezing and/or swelling of rock mass etc. Tunnelling through this type of shear zone was extremely challenging and difficult which required additional support measures in the form of pregrouting, pipe roofing, fore poling along with steel ribs support were completely embedded in SFRS.

4.4 Interception of Groundwater

With the increase in blocky nature of rock and at the boundary of anticline-Syncline boundaries, frequency of joints in the surrounding rock is noticed to be increased. The risks of hitting large quantities of high-pressure ground water during advancement was dealt by conducting advance probing. At times, the seepage encountered was acceptable and at times, it was unacceptable which was dealt with by providing drainage holes and pre grouting activities.

Also when Tunnels were driven below perennial streams through highly sheared, soft nature of Phyllite under a cover varying from 55m to 70m had initially presented considerable difficulty in terms of face stability due to seepage of water. Large inflows of pressurised water to the order of 700-1000 LPM was captured during tunnel excavation in HRT Face 3B below Kalej Khola and face 4B that caused surface subsidence. This difficulty was tackled by sequential excavation involving partial excavation of top heading leaving a core (rock ledge at the centre of face) at the face with pipe roofing techniques.

4.5 Occurrences of Flammable Gas

During initial excavation of HRT Face 4B at RD: ±41m by previous developer in the month of Nov 2009, release of flammable gas was detected at the contact of competent Quartzite-Phyllitic Quartzite with soft nature of Phyllite which eventually burst into flame. Similarly, during excavation by NHPC, incidence of concentration of flammable gases was initially reported when the HRT Face 4A was entering Kabrey Khola. The gas was releasing particularly from the tunnel arch section. The measurement of Lower Explosive Limit (LEL) recorded through the handheld equipment was up to 30% resulting in incidence of fire during heading excavation at this tunnel face. Accordingly, improvement of ventilation and strengthening monitoring measures were done. Additionally, 02 Nos., 30m to 24m long of probe holes were also done at the working face wherein LEL was detected to the order of 1-5% and tunnel advancement was attempted safely with the help of mechanised equipment.

5 Methods adopted for tunnel stability

Project had adopted various additional support measures which minimizing hindrance during progressive tunnelling. These additional support measures are as follows:

Advance Probing: Probe holes up to 20m long were conducted to explore the competency of strata and also to assess stored water ahead of the tunnel face. This method has greatly benefited in difficult ground conditions towards avoiding potential risk and was the best option to control sudden water inflows during excavation.

Pre-drainage holes: 45mm dia, 20m long, drilled in crown periphery at 10-15° upwards, followed by installation of perforated pipes. These helped in reduction of hydrostatic pressure and minimising seepage from face ahead. It was always ensured to divert the water from the face towards its rear side to facilitate smooth excavation works.

Pre-excavation grouting: 45mm dia, 10m long, 10-15° upwards in crown periphery and at face was drilled from the tunnel excavation face towards the advancement. The grout was pumped in and allowed to set before advancing. The activities were performed ensuring 3m overlapping with the next round of pre-grouting. Microfine cement grouting in addition to normal cement grouting was provided during pre-grouting / consolidation grouting. In Kalej Khola nala stretch, permeason grouting was also executed from the ground surface. The risk of unexpectedly running of water ingress into extremely poor and unstable ground ahead of the face was avoided through these activities and also stand-up time of the rock face was improved considerably.

Fore-poling: 32mm dia reinforcing bars, 10m long, at a close interval of 200-300mm, 10-15° upwards in crown periphery were provided at the tunnel periphery by hammering or by drilling. In case of drilling, the holes were grouted after installation of forepoles. The activities were performed ensuring 3m overlapping with the next round of forepoling.

Pipe Roofing: 89mm dia, 21m long, casing perforated pipes using sacrificial drill bits were inserted around the arch section of the tunnel face. The pipes are spaced 300-400mm c/c and inclined 10-15° upwards from the periphery of the tunnel face. The perforated pipes are then grouted in stages with a maximum pressure of 4bars. So, the arrangement of overall grout pipes was ensured to form an umbrella around the roof of the tunnel and its advancement zone. This methodology was adopted where Class V (very poor) rock was anticipated at the advancement zone.

Face sealing: When full face heading excavation of the tunnel was being done against the dip in sheared nature and soft nature of Phyllite, frequent collapse of the rock face has hampered the progress. Without any perceptible movement and before any kind of alarm could be given, the exposed tunnel rock face often collapsed which posed a threat to the workers. Subsequently, this adverse incidence was controlled by application of layers of fibre shotcrete on the rock face timely. The advancement of the tunnel was restricted to 1-2m in each cycle with concurrent support measures.

6 Conclusion

Tunnelling in Himalayan regions presents numerous challenges due to the presence of adverse geological conditions. Most of the problems in Himalayan tunnelling are attributed due to lack of knowledge of the adverse geological features of the area and their potential risk and resulted in time and cost overruns of the project. The excavation of HRTs in Teesta VI HE Project was challenging due to encountering weak, fragile and sheared rocks. As the alignment of the HRTs passes through a series of folds, sheared rock mass with varied lithology, low cover, flammable gas etc, the tunnelling so far has required more steel rib support, Pipe roofing and forepoling arrangement than expected. Accumulation of progressive geological data; both surface and subsurface has helped in tackling many geological problems that were anticipated initially. Almost all the nala stretch had been successfully crossed with utmost care and giving attention to geological details.

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