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Unpredictable Geological Features on Rishikesh -Karnprayag Rail Project in Uttarakhand Himalayas- A Case Study

*Rishi Sharma**
Pooja Swami

Turkish Engineering Consulting & Contracting – TUMAS India Pvt. Ltd., Gurugram

**Email: geologistrishi.1978@gmail.com*

ABSTRACT

The success of tunnelling in the Himalayan region depends on adequate available geological information and geotechnical investigations. Properly planned investigations give higher degree of confidence on the anticipated geology and give less surprises during execution of tunnel projects. The tunnelling through youngest folded mountain is a huge challenge due to complex geological condition having thrust / fault zone, lithological contact, and multiple shear zones.

In this paper, importance of geological investigations, comparison between the anticipated and actual ground conditions have been discussed along the Adit 6, Adit 6A & Adit 7 in connection with new single line broad gauge rail link between Rishikesh and Karnprayag in the State of Uttarakhand, India. It also highlights the predicted and actual encountered Q-value/rock mass class, ground water conditions, and expected weak zones.

Keywords: Geological investigation; Tunnelling; Thrust zone; Rock mass classification; Probe drilling; Pipe-roofing

1. INTRODUCTION

Indian Railways is constructing a 125 km long new broad gauge rail line in Uttarakhand state of India between Rishikesh and Karnprayag to make train journeys comfortable and convenient for the traveler. This broad-gauge railway line will boost tourism, trade, and connectivity between five districts of the state. Out of total length of 125.20km, 105.47 km (84.24%) comprises of tunnels. All along the route there will be 12 railway stations, 17 tunnels as well as 16 bridges.

The project alignment passes through the rugged, mountainous and steep terrain. Three construction Adits were proposed to facilitate the main and escape tunnels construction between Srinagar and Rudraprayag stations. The length of Adits 6, 6A and 7 is 1021m, 572m and 622m respectively.

Construction of Adits 6, 6A & 7 was utmost important as it would increase number of faces for construction of the main and escape tunnel works which would play an instrumental role in successful and timely completion of the work for packages 6, 7A and 7B. To access the geology along the tunnels, detailed geological mapping and traversing was performed along the project alignment along with desk study of geological maps, previous case histories etc. (IS 11315-12, 1992; IS 13365-1,1998; Lisle et al., 2011).

The cross sections sizes of all Adits were governed by the functional requirements such as lighting, construction equipment and ventilation system. The Adits diameter was chosen as 8.6m (height) and 7.04m (width). All three Adits were having modified horseshoe shape with 2 radii cross section. The finished cross section area was 52.0m^2. Figure 1 shows the typical cross section of construction Adit.

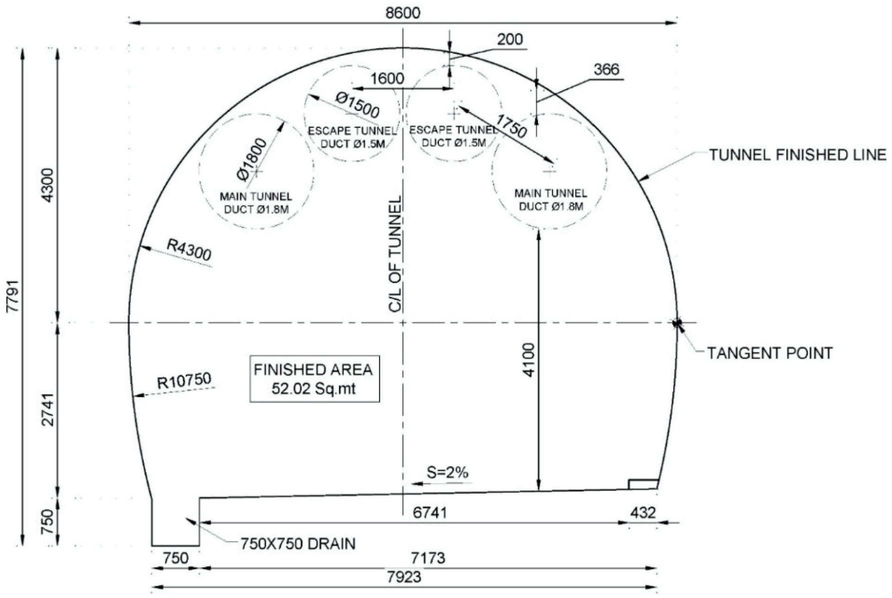

Figure 1 - Typical cross-section of construction Adit

This paper covers the importance of geological investigations for planning, design and construction of Adits. The geological aspects (geology, investigation), construction approach, geological challenges and mitigation measures have been discussed in this paper. The comparison between predicted geological and encountered geological conditions like rock mass classes and ground water conditions were studied and have been presented.

2. REGIONAL GEOLOGY

The area consists of metapelites, metapsammites and carbonate rocks which are associated with metabasics along the gneiss. The lithological units in area are folded into broad anticlines and synclines with recumbency, which in turn is displaced along the major shear plane (North Almora Thrust and Dharkot Thrust). Subsequently, during the post thrusting time, the metamorphosed and deformed rocks again witnessed folding movements as a result of which the thrust planes were folded juxtaposed over one another. The end of the structural play was characterized by prevalence of erosional agencies which designed the present configuration of the area with the formation of the windows and Klippen (the window at Sumari Jaletha etc. and the klippe at Uphalda). The lithotectonic setting of the area is given in Table 1.

2.1 Pauri Phyllites

The Pauri phyllites are bound by Garhwal thrust and North Almora thrust. The greyish green to dark green phyllite strikes NW-SE and is characterized by moderate to high angles of dip towards SW as shown in Fig. 2. It is folded and schistose near Srinagar. The folds are open and angular too. It is compact and slaty near Khola. A metabasic in sill form (upto 5m thick) traverses the phyllite exposed 3 km SE of Srinagar. The Pauri phyllite comes in tectonic contact with ferruginous Nagthat quartzite at a distance of 4.5 km SE of Srinagar. The Adit 6 is located in Pauri phyllites.

Table 1 - Lithotectonic setting of project area (Khan et al., 2024)

Thrust	Tectonic Units	Rock Units
Garhwal	Pauri Phyllite (Adit 6)	Chlorite-sericite-quartz phyllite, well folded with development of strain slip cleavage
North Almora	Nagthat Quartzite (Adits 6A & 7)	Quartzite: Ferruginous, occasionally schistose and gritty Slate: Ferruginous greyish black slate with slaty cleavage Limestone: Bluish-grey microcrystalline dolomitic

Figure 2 - Foliated phyllites

2.2 Nagthat Quartzite

Barring small outcrop in the form of a window towards SE of Srinagar, the quartzite occupies the northern half of the area. The regional strike of the quartzite is WNW-ESE and it dips towards SSW. The quartzite can be sub-divided into three types: massive, gritty and schistose. The massive variety is white to pink in color and is mainly exposed away from the thrust plane near Gulab Rae and Rudraprayag. This quartzite at Pharasu contains rounded and sub-rounded to elongate quatzitic pebbles measuring 25mmx5cm. The quartzite becomes gritty at some places especially near Kaliasaur and Khankra and NE of Rudraprayag. The schistose variety is confined along the North Almora thrust near Koteshwar (6 km NE of Srinagar). The Adits 6A and 7 are located in this quartzite as shown in Figs. 3 and 4 respectively.

2.3 Metabasics

The metabasics are comprised of metadolerite and epidiorite, which are compact in their core parts (rich in pyroxenes and plagioclase) and grade into foliated type towards their marginal parts with the occurrence of hornblende, chlorite and epidote. The coarse grained metadolerite dyke is exposed at Bhainskot. An extensive bend about 250 m green, highly massive metadolerite is exposed at Pharasu and extend across the Alaknanda-river. It is highly jointed and is foliated at the margins. Several quartz veins running parallel to the foliation traverse the rock. A small band is exposed near Dhari, Epidioritic sill is exposed at Khankra and Rudraprayag. The geological map of Adits is given Fig. 5.

Figure 3 - Quartzite at Adit 6A

Figure 4 - Quartzite at Adit 7

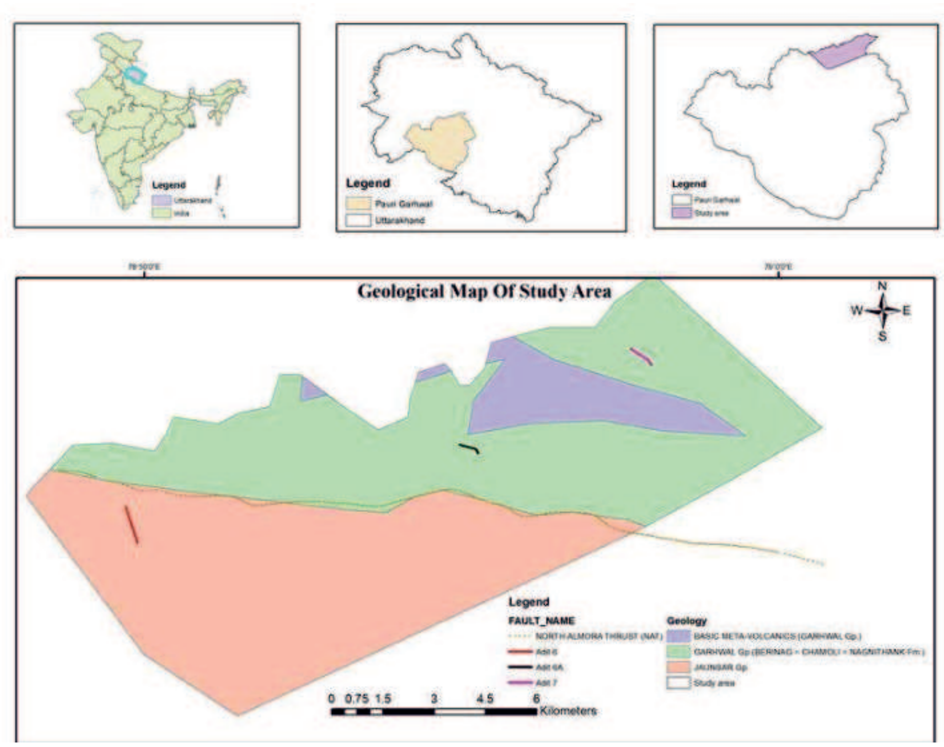

Figure 5 - Geological map of Adits (source: https://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx)

3. ANTICIPATED GEOLOGY ALONG ADITS

No geotechnical, geophysical or laboratory testing was conducted along all three construction Adits. Only surface geological mapping was carried out and the geological information along the Adits alignment have been collected.

3.1 Construction Adit-6

A 1021m long construction Adit 6 was proposed for the construction of main tunnel T-11 on the left bank of the Nala. The direction of the proposed adit/tunnel was N 165°. The portal and tunnel alignment were primarily covered with thin slope wash material, which consisted of boulders and gravels of phyllite mixed with silty soil. The anticipated approximate depth of overburden ranged from 2.0m to 5.0m. The maximum and minimum ground cover measured 192m and 70m respectively along the Adit 6 alignment. The Pradhan Mantri Gram Sadak Yojana (PMGSY) road was passing above the adit. Due to the PMGSY road, the portal tunnel extended up to 35.0m in length and passed through 19m of ground cover.

Rock outcrops of foliated phyllite were also present near and along the road which was passing above the adit (50m away from portal) and in the dry nalas situated upstream and downstream of the adit alignment. The adit passes through slightly fractured phyllite from the Chandpur Formation of the Jaunsar Group. Slight folding was also observed in the phyllite above the road. The rock mass was dissected by five joint sets.

Based on the Q-system (Barton, 1988) the rock mass was assessed as fair in condition, though patches of poor to very poor rock mass were encountered during the construction. The seepage condition ranged from dry to dripping. Pre-grouting was proposed to improve the rock quality designation (RQD) and to control the seepage condition. Probe holes were also provisioned for the pre-assessment of rock mass conditions.

During pre-construction stage, the rock mass has been anticipated along the Adit 6 as given in Table 2 and geological section in Fig. 6.

Table 2 - Anticipated rock mass classification based on Q-value along the construction Adit 6

<table>
<tr><th>Chainage(m)</th><th>0-35</th><th>35-50</th><th>50-240</th><th>240-550</th><th>550-660</th><th>660-1000</th><th>1000-1021</th></tr>
<tr><td>Rock Type</td><td colspan="6">Foliated Phyllite</td><td>Phyllite with slightly folding</td></tr>
<tr><td>Corrected Q-Values</td><td>1.1</td><td>2.89</td><td>6.67</td><td>7.78</td><td>5.56</td><td>6.44</td><td>10.00</td></tr>
<tr><td>Remark</td><td>Portal Tunnel</td><td colspan="6">Tunnel</td></tr>
<tr><td>Rock Class</td><td>V</td><td>IV</td><td>III</td><td>III</td><td colspan="3">III</td></tr>
</table>

3.2 Construction Adit 6A

A 572m long Adit 6A was proposed for the construction of main tunnel T-12 on the right bank of the nala and the left bank of the Alaknanda-river. The direction of the proposed tunnel up to 326m was N107°, while from 326 to 572m it was N159°. The portal area was covered with very thin slope wash material, and rock outcrops were predominantly present in this area. The tunnel alignment was primarily covered with thin slope wash material consisting of boulders and gravels of quartzite mixed with silty soil.

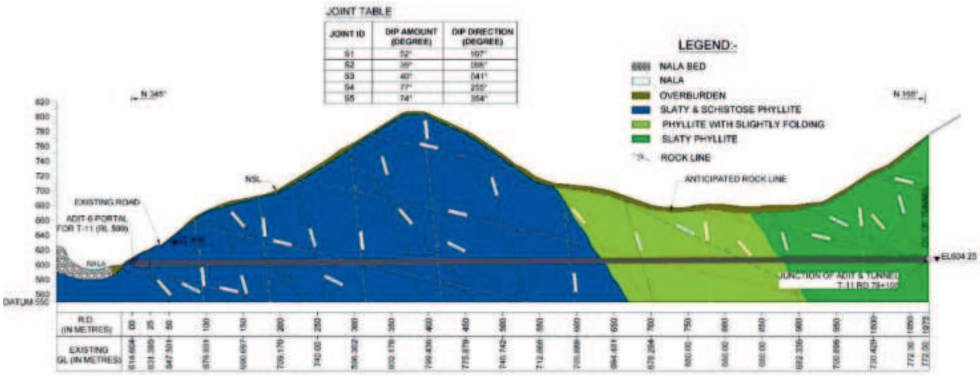

Figure 6 - Geological L-section along construction Adit 6

The anticipated overburden depth ranged approximately from 2m to 5m. Quartzite rock outcrops were also observed along the road and in the portal area. The maximum and minimum ground cover measured 211m and 19m, respectively. Due to the passing of road above the tunnel, the portal tunnel extended up to 25.0m in length and passed through 23m of ground cover.

The anticipated rock mass was jointed and comprised medium to strong quartzite, with intrusive bodies of metadolerite. The seepage condition varied from dry to dripping, and a medium inflow was anticipated. Flowing conditions were also expected at the contact between the quartzite and metadolerite rock. The contact zone / Khankra thrust projected from surface geological mapping which was passing through the nala depression was anticipated to be located between Ch. 260m to 500m in the adit. Pre-grouting was proposed to improve the rock mass quality and to control the seepage conditions during construction. Probe holes were provisioned during construction for assessing the rock mass before advancing the face.

Based on the Q-system rock mass classification, the rock mass was classified as poor to very poor, with fair conditions also anticipated. During pre-construction stage, the rock mass conditions have been anticipated along the tunnel which is given in Table 3 and geological L-section is given in Fig. 7.

3.3 Construction Adit 7

A 622.7m long Adit 7 was proposed for the construction of main tunnel T-13 on the left bank of the Alaknanda-river. The directions of the adit were N120° and N148°. The adit/tunnel alignment passed through the steep left bank of the Alaknanda-river, which was mostly rocky and, in some areas, covered with slope wash material. The slope wash material consisted of boulders of quartzite mixed with silty soil. The anticipated overburden ranged from approximately 2m to 5m.

Table 3 Anticipated rock mass classifications based on Q-value along construction Adit 6A

Chainage (m)	0-25	25-125	125-200	200-260	260-421
Lithology		Quartzite			Contact Zone
Q-Value	0.75	5.00	3.58	3.85	0.73
Corrected Q-Values	0.38		Tunnel		
Remark	Portal Tunnel		Tunnel		
Rock Class	V	III	IV		V

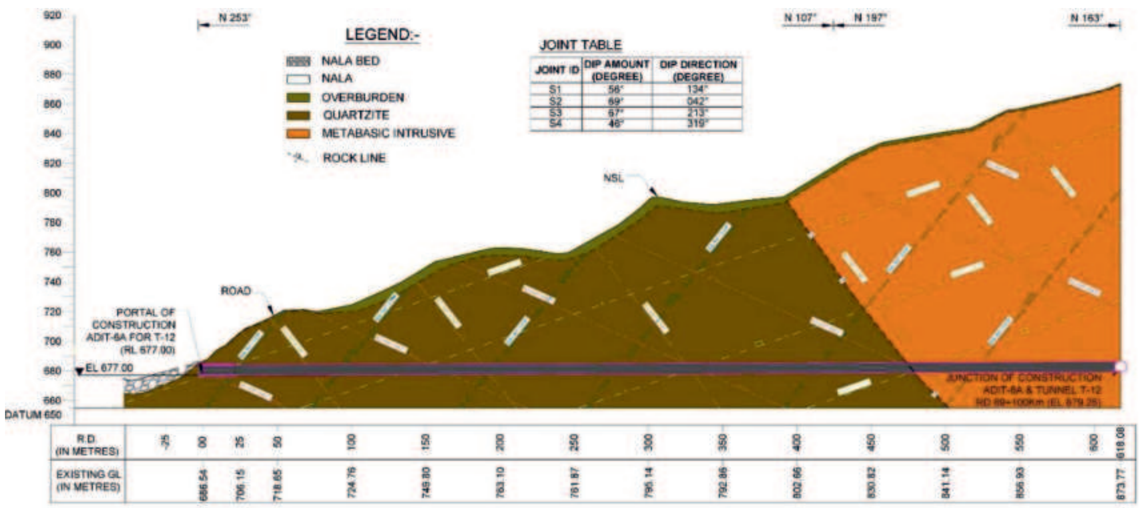

Figure 7 - Geological L- section along the Adit 6A

The portal was located at a well-exposed area of strong, fresh to slightly weathered, slightly fractured, and moderately jointed quartzite. The tunnel alignment was also covered with thin slope wash material, and exposed rock outcrops were observed along the Adit alignment, portal area, and along the road.

The tunnel passed through quartzite and intrusive meta-dolerite rock masses. The rock mass was classified as strong to very strong, slightly fractured in nature, and belonged to the Nagthat Formation of the Garhwal Group. The rock mass was dissected by four joint sets, with three prominent sets. The maximum and minimum ground cover measured 451m and 28.60m, respectively. The portal tunnel extended up to 30.0m in length and passed through 25m of ground cover.

The anticipated groundwater condition ranged from dry to dripping, and flowing conditions were also expected due to a nala running across the alignment from Ch. 240m to 350m. Pre-grouting was proposed to improve the rock mass quality and to control seepage conditions during construction. Probe holes were provisioned during construction for assessing the rock mass before advancing the face.

Based on the Q-system rock mass classification, the rock mass was classified as fair, poor and very poor. The rock mass condition was expected to vary during construction. The anticipated rock class is given in Table 4 and geological section along the adit is given in Fig. 8.

Table 4 - Anticipated Rock mass classifications based on Q-value along construction Adit 7

Chainage (m)	0-25	25-150	150-220	220-350	350-450	450-622
Lithology	Quartzite					
Q-Value	0.8	5.4	3.3	3.9	3.3	5.8
Corrected Q-Values	0.38			Tunnel		
Remark	Portal Tunnel			Tunnel		
Rock Class	V	III		IV		III

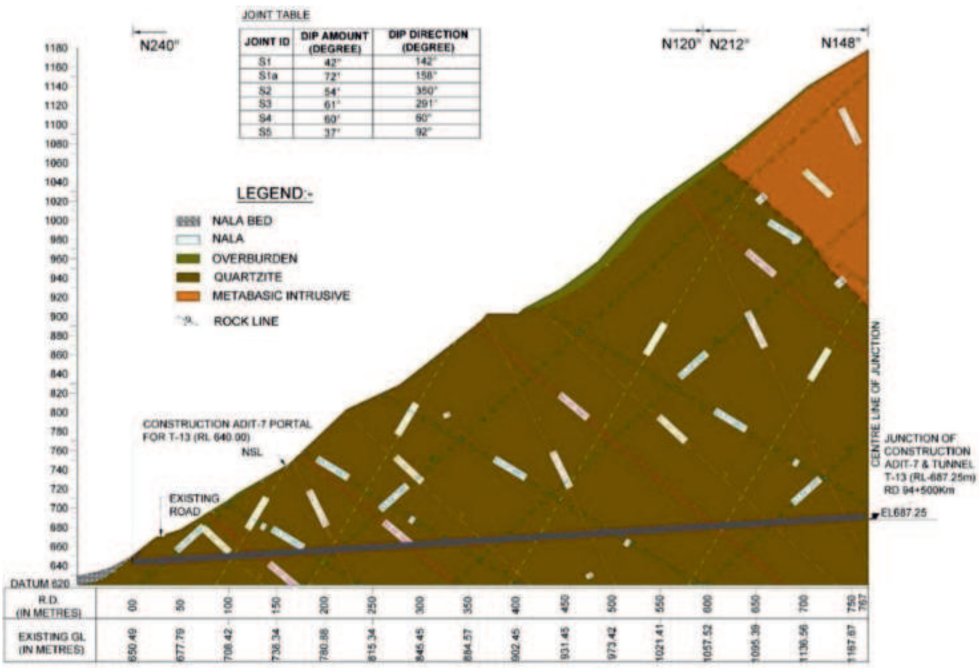

Figure 8 - Geological L-section along the Adit 7

4. SEISMICITY

Uttarakhand Himalaya is one of the seismically active regions and have experienced earthquake since times immemorial. The regions have also experienced tectonic movements. This is evident from the thrusts and faults present in and around the state. Two regional tectonic features in Uttarakhand, which have earthquake potential are the MCT and MBT. In fact, these features are present all along the Himalayan tectonic features.

As per seismic zoning map of India, as incorporated in Indian standard provision (IS 1893-1, 2002) the project area has been assigned to seismic zone IV and V. Seismic zones play a serious role in tunnel design, as determine the level of earthquake risk. Tunnels in areas near shear and thrust zones require strong design strategies to withstand the extreme seismic forces that can occur in these active tectonic environments. The combination of geotechnical analysis, seismic-resistant tunnel linings, adaptive support systems, careful tunnel construction methods, and post-event monitoring ensures that these tunnels can tolerate and protect both the structure and the people within it during an earthquake.

The design of tunnels needs to accommodate seismic activity to ensure safety, structural integrity, and minimal damage during seismic events.

5. ACTUAL GEOLOGY ALONG ADITS

5.1 Construction Adit 6

The entire construction of adit 6 has been done with full face. The rock mass of fresh to slightly weathered and thinly foliated phyllite with mica content has been encountered. The direction of the proposed tunnel was N 165°. The strike of strata was N13°E - S77°W dipping ES direction. Due to thinly foliated phyllites and unfavorable discontinuities/joints condition, overbreak/cavity formation have been experienced at three locations. The one was major cavity formation (chimney type), second was minor occurred due to wedge failure and third one was identical of first one. The detailed description of rock mass failures is as under.

Cavity No. 1 – A cavity had occurred from Ch.199m to 201m at right crown on 8th November 2019 (Fig. 9). The rock fall was circular in shape with initial diameter of 4m with approximate height of 3m. The rock mass of cavity area was thinly foliated phyllite with mica schist with Q-value 0.36. Water seepage was around 30 lit / hours. Reason behind the cavity formation was high percentage of mica schist along the foliation plane with seepage. Shear thickness was 10 to 15cm.

As its treatment, initially 76mm diameter, 6m long, umbrella of pipes was made with spacing of 300-400mm, touching the face. Above that MS sheet of 3.15mm was placed and filled approximately up to 2m depth with concrete in stages. After that structural steel (UC 150) support was provided with 0.5m spacing below that followed by backfill concrete and later contact grouting. the cycle time of this treatment was 48hours.

Cavity No. 2 - Cavity occurred from Ch. 257m to 258m at right side (above SPL) on 17th December 2019 as shown in Fig. 10. It occurred during scaling of face. Profile of cavity was conical in shape with initial diameter of 2.5 m with approximate height of 2m. Type of rock mass was thinly foliated phyllite with Q-value 0.96. Due to intersection of multiple joints set in thinly foliated phyllite, the cavity had occurred. The thin shear seams were also noticed having thickness from 5 to 8cm. There was no underground water seepage.

As treatment, initially 50mm thick shotcrete was applied to control loose fall. After that structural steel support was erected with spacing of 1m, followed by backfill concrete. The total 36 hour was taken for the support and treatment of this cavity.

Figure 9 - Cavity at Ch. 199 m

Figure 10 - Cavity at Ch. 257 m

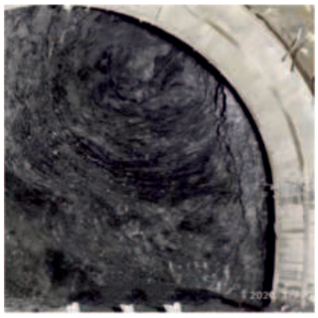

Figure 11-Cavity at Ch 547 m

Cavity No. 3 – The 3rd cavity had occurred at Ch. 547m on 1st Marchm 2020 as shown in Fig. 11. The cavity was circular in shape with initial diameter of 4.5m with approximate height of 1.5m towards the face. Rock mass was weak, foliated and dark grey colour schistose phyllite with 3 sets of joints including random joint. There is no water seepage. The Q-value was 2.23. Reason behind the cavity formation is clay band along foliation plane. Shear thickness is 7 to 8cm.

As treatment, initially sealing shotcrete was applied to control loose fall and umbrella/ canopy was made. Structural steel supports were provided with spacing of 1m followed by backfill concrete. The cycle time of this support and treatments of this cavity was 13hours. Same strata have been encountered at Ch. 763 m also and continued till Ch. 987m. The structural steel supports of UC150 section were used with back fill concrete.

5.2 Construction Adit 6A

The adit construction has been done with full face from Ch.0.0m to 115.0m, 120.0m to 291.0m, 316.0m to 366.0m and 373.0m to 421m, due to the cavity formation, the heading & benching methodology was adopted between Ch.115.0m to 120.0m and 366.0m to 373.0m, whereas due to Khankra fault, the multi-drift method was adopted from Ch. 291.0m to 316.0m. The rock masses encountered were jointed to fractured, slightly to moderately weathered quartzite and greenish colored metabasic. In the Khankra faulted zone the rock mass is moderately to highly weathered and highly fractured to crushed quartzite with water seepage.

The direction of the proposed tunnel up to Ch.326m was N107°, while from Ch. 326 to 572m it was N159°. The strike of strata was N44°E-S224°W, dipping towards ES direction. Due to unfavourable condition of discontinuities / joints, the tunnel especially in the crown has experienced wedge and block failure which had resulted into cavity formation at three locations.

Structural steel (UC150) supports were installed all along the tunnel due to minor / major cavity/rock fall. In Adit 6A, three-time poor rock strata encountered during the excavation, out of three, one was major due to which major cavity formed mainly because of Khankra fault zone and other two in which tunnelling done through heading and benching method encountered between Ch. 115 to 120m and Ch. 366 to 373m. The brief details of all three are as under.

The first cavity had occurred between Ch. 115m to 120m at the right crown of the tunnel. During the excavation of face through breaking, the cavity was formed. The maximum height of cavity was 2.7m and 10m around the perimeter. The rock mass was highly fractured, sheared and crushed quartzite. The Q-value of the rock mass varies from 0.22 to 0.27. The ground water was 10 to 15 lit/ min.

The second and major cavity was formed due to the Khankra fault zone, which was encountered from Ch.291m to 316m. The encountered rock mass is highly crushed and fractured of metabasic and quartzite. The rock mass was in the form of a rock flour/sugar cube with almost no cohesion. The shearing has also been noticed. Based on lab testing the material consists of sand, silt and fine silt. The water condition is dripping to flowing. The pore water pressure has been increased (water ponding behind the face) after face sealing. Chemical grouting (urea silicate and colloidal silicate) has been injected for stabilizing the face.

The third cavity was observed between Ch. 363m and 373m at the top of the crown, occurring during the face breaking process. A loose fall of 3.7m in height and 9m around the perimeter preceded its formation. The rock mass was fractured into crushed quartzite with a moderate flow of water present at face with a Q-value of 0.22.

5.3 Construction Adit 7

The encountered rock mass in the adit/tunnel is fresh to slightly weathered, fractured, strong quartzite. Not any major rockfall failure had occurred in entire length during construction. The rock mass encountered was fair to good in condition. The groundwater condition along the entire length of adit is dry to damp. However, ground water has been encountered form Ch. 592m to 622m.

During the portal tunnel development, left crown was collapsed. The loose fall material was overburden material consisting of debris/dumped material (Excavated muck of road). The total quantity of material was 15cum created a natural slope. Due to this movement of the dumped material inside the adit/tunnel, the funnel type cavity was formed above the portal. Figures 12 and 13 show the loose fall inside the tunnel and the subsidence on the ground surface above the adit/tunnel respectively.

6. COMPARISON BETWEEN ANTICIPATED AND ACTUAL GEOLOGY

Due to the complexity of Himalayan geology and unavailability of enough geological and geotechnical data, the discrepancy between predicted and actual geology observed become certain. The comparison of rock class of all three construction Adits are shown in Figuers 14, 15 and 16.

Above Figures shows notable disparities between the anticipated and actual rock mass classes in the three construction Adits.

Figure 12 - Loose fall inside the tunnel

Figure 13 - Subsidence above tunnel

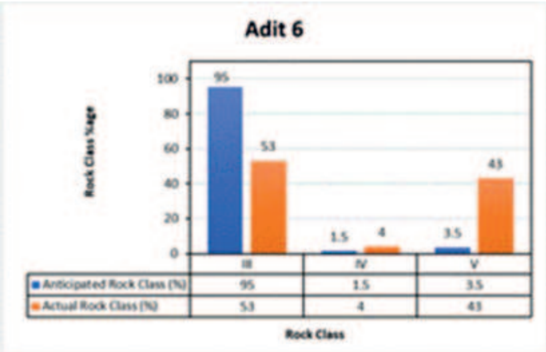

Figure 14 - Comparison between anticipated rock class and actual rock class along of Adit 6

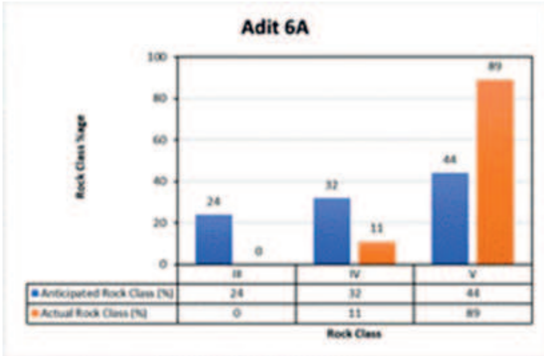

Figure 15 - Comparison between anticipated rock class and actual rock class of along Adit 6A

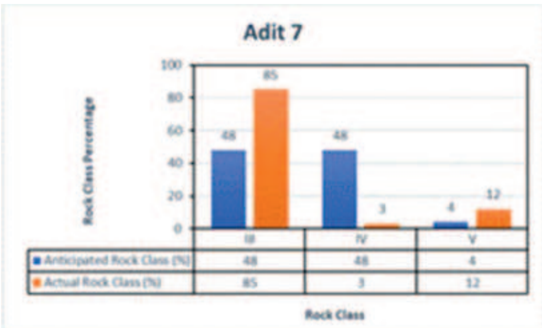

Figure 16 - Comparison between anticipated rock class and actual rock class along Adit 7

Geological mapping led us to anticipate the presence of the Khankra fault in Adit 6A, spanning from Ch. 260m to 500m. As we proceeded with the tunnelling process, we indeed encountered the fault between Ch. 291m and Ch. 316m. The prediction was accurate in terms of the location of the fault; however, the length of the fault zone differs. It is due to the following reasons:

- Inadequate or insufficient geological and geotechnical investigations and testing conducted during the planning and design Stage.
- In the Himalayan region, complex geology makes it difficult to accurately predict the deep geological conditions of rocks based only on surface geological mapping.

7. PROBE DRILLING AND GEOLOGICAL MITIGATION STRATEGIES

During construction, three probe holes (each 21m long and 50mm in diameter) were drilled at the tunnel crown and spring level (SPL), inclined outward at 7-14°. These probe holes, verified for angle accuracy prior to drilling, were later incorporated into the grouting pattern and the rock mass was grouted using ordinary portland cement (OPC). A qualified engineer and geologist monitored key drilling parameters such as penetration rates, weak zones, water inflow, and flushing losses to assess rock mass conditions ahead of the tunnel face.

Key strategies and insights from the project include:

- Surface geological mapping alone is inadequate in complex terrains like the Himalayas, especially near faults and thrust zones.
- Comprehensive geological surveys and assessments are crucial before construction begins. Incomplete data can lead to unexpected challenges.
- Geophysical studies, including seismic refraction, seismic reflection and electrical resistivity, provide more precise predictions of weathering depth, groundwater conditions and various stability analyses.
- A minimum of three probe holes should be drilled in advance of suspected fault zones to determine their exact location and width.
- The length of the probe hole should be sufficient to intersect the maximum possible extent of varying geological formations ahead of the tunnel face.
- Probe data should be immediately shared with the design team to revise support systems where faults or weak zones are encountered.
- Techniques like pipe roofing and invert closure should be implemented in identified weak or fault zones in consultation with the design team.
- Construction designs must be flexible and adaptable to accommodate unexpected geological conditions.
- Ensure the availability of essential machinery including drill jumbo, shotcrete machine, and grout pump.
- Maintain a sufficient number of skilled personnel experienced in multi-drifting tunneling techniques.

8. CONCLUSIONS

- Significant inconsistencies were observed between the anticipated geological assessments and the actual geological conditions encountered during the construction of the three Adits.
- In the tectonically active Himalayan region, geological mapping alone is insufficient due to the inherent complexity. It must be supported by integrated investigation methods.
- Comprehensive geomorphological studies and remote sensing investigations should be conducted to identify lineaments, fault zones, thrusts, and land use patterns within the project area.
- Surface investigations, including trench pits, should be carried out to understand shallow strata characteristics.
- In-situ permeability testing should be conducted to identify joint openings, fractured zones, and potential cavities, which are critical for assessing tunnel stability and groundwater behavior

- These findings underscore the critical importance of conducting thorough geological investigations using advanced techniques such as exploratory drilling, geophysical surveys, and Tunnel Seismic Prediction (TSP). These methods aid in accurate rock mass characterization and help develop effective mitigation plans.
- Project design reports must clearly document commonly encountered geological challenges and outline specific strategies to address such conditions. This will enable both the construction agency and site engineers to proactively manage unexpected geological scenarios.

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