Rock Mass Characterization using Rock Mass Rating and Encountered Geological Problems in TRT's Component of Tehri Pumped Storage Plant, Uttarakhand, India

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Abstract: As an integral part of Tehri Hydro Power Complex (HPC) located in the state of Uttarakhand in Northern India; an underground 4x250 MW Tehri Pump Storage Plant (PSP) parallel and close to the existing 1000 MW Tehri Hydro Power Plant (HPP). Tehri PSP is located on the left bank of Bhagirathi River in the district of Tehri about 1.5 km downstream of its confluence with River Bhilangana. The major project components are machine hall, upstream surge shafts, Butterfly valve chamber (BVC), Penstock assembly chambers (PAC), downstream Surge Shafts, a pair of Tail Race Tunnels (TRTs) and outlet structures are in construction stage. During underground excavation, one of the important aspects for a speedy and safe excavation is to characterize rock mass for its stand up time. Case history of Himalayan tunnel reveals that Barton's & Bieniawski's classification system provide better assessment of the rock mass behavior. In TRTs of Tehri PSP, Rock Mass Rating (RMR) classifications were implemented during excavation and based on their ratings, rock mass was supported. Construction stage geotechnical assessments were made, and suitable remedies were adopted for all the components of the project after geological traverses, detailed geological mapping, drift logs and logging of cores was done. This paper deals with rock mass characterization of underground structures specially in TRT's using RMR classification and encountered geological problems during excavation.

Keywords: Weak rock, shear zones, chimney formation, rock supports, Tehri, India

Introduction

Tunneling is an important component of any hydroelectric project located in the Himalayas. Due to the rugged and uncongenial nature of the terrain, it is usually not possible to carry out thorough investigations along the tunnel alignments. The use of rock mass classification systems for the underground excavation under such condition provides better idea for their design. The 2400 MW Tehri Hydro Power Complex comprises of Tehri Dam and 1000 MW Tehri Hydro Power Project (HPP) Stage-I, 400 MW Koteshwar HEP and 1000 MW Tehri Pumped Storage Project (PSP). Tehri Pumped Storage Project comprising of four reversible turbines of 250 MW each, involves construction of underground caverns, chambers, TRTs and shafts on the left bank of River Bhagirathi.

The present case study is of a typical Himalayan tunnel, where application of rock mass classification systems formed a major part of geotechnical studies conducted for the evaluation of tunneling conditions. Tehri PSP is implemented by two TRTs which is known as TRT-3 and TRT-4 having length of 1078 km and 1187 m respectively. These tunnels are constructed in a single litho unit of meta-sedimentary rock which is Phyllites. In order to facilitate the excavation of TRTs, one single Adit (EA-7) was provided at chainage 148.5 m and 214 m in TRT-3 and TRT-4 respectively. RMR classification was used for identifying the rock class, and based on rock mass rating, support was provided. The general layout plan along with encountered geology of TRTs of Tehri PSP is shown below in Figure 1.

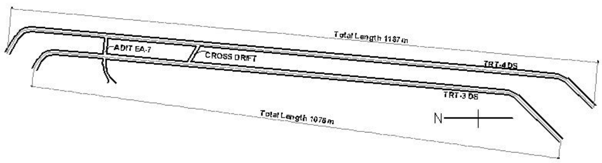

Figure1: Showing Layout Plan of TRTs.

Regional Geological Setting

Project site is within the Lesser Himalaya which lies tectonically between the Main Central Thrust and the Main Boundary Thrust. The former separates meta sedimentary sequence of Lesser Himalaya to the north from crystalline rocks of Higher Himalaya and latter disjoins the Lesser Himalayan sequence from molasses sediments of Frontal Fold Belt (FFB), in the south. Phyllites of Chandpur formation of Jaunsar group, and quartzites and metabasics of Garhwal group are exposed along the project. Most prominent tectonic features; Srinagar Thrust lies 5 km north of the project and it crosses Bhagirathi River at Nalupani, and Bhilangana River at Gadolia. Rock units are part of the low grade metamorphic rock that have been thrusted, folded and deformed. There are two main tectono-stratigraphic units: the Krol Super Group and the Gharwal Group. This former Super Group is subdivided into the Jaunsar Group and Krol Group. Jaunsar Group is found at the Tehri site and includes quartzites and phyllites in varying proportions that have undergone various phases of deformation leading to development of numerous tectonic dislocations, sheared zones, seams and joints of different scales and categories. Type of lithology categorized in the Tehri site have been classified during the dam and HPP design and construction by Geological Survey of India, and same has been adopted for the PSP. The nomenclature has been based on variable proportions, and quality of quartzite and Phyllite include: PQM – Phyllitic Quartzite Massive; PQT – Phyllitic Quartzite, Thinly Bedded; QP – Quartzitic Phyllite; SP – Sheared/ Shattered Phyllite.

Rock Mass Characterization in Tail Race Tunnel

The working faces of the tailrace tunnels are accessed by the Exploratory Adit (EA-7) having 10.90 m diameter of tunnels, excavated through heading and benching methods. The excavated horse shoe shaped TRTs have 850 mm thick reinforced concrete lining in circular shape. The excavation traversed through diverse geological conditions and it was found that the rock mass was discontinuous mainly due to joints, shear planes, bedding planes, foliations, puckered/warped zone, and at places due to presence of shearing/ minor faults.

The quartzite is mid- to dark grey mainly composed of quartz but has thin phyllitic bands through it that are reported to contain mostly the fine mica (sericite) and chlorite. The phyllite, where described as SP, has a high proportion of fine quartz and may be better described as siliceous phyllite; but the term "quartzitic phyllite" has been adopted. There are also gradations or mixtures between these main groups such as PQM/PQT, or PQT with SP. Additionally the rock quality is grouped according to physical and mechanical competency and anisotropic behavior in relation to their disposition. All these rock variants were encountered in underground excavation in the form of alternative bands with varying extent.

Phyllitic Quartzites Massive (PQM)

PQM represents the massive and blocky Phyllitic quartzites rock, grey, dark grey, brownish grey, greenish grey, greyish green in color. They are more arenaceous and occasionally micaceous in composition and are coarser in grain size. Foliations which are the dominant joint set are moderately spaced with medium to high persistence. Sedimentary structures like primary bedding, current bedding and ripple marks are better preserved in these rocks. The bedding surface is rough, undulating with sound and un-weathered to slightly weathered in nature. These rocks are composed mainly of Quartz (60-80%) and feldspar (10-15%), sizes varying from 0.05 mm to 0.15 mm.

Phyllitic Quartzites Thinly Foliated (PQT)

PQT represents the thinly foliated Phyllitic quartzites rock, grey, dark grey, brownish grey, greenish grey, greyish green in color. They are more arenaceous and occasionally micaceous in composition and are coarser in grain size. Foliations which are the dominant joint set are very closely to closely spaced with medium to high persistence. The bedding surface is rough, undulating with un-weathered to slightly weathered in nature. These rocks are composed mainly of Quartz (60-80%) and feldspar (10-15%), sizes varying from 0.05 mm to 0.15 mm

Quartzitic Phyllites (QP)

QP represents more argillaceous, fine grained and dark colored. Foliations are well developed with close to moderate spacing. Minor folds and puckers are better preserved in QP rocks. Silicification along joints planes is very common. This rock is composed of Quartz (60-60%), and feldspar (5-15%), represented by isometric grains of 0.03 mm to 0.05 mm size.

Sheared Phyllites (SP)

Sheared Phyllites are tectonied variants of PQM, PQT and QP rocks, developed mostly in the vicinity of major shears, and form weak zones characterized by mylonites, phyllonites, - highly fissured rock, crumpling and intensive Schistosity. The strength of rock represents R0 to R1 grade, and degree of weathering as completely weathered to highly weathered. Sheared Phyllites are predominantly argillaceous in composition. The encountered geology during tunneling of TRT is marked in the following L-section along TRT.

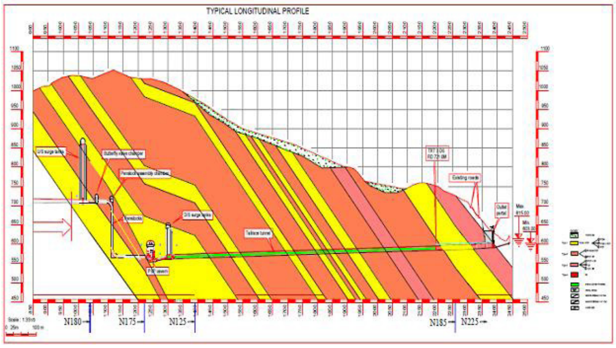

Figure 2: L section of encountered geology during tunneling of TRTs of Tehri PSP.

The rock formations at the project site are Phyllites of Chandpur series. Phyllites, in general, are banded in appearance; the bands are constituted of variable proportions of argillaceous and arenaceous material. The Phyllites have found to be traversed by numerous major and minor shear zones and weak planes. The TRTs are crossing through different rock variant called PQM+PQT, PQT+SP, QP+SP and SP. Four sets of discontinuities were frequented, and their discontinuity characteristics are given below:

Set No.	Feature	Average Orientation	Persistence	Aperture	Spacing	Condition
J1	Bedding	N210^0/45^0	3 to 10 m	Tight to 8 mm	3 to 20 cm	Smooth Undulating
J2	Foliation	N150^0/40^0	1 to 5 m	Tight to 5 mm	10 to 30 cm	Smooth Planner
J3	Joints	N025^0/60^0	1 to 5 m	Tight	30 to 60 cm	Slightly rough/ Planner
J4	Joints	N285^0/70^0	1 to 3 m	Tight	50 to 90 cm	Slightly rough/ Planner

Table 1: Showing Characteristics of Joint Sets Observed in TRTs.

All the rock units along the TRTs have been classified using RMR system proposed by Bieniawski, 1989. Different rock units along the TRTs that are classified using RMR system, have poor to fair rock quality. Occurrences of shear zones and weak Phyllite bands in the rock mass almost always was associated with loose falls and cavity formations. In such reaches, class IV and V kind of conditions had to be negotiated. The percentages of classes as per Beiniawski's Rock Mass Rating (RMR) system evaluated in the TRTs are shown in the following graph (Figure 3).

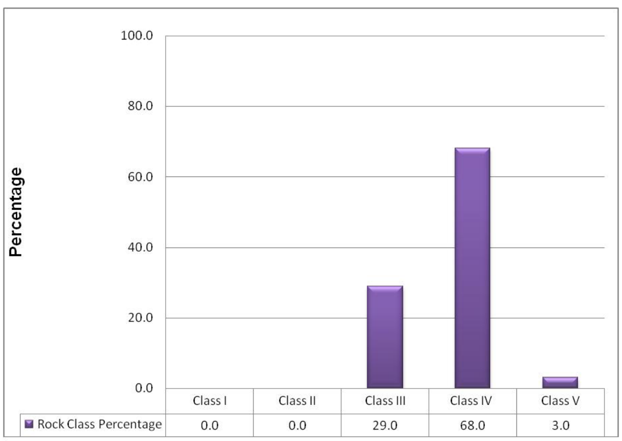

Figure 3: Percentage of rock class encountered during excavation of TRT-3 and TRT-4.

Engineering Properties of Rock Mass

In-situ stress in Himalayan region varies from place to place. A major uncertainty lies in forecasting the magnitude of the stresses in different sections of tunnel alignment, due to the rock cover and closer valley side associated with poly phase deformations in Himalayan region. Hence, in-situ stresses are measured by means of hydraulic fracturing or flat jack test at different locations. The phenomenon of squeezing, which cause an inward movement of the tunnel periphery due to dilation or distressing, needs to be accounted to ensure safety of tunnel support (Bieniawski, 1979). To depict the physico-mechanical properties of rock mass along the various project components, in-situ rock mechanics testing has been conducted at site. A variation in tested value of same drill hole samples indicated complex geology of PSP. Due to this complex geology and local folding/ warping within rock variants, no linear persistence of litho units were found at site and is confirmed with excavation of opening. Some of the engineering properties of the rock samples are tabulated below.

Parameters	Ground Type	As per test results/ site
Uniaxial Compressive Strength (UCS-MPa)	PQT	68.66/22
	PQT with SP	51.99/29/26
	SP	-
Deformation Modulus (Ed-GPa)	PQT	5.4/4.0
	PQT with SP	4.7/4.4/3.1
	SP	
Geological Strength Index (GSI)	PQT	45/38
	PQT with SP	37/33
	SP	25/20
Rock shear parameters (C -MPa & φ-degree)	PQT	3.0 (C) 24.88(φ)
	PQT with SP	1.53/1.36 (C) 38.40/33.95/20.33 (φ)
	SP	-
Joint shear parameters (C -MPa & φ-degree)	PQT	0.91/0.71(C) 28.69/29.05(φ)

Table 2: Engineering properties of rock mass encountered in TRTs.

Problems Encountered During Tunneling

The tunneling in the soft rocks of Himalayas with adverse geological and hydrological condition poses a number of problems, such as, squeezing condition, cavity or chimney formation and roof collapse etc. The geological problems were mainly encountered due to shear zones, high rock stresses and water ingress. The main problems encountered during tunneling are mentioned below.

Encounter of Shear Zones

A number of shear zones were encountered and negotiated during excavation of TRTs. The thickness of these shear zones varied from 5 mm to 50 cm. The shear zones were comprised of clayey and crushed rock infilling matrix. Sometimes big cavities are formed due to the intersection of shear zones. From the 3-D geological mapping of the TRTs, it is observed that if PQM with PQT is encountered during tunneling which is hard & massive in comparison to PQT with SP and SP alone falls in class III & RMR value ranges between

41 to 50. If PQT with SP is encountered, it falls in class IV and RMR value ranging from 32 to 40. If only SP is encountered during tunneling, it falls in class V and RMR value ranges between 17-20. Geological face logs of different litho units correlated with rock classes during excavation of TRTs is shown in Fig 4 below.

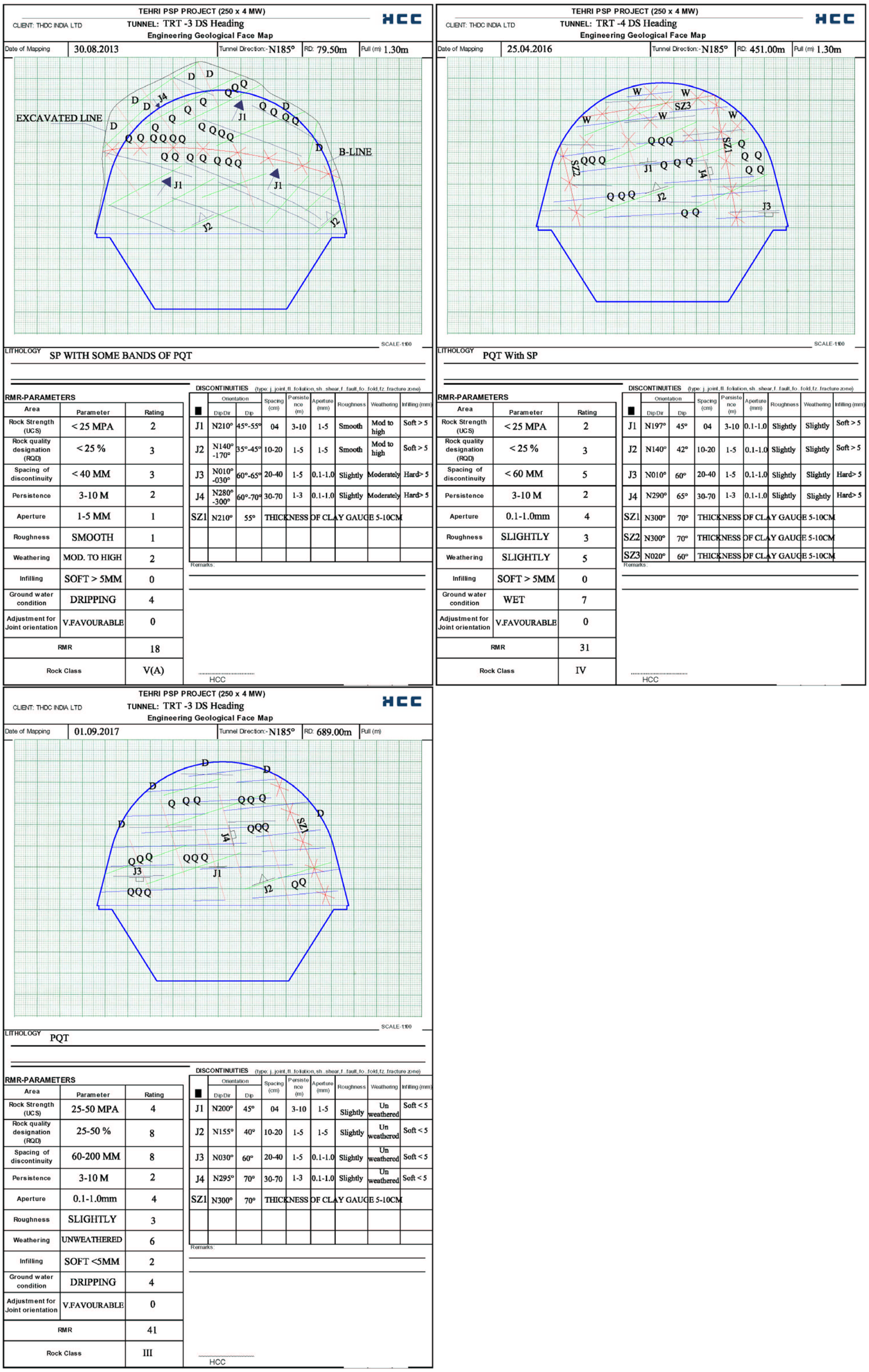

Figure 4. Geological face logs in different litho units at different locations in both TRTs

Many shear zones are encountered during excavation of TRTs which include minor, major and mega shear zones. Details of encountered mega shear zones are tabulated below.

Seepage conditions

Groundwater conditions along both TRTs are normal. The excavated reaches of TRT-3 and 4 present essentially dry conditions with some wet and damp areas. Dripping has also been found at localized zones. No flowing conditions have been reported from PSP excavations.

S. No.	Shear Zone Chainage (m)	Orientation	Thickness	Supports Provided
1	187-194m	N095^0/45^0	Bedding shear, clay infilling, 10-15 cm thick	Steel Rib support with backfill concrete
2	173-177m	N185^0/45^0	Foliation shear, clay gouge infilling, 20 to 25cm thick	Steel Rib support with backfill concrete
3	151-155m	N150^0/45^0	Bedding shear, clay infilling, 10-15 cm thick	Steel Rib support with backfill concrete
4	123-135m	N025^0/60^0	Gouge infilling, 35-50 cm thick	Steel Rib support with backfill concrete
5	113-117m	N190^0/50^0	Foliation shear, gouge infilling, 30 to 35cm thick	Steel Rib support with backfill concrete
6	102-117m	N140^0/45^0	Bedding shear, clay infilling, 30-35 cm thick	Steel Rib support with backfill concrete
7	226-254m	N015^0/65^0-75^0	Sub vertical; 25-35 cm thick	Steel Rib support with backfill concrete
8	288-316m	N090^0/50^0	Bedding shear, clay infilling, 10-150 cm thick	Steel Rib support with backfill concrete
9	472-484m	N210^0/65^0	Foliation shear, gouge infilling, 40 to 50cm thick	Steel Rib support with backfill concrete
10	534-545m	N210^0/65^0	Foliation shear, gouge infilling, 15 to 20cm thick	Steel Rib support with backfill concrete
11	550-554m	N030^0/50^0	Clay infilling; 20-30 cm thick	Steel Rib support with backfill concrete
12	654-701m	N300^0/65^0	Sub vertical; 30 cm thick	Steel Rib support with backfill concrete
13	800-814m	N300^0/70^0	Sub vertical; clay infilling; 30-40 cm thick	Steel Rib support with backfill concrete
14	108-144m	N110^0/70^0	Sub vertical; clay infilling; 20-25 cm thick	Steel Rib support with backfill concrete
15	387-389m	N030^0/65^0	Sub vertical; clay infilling; 20-25 cm thick	Steel Rib support with backfill concrete
16	415-418m	N020^0/30^0	Clay infilling; 25-35 cm thick	Steel Rib support with backfill concrete
17	565-587m	N010^0/68^0	Sub vertical; clay infilling; 20-30 cm thick	Steel Rib support with backfill concrete
18	671-681m	N190^0/48^0	Foliation shear, clay infilling, 40 to 50cm thick	Steel Rib support with backfill concrete

Table 3. Details of encountered mega shear zones

Remedial Measures for Cavity Zones

Cavities are mainly formed due to presence of shear zones along with seepage condition. Shear seams are categorized in three types based on thickness of filling materials, such as clay gauge. Filling material less than 5 cm are termed as minor shear, whereas 5-10 cm and >10 cm are termed as major and mega shears, respectively. Most of the encountered shear seams are major shears. A number of minor to major shear zones (clay filled) have also been encountered from the 3D geological logs of TRTs.

A number of shear zones have been mapped in 3D logs of TRT-3 and 4 excavations till date. Geological mapping show that most of the shear zones are aligned parallel to the foliation orientation. However, shear zones along other joint sets have also been mapped, but, these are less frequent. The shear zones vary in thickness ranging from 2 cm to 15 cm. Occasionally, these may reach 50 cm and more. Many shear zones are clay filled and wet to damp in places. A lot of time was lapsed in treatment and crossing of shear zones. Following are the remedial measures adopted to cross the weak zones encountered during tunneling to prevent the formation of major cavities.

i) First spray the initial layer of shotcrete on face and crown to prevent the loose fall and sealing of the open joints.
ii) Fore polling from the crown.
iii) Erection of ribs ISMB 350 mm with spacing of 750 mm C/C with backfill concrete.
iv) Drainage holes to release the water pressure.
v) Use of Self Drill Anchor in benching where thinly foliated Phyllitic quartzite intermitted with sheared Phyllite (SP).

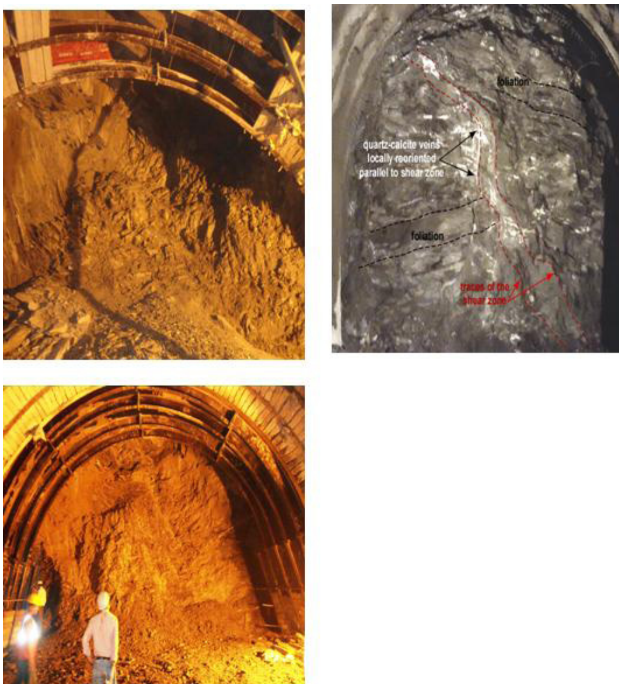

Figure 5. Showing shattered rock mass due to presence of many shear zones and damp to dripping water condition just after excavation in TRTs.

S. No.	Rock Support	TRT-3	TRT-4	Total Support
1	Rock Bolts (25mm dia.)	33883 m	32257 m	96464 m
2	Rock Bolts (32mm dia.)	11694 m	18630 m	
3	Shotcrete	1600 m^3	1623 m^3	3223 m^3
4	Ribs	512.3 MT	728.7 MT	1241 MT
5	Backfill Concrete	6642 m^3	10375 m^3	17017 m^3

Table 4. shows the details of all rock support installed in both TRTs to protect the wedge failure, plane failure, and chimney/cavity formation.

Construction Stage Instrumentation

The geotechnical instrumentation plays a vital role in evaluating the structural performance of an underground structure. The natural ground or rock mass tends to deform and de-stress when subjected to excavations, foundation and other loadings etc. Activities like squeezing, swelling and creeping, depending upon the mechanical characteristics of the material, are also responsible for the disturbances inside the underground rock mass.

The monitoring instruments installed till date, at various locations in the TRTs, are mentioned below.

Bi-Reflex Targets

Bi-Reflex Targets consists of reflector plate mounted on a robust frame. The target has reflectors on both sides and is mounted on a universal joint such that it can be oriented in any direction as required. The target has a cross mark to allow precise targeting. The deformation of different rocks exposed at tunnel periphery has been monitored at one and five places (targets T1 and T1 to T5) by fixing bi-reflex targets as shown in figure, according to encountered rock class. A maximum value of movement with respect to initial in TRT-3 and TRT-4 was observed as 4.5 mm and 5.4 mm at RD 146 m & 724 m respectively. Movement observed in other RD's are negligible.

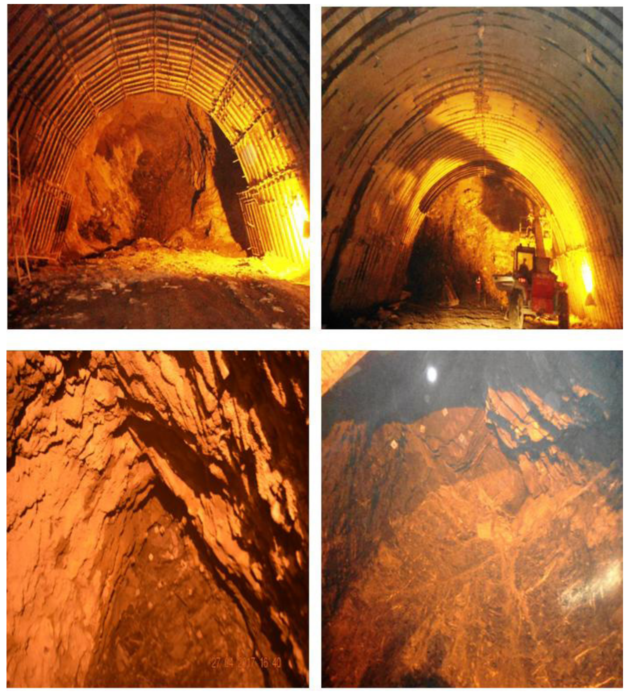

Figure 6: Encountered poor rock condition and their treatment at different locations in both TRTs.

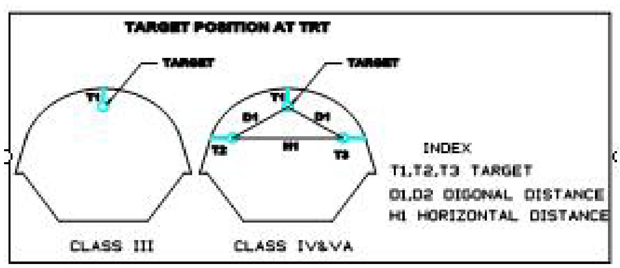

Figure 7: Array of target points at one location in different rock classes to measure tunnel deformation in TRTs.

Conclusion

In TRTs of Tehri PSP, RMR classification was used to characterize the rock mass and accordingly, rock support was provided to increase the stand-up time. From the geological logging of the TRTs, it is observed that there are mainly 3 types of rock units i.e. PQT, PQT with SP and SP. Encounter of PQT, PQT with SP and SP will fall in class III, IV and V respectively. Construction stage geotechnical assessments were made and suitable remedies were adopted after geological traverses, detailed geological mapping and logging of cores.

Excavation methodology for critical reaches and recommendation of additional rock support system for treatment of adverse geological condition are very challenging. Moreover, presence of shear seams and soft infilling reduces the overall strength of rock mass.

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Acknowledgements

Authors are thankful to the management of THDC India Ltd. and M/s. Hindustan Construction Co. Ltd. for providing necessary support to carry out the work. The authors are also very thankful to Dr. R. Anbalagan, Professor, Department of Earth Science, IIT Roorkee for his overall guidance to represent the paper.

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