Encountered geological & geotechnical challenges and their remedial measures during construction of large chambers in weak rocks - A case study from Lesser Himalayas, Uttarakhand, India

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Received: November 2020/ Accepted: December 2020

Abstract

As an integral part of Tehri Hydro Power Complex (HPC) located in the state of Uttarakhand in Northern India; an underground 4 x250 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 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. The encountered litho-assemblages are Massive Phyllitic Quartzite (PQM), thinly foliated Phyllitic Quartzite (PQT), Sheared Phyllite (SP) (is observed only in the close vicinity of the shears). Several challenges are facing during construction of these structures which are overcome by adopting proper design measures from day to day monitoring instruments data of deformation and construction methodology.

This paper briefly describes the correlation between the orientation of large chambers and prominent joint set, encountered geological and geotechnical challenges during excavation and their remedial measures by adopting the NATM construction methodology with excavation sequence and strengthening of weak rock mass by cable anchors, Shotcrete and Rock Bolts.

Key words: Poor Rock, Deformation, Cable Anchors, Rock bolts and Shotcrete.

1. Introduction:

Tehri Project, a prestigious hydropower project is the first major attempt to harness vast hydro potential of Bhagirathi River which is fed by Gangotri Glacier. The storage project in the Bhagirathi valley in Uttarakhand Himalaya, envisages impounding of surplus monsoon water of the river for utilizing it in regulated manner for hydropower generation. As an integral part of Tehri hydropower complex (HPC), an underground 4 X 250 MW Tehri pump storage plant (PSP) is aligned parallel and close vicinity of existing 1000 MW Tehri hydropower project (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 Bhilangana (now forming a part of Tehri reservoir) falling between 78°30´ and 79°00´ E longitudes and corresponding 30° 30´ and 33°30´ N latitudes. The availability of water for Tehri pump storage plant (PSP) shall be governed by mode of operation of Tehri hydropower complex (HPC). During non-peak hours water from lower reservoir would be pumped back to upper reservoir by utilizing the surplus available power in the grid.

The construction of Tehri PSP is under progress. The major project components are machine hall, upstream surge shafts, butterfly valve chamber (BVC), penstock assembly chamber (PAC), downstream surge shafts, a pair of tail race tunnels (TRT'S) and outlet structure. An underground butterfly valve chamber (BVC) has been provided to house four butterfly valves. A penstock assembly chamber (PAC) is excavated for the construction of vertical penstock and erection of penstock steel liners. These chambers are aligned in N303° direction and are separated by 19.0m wide rock pillar in between them. The sizes of these chambers are as follows:-

Butterfly Valve Chamber – 78m (L) X 23.55m (H) X 10.2m (W)
Penstock Assembly Chamber – 83m (L) X19.30m (H) X 13.30m (W)

The geological and geotechnical condition in these components is significantly worse than the other project components because the axis of chambers is sub-parallel to foliation plane. Further intersection of tunnels in this area possesses difficulties to be tackled. Three dimensional view and longitudinal section gives clear picture of BVC and PAC along with associated tunnels, shafts and adits as shown in Figures 1 and 2. Moreover, poor and very poor quality of rock mass encountered poses difficulties in construction. Deformation has also been observed at various locations. This paper briefly describes the analysis carried out during excavation with the help of monitoring instruments (MPBX, BRT and load cells) in such type of adverse geology with suitable construction methodology.

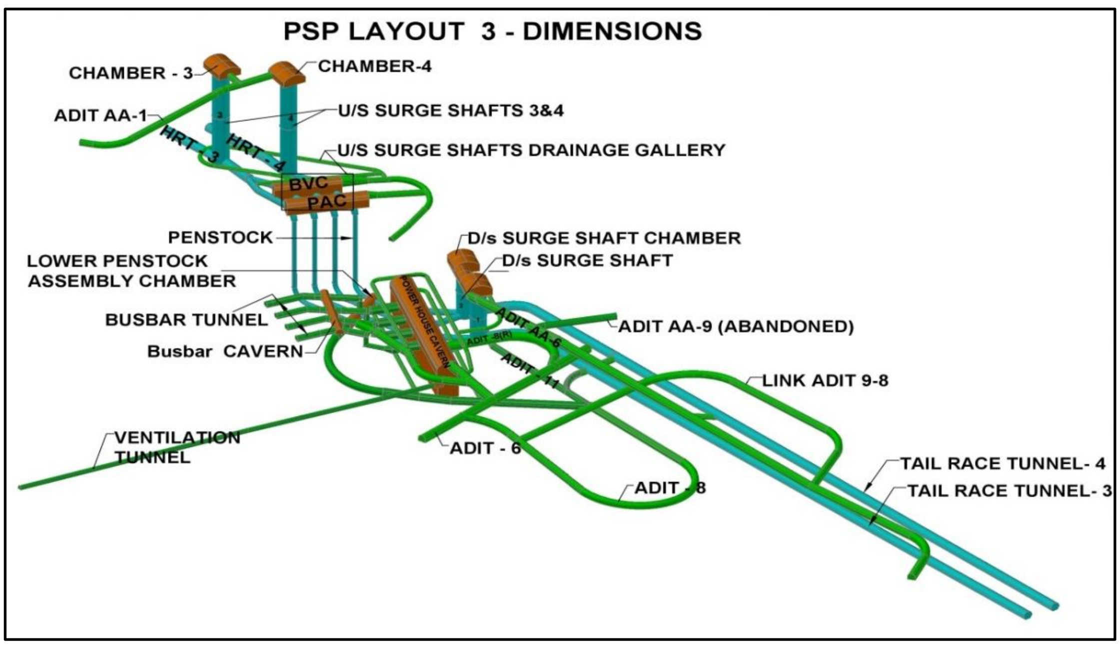


Figure 1 Layout of Tehri Pumped Storage Plant

1. Regional Geology:

Tehri Project area lies within the Main Himalayan Block (MHB), in the midlands of Lesser Himalayas, bounded to the north and south by regional tectonic lineaments – the Main Central Thrust (MCT) and Main Boundary Fault (MBF) respectively. The former, to the north separates the meta-sedimentary sequence of lesser Himalaya from the crystalline rocks of higher Himalaya and the latter marks boundary between lesser Himalaya and tertiary sequence of Frontal Foothill Belt (FFB), in the south.

The rock stratigraphy of lesser Himalaya exposed around the Tehri project area are broadly classified in to Garhwal, Simla, Jaunsar, Bailana, Krol and Tal groups (R. Shankar et al. 1989). The folded meta-sedimentary rocks exposed around the project site form an uninterrupted sequence of Chandpur phyllites having variable proportion of argillaceous and arenaceous constituents. Considering the rhythmicity of intercalated bands and varied degree of tectonic effects in them, the phyllites at project side has been classified in to mainly four lithological variants.

Rock mass in this area are mainly variants of phyllites and are classified as below:-

Phyllitic quartzite massive (PQM)
Phyllitic quartzite thinly bedded (PQT)
Sheared/schistose phyllite (SP)

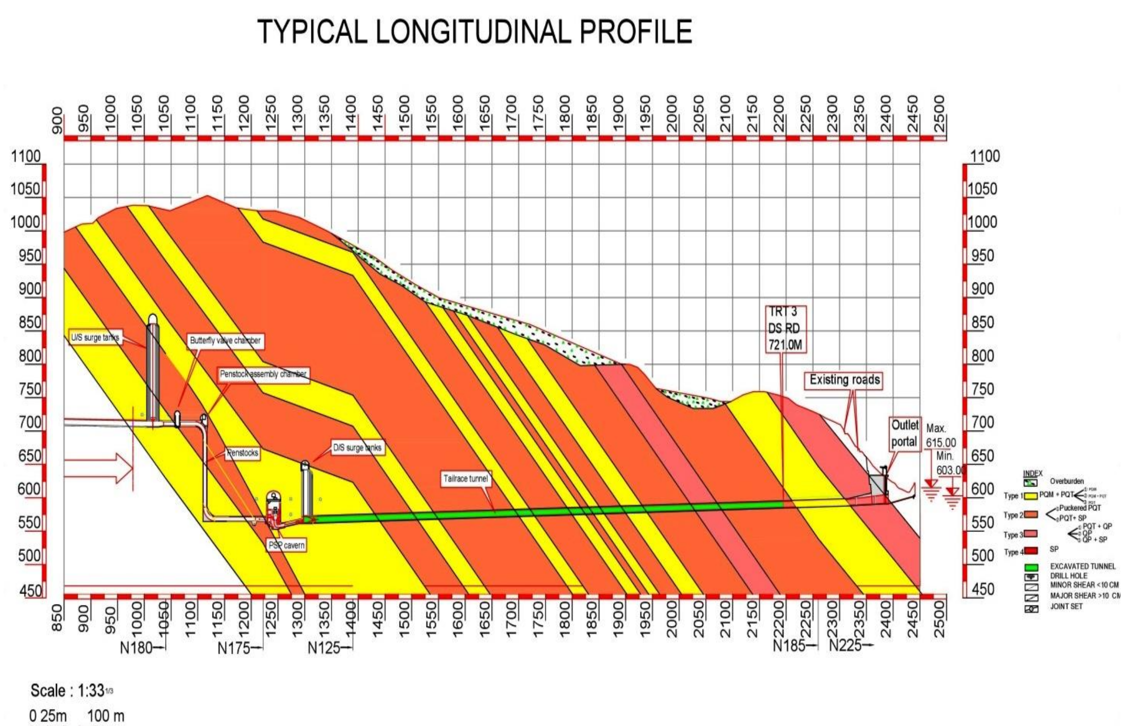


Figure 2 L-section of encountered geology during excavation of various components.

PQM and PQT are more quartzite (arenaceous) and rarely micaceous in composition and are coarser in grain size. These rocks are grey, dark grey, brownish grey, greenish grey, greyish grey and green in colour. It is mainly comprises of quartz, feldspar and oriented leths of micaceous minerals. QP is more areno-argillaceous in composition, fine grained and dark colored. SP comprises of argillaceous and deformed variants of PQM and PQT rock, formed in sheared zone area which has weak rock mass characteristics.

4. Site Specific Geology:

a) *Penstock Assembly Chamber (PAC):*

Crown portion of PAC heading has been excavated throughout its length and supported with ISMB steel sets and 500mm C/C spacing along with 25 mm thick SFRS. The lithological units QP, PQT and SP have been encountered in the excavated reach belonging to Chandpur Phyllites of Jaunsar Group. The rock mass is foliated, bedded, jointed, slightly weathered and sheared at places. The cavern encountered the following:-

- QP with SP in its initial length of 0.0m to 9.0m.
- SP with QP in a stretch of 18m, i.e. from 9.0 to 27.0m
- QP with PQT from 27.0 to 65.0m ,and
- PQT with SP in a remaining length i.e. from 65.0 to 83.0m

Two numbers of SP zones have been recorded, i.e. one from Rd:-0.0m to 27.0m and 65.0 to 83.0m. Over the formal interval there are two SP bands which cross each other in the central part of crown. These bands are about 2-3m wide and are aligned along the orientations of N250°/65° and N180°/55°. In this section over break has been recorded in the left side of crown where SP exposed. Despite the extent of SP exposure few shear zones have been also recorded.

The other SP occupied stretch has been encountered at the end of cavern crown portion where it is around 4-6m wide and oriented more or less along the bedding. This SP bands appears at the crown and terminated at the end wall. The remaining area is in QP and PQT. Additionally a few quartz veins/intrusions have been encountered along foliation/ bedding planes.

In general, the rock mass has been traversed by four sets of joints including bedding/ foliation planes. Bedding and foliation (Set No. 1 and 2) have a persistence of 15-20m, but in general ranges from 3-10m. Set No.3 and 4 have a shorter persistence of 5-7m. Joints have a separation of about 0.1mm to 5mm. In-filled material along joints is hard and soft. Hard material has been observed in between RD:-0.0 to 9.0 and 27.0 to 65.0m whereas the softer material has been found between RD:-9.0 to 27.0m and 65.0 to 83.0m

Ten numbers of major shear zones intersected the cavern during excavation. All the Shear zones are filled with clay gauge. Excavated crown portion was found to be dry to damp no flowing condition recorded. PAC is aligned in N 303° direction and makes an angle of about 3° to 33° with the strike of main bedding joints, which is an unfavorable situation.

The rock mass classification is based on Rock mass Rating (RMR). It shows that cavern encountered of class IV and V (A) as follows:-

- Very Poor and Poor RMR value ranges from 19-39 respectively.
- RMR value of 23 -39 in zone of Rd:-0.0 to 9.0m and 27.0 to 83.0m
- RMR value of 19 has been assigned to a zone of 18m between Rd:-9.0 to 27.0m

b) ***Butterfly Valve Chamber (BVC):***

The BVC underground chamber is currently under construction, located downstream of U/S Surge Shaft. The crown portion has been completely excavated in length and the remaining benching section of the BVC is still in progress. The alignment of the long section has bearing N303^0. The crown portion of the BVC has been completely excavated.

The lithological units of QP, PQT and SP have been encountered in the excavated reach belonging to Chandpur Phyllites of Jaunsar Group. The rock mass is foliated, bedded, jointed, slightly weathered and sheared at places.

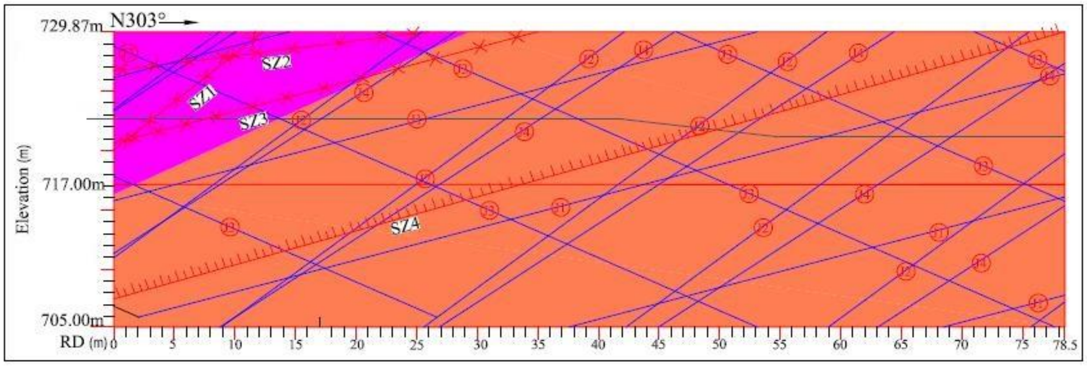
The cavern has encountered the following:

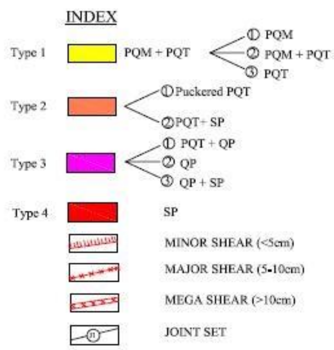
(i) Very Poor to Poor RMR value ranges from 16 to 38 respectively
(ii) RMR value of 22-38 in zone of Rd:- 15.0 to 78.0m
(iii) RMR value of 16-19 in zone of Rd:- 0.0 to 15.0m

A thick continuous SP band has been encountered from the left center crown portion (RD. 0m) and reached left the SPL at RD. 8m. Further, this band extends from RD. 8m to 22m in left SPL and crosses the center line at RD. 21m and continues to the end of excavated stretch of the crown. The SP band is observed to be distributed randomly and does not follow any particular discontinuity set. A few quartz veins/intrusions have been encountered along the alignments of the foliation and bedding planes.

In general, the rock mass is intersected by four sets of joints including bedding and foliation. Bedding and foliation (Sets Nos.1 and 2) have a persistence of about 15-20m, but, in general, ranges from 3-10m. Sets Nos.3 and 4 have a shorter persistence of about 5 to 7m. The joints have a separation of about 0.1mm to 5mm. Joint separation is 0.1-1mm from RD. 0m to 11m and 24m to 27m. In rest of the excavated area, joints separation is 1mm to 5mm.

Joints are found to be spaced at <60cm of spacing and have smooth to slightly rough surface. The in filled material along joints is hard and soft.



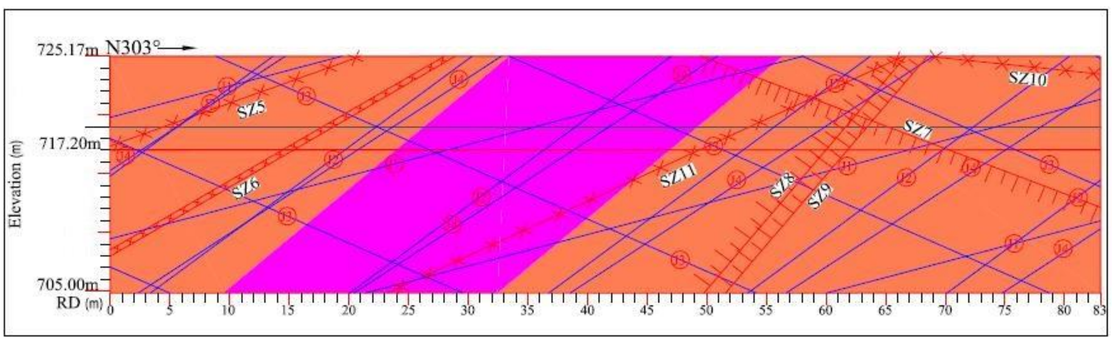


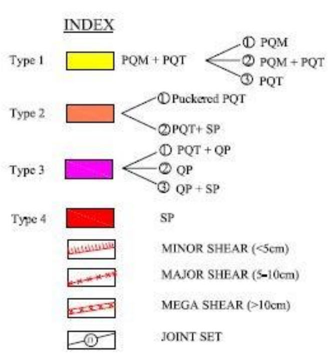
Discontinuties

S.No.	Set	Dip Direction	Dip Amount	Spacing
1.	Bedding (J1)	N180° - 220°	45° - 55°	02 to 20 cm.
2.	Foliation (J2)	N140° - 160°	35° - 45°	10 to 30 cm.
3.	Joint (J3)	N010° - 030°	60° - 65°	15 to 60 cm.
4.	Joint (J4)	N280° - 310°	60° - 70°	50 to 90 cm.

Shear

Set	Dip Direction	Dip Amount	Thickness	Apparent dip
SZ-1	N135° - 140°	40°	5 - 10 cm	39°
SZ-2	N190°	15°-20°	5 - 10 cm	07°
SZ-3	N200°	50°	5 - 10 cm	15°
SZ-4	N200°	52°	<5 cm	16°





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3.	Joint (J3)	N010° - 030°	60° - 65°	15 to 60 cm.
4.	Joint (J4)	N280° - 310°	60° - 70°	50 to 90 cm.

Shear

Set	Dip Direction	Dip Amount	Thickness	Apparent dip
SZ-5	N190° - 200°	50°	5 - 10 cm	20°
SZ-6	N090°	35°	5 - 10 cm	31°
SZ-7	N025°	70°	<5 cm	21°
SZ-8	N110°-120°	50°	<5 cm	50°
SZ-9	N110°-120°	50°	<5 cm	50°
SZ-10	N030°	65°	5 - 10 cm	06°
SZ-11	N190°	50°	5 - 10 cm	25°
SZ-12	N145°	40°	<5 cm	38°

Figure 3 L section of encountered geology during tunneling of BVC & PAC

5. Geotechnical Investigation:

a) *Drilling of Core Holes*

Sub-surface exploration for any underground structure is done by drilling of core holes at different locations along the proposed alignment of structure. Total 10 nos. of drill holes have been done to investigate the subsurface condition & behavior of rock mass. The details of core holes are given below in table no. 1

Table-1
Showing the details of core holes executed at different locations in BVC & PAC.

Sl. No.	Name of Hole	RD/Location	Size of Hole (mm)	Length of Hole	Angle with Horiz.	Start Date of Bore hole	Finish Date of Boring	Remarks
1	CH13	PAC drift at RD-61.57m	76(Nx)	16.00	90	18-Oct-12	25-Oct-12	
2	CH12	PAC drift at RD-2.60m	76(Nx)	16.00	90	14-Nov-12	19-Nov-12	
3	CH12a	PAC	76(Nx)	5.10	90	25-Oct-12	29-Oct-12	Abundant due to collapsing of hole
4	CH12b	PAC	76(Nx)	30.00	65	17-Dec-12	31-Dec-12	
5	CH69	Upward of Drift in RD 50m of PAC drift	76(Nx)	6.00	0	16-Feb-13	16-Feb-13	
6	CH70	Downward of Drift at RD50m of PAC drift	76(Nx)	6.00	90	17-Feb-13	18-Feb-13	
7	CH71	L/S of Drift at RD50m of PAC drift	76(Nx)	6.00	180	13-Feb-13	14-Feb-13	
8	CH72	R/S of Drift at RD50m of PAC drift	76(Nx)	6.00	180	15-Feb-13	15-Feb-13	
9	CH06	RD 9 m in BVC Drift	76(Nx)	20.50	90	8-May-13	17-May-13	
10	CH-H	RD 20 in PAC axis	76 (Nx)	30.00	65	27-Mar-15	8-Apr-15	Additional investigation

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b) *Pilot Tunnel / Central Gullet*

A pilot tunnel/Central Gullet was proposed in the center part of both chambers i.e. BVC & PAC to verify the actual subsurface condition along the proposed chambers. From the 3-D geological mapping of the pilot tunnel, necessary geological information were obtained i.e. shear zones, strength of rock mass, seepage condition etc. This pilot tunnel assists extremely to designers for review their support system.

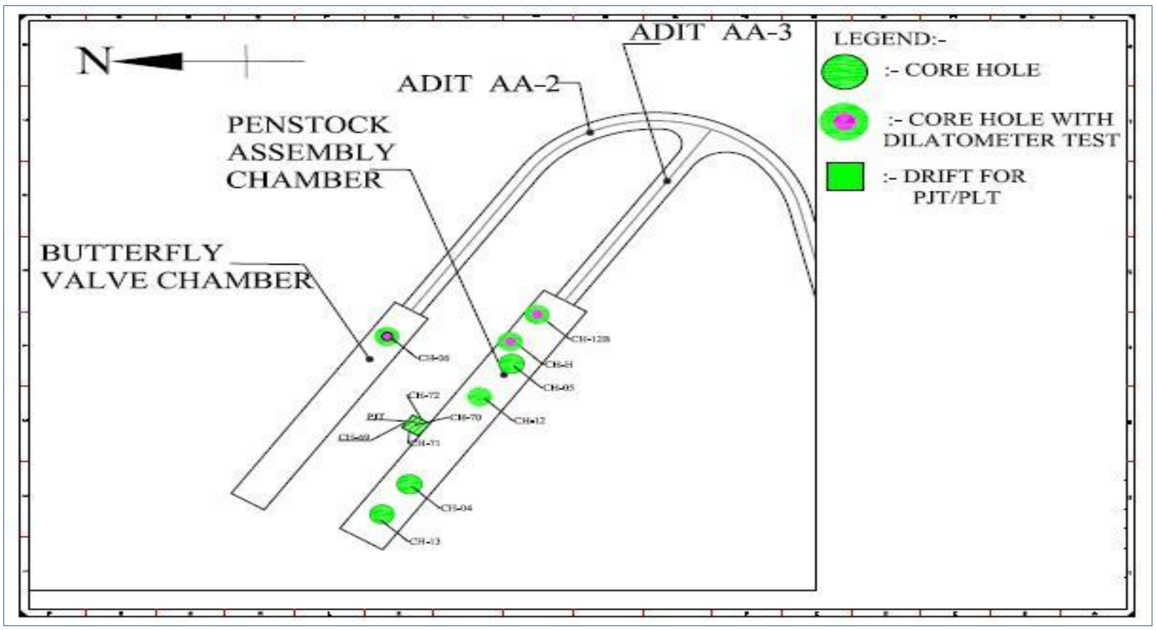


Figure 4 Location of core hole drilling executed for subsurface investigation of BVC & PAC.

6. Engineering Geological Mapping:

Geological face mapping & 3-D geological logging was carried out on 1:100 scale. Pilot tunnel was excavated in weak to very weak Phyllite rock. Joint planes are stained to slightly altered in nature. Excavation was done in dry to damp tunneling media. Following joint sets encountered during the excavation of pilot tunnel and side slashing of BVC & PAC. RQD ranges from <25% to 25-50% in PAC & <25% to 25-50% in BVC. RMR value ranges between 19 to 39 in PAC & 16 to 38 in BVC.

Table-2
Showing the details of joint sets of BVC & PAC.

Joint Set	Dip/ Amount	Persistence (m)	Aperture (mm)	Filling	Roughness	Weathering
J1	N185^0-210^0/45^0-55^0	3-10m	1-5mm & 0.1-1.0mm	Soft >5mm	Smooth	Slightly Weathered
J2	N140^0-165^0/35^0-45^0	1-5m	1-5mm & 0.1-1.0mm	Soft >5mm	Slightly rough to Smooth	Slightly Weathered
J3	N010^0-030^0/60^0-65^0	1-5m	1-5mm & 0.1-1.0mm	Hard >5mm	Slightly rough to Smooth	Slightly Weathered
J4	N280^0-310^0/60^0-70^0	1-3m	1-5mm & 0.1-1.0mm	Hard >5mm	Slightly rough to Smooth	Slightly Weathered

7. Tunneling Challenges and Excavation Methodology Applied:

a) Excavation of Pilot Tunnel and adverse geological reaches

In the Ist stage, the excavation of approach adit to PAC & BVC was completed which is known as AA-3 & AA-2 respectively. After this excavation crown was started through slashing of pilot tunnel in the IInd stage & completed the designed support system of BVC. In IIIrd stage the excavation of PAC crown was started through slashing of pilot tunnel. Then excavation of Ist & IInd bench of BVC was excavated in IVth & Vth stage & installed all the support system. After this excavation of PAC Ist bench stated in VIth stage. After this the excavation was done with alternate bench of BVC & PAC along with installation of designed support system as mention in figure 5.

Pilot tunnel was excavated in Poor to Very Poor Phyllite rock tunneling media throughout its alignment. The proposed alignment of both chambers are parallel to strike of rock bedding joints which is very unfavorable tunneling condition. Eight major shears along with four minor shear zones and one mega shear are encountered during excavation of BVC. Four minor, four major & tow mega shear zones are encountered during excavation of PAC.

Very adverse geological condition encountered in BVC between RD 11m to 24m, RD 55m to 60m & in PAC at RD 9m to 27m due to high concentration of Sheared Phyllite bands & shear zones. The rock class between above mentioned RD are class V having RMR value 17-19. The rock type is thinly bedded PQT with Sheared Phyllite (SP) having the thickness of <60 mm. The UCS & RQD of rock is 15-20 MPa & 10-20%. The joints are in filled with clay gauge. Dampness is also observed at many places. The joints are open having 1-5 mm of opening & the joints are smooth & slightly weathered. After the excavation of pilot tunnel of BVC & PAC, one row of design rock bolts were installed at the center of crown along with a layer of ceiling shotcrete (SFRS).

After the excavation of pilot tunnel, problems were anticipated with these joints / rock condition during side slashing and bench down time. Potential wedge formation in combination with other joints was also analyzed using some software.

b) Downstream Wall Slashing:

During the excavation of pilot tunnel, controlled blasting with maximum pull of 1.0m was taken in view of poor to very poor rock condition in BVC & PAC. After excavation of each face, rock mass was supported with the help of a layer of SFRS. After the successful excavation of pilot tunnel, side slashing was very challenging because critical joints, major to mega shear zones and poor rock condition were projected in the walls of side slashing of the cavern.

D/S wall slashing was done with help of controlled blasting throughout the length of chambers. Minor to major critical shear zones was mapped during the pilot tunnel excavation along the bedding joints. Side slashing from D/S wall was done from RD 0m to 78.5m in BVC & 0m to 83m in PAC. The top crown level of BVC & PAC is 729.87m & 725.17m. The D/S wall slashing of both chambers was done up to El 725.5m & 719.2m in BVC & PAC respectively. During the scaling of rock mass after the blasting, huge chunks of rock was fallen due to shear zone & weak rock condition at many places in both chambers.

c) Upstream Wall Slashing:

After completing the D/S side slashing, a layer of shotcrete to seal the joints opening along with some temporary rock bolts was installed wherever required. Then U/S side slashing work was started with controlled blasting and temporary rock bolt support wherever required. Design rock supports were installed after the excavation of heading portion of BVC & PAC. Controlled blasting technique was also adopted during the right side slashing of both chambers.

The rock mass between RD 11m to 24m & 55m to 60m falls in very poor rock condition having RMR value 17-19 in BVC. The major rock type between these RD are Sheared Phyllite having UCS & RQD <25MPa & 25% respectively along with damp ground water condition. The joints are open having an opening of 1-5mm in filled with soft filling with slightly rough & weathered condition. The remaining part of the BVC falls in class IV having RMR value 23-26 & shows better slightly improved condition. After the D/S and U/S side slashing of the heading portion all design rock supports were installed.

The rock mass between RD 9m to 27m falls in very poor rock condition having RMR value 19 in PAC. The major rock type between these RD are Sheared Phyllite having UCS & RQD <25MPa & 25% respectively along with damp ground water condition. The joints are open having an opening of 1-5mm in filled with soft filling with slightly rough & weathered condition. The remaining part of the PAC falls in class IV having RMR value 23-36 & shows better slightly improved condition. After the D/S & U/S side slashing of the heading portion all design rock support were installed in the PAC.

d) Systematic Benching of BVC & PAC:

The following sketch is showing the systematic excavation plan of BVC & PAC. After completion of heading excavation of BVC & PAC along with installation of design support, the benching of BVC & PAC was started from El. 725m & 719m respectively. First, the benching of BVC D/S wall was started. The height of each bench was 2m. All the approved design support system was installed just after the excavation. After excavation & completion of all design supports in Ist bench of D/S wall of BVC, the excavation of U/S wall bench of same level in BVC was started. After the D/S and U/S side slashing up to El. 723m all design rock support were installed. Same methodology for excavation & installation of support system was adapted to achieve the invert level of 705.0m.

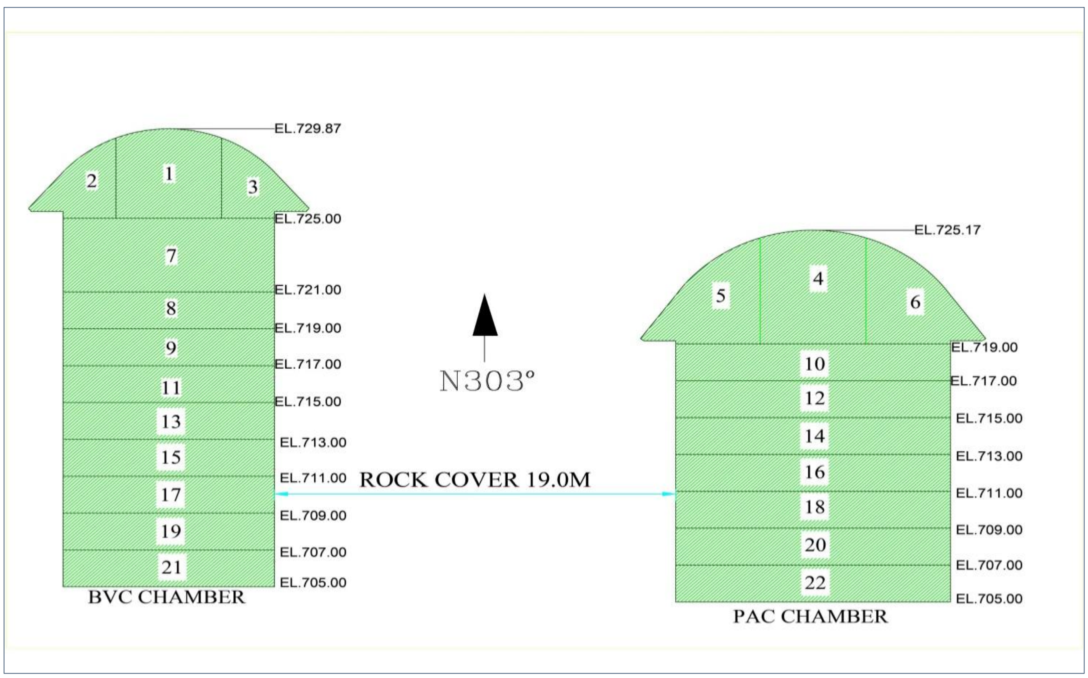


Figure 5 Stage wise systematic excavation sequences of BVC & PAC.

After achieving the El. of 717m in BVC, the excavation of PAC D/S wall benching was started. The height of each bench was 2m. After excavation & completion of all design supports in Ist bench of D/S wall of PAC, the excavation of U/S wall bench of same level in PAC was started & achieved the EL of 717m. After completion of IVth bench of BVC, the excavation of Ist bench of PAC was started & completed along with all design support system. Then after Vth bench of BVC excavation started & rock support work is in progress. When the support work will be completed, the excavation of PAC IInd bench will be started. Hence, alternate excavation of benches in BVC & PAC is carried out to achieve the required level as shown in figure 5.

Distressing problem in D/s wall between El. 725.37m to El. 723.87m (December 2016): At RD 51.0m, two numbers of rock bolts were failed. The bearing plates of these rock bolts were detached from the bars (Figure 6). Apart from that, the bearing plates of the rock bolts between RD 45.0m to RD 56.0m and RD 66.0m to RD 70.0m were showing bending along with few cracks (Figure 7). The rock type in this stretch mainly consists of phyllitic quartzite thinly bedded with sheared phyllite (PQT+SP) and rockmass class belongs to Class IV (mostly) and V. Instrumentation monitoring through BRTs and MPBX is continuously being done and no major fluctuations have been noticed during this period.

Figure 6 Rock bolt failures at RD 51.0 m

Figure 7 Bending in bearing plates of rock bolts (encircled in red)

8. Rock Support System:

Cavities are mainly formed due to presence of shear zones along with seepage condition. 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 BVC & PAC.

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 20 cm. Many shear zones are clay filled and wet to damp in places. Lot of time was lapsed in treatment and crossing of shear zones.

In initial stage the crown of BVC & PAC was supported by a layer of ceiling shotcrete (SFRS). Then fixing of structural ribs ISMB 300 @ 600 mm c-c spaced & 500 mm c-c spaced throughout the BVC & PAC crown respectively. After this, 32mm dia., 8m long & 1.2 m c-c & 1.0 m c-c spaced rock bolts are fixed in BVC & PAC respectively to protect the crown.

After the completion of support system of BVC & PAC crown, the sequential bench excavation of BVC & PAC was started. Each excavated bench was fully supported just after the excavation & after this the excavation of next bench was started.

The BVC U/S wall was supported by 150mm thick SFRS along with 32mm dia., 10m long & 2m c-c spaced rock bolts from El 720m to 718m. In the BVC U/S wall, 133 nos & 39 nos cable anchors having a length of 12m & 14m respectively was installed between El 725m to 717m. The load bearing capacity of the cable anchors was designed for 120 ton capacity. The cable anchor was 2m c-c spaced in BVC. Total 377 numbers of Cable anchor were installed. As some location bundle anchors were installed in between upstream and downstream wall of BVC between 724.0m to 719.5m.

The BVC D/S wall was also supported by 150 mm thick layer of SFRS, followed by 228 nos of rock bolts having 10 m long, 32mm dia. & 1.25m c-c spaced. Additional rock bolts was also provided in D/S wall due to low rock cover & poor geological conditions between BVC & PAC. The BVC D/S wall was supported with help of additional 60 nos rock bolts having dia. 32mm, length 10m & 2m c-c spaced and 115 nos rock bolts having dia. 25mm, length 6m & 2m c-c spaced. 57 nos & 19 m long cable anchors was installed from El. 722.5m to 717m in D/S wall of BVC having 120 ton designed load bearing capacity.

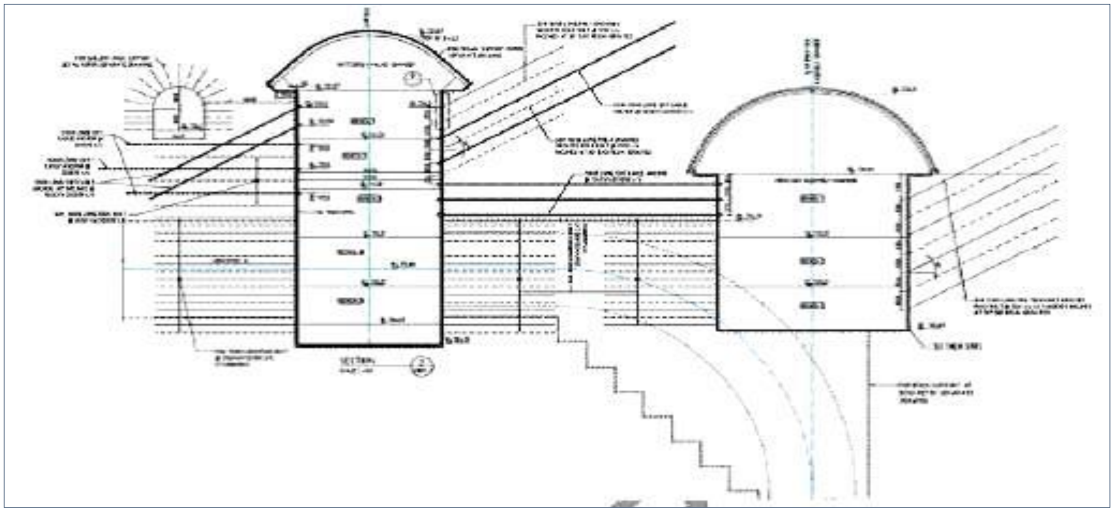


Figure 8 Design of rock support system installed in BVC& PAC

In PAC D/S wall, the Ist bench between El 719m to 717m was completed & supported by 150 mm thick SFRS followed by 54 nos of rock bolts having 32 mm dia., 4m long & 1.5m c-c spaced. The U/S wall of PAC Ist bench was supported by 150 mm thick SFRS followed by 16 nos of rock bolts having 32 mm dia., 8m long & 1.2 m c-c spaced. Above mentioned rock support was installed at El 717m in BVC & PAC. Further same support system was installed in BVC and PAC up to El. 705.0m.

9. Geological and Geotechnical Assessment of BVC and PAC:

Adverse condition encountered during the excavation of BVC:

- At some places planar failure and toppling on the crown along foliation planes.
- Formation of unstable structural wedges due to intersection of J1, J2 & J3.
- Water dripping to damp at places are found at some place.
- The bedding and foliations are very unfavorable due the strike of the bedding and foliations sub-parallel to orientation of the chamber axis being N 303°.
- A number of minor, major and mega shears has been encountered entire excavated length.
- These shears has varies in thickness <15cm, along and cross the bedding and foliation joints.
- The rock mass has been intersected by two prominent set of joints, other than the Bedding/foliation joints, silicification along foliation joints, dipping towards N140° – 160° / 35° -45°, was prominently recorded.

Table 3
Showing the Shear zones observed in BVC

Sl. No.	Shear No.	Dip/Amount	Width	Types of Filling
1.	SZ1	N 115^0/40^0	<5 cm	Clay Gauge
2.	SZ2	N 165^0/45^0	<5 cm	Clay Gauge
3.	SZ3	N 200^0/50^0	5-10 cm	Clay Gauge
4.	SZ4	N 190^0/55^0	<5 cm	Clay Gauge
5.	SZ5	N 200^0/50^0	5-10 cm	Clay Gauge
6.	SZ6	N 195^0/50^0	5-10 cm	Clay Gauge
7.	SZ7	N 115^0/40^0	< 5 cm	Clay Gauge
8	SZ8	N 205^0/50^0	>10 cm	Clay Gauge
9	SZ9	N 210^0/55^0	5-10 cm	Clay Gauge
10	SZ10	N 160^0/40^0	5-10 cm	Clay Gauge
11	SZ11	N 160^0/40^0	5-10 cm	Clay Gauge
12	SZ12	N 205^0/45^0	5-10 cm	Clay Gauge
13	SZ13	N 160^0/40^0	5-10 cm	Clay Gauge

Table 4
Showing the Shear zones observed in PAC

Sl. No.	Shear No.	Dip/Amount	Width	Types of Filling
1.	SZ1	N 090°/35°	>10cm	Clay Gauge
2.	SZ2	N 190°/50°	<5-10cm	Clay Gauge
3.	SZ3	N 140°/50°	<5cm	Clay Gauge
4.	SZ4	N 195°/45°	5-10cm	Clay Gauge
5.	SZ5	N 200°/50°	5-10cm	Clay Gauge
6	SZ6	N090°/35°	<10 cm	Clay Gauge
7	SZ7	N290°/60°	<5cm	Clay Gauge
8	SZ8	N290°/75°	<5cm	Clay Gauge
9	SZ9	N115°/50°	<5cm	Clay Gauge
10	SZ10	N200°/50°	5-10cm	Clay Gauge

Geotechnical Parameters

Two types of rocks i.e. PQT and QP+SP considered for the 3-D analysis of BVC and PAC. The geotechnical parameters adopted/considered for the 3-D analysis was provided by design consultant as mention in table number 5&6 Blast damage or disturbance zone is considered to be the first 3m of the rock surrounding the excavation.

Table 5

Geotechnical Parameters considered in the analysis of BVC

Rock Category		Parameters	Units	PQT (Isotropic/ Oriented)	QP+SP (Homogenous)
Intact Rock		GSI	-	50	25
		mi	-	10	10
		UCS	MPa	45	25
		Poisson's Ratio	-	0.22	0.25
		Bulk Density	kN/m^3	27	27
		Overburden depth	m	330	330
Disturbance factor D=0		Elastic Modulus	GPa	5.0	2.5
	Mohr-Coulomb	Cohesion	MPa	1.2	0.5
		Friction angle	Degree	40	27
Disturbance factor D=0.3		Elastic Modulus	GPa	5.0	2.5
	Mohr-Coulomb	Cohesion	MPa	1.0	0.4
		Friction angle	Degree	38	23

Table 6

Geotechnical Parameters considered in the analysis of PAC

Rock Category		Parameters	Units	PQT (Isotropic/Oriented)	QP+SP (Homogenous)
Intact Rock		GSI		50	25
		mi		10	10
		UCS	MPa	45	25
		Poisson's Ratio		0.22	0.25
		Bulk Density	kN/m^3	27	27
		Overburden depth	m	330	330
Disturbance factor D=0		Elastic Modulus	GPa	5.0	2.5
	Mohr-Coulomb	Cohesion	MPa	1.2	0.5
		Friction angle	Degree	40	27
Disturbance factor D=0.3		Elastic Modulus	GPa	5.0	2.5
	Mohr-Coulomb	Cohesion	MPa	1.0	0.4
		Friction angle	Degree	38	23

10. 3-D Modeling of Butterfly Valve Chamber (BVC) & Penstock Assembly Chamber (PAC):

Geological model of Butterfly Valve Chamber & Penstock Assembly Chamber initially established based on 3-D geological logs of Adit AA-3, AA-2, PAC drift, 3-D log of U/s BVC Drainage gallery, Drill hole logs of CH-4, CH-5, CH-6, CH-12, CH-13 & CH-12b. However, the geological model further modified based on geology encountered & recorded during 3-D geological logs of overt portion of BVC & PAC.

As per 3-D geological log of the overt portion of BVC, two types of rock variants QP+SP & PQT+SP encountered. 86% length of cavern belongs to PQT+SP rock mass however 14% length belongs QP+SP rock mass. QP+SP represent Quartzitic Phyllites rock with highly weathered & sheared in nature, closely to moderately spaced & medium persistence rock mass. The strength of rock mass belong to R2 grade (weak strength <25 MPa). Very poor RQD (<25%), slightly rough & undulating surface, with soft to hard filling discontinuities. These properties of rock mass represent poor ground media for excavation.

PQT+SP represents thinly foliated Phyllitic Quartzites of highly weathered & sheared, closely to moderately spaced & medium persistence rock mass. The strength of rock mass belongs to R2 grade strength <25 MPa). Very Poor RQD (<25%), smooth & planner surface, with soft (clay) filling discontinuities. These properties of rock mass represent very poor ground media for excavation.

As per 3-D geological log of the overt portion of PAC, four types of rock variants QP+SP, QP+PQT & PQT+SP encountered. 37% length of chamber belongs to QP+PQT rock mass, 30% belongs to PQT+SP, 33% belongs to QP+SP rock mass. QP+SP represent Quartzitic Phyllites rock with highly weathered & sheared in nature, closely to moderately spaced & medium persistence rock mass. The strength of rock mass belong to R2 grade (weak strength <25 MPa). Very poor RQD (<25%), slightly rough & undulating surface, with soft to hard filling discontinuities. These properties of rock mass represent poor ground media for excavation.

PQT+SP represents thinly foliated Phyllitic Quartzites of highly weathered & sheared, closely to moderately spaced & medium persistence rock mass. The strength of rock mass belongs to R2 grade (strength <25 MPa). Very Poor RQD (<25%), smooth & planner surface, with soft (clay) filling discontinuities. These properties of rock mass represent very poor ground media for excavation.

QP+PQT represents assembles of Quartzitic Phyllites & Thinly foliated Phyllitic Quartzites, closely spaced & medium persistence rock mass. The strength of rock mass belongs to R3 grade (strength 25-50 MPa). Poor RQD (25-50%), slightly rough, undulating surface, with hard (rock floor) filling discontinuities. These properties of rock mass represent poor ground media for excavation.

Table 7
Percentages of Rock Variants in BVC

Sl. No.	Rock Variants	RD/ Elevation	Percentages
1.	PQT+SP	67.5 m	86 %
2.	QP+SP	11 m	14 %

Table 8
Percentages of Rock Variants in PAC

Sl. No.	Rock Variants	Chainag/Elevation	Percentages
1.	QP+PQT	31m	37 %
2.	PQT+SP	25 m	30 %
3.	QP+SP	27 m	33 %

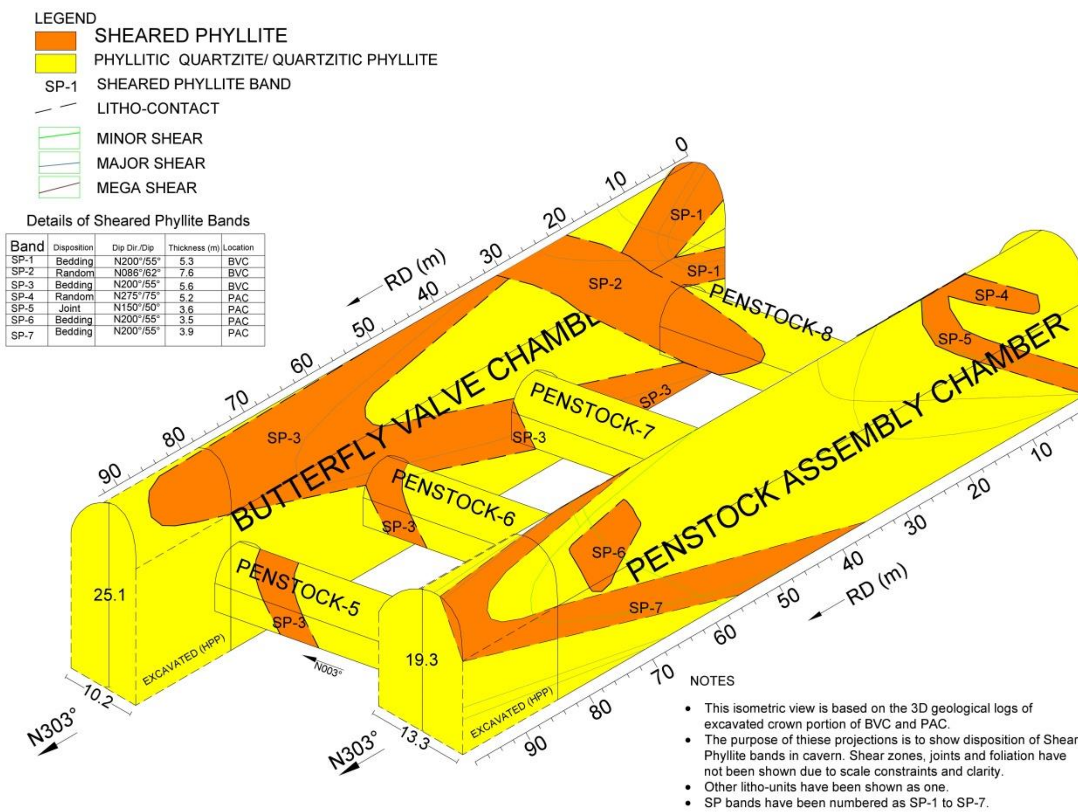


Figure 9 Isometric model of Geology of BVC & PAC complex.

11. 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 BVC & PAC are mentioned below.

a) Bi-Reflex Targets

Bi-Reflex Target 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. BVC has demonstrated maximum target movement of 130 mm at T4 (D/S) at RD 35.6m in D/S wall which seems to be stabilized in last couple of month.

In PAC opening the maximum cumulative movement is 49.75 mm till date, no significant movement observed since last month at T2 (D/S) target at RD 30.32m.

b) MPBX

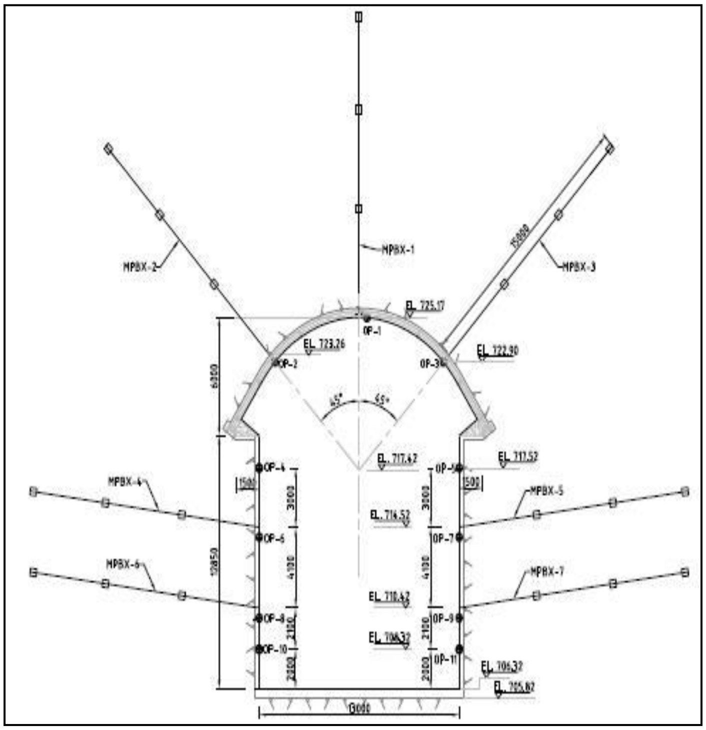
MPBX are installed in BVC and PAC based on approved drawing as shown in figure 10 (i) and (ii). The MPBX anchors were installed at 04 points i.e. 2m, 5m, 10m & 15m respectively at crown, D/S & U/S side walls.

MPBX deformations were also observed in D/S wall of BVC at RD 35m, El 722.5m with a maximum displacement of 19.92mm in 15m anchor, i.e. relative conversion towards opening. Both crown and upstream wall records indicate relative internal movement due to stiff support.

MPBX deformations were also observed in D/S wall of PAC at same RD-6.18m, with a maximum of -9.66 mm in 10m anchor.

MPBX displacements in PAC indicate nominal increase of 0.07mm at RD 80.69m at 10m depth (Crown) during till date. A maximum closer of 5.97mm is observed at 10m depth anchor at RD 6.18m on downstream wall till date and 0.49mm variation was observed since last month.

Most of the MPBX deformation indicting closing of sensor, i.e. the installed support are rigid and all internal movement are small and terminate at the walls, Hence, the PAC opening may be considered safe till date.



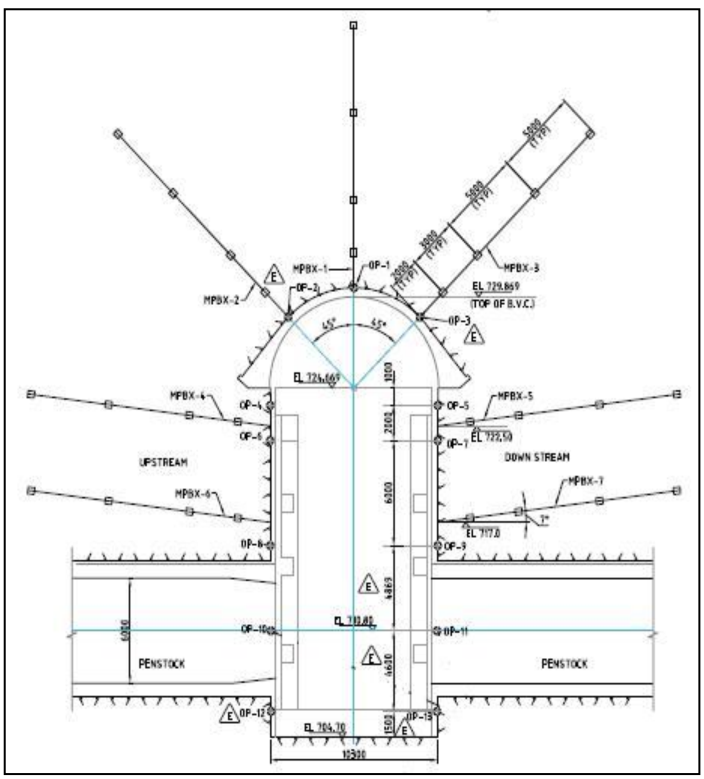


Figure 10 (i) & (ii) Locations for installation of monitoring instruments in BVC & PAC.

c) Load Cells at Cable Anchors

Load Cells are installed at 08 locations in BVC installed with an initially provided axial tensile load and the initial load is recorded after the load reading becomes stable just after installation. The load cells are installed in the BVC at RD 11m, 17m, 43m, 55m, 63m, 69m (El 715.25m,715.25m,719.5m,715.25m,719.0m) respectively in the D/S wall and RD 32.0m, 74m (El. 717.50m) respectively in the U/S wall.

In downstream wall of BVC,maximum cumulative load increment of 51.35 ton is observed ar RD 43.0m with the decrement of -2.77 ton till date.Maximum displacment in PAC indicate nominal increse of 0.07mm ad RD 80.69m ar 10m depth till date.

d) Load Cell at Rock bolts

Total 6 numbers of load cells installed in BVC and PAC at 32 Ø rock bolts. Maximum load 2.97 ton is observed at Rd 18.9m & El. 712.5m U/S wall of BVC .At Rd.13.12m & El. 711.9m decrease in load value of -1.1 ton observed in BVC U/S wall.


11B


11C


11D


11E

Photo 11(A) Heading Excavation after full rock support, 11(B) Pilot tunnel excavation in BVC along with side slashing, 11(C) Weak rock condition in BVC,11(D) showing the installation of cable anchors in the walls.11 (E&F) Complete excavation of BVC&PAC

12. Conclusion:

During the excavation of large underground cavern, identification of weak geological Condition, selection of excavation methodology for geologically challenging reaches and additional rock support system for treatment of adverse geological features are very significant. Temporary & additional rock support assessment is some important responsibility for treatment of geological features. 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. After completion of heading excavation of chambers, the tunnel deformation monitoring instruments are installed i.e. BRTs, Load Cell, MPBX, Tape extensometer. Based on outcome of deformation data, the support design & excavation methodology was reviewed during construction stage. Moreover, presence of shear seams and soft infilling reduces the overall strength of rock mass & these weak rocks mass stabilized with the help of proper design support system & some additional longer rock bolts, thick shotcrete.

Acknowledgements:
Authors are thankful to the management of THDC India Ltd. & M/s. Hindustan Construction Co. Ltd. for providing necessary support to carry out the work.

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