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Geological and geotechnical investigations of Tapovan–Vishnugad Hydroelectric Project, Chamoli District, Uttarakhand, India

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ABSTRACT

The Tapovan–Vishnugad Hydroelectric Project is located in the Dhauliganga and Alaknanda valleys, where the Central Crystallines are composed mainly of medium- to high-grade metamorphics represented by augen gneisses, metabasics, fine-grained quartz-mica gneisses, micaschists, quartzites, and coarse-grained garnet-biotite-kyanite gneisses. Towards the south, they are thrust over the Lesser Himalayan rocks of the Garhwal Group along the Main Central Thrust. The study aims at modelling the effects of geological structures for determining the potentially fractured or weak zones in underground excavations. For this purpose, Q and RMR values are obtained for each rock type. The in situ deformation modulus, cohesion, and friction angle are estimated to design support systems in unstable zones.

INTRODUCTION

The Tapovan–Vishnugad Hydroelectric Project is a run-of-the-river scheme across the river Dhauliganga in the Chamoli district of the Garhwal Himalaya (Fig. 1). The salient features of the project are given in Table 1. The project envisages utilising a 518.50 m drop available in the river Dhauliganga. Its installed capacity is 520 MW (4 x 130 MW) with a design discharge of 90 cumecs, which is available from the middle of June to 10 September during a 90% dependable year. The project will contribute towards the base load requirements of the Northern Grid of India. A barrage will be constructed near Tapovan across the river Dhauliganga. It will consist of four bays, each of which will be 12 m wide and separated by 2.5 m thick piers. There will be an intake separated into four bays each of 8.0 m width and separated by 1.5 m thick piers with 2.8 m high gates. Breast walls will support the piers to hold the water up to a head of about 12 m above the crest level of the intake. A 4.8 m wide horseshoe-shaped headrace tunnel will be 11.646 km long. Another 8 m wide intake with a side channel is also planned to feed the pool water directly to the headrace tunnel during a dry season. There will be 2.304 km and 0.38 km long two adits to facilitate the tunnel construction. A restricted orifice-type of surge tank will be 6.5 m in diameter and have two expansion chambers. Two underground main pressure shafts (3.55 m in diameter each) will be constructed with a bifurcation to four penstocks of 2.7 m diameter each feeding the Pelton turbines. An underground powerhouse and a transformer cavity will also be excavated. There will also be a 500 m long and 5.3 m wide horseshoe-shaped tailrace tunnel and a 130 m long open channel.

The engineering geological and geotechnical classification of rocks in the project area is based on the study of a number of drill holes as well as observations in an exploratory drift and during surface mapping. The main geotechnical methods employed are rock mass classification using Tunnelling Quality Index (Q) and Rock Mass Rating (RMR) systems. The study aims at modelling the effects of geological structures for determining the potentially fractured or weak zones in underground excavations. The in situ deformation modulus, cohesion, and friction angle are estimated following the methodology proposed by a number of experts (e.g. Hoek and Brown 1980, 1988; Hoek et al. 1992; Jalote et al. 1996; Kumar et al. 1999; Ahmed et al. 2002).

GEOLOGICAL SETTING

The project area covers parts of the Dhauliganga and Alaknanda valleys. The bedrock belongs to the Central Crystallines (Heim and Gansser 1939) composed mainly of medium- to high-grade metamorphics derived from pelitic, semi-pelitic, and psammitic sediments, which are sporadically interlayered with metabasics and, to a lesser extent (i.e. in the Dhak and Jharkula areas), calcareous rocks. Towards the south, the Central Crystallines are thrust over the Lesser Himalayan rocks of the Garhwal Group along the Main Central Thrust (Srivastava and Ahmed 1979; Valdiya 1980; Virdi 1986), which passes through the village of Helong located about 2 km downstream from the proposed powerhouse site.

The grade of metamorphism increases northwards from Helong and Tapovan to Joshimath, ranging from biotite grade near the Karchhi and Animath villages to garnet grade near Tapovan and Shelong, and to kyanite grade near the Bargaon, Parsari, and Jogi Dhara areas. In a broader sense, the rocks of this area can be categorised into the Tapovan-Helong

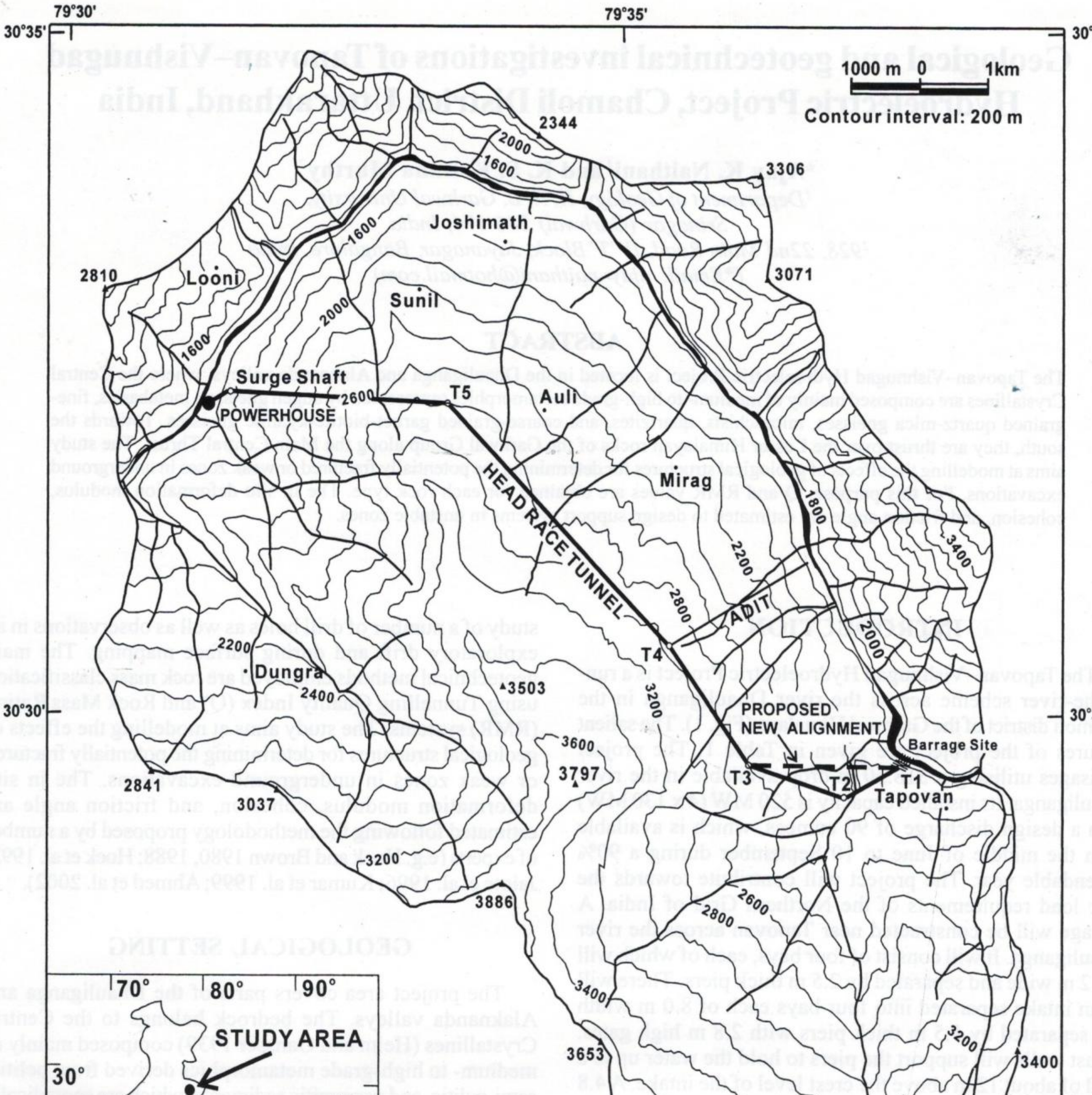

Fig. 1: Location map and layout of the Tapovan–Vishnugad Hydroelectric Project

Table 1: Salient features of Tapovan–Vishnugad Hydroelectric Project

S. No	Description		
1.	**Location:**		
	District	Chamoli	
	Tehsil	Joshimath	
	Longitude	79°37'30"	
	Latitude	30°29'30"	
	Topographic map nos.	53N/10 and 53 N/11	
2.	**Source of supply:**		
	Name of tributary	Dhauliganga	
	Main river	Alaknanda	
3.	**Catchment area:**		
	Gross catchment area	3100 sq km	
	Of other states	Nil	
	Snow-bound area	1900 sq km	
4.	**Design flood:**		
	Hydraulic design of barrage	4900 cumecs	
	Freeboard	6600 cumecs	
	Diversion	250 cumecs	
5.	**Barrage:**		
	Length of barrage	55.50 m	
	No. and size of bays	4 x 12 m	
	No. and size of gates	4 nos, 12.30 x 9.20 m	
	Crest elevation	1785.00 m	
	Road level	1801.00 m	
	Pond level	Maximum Level	1794.00 m
		Minimum Level	1790.50 m
	Energy dissipation	Hydraulic jump type stilling basin and horizontal apron	
6.	**Head regulator (intake):**		
	Overall length	46m (including side channel)	
	No. and size of spans	4 nos., 4 x 8.00 m	
	No. and size of gates	4 nos., 4 x 8.30 x 2.80 m	
	Crest elevation	1788.00 m	
7.	**Sedimentation tank:**		
	Size of tank	135.00 x 64.00 m	
	Size of hoppers	15.00 x 16.00 m in 4 rows	
	Top levels of hoppers	1783.95 m	
	Bottom level of conduits	1774.45 m	
	Design discharge (for flushing)	25 cumecs	
	Full supply level in tanks	Maximum level	1792.50 m
		Minimum level	1789.50 m
S. No.	**Description**		
	Particle size to be removed	0.25 mm	
8.	**Power tunnel:**		
	Shape	Standard Horseshoe	
	Length and diameter	11.646 km, 4.80 m	
	Thickness of lining	30 cm.	
	Design discharge	90 cumecs	
	Slope	1 in 154	
	Invert elevation at	Inlet	1780.00 m
		Surge tank	1704.00 m
9.	**Surge tank (ST):**		
	Type	Restricted orifice	
	Size	6.50 m diameter	
	Top level of ST	1831.00 m	
	Bottom level of ST	1704.20 m	
	Height of riser	5.00 m	
10.	**Penstocks:**		
	Main penstock diameter	3.55 and 3.55 m diameter	
	Thickness of steel lining	10 mm to 50 mm	
	No. and size of unit penstock	4 nos., 2.70 m diameter	
11.	**Powerhouse:**		
	Location of PH	Nearly 200 m upstream of confluence of Animath gad with Alaknanda	
	Type	Underground	
	Head	Gross	518.50 m
		Net head/ discharge	476.40 m
	Tailrace level	1267.00 m	
	Installed capacity	520 MW (4 x 130 MW)	
	Type of turbine	Pelton wheel	
12.	**Tailrace tunnel:**		
	Length of TRT	500.00 m	
	Size and shape of TRT	5.30 m diameter, horseshoe	
	Bottom level of exit	1267.56 m	
	Length of TRC	130.00 m	
	Size and shape of TRC	5.30 m wide square	
	Energy dissipation device	Submerged slotted bucket	
	Top level of bucket	1257.00 mm	
	Maximum tail water level	1267.00 m	
13.	**Construction details:**		
	Period of Construction	9 Years	
	Total cost (Indian Rupees)	15000.00 million	

Table 2: Lithological units and metamorphic grades in the Tapovan – Vishnugad area

Litho units	Lithology	Metamorphic facies	Metamorphic zones	Type locality
Garhwal Group	Limestones, shales, quartzites, and marbles	Greenschist	Chlorite	South of Helong in Alaknanda valley
	Quartzites	Greenschist	Biotite	
Tapovan-Helong Formation	Mica schists, augen gneisses, amphibolites, garnet-mica schists, fine-grained banded gneisses	Amphibolite	Garnet	Between Helong and Jharkula in Alaknanda valley and Bargaon to Tapovan in Dhauliganga valley
Joshimath Formation	Coarse-grained garnet-mica gneisses, garnet-kyanite gneisses	Amphibolite	Kyanite	Joshimath, Bargaon, Auli, Sunil, Parsari, and Mirag

and Joshimath Formations (Table 2). The Joshimath Formation comprises coarse-grained garnet gneisses and garnet-kyanite gneisses while the Tapovan-Helong Formation contains micaschists, garnet schists, amphibolites, augen gneisses, banded gneisses, and foliated gneisses dominated by biotite and quartz.

The metabasics range in thickness from 1 to 10 m and are found in the pelitic schists and gneisses. The amphibolites in the area are represented by greenish grey to dark green melanocratic rocks. These medium- to fine-grained rocks possess well developed preferred orientation at times. The amphibolites exhibit a blasto-subophitic texture marked by plagioclase laths and amphiboles. Hornblende is the most prominent mineral in the rock and its orientation defines foliation. The hornblende is intimately associated with biotite, magnetite, limonite, epidote, sphene, and quartz. The inclusions of quartz, magnetite, ilmenite, epidote, biotite, and apatite occur within the hornblende. The metabasics are sporadically observed in the barrage site and Dhak area where they are alternating with augen gneisses and schists of the Tapovan-Helong Formation. These metabasics vary in thickness from a metre to 20 m and are traceable for 20 to 60 m along their strike. Marble bands measuring about 0.5 to 2 m in thickness occur in the micaschists of the Dhak and Jharkula areas. Fine- to medium-grained, grey to light green schistose quartzites also occur in this area. At times they exhibit weathered brown bands, which demarcate the bedding plane, and the preferred orientation of flaky minerals imparting the schistosity.

The coarse- to fine-grained gneisses show finely foliated to sub-augen variations. Their foliation is defined by the preferred orientation of flaky minerals. Feldspar augens are well developed and they become streaky near the thrust zone. These gneisses are characterised by the occurrence of well developed idioblasts of garnet whose size varies from a few mm to 1 cm. At a few places the deformed garnet grains are elongated along the foliation and at some locations they exhibit rotation, whereas at some other places they are oriented parallel to the mica flakes defining the axial planes of microfolds. The inclusions of quartz, muscovite, and biotite frequently occur towards the core of garnet grains. The biotite inclusions defining S1 surfaces are generally parallel to the schistosity and suggest the post-tectonic recrystallisation of garnets (Sati 1988). Micaschists form a wide zone in the tailrace tunnel alignment and powerhouse area where they are intercalated with gneisses. The garnets present in the schist horizon of the powerhouse area are commonly smaller in size (a millimetre to 0.5 cm) in comparison with those of Joshimath (which are up to 10 mm across and of euhedral shape).

The gneisses are characterised by alternating leucocratic (quartzo-feldspathic) and mesocratic to melanocratic (micaceous) bands. The mica flakes are aligned parallel to the foliation. Crenulation cleavage can also be seen in the gneisses of the Joshimath area. Kyanite first appears near Joghi Dhara where it ranges in size from 1.5 to 4 cm. Virdi (1986) reported the first kyanite blades from Bargaon. The general strike of foliation is NW–SE and its angle of dip ranges from 30° to 45° due NE with considerable local variations. The foliation is very well marked by the preferred orientation of biotite, muscovite, and also chlorite when present. There are several small-scale folds, ptygmatic folds, pinch and swell structures as well as boudinage, mineral lineation, and crenulation lineation. According to Sinha (1989), Joshimath is situated within the zone of biotite-muscovite schists and subordinate gneisses. Rb/Sr dating and isotopic studies have revealed a Precambrian age with a varying ratio of radioactive isotopes of strontium in the sequence. According to Heim and Gansser (1939), Joshimath is situated within the zone of biotite-muscovite injection gneisses that resemble certain types of Darjeeling gneiss. The Tapovan-Helong and Joshimath Formations show a great variation in the amount of dip and small-scale folding, indicating polyphase deformation.

Barrage area

The proposed barrage site across the river Dhauliganga is located near Tapovan, at the suspension bridge to the Bhangual village. Detailed geological mapping was carried out on the scale of 1:1000 for about 300 m downstream and upstream of the barrage site. The river flows in the southwest direction up to Tapovan, then it takes an essentially N–S

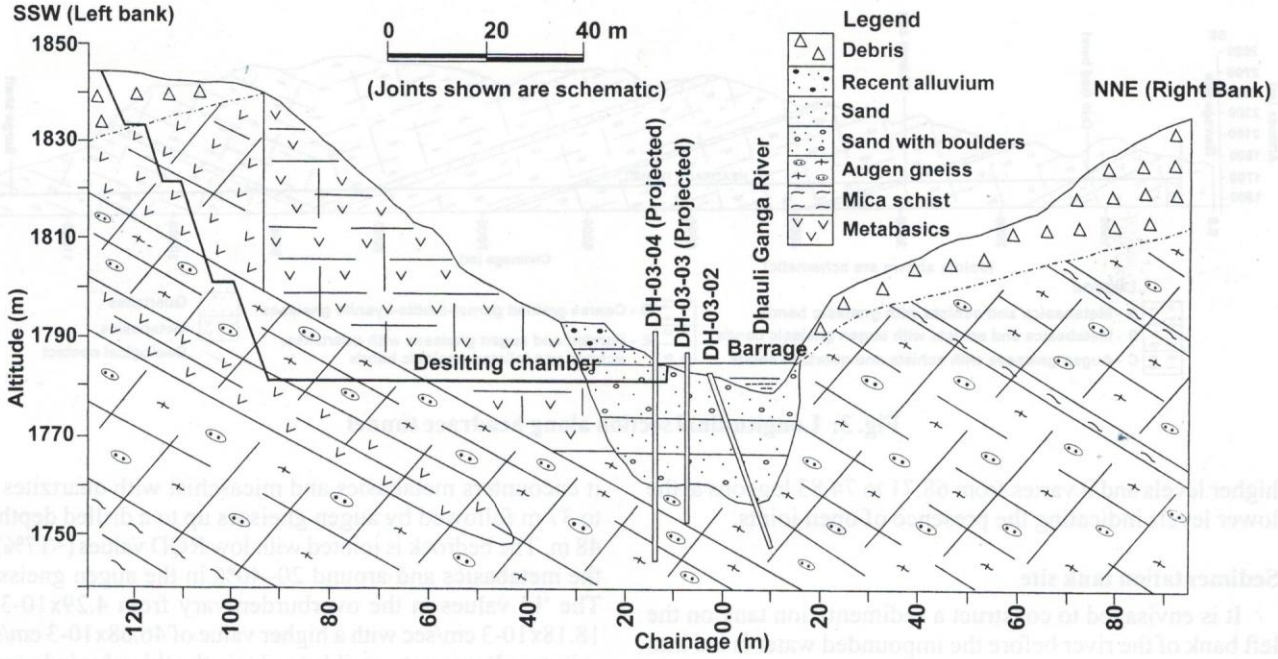

Fig. 2: Geological section along barrage axis

course for about 800 m, and onwards it follows a northerly course. The river at the barrage site flows due NW for a distance of 400 m. The river channel is closer to the right bank and there is a sand and gravel bar on the left bank with the boulders of gneisses, granites, schists, and metabasics.

On the right bank, the augen gneisses are exposed upstream of the barrage site for 400 m as well as upslope from the riverbed for a distance of 150 m (up to an altitude of 1816 m). Beyond that, the slopes are covered by colluvial deposits, which extend up to Bhangual. Towards the downstream, rock exposures at the bed level are noted only after a distance of 180 m where the gneisses form a ledge. The gneisses strike N70°W and dip at 40°–45° towards NE. The four prominent joint sets recorded in them have the following attitudes: N70°W (strike) /40°–45° (angle of dip) NE (dip direction) with 50–80 cm spacings, N20°W/70°NE with 10–30 cm spacings, N45°E/60°NW with 20–100 cm spacings, and N0°E/75°W with 10–50 cm spacings.

On the left bank, boulders and excavated debris extend for 30 m downstream from the barrage axis and up to an altitude of 1793 m. From that altitude onwards (up to about 1840 m) a steep scarp of highly jointed and sheared metabasics with bands of gneisses and schists is present. This outcrop also extends upstream of the barrage axis for a distance of about 30 m, beyond which the slopes are occupied by debris and fluvial deposits. There is an isolated exposure of augen gneisses at the riverbed (1795 m), about 200 m upstream from the axis. At an altitude of 1850 m, there is a wide and long river terrace on the metabasics and augen gneisses. Quartz-mica gneisses and augen gneisses occupy the rock slopes adjoining the terrace on the southern side. The foliation in the metabasics at the barrage axis is almost horizontal with the following major four joint sets: i) horizontal with 2–12 cm spacings, ii) N40°E/vertical with 4–18 cm spacings, iii) N20°W/vertical with 10–50 cm spacings, and iv) N70°E/52°NW with an average spacing of 10 cm. The geological cross-section along the barrage axis (Fig. 2) shows the attitude of foliation and position of drill holes.

The inclined (70° due N20°E) drill hole DH-03-02 is located on the left bank at an altitude of 1783.282 m and it intersects the barrage axis. This hole goes through the boulders of gneisses, quartzites, and granites in a sandy matrix and it also encounters a sandy layer from a depth of 2 to 12 m. The bedrock of augen gneisses is met from a depth of 27 to 40.20 m. The core recovery in the bedrock varies from 80 to 93% with RQD values ranging from 60 to 93%. The overburden indicates low packer permeability values of 0.45 to 3.05 l/m with the higher ones at lower depths of 24 and 27 m. The packer permeability tests carried out in the bedrock yield values varying from 0.10 to 1.05 l/m indicating tight joints.

The drill hole DH-03-03 is located near the barrage axis on the left bank of the river at an altitude of 1787.931 m. It encounters the overburden up to a depth of 25.5 m and below which augen gneisses with the bands of schists and quartzites are met up to a drilled depth of 35.30 m. The overburden consists of sand layers up to a depth of 3 m and again between 15 and 22.5 m whereas the intermediate portion is silt with the boulders of quartzites and gneisses. The core recovery in the bedrock varies from 70 to 100% and the RQD values range from 70 to 90%. The constant-head permeability tests in the overburden yielded moderate values (0.44x10-3 to 6.95 x 10-3 cm/sec). The packer permeability tests in the bedrock indicate the 'k' value to be of a lower order in the

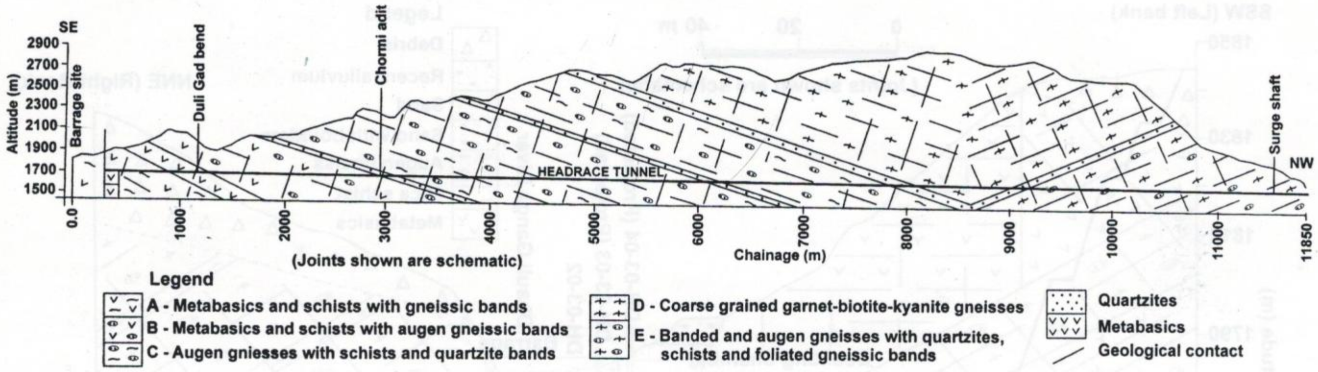

Fig. 3: Longitudinal section along headrace tunnel

higher levels and it varies from 68.71 to 74.83 lugeons at the lower levels indicating the presence of open joints.

Sedimentation tank site

It is envisaged to construct a sedimentation tank on the left bank of the river before the impounded water is led into the headrace tunnel. The tank site occupies an old riverbed with fluvial deposits (towards the intake) and scree (in the left cut slope). Its base contains fluvial deposits whereas the left bank is made up of highly jointed metabasics alternating with gneisses and schists.

The drill hole DH-03-04 lies at the upstream end of the desilting chamber (altitude =1792.813 m). It encounters the overburden up to a depth of 27 m, and below which are augen and quartz-mica gneisses up to a drilled depth of 50.15 m. The overburden contains the boulders of gneisses and quartzites in a sandy matrix. Two sandy horizons are met from 5 to 12 m and from 20 to 25 m depths in the borehole. The constant-head permeability tests conducted in the overburden yield values ranging from 2.02x10-3 to 4.71x10-3 cm/sec at its top and from 11.87x10-3 to 36.88x10-3 cm/sec at its bottom. The bedrock has 'k' values ranging from 1.21 to 19.56 lugeons indicating the presence of tight to open joints. The Standard Penetration Tests (SPTs) indicate a dense and bouldery overburden.

The drill hole DH-03-05 lies 110 m downstream of the barrage axis at an altitude of 1790.199 m, near the desilting basin. Up to a depth of 9 m, the hole penetrates the overburden consisting of pebbles and boulders of quartzites, metabasics, and gneisses in a sandy matrix. Onwards, metabasics and gneisses are found up to a drilled depth of 40 m. The bedrock is fractured and jointed with low RQD values (<30%). The overburden exhibits high permeability values of 0.61x10-3 to 67.82x10-3 cm/sec. The bedrock has 'k' values lying between 14.35 and 30.16 lugeons. The SPTs indicate a dense overburden.

The drill hole DH-03-06 is located upstream of the barrage axis on the left bank at an altitude of 1820.903 m. This hole has the overburden up to a depth of 14 m and below which it encounters metabasics and micaschist with quartzites up to 37 m followed by augen gneisses up to a drilled depth of 48 m. The bedrock is jointed with low RQD values (<17%) in the metabasics and around 20–40% in the augen gneisses. The 'k' values in the overburden vary from 4.29x10-3 to 18.18x10-3 cm/sec with a higher value of 46.68x10-3 cm/sec at its top. It was not possible to obtain the 'k' value in lugeons owing to a complete loss of water pressure during testing.

An approach drift lies about 200 m downstream of the barrage axis, on the left bank of the Dhauliganga. It was excavated from an altitude of 1782.6 m in the S40°W direction for a total length of 60.5 m. The portal of the drift is located in the metabasics, which appear to be an unstable mass. The rock types in the drift are metabasics and augen gneisses ramified by numerous quartz veins. Overbreaks were reported up to a 26 m length of the drift where the joints are open and the drift is unsupported.

Headrace tunnel

The proposed headrace tunnel alignment passes under a rough and rugged terrain constituting the left banks of the rivers Dhauliganga and Alaknanda. It is 11.646 km long with a diameter of 4.8 m and has a gradient of 1:154. The tunnel has four kinks namely T2, T3, T4, and T5. Initially it is aligned in the southwest direction normal to the hill slope and then parallel to the Auli ridge where it passes under a maximum cover of 1200 m below the highest peak (about 3000 m) of Auli. The cover over the tunnel reaches about 300 m up to T2, beyond which it increases gradually to 900 m up to T3, and then about 1000 m in the vicinity of T4 and T5. From T5, it gradually decreases to 200 m near the surge shaft.

There are sporadic rock exposures in a few ridges and streams, particularly in the stretch from Parsari to Helong via Auli and in the upper slopes of Bargaon and Mirag. The tunnel will encounter the Tapovan Formation consisting of augen gneisses, fine-grained quartz-mica gneisses, quartzites, and micaschists alternating with metabasic bands, and the Joshimath Formation represented by coarse-grained garnet-biotite-kyanite gneisses with schist bands (Fig. 3).

Table 3: Rock mass classification of headrace tunnel

S. N.	Category	Lithology	Rock mass	UCS	Q	RMR Value	RMR Class	Length of headrace tunnel (m)
1	A	Metabasics and schists with gneissic bands	Metabasics and schists	25–50	2–5	35–45	III–IV	0.82
2	B	Metabasics and schists with augen gneissic bands	Metabasics with gneisses	50–100	3–8	55–60	III	2.20
3	C	Augen gneisses with schists and quartzites bands	Augen gneisses	100–250	7–14	60–65	II–III	5.21
			Quartzites	100–250	6–10	55–60	III	
4	D	Coarse grained garnet-biotite-kyanite gneisses	Gneisses	100–250	6–10	60–65	II–III	0.72
5	E	Banded and augen gneisses with quartzites, schists, and foliated gneissic bands	Banded gneisses	100–250	3–7	55–60	III	2.70
			Foliated gneisses	100–250	6–10	60–65	II–III	
			Schists	50–100	2–4	40–50	III–IV	

The foliation in the Tapovan Formation varies in strike from WNW to NW with dips of 20° to 40° due NNE to NE at the powerhouse and barrage sites. The coarse-grained gneisses of the Joshimath Formation dip due NE at the powerhouse site, N in the Auli area, and NNW at its eastern end, forming a broad syncline (Virdi 1986; Virdi and Kumar 1985; Gairola 1975). From the barrage site to the kink point T2, the tunnel is aligned in the SW direction. In this reach, there are jointed metabasics and schists alternating with fine-grained gneisses and augen gneisses. The rock mass contains from 8 to 12 cm wide shear zones filled up with silica or micaceous and clayey gouge. The foliation varies in strike from N70°E to E with dips less than 40° towards N20°E making obliquities of 70° to 80° with the tunnel alignment. The metabasics are greenish grey in colour, foliated and highly jointed, and are horizontal at the intake, but further up their dips range from 20° to 30°. The schists are crenulated and puckered, and vary in thickness from a few centimetres to a metre. The four prominent joint sets recorded are: N35°W/57°NE, N40°W/vertical, N75°E/35°NW, and N0°E–N5°E/60°E. The Q and RMR values estimated for this rock mass are 2–5 and 35–45, respectively (Table 3).

The tunnel between T2 and T3 passes through the left bank of the Dhuligad and is aligned in the WNW direction. In this stretch, metabasics, schists, and gneisses of the Tapovan Formation are exposed. The attitude of foliation in the rocks is N70°–80°W/20°–40°NNE. The jointed green-grey metabasics have an exposed width of 50–60 m and contain alternations of schist. On the right bank of the Dhuligad, upstream from the bridge, there are scarps of augen gneisses. This rock succession strikes nearly parallel to the tunnel alignment for about 2.20 km of its length. This rock mass also has the same joint sets as mentioned above, and its Q and RMR values are 3–8 and 55–65, respectively.

The above rocks are followed by fine- to medium-grained quartz-mica gneisses intercalated with schists and 25–55 m thick two quartzite bands. In the Chormi area, the quartzites contain the three prominent joint sets: N70°W/35°–40°N20°E with 10–50 cm spacings, N90°E/80°N with 20–50 cm spacings, and N10°E/vertical with 50–100 cm spacings. The first and second sets have planar and rough surfaces while the vertical joints are rough and undulating. In the quartz-mica gneisses the following three joint sets are present: N65°W/30°–40°N25°E with planar and rough surfaces, N60°E/vertical with rough and undulating surfaces, and N70°E/45°–55°S20°E with smooth and planar surfaces. Their spacings are respectively 4–30, 50–80, and 40–85 cm. The tunnel alignment will encounter this rock mass for about 5.21 km with an overburden of 800–1000 m. The augen gneisses exposed in the road sections between the barrage site and Joshimath have Q and RMR values of 7–14 and 60–65 respectively, whereas a quartzite band exposed in the road sections and near Chormi yields Q and RMR values of 6–10 and 55–60 respectively.

From T3 to T5, the tunnel alignment follows essentially an NW–SE trend where the foliation makes obliquities of 20°–30°. It passes through the augen gneisses and quartzites of the Tapovan Formation overlain by the coarse-grained garnet-biotite-kyanite gneisses belonging to the Joshimath Formation and cropping out near Bhargaon and Jharkula (at the powerhouse site). Good exposures of these gneisses are also noted in the stream sections immediately east of and above Bhargaon as well as west of Mirag. A few isolated exposures are also found in the Joshimath–Auli and Joshimath–Helong road sections. The gneisses are coarse- to fine-grained and thinly foliated with some sub-augen variations. In them feldspar augens are well developed and the foliation is defined by the preferred orientation of flaky minerals. Garnet idioblasts and kyanite blades are also present. They dip essentially due NE with considerable local variations forming a broad syncline. Small-scale folds, ptygmatic folds, pinch and swell structure, and boudins are commonly noted in them. This succession is expected to comprise about 0.72 km tunnel length with an overburden cover of 1000–1200 m. The coarse-grained biotite-kyanite gneisses of Joshimath formation are estimated to have Q and RMR values of 6–10 and 60–65 respectively.

The tunnel alignment continues towards the surge tank in the favourable E–W direction, where the foliation makes obliquities of 60°–70°. In this reach, surface exposures consist of quartzites, micaschists, augen gneisses, and fine-grained quartz-mica gneisses along with augen gneiss bands. This rock mass is expected in the tunnel for about 2.70 km length. The estimated Q values for quartzites, banded gneisses, foliated gneisses, and schists are 6–10, 3–7, 6–10, and 2–4 respectively, while their RMR values are 60–65, 55–60, 60–65, and 40–50 respectively.

The drill hole DH-03-07 is located on the Dhuligad riverbed at an altitude of 1856.126 m, near its confluence with the Dhauliganga River. It passed through the overburden up to a 12 m depth and below which the metabasics were met up to a depth of 54 m. The core recovery in this zone varies from 28 to 100%, but it ranges mostly from 66 to 100%. The values of RQD vary from 10 to 93% but at a lower depth, they range from 48 to 93%. Below the metabasics, quartz-mica gneisses and augen gneisses with metabasics are met up to a drilled depth of 80.30 m. The core recovery in the augen gneisses varies from 44 to 96% and the RQD values are 21 to 84%. In the quartz-mica gneisses, the core recovery ranges from 63 to 100% with RQD values of 56 to 100%. The overburden consists of boulders of augen gneisses and quartzites with a sandy–silty matrix. The bedrock is fractured and jointed. The permeability of overburden was measured applying a constant-head method whereas the bedrock was assessed with a packer permeability test. The test results give 'k' values varying from 8.33 to 104.31 lugeons in the bedrock and permeability values ranging from 5.86 x10-3 to 18.23x10-3 cm/sec in the overburden.

Surge shaft

The proposed surge tank is 126.8 m deep and its top and bottom altitudes are 1831 and 1704.2 m respectively. The area around the surge tank is occupied by the augen gneisses, quartz-mica gneisses with bands of augen gneisses, and schists belonging to the Tapovan Formation (Fig. 4). The northern slope (20°–30°) of the ridge is occupied by cultivated fields near the road level. A few exposures of augen gneisses are noted in the steeper southern slope of the ridge as well as in the road cuts. The attitude of foliation is N60°–80°W/20°–45°NE. The four prominent joint sets are: (i) N60°–80°W/20°–45°NE with 20–80 cm spacings and rough-planar

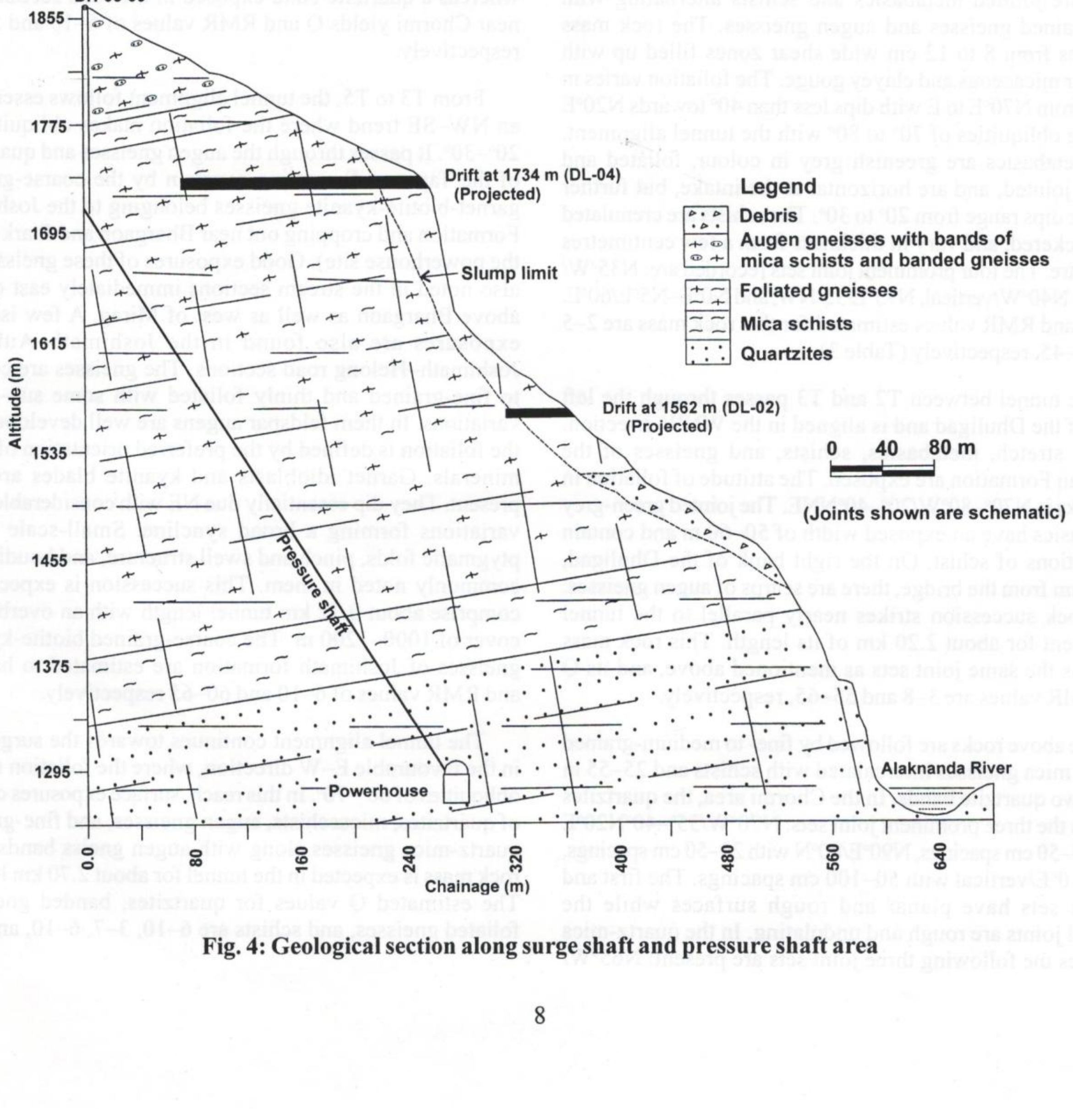

Fig. 4: Geological section along surge shaft and pressure shaft area

to rough-undulating surfaces, ii)N60°–70°W/40°–60°SW with 80–200 cm spacings and smooth-undulating to rough-smooth surfaces, iii) N30°–50°E/vertical with 70–200 cm spacings and rough-undulating surfaces; and iv) N–S trending vertical joints with 60–200 cm spacings and rough-undulating surfaces.

At the surge shaft location, the drill hole DH-03-09 sunk from an altitude of 1857.984 m encounters the overburden up to a depth of 1.5 m and then augen gneisses with schist bands and quartz veins are found up to a depth of 86.0 m. Though the core recovery in the rock mass varies from 57 to 100%, it frequently ranges from 80 to 90%. The RQD values are variable (16 to 100%) in different rocks and at lower depths they are very low (10 to 20%). Below the augen gneisses, fine-grained gneisses and micaceous gneisses are encountered up to a drilled depth of 150.30 m, in which the core recovery varies from 60 to 96% with low (13 to 60%) RQD values. Most of this rock mass has low RQD values of 10 to 25% with varying lengths (25–100 mm) of the recovered core pieces.

Two exploratory drifts were excavated at the surge shaft location from the Joshimath–Haridwar road level. The drift DL-01 was excavated in the S40°E direction from an altitude of 1746.785 m for a total length of 78.40 m. It lies to the south of the ridge on which the Shelong village is located. The unsupported drift is 2 m x 1.8 m in cross-sectional area and passes through the fine-grained gneisses, quartz-mica gneisses with bands of augen gneisses, and schists. It encounters an unstable zone up to an initial 15 m length and beyond which the rock is intact. Water is seeping between 0–20 and 77.70–78.20 m of the drift length. The rest of the reach is essentially dry. The following four prominent joint sets are recorded: i) N80°W/40°NE with 50–100 cm spacings and rough-undulating surfaces, ii)N10°E/70°SE with 50–80 cm spacings and smooth-undulating surfaces, iii) N70°E/ vertical with 30–90 cm spacings and rough-undulating surfaces, and iv) N40°W/75°SW with 50–80 cm spacings and rough-undulating surfaces. A number of shear zone (varying in thickness from less than 10 cm to 65 cm) are recorded at regular intervals.

The drift DL-04 was excavated in the N80°E direction from an altitude of 1734.508 m for a total length of 180 m. This drift is located to the north of Shelong. Its cross-sectional area is 2 m x 1.8 m in the initial reach and at the end it is 2 m wide at the bottom, 1.3 m wide at the top, and 1.7 m high. The drift is unsupported for its whole length. Seepage is noticed around 50 and 84 m of the tunnel length and the rest of the reach is almost dry. The drift passes through fine-grained quartz-mica gneisses, augen gneisses, and schists with quartz veins and shear zones. The attitude of foliation is N65°W–N80°W/30°–45°NE. The shear zone consisting of crush rock to closely jointed mass is logged at 4 m (8 cm), 12 m (12 cm), 35 m (20 cm), 84 m (15 cm), 96 m (20 cm), 109–112.50 m (gouge), 142 m (20 cm), 156 m (6 cm), and 166–167 m (29 cm). Overbreaks have affected 2–3 m wide crown area at 35 m of drift length. The drift passes through an unstable zone up to a length of 50 m and beyond it the rock mass is intact.

Two underground main pressure shafts (3.55 m in diameter each) will be constructed with a bifurcation to four penstocks of 2.7 m diameter each feeding the Pelton turbines.

Pressure shaft area

The surge tank and each turbine are proposed to be connected through two pressure shafts of 3.55 m in diameter each and they will be further bifurcated into two halves to feed four units. The pressure shafts are aligned along the ridgeline extending from Shelong to the river Alaknanda. The ridgeline is occupied by fine-grained quartz-mica gneisses (banded gneisses) in the higher areas, and schists and quartzites in the lower portion. Their foliation trends N70°–80°W/20°–40°NE. The rock mass is jointed and the prominent sets are i) N60°–80°W/20°–45°NE with 20–80 cm spacings and rough-planar to rough-undulating surfaces, ii) N60°–70°W/40°–60°SW with 80–200 cm spacings and smooth-undulating to rough-smooth surfaces, iii) N30°–50°E/ vertical with 70–200 cm spacings and rough-undulating surfaces, v) N–S/vertical with 60–200 cm spacings and rough-undulating surfaces. The geological section (Fig. 4) indicates that the pressure shaft has to be located in the fine-grained quartz-mica gneisses for an inclined length of 380 m. It encounters the micaschists for 65 m length and the remaining stretch encounters quartzites.

The drift DL-02 was excavated from an altitude of 1562.691 m in the N70°E direction along the pressure shaft alignment and its portal is located at a ridge below the road level. This drift has been excavated for a total length of 58 m during an earlier investigation stage of the project. Its cross-sectional area is 2 m x 2 m at the portal and changes to 1.3 m x 1.3 m at the other end. The drift passes entirely through fine-grained quartz gneisses with minor schist bands. The attitude of foliation is N80°W/40°–65°NE. The prominent joints are i) N60°–80°W/20°–45°NE with 20–80 cm spacings and rough-planar to rough-undulating surfaces, ii) N60°–70°W/40°–60°SW with 80–200 cm spacings and smooth-undulating to smooth-rough surfaces, iii) N30°–50°E/vertical with 70–200 cm spacings and rough-undulating surfaces, and iv) N–S/ vertical with 60–200 cm spacings and rough-undulating surfaces. The drift is unsupported for its whole length. Seepage is noted at 13, 23.50, and 36.40 m of the drift length. Minor shear zones (with respective thicknesses) are observed along the foliation at 16 m (15 cm), 39 m (16 cm), and 55 m (20 cm) of the tunnel length. The drift encounters an unstable ground up to a length of 50 m, and beyond which the rock is intact.

Powerhouse area

An underground powerhouse having dimensions of 95 m (length) x 24 m (width) x 40 m (height) and a transfer cavern of 95 m (length) x 15 m (width) x 20 m (height) are proposed to construct in the left bank of the river Alaknanda. They are bounded by a ridge and a stream lying to the north of Shelong, and the Animath Nala in the south. The bedrock consists of the micaschists, quartzites, fine-grained quartz-mica gneisses, and augen gneisses belonging to the Tapovan-Helong Formation of the Central Crystallines.

The rock forms the Animath Nala ridge occupied by quartzites and the ridge of Shelong made up of quartz-mica gneisses with schist bands. The valley between the two ridges is occupied by debris deposits at the bottom and micaschists in the vicinity of the Joshimath- Helong road. The slope below the Animath ridge is occupied mostly by micaschists with quartz veins. The trend of foliation varies from N70°W to NW with dips of 40° to 60° towards NE. In the micaschists the following four sets of joints are prominent i) N70°–80°W/40°NE with 10–20 cm spacings and smooth-undulating to smooth-planar surfaces, ii) N70°W/30°–60°S20°W with 40–50 cm spacings and smooth-undulating to smooth-planar surfaces, iii) N0°E/vertical with 80–100 cm spacings and rough-undulating surfaces, and iv) N90°E/30°–50°S with 60–80 cm spacings and smooth-undulating to rough-undulating surfaces. In the quartz-mica gneisses the prominent joint sets are i) N60°–75°W/20°–40°NE with 20–80 cm spacings and rough-planar to rough-undulating surfaces, ii) N60°–70°W/40°–60°SW with 80–200 cm spacings and smooth-undulating to rough-smooth surfaces, iii) N–S/vertical with 80–200 cm spacings and rough-undulating surfaces, and iv) N30°–50°E/vertical with 70–200 cm spacings and rough-smooth surfaces. In the augen gneisses four prominent joint sets are i) N75°–80°W/30°–40°NE with 10–90 cm spacings and rough-undulating surfaces, ii) N60°–70°W/40°–60°NE with 30–80 cm spacings and smooth-undulating surfaces, iii) N45°W/70°SW with 10–40 cm spacings and rough-undulating surfaces, and iv) NNE/vertical with 50–150 cm spacings and rough-smooth surfaces.

The drift DL-03 is located on the right bank of the Animath Nala, a tributary of the river Alaknanda. It is 2 m high and 2 m wide with 1.6 to 1.8 m high walls, and was excavated essentially due N60°E from an altitude of 1302.43 m for a total length of 376 m. In the drift, the contact between the schists and quartzites is observed at a distance of 262 m and then it continues further for 114 m to reach the proposed powerhouse site in the quartzites. The drift is supported between 42 and 47 m lengths in view of poor rock conditions and a possibility of rock fall, and rock support is also recommended for the reach between 83 and 105 m lengths. The drift passes through the micaschists, which are thinly foliated and crenulated with a number of quartz veins and shear zones varying in thickness from a few centimetres to one metre. Based on the physical character of schists, they have been classified along the length of the drift as massive schists, crenulated micaschists, foliated micaschists with quartz veins, and garnetiferous micaschists.

In the schists the prominent joint sets are i) N80°W/40°NE with 5–10 cm spacings, ii) N10°E/70°–80°SE with 10–20 cm spacings, iii) N70°E/vertical with 1–3 cm spacings, and iv) N40°W/75°SW with 1–3 cm spacings. The surfaces of all the joint sets are rough-undulating. The shear zones consist mostly of closely jointed and fractured schist and gouge. They are encountered at the following locations (with respective thicknesses): at 9 m (60 cm), 63 m (10 cm), 65 m (15 cm), 70 m (6 cm), 121m (20 cm), 144 m (10 cm), 177 m (100 cm), 198 m (10 cm), and 240 m (15 cm) lengths. The drift is dripping between 0 and 20 m, 77.70 and 78.20 m, 107 and 118 m, and 176 and 189 m lengths whereas a number of other places are damp.

The data collected at an interval of 10 m during detailed (1:500) geological mapping of the quartzites exposed at an altitude of 1375 m in the old road cut near the Animath ridge indicated that they can be classified into massive or blocky, jointed, and highly jointed types based on joint spacings and other physical characteristics (Fig. 5, Table 4). The quartzites have a general attitude of N70°W/30°–40°NE. The prominent joint sets recorded in the quartzites are i)N70°–80°W/30°–40°NE with 10–50 cm spacings and planar-rough surfaces, ii) N45°W/20°–50°SW with 20–50 cm spacings and planar-rough surfaces, and iii) NNE/vertical with 50–150 cm spacings and rough-undulating surfaces.

The fine- to medium-grained quartzites contain muscovite and traces of magnetite and zircon. The quartz is medium-grained, granoblastic, polygonal in shape, depicting triple-point junctions and the effects of recrystallisation. About 8–10% of the total quartz grains show strain effects with undulatory extinction angles varying from 15° to 20°. Muscovite, magnetite, and zircon are other minerals present in traces. As the quartzites of the powerhouse area show negligible strain effects, they can be used as coarse aggregates.

For the purpose of numerical modelling, geological data were collected from the drift DL-03 and surface mapping (Table 5). The laboratory tests carried out on quartzite specimens at the Central Soil and Material Research Station (CSMRS), New Delhi, gave a uniaxial compressive strength (UCS) of 100 MPa, a deformation modulus (E_d) of 55 GPa, and Poisson's ratio (m) 0.20. Some empirical relationships were developed to estimate various input parameters using such rock mass indices as Q, RMR, and Geological Strength Index (GSI) proposed by Hoek (1995). GSI can be estimated from RMR (Bieniawski 1989) and Q values (Barton et al. 1974) of the rock mass. The RMR values cannot be used to estimate GSI when $RMR_{89} < 23$, and instead Q values are applied.

$$GSI = RMR_{89} - 5 \text{ (for } RMR_{89} \geq 23)$$

$$GSI = 9 \log_e Q' + 44 \text{ (for } RMR_{89} < 23)$$

$$Q = (RQD/Jn)x(Jr/Ja)x(Jw/SRF)$$

where Jn = joint set number, Jr = joint roughness number, Ja = joint alteration number, Jw = joint water reduction factor, and SRF = stress reduction factor.

If SRF and Jw = 1, then the modified tunnelling quality index Q' is defined as follows.

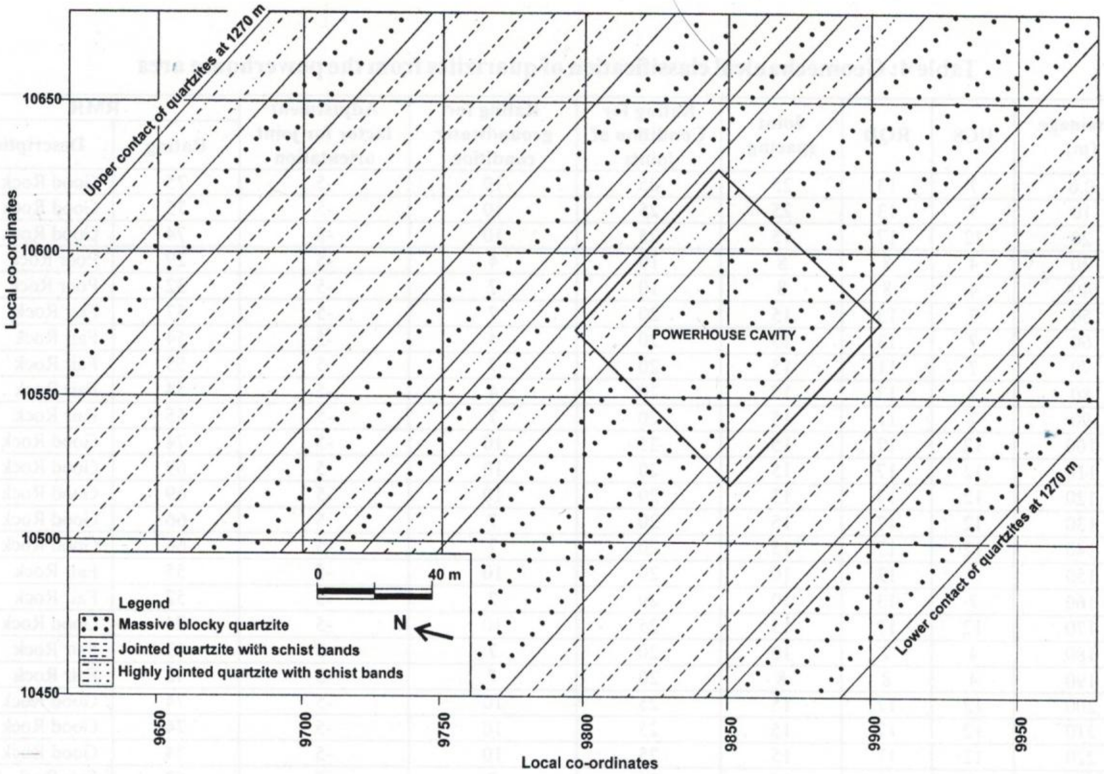

Fig. 5: Traces of quartzites at the powerhouse grade (1270 m)

Q' = (RQD/Jn) x (Jr/Ja)

The processed data were synthesised (Table 6) and approximate correlation between the modulus of deformation and rock mass rating for hard rocks (UCS of intact rock mass (qc) e” 50 MPa) was obtained.

$E_d = 2\,RMR - 100$ in GPa (Bieniawski 1984))

$E_d = 10^{(RMR-10)/40}$ in GPa for all values of RMR (Serafim and Pereira 1983; IS 13365: Part 1 1998).

The relationship between the modulus of deformation and Tunnelling Quality Index is as follows:

$E_d = 25\,Log_{10}\,Q$ (Barton et al. 1980).

The estimation of in situ deformation modulus based on the RMR and Q values suggested by Bieniawski (1984), Serafim and Pereira (1983), and Barton et al. (1980) as well as the values of cohesion and friction angle based on the RMR system (Bieniawski 1989) for the massive or blocky, jointed, and highly jointed quartzites to be encountered in the powerhouse area is given in Table 7.

Tailrace tunnel area

It is proposed to take out the water from the powerhouse to the river Alaknanda through a 5.3 m wide and 500 m long horseshoe-shaped tunnel and a 130 m long open channel to be constructed downstream of the Animath Nala. Its invert grade is at an altitude of 1260 m. The quartzites forming the Animath ridge occupy the tailrace tunnel area and micaschists form its southern slope as well as both banks of the Animath Nala whereas the terraces of the river Alaknanda are noted further downstream.

Quartzites and micaschists of different categories will be encountered up to a 500 m tunnel length and the open channel will be constructed in the alluvial deposits (Fig. 6). The initial reaches of the tunnel will be through moderately to highly jointed and massive to blocky quartzites up to a distance of 110 m and they will be followed by different categories of micaschists up to a 500 m tunnel length (Table 8).

These rocks are ramified by 15 to 100 cm wide shear zones which are frequent in the crenulated micaschists. In the micaschists the prominent joint sets are i) N70°–80°W/40°NE with 10–20 cm spacings and rough-undulating surfaces, ii) N70°W/30°–60°SW with 10–20 cm spacings and rough-undulating surfaces, iii) N–S/vertical with 10–20 cm spacings and rough-undulating surfaces, and iv) N90°E/30°–50°S with 60–80 cm spacings and rough-undulating surfaces. In quartzites the following three joints sets are prominent: i) N70°–80°W/30°–40°NE with 10–50 cm spacings and planar-rough surfaces, ii)N45°W/20°–50°SW with 20–50 cm

Table 4: Geomechanical classification of quartzites from the powerhouse area

Chainage (m)	UCS	RQD	Joint spacing	Rating for Condition of joints	Rating for groundwater condition	Adjustment factor for joint orientation	RMR Rating	RMR Description
0.0	7	13	25	25	10	-5	75	Good Rock
10	7	13	25	25	10	-5	75	Good Rock
20	12	17	15	25	10	-5	74	Good Rock
30	4	8	8	10	4	-5	29	Poor Rock
40	4	8	8	10	7	-5	32	Poor Rock
50	7	13	15	20	7	-5	57	Fair Rock
60	7	13	15	20	4	-5	54	Fair Rock
70	7	11	15	20	7	-5	55	Fair Rock
80	7	13	15	20	4	-5	54	Fair Rock
90	7	11	15	20	7	-5	55	Fair Rock
100	12	17	15	25	10	-5	74	Good Rock
110	12	17	15	20	10	-5	69	Good Rock
120	12	17	15	20	10	-5	69	Good Rock
130	12	17	15	20	7	-5	66	Good Rock
140	12	17	15	20	7	-5	66	Good Rock
150	7	13	10	20	10	-5	55	Fair Rock
160	7	13	10	20	7	-5	52	Fair Rock
170	12	17	15	25	10	-5	74	Good Rock
180	4	7	10	20	7	-5	43	Fair Rock
190	4	8	8	20	7	-5	42	Fair Rock
200	12	17	15	25	10	-5	74	Good Rock
210	12	17	15	25	10	-5	74	Good Rock
220	12	17	15	25	10	-5	74	Good Rock
230	7	13	10	20	7	-5	52	Fair Rock
240	7	13	10	20	7	-5	52	Fair Rock
250	7	13	10	20	7	-5	52	Fair Rock
260	7	13	10	20	7	-5	52	Fair Rock
270	7	13	10	20	7	-5	52	Fair Rock
280	7	13	10	20	7	-5	52	Fair Rock
290	7	13	10	20	7	-5	52	Fair Rock
300	7	13	25	25	10	-5	75	Good Rock
310	7	13	25	25	10	-5	75	Good Rock
320	4	13	10	10	4	-5	36	Poor Rock
330	4	8	10	10	4	-5	31	Poor Rock

This classification is based on surface mapping and logging of drift.

Table 5: Q, Q' and RMR values of quartzites in powerhouse area

S. N.	Rock type	UCS in MPa	RQD (%)	Q (Average)	Q' (Average)	RMR Value	RMR Class
1.	Massive or blocky quartzite	100-250	69-82	8.8	8.8	67-75	II
2.	Jointed quartzite with schist bands	50-100	49-63	3.3	4.78	52-63	III
3.	Highly jointed quartzite with schist bands	25-50	Av. 50	1.8	3.0	29-42	IV

Note: The above values are based on surface mapping and logging of drift.

Table 6: Rock mass classification of powerhouse area

Chainage (m)	Rock type	Grade	RQD	Q Values		RMR		GSI	UCS	Ed	
				Q	Q′	Value	Class			1	2
0.0	Massive Blocky Quartzite	R5	69	10.8	10.8	75	II	65.42	100–250	42.17	25.83
10	Massive Blocky Quartzite	R5	69	10	10	75	II	64.73	100–250	42.17	25.0
20	Massive Blocky Quartzite	R5	76	12	12	74	II	66.37	100–250	39.81	26.98
30	Highly Jointed Quartzite	R3	50	1.18	3.5	29	IV	55.27	25–50	2.98	-
40	Highly Jointed Quartzite	R3	50	1.18	3.5	32	IV	55.27	25–50	3.55	-
50	Jointed Quartzite	R4	60	3.3	5.4	57	III	59.18	50–100	14.96	12.96
60	Jointed Quartzite	R4	60	3.3	4	53	III	56.48	50–100	11.88	12.96
70	Jointed Quartzite	R4	63	4.2	4	55	III	56.48	50–100	13.33	15.58
80	Jointed Quartzite	R4	62	2.47	4	53	III	56.48	50–100	11.88	9.82
90	Jointed Quartzite	R4	62	2.47	7.5	55	III	62.13	50–100	13.33	9.82
100	Massive Blocky Quartzite	R5	82	10	10	74	II	64.73	100–250	39.81	25.0
110	Massive Blocky Quartzite	R5	79	6	6	69	II	60.13	100–250	29.85	19.45
120	Massive Blocky Quartzite	R5	82	7	7	69	II	61.51	100–250	29.85	21.13
130	Massive Blocky Quartzite	R5	82	10	10	67	II	64.73	100–250	26.61	25.0
140	Massive Blocky Quartzite	R5	80	9	9	67	II	63.78	100–250	26.61	23.85
150	Highly Jointed Quartzite	R4	62	5	5	55	III	58.48	50–100	13.33	17.47
160	Highly Jointed Quartzite	R4	58	4	4	52	III	56.48	50–100	11.22	15.05
170	Massive Blocky Quartzite	R5	88	9	9	74	II	63.78	100–250	39.81	23.85
180	Highly Jointed Quartzite	R3	56	1.2	3.66	43	IV	55.68	25–50	6.69	-
190	Highly Jointed Quartzite	R3	49	1.08	3.02	42	IV	53.95	25–50	6.31	-
200	Massive Blocky Quartzite	R5	78	6.5	6.5	74	II	60.85	100–250	39.81	20.32
210	Massive Blocky Quartzite	R5	82	10.2	10.2	74	II	64.90	100–250	39.81	25.21
220	Massive Blocky Quartzite	R4	88	10.2	10.2	74	II	64.90	100–250	39.81	25.21
230	Jointed Quartzite	R4	63	2.59	4	52	III	56.48	50–100	11.22	10.33
240	Jointed Quartzite	R4	62	3.41	5	52	III	58.48	50–100	11.22	13.32
250	Jointed Quartzite	R4	62	2.72	4	52	III	56.48	50–100	11.22	10.86
260	Jointed Quartzite	R4	60	4.95	7.5	52	III	62.13	50–100	11.22	17.36
270	Jointed Quartzite	R4	62	2.56	4	52	III	56.48	50–100	11.22	10.21
280	Jointed Quartzite	R4	61	3.35	5	52	III	58.48	50–100	11.22	13.12
290	Jointed Quartzite	R4	63	2.31	3.5	52	III	55.27	50–100	11.22	9.09
300	Massive Blocky Quartzite	R5	82	7	7	75	II	61.51	100–250	42.17	21.13
310	Massive Blocky Quartzite	R5	82	7	7	75	II	61.51	100–250	42.17	21.13
320	Highly Jointed Quartzite	R3	59	3.1	4.5	34	IV	57.54	25–50	3.98	12.28
330	Highly Jointed Quartzite	R3	49	2.7	4	31	IV	56.48	25–50	3.35	10.78

Grade – Visual estimate of rock as per ISRM (1978), Q – Tunneling Quality Index, Q′ – Modified Tunneling Quality Index, GSI – Geological Strength Index (calculated from Q′), UCS – Uniaxial Compressive Strength (estimated) in MPa, Ed – Modulus of Deformation calculated from RMR (1) which is applicable for all RMR values and (2) from Q values

Table 7: Engineering properties of quartzites in powerhouse area

S. N.	RMR			Q value	Modulus of deformation (Ed) in GPa			Bieniawski (1989)	
	Min	Max	Avg.		Bieniawski (1978)	Serafim and Pereira (1983)	Barton (1980)	Cohesion	Friction angle
1	67	72	69.5	8.8	39	30.73	23.612	300 kPa	40°
2	52	63	57.5	3.3	15	15.40	12.962	300 kPa	30°
3	29	22	25.5	1.8	NA	2.45	6.3818	200 kPa	25°

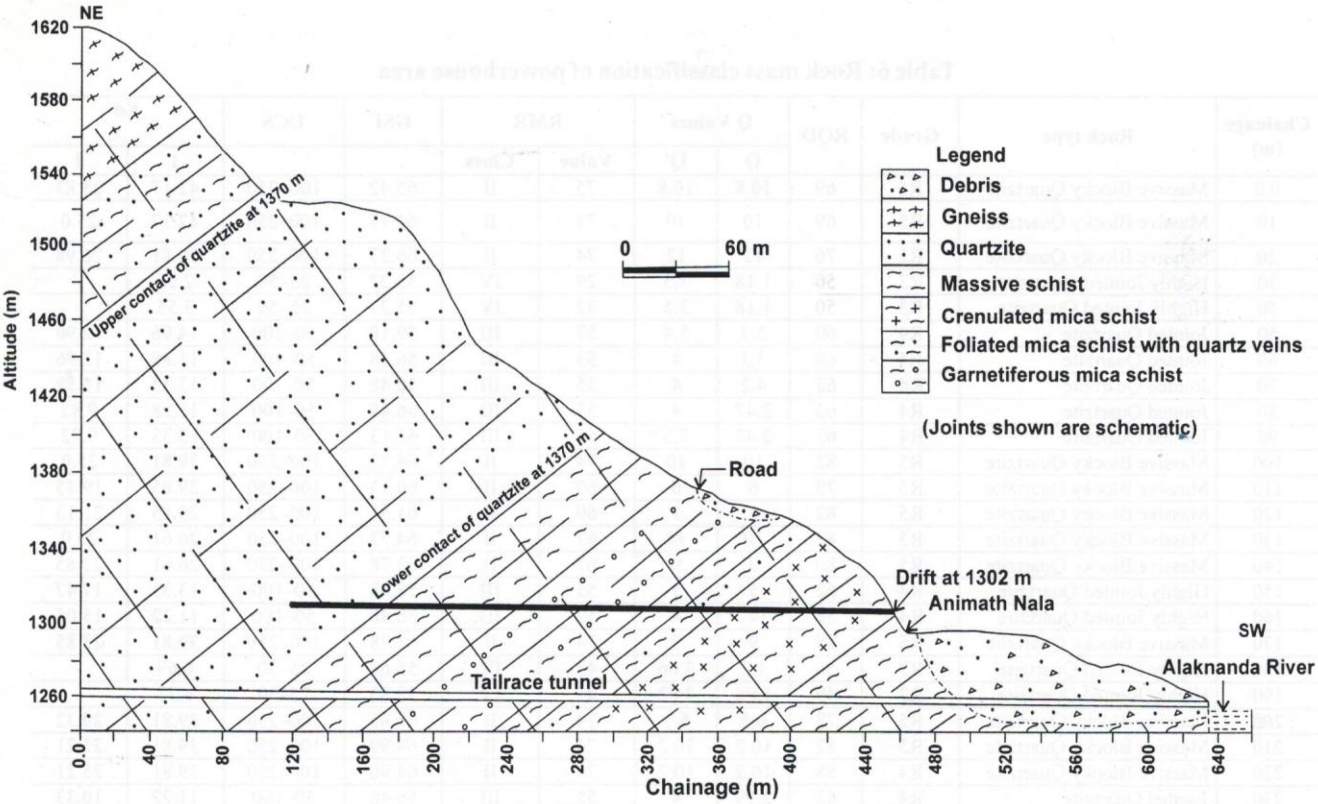

Fig. 6: Geological section through tailrace tunnel alignment

Table 8: Types of schist to be encountered in different chainages of tailrace tunnel

Chainage (m)	Rock type
110–165 m	Massive schist
165–250 m	Garnetiferous mica schist
250–270m	Massive schist
270–290m	Foliated mica schist with quartz veins
290–390m	Crenulated mica schists
390–500m	Massive schist

Table 9: Rock mass classification in tailrace tunnel alignment

S. N.	Rock type	UCS	RQD (%)	Q (Av.)	RMR	
					Value	Class
1.	Quartzites	100-250	69-82	8.8	67-75	II
2.	Massive schists	50-100	25-50	1.0	30-40	III
3.	Crenulated mica schists	25-50	0-25	0.5	0-25	IV
4.	Foliated mica schists with quartz veins	50-100	25-50	1.0	30-40	III
5.	Garnetiferous mica schists	25-50	0-25	0.5	0-25	IV

Note: The estimate of Q and RMR values are from surface mapping and logging of drift.

spacings and planar-rough surfaces, and iii) NNE/vertical joints with 50–150 cm spacings and rough-undulating surfaces. The Q and RMR values are estimated respectively at 8.8 and 67–75 for the quartzites. The massive and foliated micaschists have a Q value of 1 and RMR values varying from 30 to 40. The crenulated micaschists and garnetiferous micaschists have a Q value of 0.5 and a maximum RMR value of 25 (Table 9).

CONCLUSIONS

In the barrage area, augen gneisses extend all along the right bank of the river on either side of the axis and their foliation dips into the right abutment. On the left bank, a steep scarp of highly jointed and sheared metabasics with gneiss and schist bands are exposed on the hill slope whereas the lower river levels are occupied by alluvial deposits. There is a 25 to 27 m deep overburden and below it the bedrock consists of augen gneisses with the bands of quartz-mica gneisses and schists. Therefore, the barrage has to be designed on a permeable foundation. The sedimentation tank will be constructed essentially on the alluvial deposits with some metabasics at its upstream end. It is also necessary to protect the cut slopes of the barrage area and the sedimentation tank with rock bolts and shotcrete.

The headrace tunnel begins at T1 (at the barrage) and passes through the Tapovan Formation up to T2 consisting basically of metabasics and schists. They have Q and RMR values of 2–5 and 35–45 respectively. In the reach from T2 to T3 the foliation of metabasics, schists, quartzite, and gneisses strikes very close to the tunnel direction. They have Q values of 3 to 8 and RMR values of 55 to 60. The tunnel alignment from T3 to T4 and towards T5 will be through augen gneisses, schists and quartzites. In this stretch also, the tunnel is essentially parallel to the foliation. Its initial reach of 2.2 km will be through a rock mass with Q = 3 to 8 and RMR = 55 to 60, and the remaining stretch will be through a rock mass with Q = 7 to 14 and RMR = 60 to 65.

The tunnel alignment around T5 passes under the high ranges of Auli where the rock is covered by debris deposits. The rock exposures in depressions and road cuts consist of coarse-grained garnet-biotite-kyanite gneisses forming a broad syncline. This rock type will be observed for about 720 m of the tunnel length and will have Q and RMR values of 6–10 and 60–65 respectively. The last stretch of the tunnel before the surge shaft has Q = 6 to 10 and RMR = 50 to 65. During the excavation, seepage is apprehended below the Dhuli Gad, one of the major perennial streams crossing the tunnel alignment. Since there are no perennial streams draining the Auli area which experiences a heavy snowfall, some seeps are anticipated in this zone.

In the surge shaft area, there is a shallow (1.5 m) overburden and below it augen gneisses continue up to 86 m and then quartz-mica gneisses with schist bands follow. The RQD values of augen gneisses are significantly higher than those of quartz-mica gneisses. Since there is not enough lateral rock cover in the upper part, a suitable design is required.

The pressure shaft will encounter foliated quartz-mica gneisses, micaschists, and quartzites. The rock mass is unstable up to a depth of 50 m and at a depth of 15 m. The quartz-mica gneisses have Q values of 6–10 and RMR values of 60–65. The micaschists have Q values of 2–4 and RMR values of 40–50. The quartzites have an estimated Q value of 8.8 and RMR values of 67–75.

The powerhouse is proposed in massive or blocky quartzite with a Q value of 8.8 and RMR values of 67–72. The mid portion of powerhouse will be in jointed quartzite with an estimated Q value of 3.3 and RMR values of 52–63 and a small part of it falls on highly jointed quartzites with an estimated Q value of 1.8 and RMR values of 29–22. The powerhouse area calls for suitable support and it also needs careful monitoring during excavation.

The crenulated micaschists and garnetiferous micaschist in the tailrace tunnel have a Q value of 0.5 and a maximum RMR value of 25. Consequently, it calls for suitable tunnelling techniques and support systems.

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