Geotechnical appraisal of powerhouse cavern, Kotli-Bhel Hydroelectric Project, Stage-II, Uttarakhand

A.Dasgupta* and Ratan Kr. Das**

Abstract

The underground powerhouse cavern of the Kotli Bhel H.E.Project, stage-II is proposed on left bank of river Ganga for installation of eight no of units having capacity of 66.25MW each to generate 530MW of power near village Kaudiyala on NH-58 in Tehri-Garhwal district. The present paper deals with various aspects of survey and investigation involved in geotechnical appraisal of powerhouse cavern.

Introduction

Hydropower projects are the best source of power generation due to pollution free and renewable nature, responsive to quick load changes and economical. It has less capital cost (1/3rd of thermal), highly efficiency (90% for hydro, 35%for thermal and 32% for gas turbines) without contributing to green house effect etc and many other multipurpose benefits.

The sites of hydropower projects are located at remote hilly terrain on northern and eastern himalaya from Jammu & Kashmir, Himachal Pradesh, Uttarakhand, West Bengal, Sikkim and Arunachal Pradesh.

The projects are mostly located in difficult reaches of Himalayan terrain where the topography is rugged with complex geology and covered with overburden. Sometimes the time and cost overrun in completion of project are explained by a term "geological surprise" which refers to a sudden encounter of extraordinary adverse geological conditions during excavation of foundation or underground openings, which were never anticipated at the time of investigation. This may be true in some cases but, at times, this term is loosely used to cover up the delay. This situation may arise if the interpretation and prognostication given in the detailed geological report by geologists are not properly understood and not taken in design considerations.

Brief background of the project

The Kotlibhel H.E.Project Stage-II is envisaged on river Ganga at Kaudiyala, 29 km downstream from Devprayag in Tehri Garhwal district (Fig.1). The project consists of 82m high, 246.4m long concrete gravity dam with an orifice type spillway having 9 bays. Eight nos. independent circular 6.8m dia & 140m long pressure shafts shall carry water to underground powerhouse. The underground powerhouse of size 338m long, 25m wide & 45.5m high shall accommodate

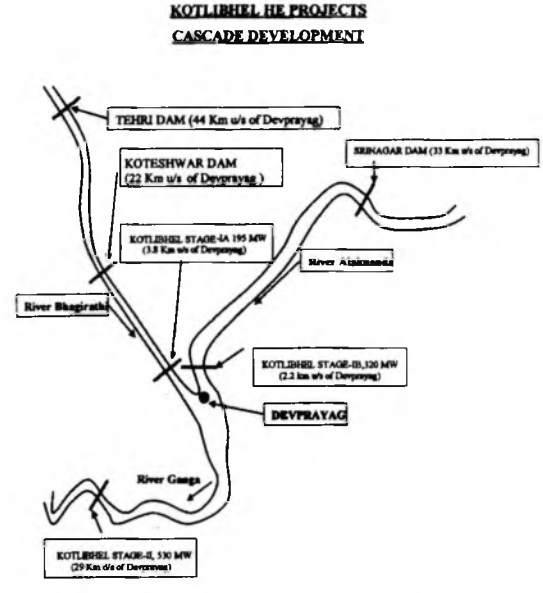

Fig. 1. Sketch of kotlibhel hydroelectric projects (Not to Scale)

NHPC, Kotlibhel project, Kotlibhel, Uttarakahand

eight units of 66.25MW each to generate 530MW of power. Both the transformer area (247m long & 21m wide) & GIS area are proposed to be placed outside on the left bank near the intakes. In the downstream of machine hall, the 4 nos. underground surge chambers of 54m length, 15.50m width & 58.5m height are present. The excavation for these 4 nos. surge chambers shall be carried out as a long cavern similar to machine hall and later on they shall be isolated by concrete walls. The ancillary structures for the powerhouse complex include 435m long main access tunnel, construction adit etc.

Geology of the project area

A major part of the KotliBhel HE Project,Stage-II is manifested by Jaunsar Group of rocks of early Neo-Proterozoic age. From about 3 to 4 km upstream of Devprayag to about 10km downstream, the Mandhali formation belonging to Jaunsar group is present. In downstream of Devprayag, after about 10 km, the rocks of undifferentiated Baliana Group overlie Mandhalies by an unconformable contact. Subsequently, Krol & Tal sequences are present having average surface manifestation of 1km each across the strike. Finally, the rocks identified as Bijni formation having purple greenish grey and white quartzite with subordinate bands of argillite occur as thrust over Blaini-Krol-Tal sequence. They are considered equivalent to Mandhali Formation (Valdiya,1980). Immediately upstream of Bijni thrust, river Ganga flows in two big loops in undifferentiated Tal sequence, which is also the site for Kotli Bhel Project Stage-II. Quaternary alluvium is present at many places along the river valleys which are shown as undifferentiated alluvium.

Geological investigation of the powerhouse area

The powerhouse area has been explored by surface geological mapping in 1:2000 scale, 635m long drifting, various in-situ & laboratory rock mechanic tests and four no. of drill holes for precise confirmation of rock conditions. (DPR, Vol.IV, KotliBhel HE Project, Stage-II)

Surface Geological Mapping

The river Ganga near Kaudiyala village takes a big loop and makes a complete 'U' turn to flow in southerly direction whereas at the dam site it is flowing in northerly direction. This semi-circular loop is utilized for power generation with an underground powerhouse inside the hill around which the river is taking a 'U' turn. Detailed geological mapping of the powerhouse area has been carried out with an objective to define the various litho-units and their geotechnical characteristics expected to be encountered at major project components. (Table.1) Boundaries of rock and overburden have been demarcated in the powerhouse area. Shear zone/ shear seams, folded and faulted structures, if present are also marked on plan.

Table.1 General characteristics of joints at powerhouse area (on surface)

Joint Set	Range of Orientation	Persistence (m)	Spacing (cm)	Joint Condition	Remarks
S_1	190^0-235^0/ 35^0-67^0	5 - 50	6-60	Rough Undulatory	Bedding (S_1) is the most prominent discontinuity having very long persistence. Shale/Siltstone/ sandstone bands are mostly observed along bedding planes. Besides bedding plane, 3 sets of joints observed.
S_2	352^0-045^0/ 18^0-40^0	1 - 3	6-20	Rough Undulatory	
S_3	098^0-129^0/ 60^0-86^0	1 – 5	6-100	Rough Undulatory	
S_4	305^0-340^0/ 45^0-80^0	1 – 12	6-60	Rough Undulatory	

The rock cover / overburden above the proposed powerhouse cavern are around 200m. The overburden has been classified according to its nature & origin. Geotechnical parameters from rock outcrops have also been recorded to assess the overall rock mass characteristics.

There are areas of slope wash deposits & boulders strewn on the flat topped hillock. Dense vegetation is also present on the slope wash deposits. The area directly above the powerhouse cavern shows exposures of strong quartzitic sandstones with minor shale bands & siltstones. Quite prominent bedding joints ($210^0/50^0$ avg.) having long persistence together with other three sets of joints have been observed. Towards the southern side of the proposed powerhouse a crushed zone interpreted as Bijni Thrust is present. The foot wall side of the thrust is represented by a huge dip surface $210^0/51^0$. The crushed zone is marked by a depression or break in topography which is filled by slope wash material on the surface (Photo.1). One or two small exposures of carbonaceous phyllite are also observed. However, the cavern is placed quite away from the disturbed zone in the area where compact and strong quartzitic sandstones are exposed.

The rock classification by RMR system indicates the percentages of rock classes Class I - Nil, Class II – 75%, Class III – 15%, Class IV – 10% and Class V-Nil. Pockets of closely jointed or fractured rock at few places are observed in siltstone/shale band zone.

Photo1: Overall View of Thrust Zone as depression near the Power House Ridge

Detailed geological plan are prepared in scale 1:2000 demarcating various litho units, boundaries of rock and overburden, rock parameters, attitude of joints and thrust. (Fig.2).

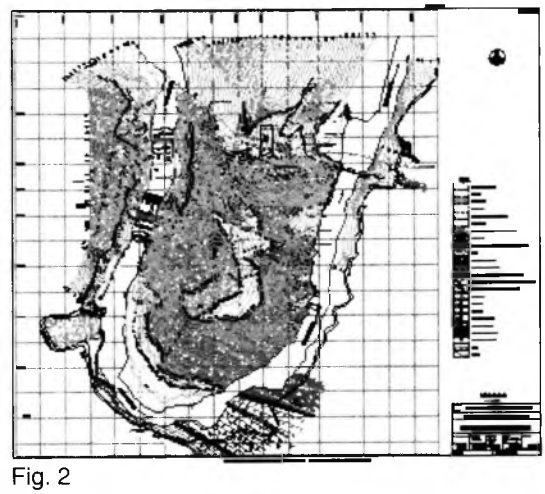

Fig. 2

Bijni Thrust

Bijni thrust is passing near the powerhouse area which is explored by surface geological mapping and an inclined drillhole for a depth of 124.50m. The hole was drilled to ascertain the true thickness of fracture / crushed zone of thrust.

The geological mapping and exploration by this drill hole indicates that the Bijni thrust shall not affect the powerhouse cavern since the thrust is dipping away from powerhouse area. However the thrust shall be encountered in the silt flushing tunnel for a length of 120 to 140m for which suitable protection measures have to be planned in advance.

Underground investigation

Powerhouse Drift

The 635m long powerhouse drift, comprises of 300m long main drift having two cross-cuts one in northern direction and another in southern direction. The northern side cross-cut is 320m long which is running along proposed alignment of powerhouse cavern whereas the southern side cross-cut is 15m

long. This cross-cut has traversed along the entire length of the powerhouse cavern and have been driven at about 5m above the crown level of the proposed powerhouse. The drift is unsupported throughout its length of 640m.

The 300m long main drift is excavated in direction North 96° at EL 430M. Very strong to strong, moderately to closely jointed quartzitic sandstone with occasional bands of Shale & Silt stone has been intercepted with four sets of prominent joints. At the initial 30-40m

Table. 2: Discontinuities observed in power-house drift

1.	S-1	180° - 230°/36°-72°
2.	S-2	034° - 116°/30°-62°
3.	S-3	315° - 345°/50°-80°
4.	S-4	270° - 290°/45°-75°

length, the discontinuities were filled by clay or rock fragments resulting in wedge failures in crown. In general the rock mass is fresh, strong to very strong. The discontinuities/joint orientation observed in the main drift are as follows:

Amongst the above discontinuities, bedding joint is very prominent having very long persistence. The 15m long southern cross-cut at the end of 300m long main drift encompasses very strong to strong quartzitic sandstones. Four sets of joint are observed in the drift where dripping is recorded at few places. The southern cross-cut is excavated particularly to observe the effect of Bijni thrust which exist at 160m away from the cavern. No sign of crushing /shearing effect / carbonaceous phyllites are observed in this cross-cut.

At northern crosscut which is 320m long, the rock mass is constituted by strong to very strong, fresh, moderately jointed quartzitic sandstone with medium strong fresh bands of siltstone and shale of thickness varying from 5cm to 15 cm and somewhere up to 50 cm thick band.

The rock mass in northern crosscut is also dissected by 4 sets of joints. It is seen that there is quite uniformity between the joint sets encountered in the main drift as well as in cross-cuts.

In the entire length of 320 m long crosscut, damp to dripping condition is observed. However at some places dry condition was also noticed. In northern crosscut wedge failure are observed at few locations by the intersection of bedding joint S-1 (191°-237°/ 37°-62°) and other joint set S-3 (070°-120°/ 35°-65°) and S-4 (309°-333°/33°-57°). Keeping in view of the joint sets observed in the powerhouse drift, the alignment of powerhouse cavern was kept in North 9° direction (Fig. 3).

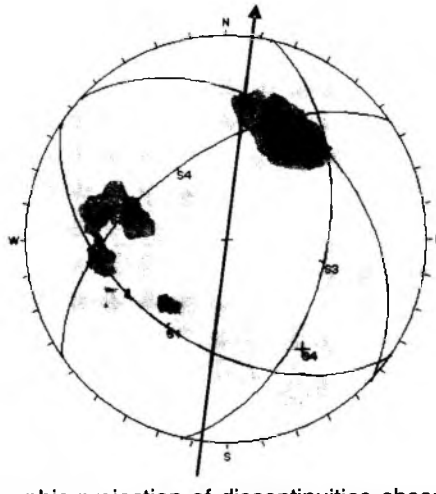

Fig. 3. Stereographic projection of discontinuities observed in Powerhouse drifts (Main & Cross cuts)

As per RMR system, the percentage of rock class encountered in the powerhouse drift are Class I - Nil, Class II - 55%, Class III – 45%, Class IV and Class V – Nil. The entire drift is self supported.

Drillholes

Four numbers of drill holes were drilled in the powerhouse area. Three no. of drill holes of 80m depth were drilled inside the exploratory drift along the alignment of powerhouse cavern (Fig.5). Fourth drillhole was drilled on the surface is an inclined drillhole of depth 124.50m. This drillhole was drilled to ascertain the true thickness of fracture / crushed zone of Bijni thrust.

The bedrock encountered in the drillhole drilled in southern crosscut at RD 4 m inside the powerhouse drift is light grey to white coloured, fresh, strong, moderately to closely jointed quartzitic sandstone interbedded with shale. Shale and Sludge of rock cutting observed at various depths. Core recovery in the drill hole ranges between 30% and 100% and RQD ranges between 7 % and 100%. Permeability values ranges between 2.573 lugeon to 11.14 lugeon, mostly turbulent in nature. Water table is observed from initial reach of drillhole, however no artesian condition is observed.

Similarly the drillhole drilled at RD 165m in northern crosscut of power house drift, the bedrock encountered is light grey to white and dark colour, fresh strong, medium to coarse grained, massive to moderately jointed quartzitic sandstone. Sludge of rock cuttings observed from depth 68m to 78.5m. No core recovery is observed from depth 74.5 to 78.5m. The zone has been interpreted as quartzitic sandstone having thick bands of weak zone in form of siltstone. Core recovery in the drillhole ranges between 7% and 100%. RQD ranges between 9 % and 100%. Permeability values ranges between 0.94 lugeon to 2.48 lugeon, mostly laminar to turbulent in nature. Water table is observed at depth of 2m.

The drillhole drilled at RD 258m in northern crosscut shows that the bedrock encountered is light to dark grey colour, fresh, strong, medium to coarse grained, massive to moderately to closely jointed quartzitic sandstone with bands of siltstone.

Sludge of rock cuttings observed in each run from depth 22.5m to 33m, 52.5 to 57.5m and 66.5m to 78.5m. Furthermore, there was no core recovery and only dark grey colored, fine grain sludge of rock cuttings collected at depth 58.5m to 66.5m. The zone has been interpreted as quartzitic sandstone along with bands of weak zone in the form of siltstone.

Core recovery in the drill hole ranges between 6% and 100% however at few places, the core recovery is nil. Similarly RQD ranges between 7% and 98% however at few places, RQD is nil. Permeability values ranges between 1.876 lugeon to 10.59 lugeon, turbulent in nature. Water table is observed from beginning of the drill hole having artesian condition.

The fourth drillhole which was drilled on surface is an inclined drillhole of depth 124.50m at EL.560.270M, about 60-70m away from the cavern on southern side. Fractures and sludge of rock cutting was encountered from the depth of 3m and 115.8m. Finally from 115.8m to 124.5m i.e. end of the hole, strong, fresh but closely jointed quartzitic sandstones were encountered.

Rock mechanic tests

Laboratory tests

Various laboratory rock mechanics tests were conducted in power house drift to know the physical properties of rock.

Furthermore, insitu deformability tests conducted for detailed design are as follows (Fig.4).

In-situ Rock mechanic tests:

Insitu deformability by Plate Load method : Plate load tests were conducted in northern

crosscut of powerhouse drift to know modulus of deformation and modulus of elasticity of rock mass. Five nos of Plate load tests were conducted in the in the northern crosscut of powerhouse drift at various places. The values of modulus of deformation and modulus of elasticity of rock mass at an applied load of 75 tonnes (applied stress of 26.52kg/cm2) vary from 0.403 GPa to 2.270 GPa and from 0.681 GPa to 2.905 GPa respectively. (CSMRS Report, 2008, New Delhi).

In-situ deformability tests by Goodman Jack method : Goodman jack tests were conducted in drill hole at RD 4 in southern crosscut and at RD 165m in northern crosscut of powerhouse drift to know the modulii of deformation and elasticity. Total twelve nos of tests were conducted in both drill holes. The test results observed in drill holes are as follows:

In drill hole at RD 4, average moduli of deformation and elasticity for moderately jointed quartzitic sandstones at an applied stress of 25 MPa were found as 7.341 Gpa and 7.762 GPa respectively.Similarly in drill hole at RD 165m, average moduli of deformation and elasticity for massive quartzitic sandstones at an applied stress of 25 MPa were found as 24.820 Gpa and 28.621 GPa respectively and for moderately jointed quartzitic sandstones were 6.359 Gpa and 7.062 GPa respectively (CSMRS Report, 2007, New Delhi).

In-situ Shear Tests (Rock to Rock interface): Five nos. of in-situ Shear tests (rock /rock interface) conducted in northern crosscut in powerhouse drift to determine the shear strength parameter ('C' and 'Ø) of rock mass. The tests results show that the value of cohesion 'C' and friction angle 'Ø' are 11.997 kg/cm2 and 73.83 respectively for peak shear strength and value of 'Cr' and 'Ør' are 8.347 kg/cm2 and 67.730 respectively for residual shear strength. (CSMRS Report, 2008, New Delhi).

Table. 3 : Various laboratory tests conducted in drill hole core samples (CMRI Dhanbad, 2006)

Sr.No	Physical properties	Dry	Saturated
1	Unit Weight (kg/m^3)	2609 to 2786	2615 to 2772
2	Uniaxial compressive strength (MPa)	126.59 to 167.66	75.12 to 156.74
3	Modulus of Elasticity (GPa)	4.72 to 19.57	1.60 to 13.97
4	Poissons Ratio	0.13 to 0.28	0.04 to 0.20
5	Tensile Strength (MPa)	5.51 to 15.88	5.19 to 7.47
6	Apparent Cohesion 'C' (MPa)	14.48 to 18.46	12.38 to16.35
7	Internal Friction Angle 'Ø'	55.55 to 58.17	54.47 to 57.11

In-situ Stress measurement by Hydro fracturing method

The in-situ stress field is one of the primary parameters influencing the performance of engineering structures located in a rock mass. The knowledge of the prevailing in-situ stress in a rock mass is necessary to design the engineering structure. In-situ Stress measurement was carried out at two locations viz. at RD 165m and 258m in northern crosscut of powerhouse drift. At each location three no. of Ex size drillhole of depth 30m were drilled in orthogonal direction, one vertical and two in horizontal direction to evaluate the stress measurement. (CSMRS Report, 2008, New Delhi).

At both locations, nineteen hydrofracturing tests were conducted. The results of hydofracturing tests are as follows:

Maximum Horizontal Stress, s_H = 7.27 MPa

Minimum Horizontal Stress, s_h = 4.72 MPa

Measured Vertical Stress, $s_{v(Meas)}$ = 3.80 MPa

Estimated Vertical

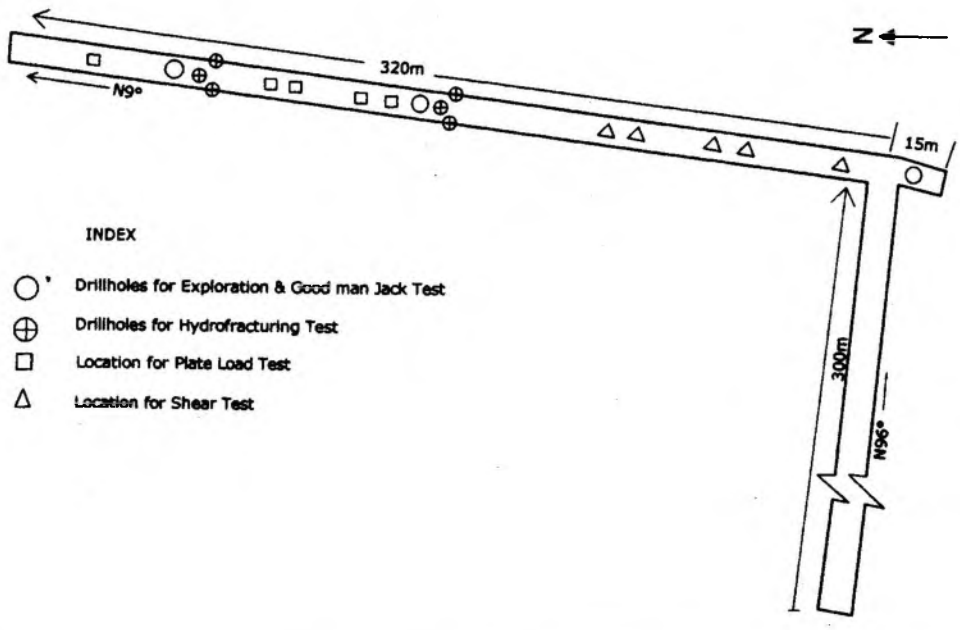

Fig. 4. Schematic diagram of Exploratory drillholes and Rock Mechanic tests conducted in powerhouse drift, Kotlibhel HE Project, Stage-II

Stress, $s_{v(Est)}$ = 4.88 MPa
Ratio, $s_H/s_{v(Meas)}$ = 1.91
Ratio, $s_h/s_{v(Meas)}$ = 1.24
Ratio, $s_H/s_{v(Est)}$ = 1.49
Ratio, $s_h/s_{v(Est)}$ = 0.97
Orientation of maximum horizontal stress = North 32.88°E

Support

The excavation of cavern is proposed with a pilot at crown level at the beginning followed by side slashing, & benching. The rock supports shall be installed concurrently & consist of 25mm dia, 3-4m long rock bolts, 36m dia up to 8.0m long rock bolts, post tensioned rock bolts (tendons) up to 25.0m length (if required). Shotcrete & double layer wire shall also be a part of the support.

Geotechnical Evaluation of proposed powerhouse cavern

Keeping in view of about 200m height of rock cover/overburden above the proposed powerhouse cavern, the powerhouse area has been explored by surface geological mapping, drill holes, drifts and various in situ and laboratory rock mechanic tests.

By means of all the explorations conducted in powerhouse area, it is evaluated that the rock mass of powerhouse cavern is strong to very strong, moderately to closely jointed quartzitic sandstone with occasional thin bands of medium strong to soft Shale & Silt stone. The rock mass is dissected by four sets of joints. Out of these bedding joint is very prominent having very long persistence. The intersection of three major joint set S-1, S-3 and S-4 form wedges in the crown as depicted from stereographic plotting of joint sets observed in powerhouse drift.

The orientation of maximum horizontal stress and results of other rock mechanic tests conducted in powerhouse drift indicates that no major problem like squeezing and rock bursting conditions will be envisaged during excavation of powerhouse cavern.

Heavy ingress of water/dripping is expected during excavation for which special provision for dewatering measures has to be kept during execution of powerhouse cavern.

As per RMR classification, the percentage of rock classes expected to be encountered in proposed powerhouse cavern during excavation are Class I - Nil, Class II – 30 % to 40%, Class III – 50% to 60%, Class IV – about 10 % and Class V – Nil.

Conclusion

The powerhouse area explored by surface geological mapping, drill holes, drifts and various laboratory and in situ rock mechanic tests helps to understand ground condition and behavior of rock mass in the geological environment under the influence of stress, deformation and groundwater.

It is concluded that the rock mass is good to very good and can host the powerhouse cavern of size 338m long, 25m wide & 45.5m high. Keeping in view of orientation of joint sets and wedge formation in the proposed powerhouse cavern, necessary support system has been designed. Adequate dewatering arrangement has been kept in view of artesian condition observed in drill holes and presence of the river on three sides of the proposed cavern.

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