

Prediction, interpretation and treatment of shear zones : A case study of an underground powerhouse cavern

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Abstract—The state-of-art technical developments in the engineering construction technology has made it now possible to implement any hydro power project, irrespective of its magnitude, wherein even geological setup of project is unfavorable & adverse. However, this poses immense challenge for the rightful selection of a suitable site for execution of huge underground excavation specifically in the heterogeneous rock conditions of Himalayan geology. The necessity of completion of project within the deadlines warrants the thorough geotechnical investigations to be conducted for avoiding geological surprise to the extent possible during the construction stage. Even detailed geological exploration carried out during investigation and pre-construction stage may not rule out presence of adverse geological features, as a fact of life. Underground power house cavern of Punatsangchhu-I H. E. Project encountered a major shear zone running across both the walls of the power house. This shear zone material was heterogeneous in nature and lost its strength in the presence of water. Managing such adverse geological feature often requires support of analytical approaches. Therefore, analytical analysis of power house cavern was carried out and shear zone treatment was evolved. Treatment included excavation of shear zone material up to a certain depth, plugging, rock bolting and shotcreting. This paper presents its prediction, interpretation & design aspects of power house cavern and methodology undertaken to treat the shear zone.

Keywords—*geotechnical investigation; tunnels; powerhouse cavern; shear zone; treatment of rock etc.*

I. INTRODUCTION

Punatsangchhu -I Hydroelectric Project (PHEP-I), a Run-of-river scheme is located about 70 km North of Thimphu, the capital, in Wangduephodrang district of Bhutan. The Project envisages construction of a 130m high Concrete Gravity Dam across Punatsangchhu river to divert water through a 9 km long Headrace Tunnel to an Underground Powerhouse for generation of 1200 MW power.

With a view to explore the geological features likely to be encountered in the major caverns, 960m long exploratory drift (including cross cut and niches) has been constructed at Powerhouse complex during DPR / preconstruction stage of the project (Fig. 1). The geotechnical information revealed on analyzing the rock strata intercepted in the drift have been

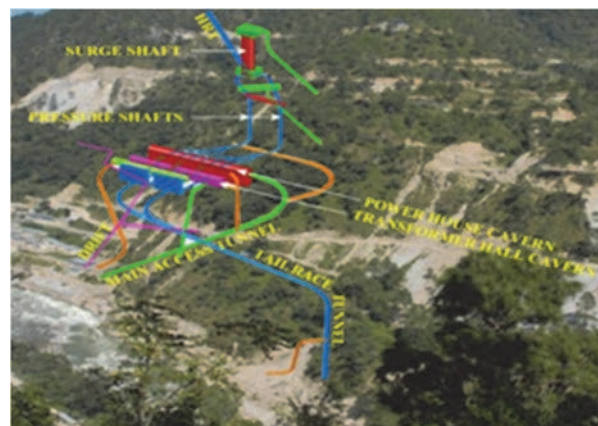


Fig.1.Pictorial 3-D view (Power house complex)

of prime importance for ascertaining the location of caverns on geological considerations. The unfavourable geology may turn even the feasible location to a site which is not acceptable. Therefore, proper prediction of such unfavourable geology become very vital to establish proper feasibility of site.

II. GEOLOGY

Regionally the PHEP-I area is located within a part of the Tethyan Belt of Bhutan Himalayas and rocks of Sure Formation of Thimphu Group of Precambrian age are exposed. The rocks of Thimphu Group in general is characterized by coarse-grained quartzofeldspathic biotite-muscovite gneiss, with bands of mica schist, quartzite and concordant veins of foliated leucogranite, migmatites with minor metabasics and interbedded limestone. Garnet crystals and porphyroblasts are also seen within this gneiss. The bedrock exposed in the project area is represented by garnetiferous, biotite bearing quartzofeldspathic gneiss showing a general foliation trend N10°E to N40°E and dips 200 to 400 towards ESE to SE. At places, the rocks exhibit broad warps as evidenced from the swing in foliation from N40°E to N-S and even upto N 10°W- S 10°E.

On the basis of study of Aerial Photographs for Punatsangchhu-I HE Project, by the PGRS Division, CHQ, GSI, three sets of Lineament have been picked up trending

(i) N-S (ii) NW-SE and (iii) NE-SW. The N-S trending lineaments aligned parallel to 900E ridge, which is reported to be neo-tectonically active mainly in the Bay of Bengal. The Punatsangchhu river probably flows along one of such sympathetic north-south trending lineaments at the dam site. The other two sets of lineament are less in abundance. A few NE-SW/NW-SE trending lineaments picked up from the aerial photographs appear to be faults as indicated by the shifting of main river course. The traces of N-S lineaments in colluvial deposits along the valley slope marked by linear topographic elements of varying relief suggest probable active neo-tectonics in the area.

A. Geology of Powerhouse Area

The Underground Powerhouse and its appurtenances are located on the left bank of the river, into the southwest spur of the hill near Ruchhekha village, WangduePhodrang district. Garnetiferous quartzofeldspathic gneiss and biotite gneiss with band of amphibolite are the country rock exposed in the area. Granite, Pegmatite, Quartz-tourmaline rock occur as intrusive veins and bodies in the country rock. The exposures are restricted to scarp/cliff faces and the remaining part of the area is covered with sediments comprising soil/scree, colluvium, glacio-fluvial deposits, and slide debris. The bed rocks in general are medium to coarse grained consisting of quartz and feldspar as major minerals, with minor minerals-biotite, hornblende, garnet, muscovite, sericite etc.

B. Discontinuities (Gneissosity / Foliation / Joints)

Litho contact (Intrusive), gneissosity / foliation, seven sets of joints and three sets of shear and fracture zones are the discontinuities recorded in the rock mass. The details of the joint sets are summarized in Table II.

C. Characteristic of major Shear Zone

The details of the Shear zone encountered in the exploratory drift are summarized in Table I, and depicted in Fig.2.

TABLE I. DETAILS OF SHEAR ZONE ENCOUNTERED IN EXPLORATORY DRIFT

| No. | Strike direction | Dip amount | Dip direction | Spacing (in cm.) | In filling |
|-----|------------------|------------|---------------|------------------|-------------------|
| SZ1 | N20°E-S20°W | 30° to 32° | N110° | 60 to 100 | Sheared Gouge |
| SZ2 | N35°W-S35°E | 35° to 47° | N235° | 2 - 5 | Main seepage zone |
| SZ3 | N40°E-S40°W | 10° to 30° | N130° | 90 - 120 | Clay Gouge |

D. Selection of location of Powerhouse cavern

The geotechnical information revealed on progression of drift towards the powerhouse cavern lead to logical step wise conclusion of locating of suitable area of Powerhouse and Transformer caverns.

TABLE II. SUMMARIZED DETAILS OF JOINT SETS

| No | Strike direction | Dip amount | Dip direction | Spacing (In cm.) | Continuity (In m.) | Opening (mm) | Roughness |
|-----|----------------------------|------------|---------------|------------------|--------------------|--------------|--|
| J1 | N05°W-S05°E to N40°E-S40°W | 20° - 40° | N85°E-S50°E | 5-50 | 2-25 | Tight | Foliation joint, Smooth Planar, warped at places |
| J2 | N25°W-S25°E to N50°W-S50°E | 50° - 70° | S40°W-S65°W | 4-30 | 1-6, 1D | Tight | Rough Planar |
| J2a | N10°W-S10°E to N15°E-S15°W | 55° - 80° | N75°W-S80°W | 5-50 | 1-8m | Tight | Rough Planar |
| J3 | N80°W-S80°E to N70°E-S70°W | 65° - 85° | N10°E-N20°W | 2-40 | 1-4, 1D | Tight | Rough Planar |
| J3a | N70°E-S70°W to N55°E-S55°W | 45° - 80° | N20°W-N35°W | 5-25 | 1-5 | Tight | Rough undulating |
| J4 | N50°E-S50°W to N70°E-S70°W | 35° - 70° | S20°E-S40°E | 10-40 | 2-5 | Tight | Rough undulating |
| J5 | N70°W-S70°E to N85°E-S85°W | 45° - 75° | S5°E-S20°W | 10-80 | 2-5 | Tight | Rough Planar, Random |
| J6 | N50°W-S50°E to N60°W-S60°E | 35° - 40° | N30°E-N40°E | occasional | 1-3 | Tight | Rough undulating Rare |

The exploratory drift of size 1.8m (W) x 2.1m (H) (with invert of portal at EL. 872.56m) envisaged to match with the crown of Transformer / Powerhouse cavern, was excavated for the total length of 960m (including cross cut and niches)

The shear zone (SZ3) along foliation as already delineated in the exploratory drift was anticipated to continue in power house cavern walls. During benching down of the cavern, the expected shear zone (SZ3) first started emerging at gable on the both the wall (RD 236.9) below EL 856.0m, which is 16m below the crown of cavern dipping gently towards service bay area thus exposing on the both the walls. This is basically a foliation parallel sheared schist band, sandwiched between comparatively competent bands, having thickness ranging from 1.5m to 3.0m with affected zone up to 4.0m. The band comprises thin clay/gouge seems, crushed rock, crushed quartzo-feldspathic veins and sheared & altered pegmatite lenses, having very less strength, cohesion & friction. The rock stratum in the cavern exhibits folding and broad warpings in the area. The shear zone/schist band also shows rolling/varying dips due to warping and folding of the beds and pinch & swelling nature, thus having varying thickness at different RD's. In general, the attitude of this band is 50- 240 / N 1400-1600 on the left wall, 100-150 / N 900-1100 on the gable end wall & 70-200 / N 600-1000 on the right wall. On the both the walls, shear zone has higher values of dips (150-240) between RD 236.9m-RD 220m and has gentle values of dips (50-100) beyond RD 220m towards service bay due to change in dip of shear zone it got exposed in longer reaches of power house than expected earlier. Shear zones along the left and right wall are given in Fig.4.

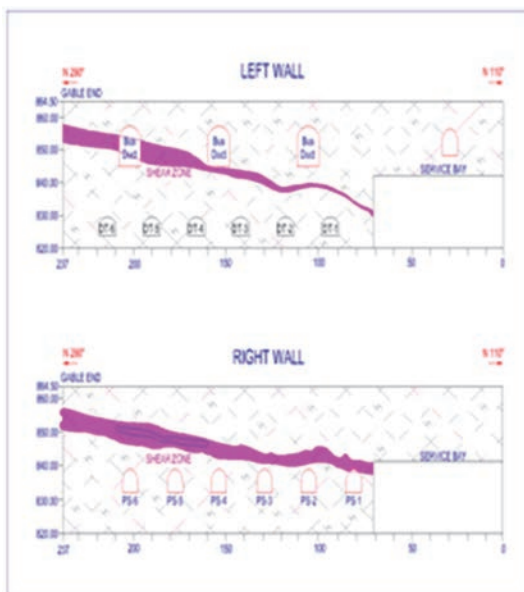


Fig.4. Shear Zone in Power house Walls

Considering the rock mass composition & filler material of the shear zone band, the “Q” value ranges from 0.1 & below, whereas the rock mass overlaying & underlying the shear zone falls in class III. A geotechnical assessment of this zone gives a low value for deformation modulus (<1 GPa) with low strength. Therefore, this has to be considered as very weak zone within competent strata forming heterogeneous rock mass condition on the walls. Under such situation, separation between stronger rock mass & the weak band cannot be ruled out, causing negative effect on the deformation & stability of the cavern.

Rock support system in crown & walls cavern was provided simultaneously. Rock mass classification along the power house from RD 0.00 (Service Bay side) to RD 236.9 (Gable end) is given in Table III.

TABLE III. ROCK MASS CLASSIFICATION

| S. No. | RD (m) between | Q | RMR | Class (Based on Q) |
|--------|----------------|----------|-------|--------------------|
| 1 | 0-40 | 3.3-3.6 | 42-44 | IV |
| 2 | 40-67.5 | 4.2-4.6 | 48-50 | III |
| 3 | 67.5-79.5 | 3.3-3.7 | 42-45 | IV |
| 4 | 79.5-85.5 | 4.5-4.80 | 50-52 | III |
| 5 | 85.5-113.5 | 3.4-3.7 | 42-46 | IV |
| 6 | 113.5-236.9 | 4.5-4.8 | 50-52 | III |

H. Support system and Shearzone treatment

Based on the rock mass classification, following three types of support system were provided in the crown of the cavern in different reached of power house:

- Type 1 : 32mm dia. Rock bolts of 12/10m length @ 2m x 1m spacing +200mm thick SFRS
- Type 2: 32mm dia. Rock bolts of 12/10m length @ 2m x 1m spacing +200mm thick SFRS + Lattice Girder having depth of 150mm embedded in SFRS.
- Type 3: 32mm dia. Rock bolts of 12/10m length @2m x 1m spacing + 200mm thick SFRS+ Steel Ribs.

In walls, 32 mm dia. Rock bolts of 12 m length @ 1.5 x 1.5m spacing inclined at 100 downward to the horizontal were provided along with 200mm thick SFRS.

The shear zone was observed to be thick and was separating the competent rock mass. This could cause excessive displacements in overlaying and underlying rock mass if not treated properly before benching down further. It was also considered necessary to join overlaying and underlying rock mass with a competent material in between upto a certain depth and then filling displacements. Hence, scooping out the shear zone material upto a certain depth and then filling it back with cement concrete/ shotcrete was considered necessary. Moreover tying of this concrete plug with surrounding rock mass was also required in order to prevent opening of joints and its movement. This plug will also prevent gouge materials of shear zone to come out in future which might cause stability problems in power house walls, therefore two dimensional stress analysis on FLAC (Version 5.00) was carried out in different conditions by IIT Delhi.

I. Two Dimensional Stress Analysis

The dimensional analysis of power house cavern with shear was carried out under following conditions:

- Considering the excavation of cavern with Stage wise Excavation sequence (5 m excavation under each stage after crown excavation), without support system as elastic model, and without and with support system using elastic Mohr-Coulomb model.

- To compute the displacements and stresses around the excavation for above.

Geotechnical parameters of rock mass and shear seam in power house area used in the analysis are given in Table IV.

TABLE IV. GEOTECHNICAL PARAMETERS OF ROCK MASS & SHEAR SEAM IN POWER HOUSE

| S. No. | Parameter | Unit | Value (for Rock Mass) | Value (for Shear Seam) |
|--------|--------------------|-------------------|-----------------------|------------------------|
| 1 | Unit Weight | kN/m ³ | 22 | 20 |
| 2 | Friction Angle | ° | 27 | 15 |
| 3 | Cohesion | MPa | 2.7 | 0.15 |
| 4 | Elasticity Modulus | MPa | 9000 | 1000 |
| 5 | Poisson's ratio | - | 0.2 | 0.35 |

The vertical stress corresponding to the rock mass cover is considered as vertical in-situ stress and in-situ stress ratio (k_0) of 1.3 is considered for horizontal and lateral stress directions.

The excavation is carried out in Powerhouse cavern and support system was provided simultaneously. "The sequence of excavations with each bench of 5 m was simulated. Following cases for analysis were considered:

Case-1: The excavation is carried out in the stages mentioned above and elastic analysis is carried out using elastic parameters of the materials

Case-2: Excavation is carried out in the stages mentioned above and elastic-plastic analysis using Mohr-Coulomb model is carried out using the elastic-plastic parameters of the materials

Case-3: The excavation is carried out in the stages mentioned above and elastic-plastic analysis using Mohr-Coulomb model is carried out using the parameters of the materials and after each stage excavation the support system in the form of rock bolts and shotcrete is installed. The concrete plug at the shear seam is also installed.

As explained earlier, the support system consisting of 32 mm dia. Rock bolts of 12/10 m length @ 2m x 1m spacing were provided in crown. In walls, 32 mm dia. Rock bolts of 12m length @ 1.5 m x 1.5 m spacing inclined at 10° downward to the horizontal were provided. Two rows of 36 mm dia. rock bolts of 15 m length @ 1.5 m c/c above and below shear seam were also provided along with 36 mm dia. Rock bolts of 20 m length @ 1.5 m c/c at an inclination of 45° through concrete plug provided in shear zone was simulated in the analysis. The shotcrete of 200 mm thick with wiremesh at crown and walls is also simulated.

Result of the analysis i.e. the x-displacement, y-displacement, major principal stress, minor principal stress

and plastic zone extent values for Case-1, 2 and 3 at crown and wall shear seam location are presented in Table V.

TABLE V. RESULTS OF ANALYSIS

| Cases | x-displacement (mm) | | y-displacement (mm) | | Major Principal Stress (MPa) | | Minor Principal Stress (MPa) | | Plastic Zone (m) Yield in Tension | |
|--------|---------------------|-----------|---------------------|-----------|------------------------------|-----------|------------------------------|-----------|-----------------------------------|-----------------------|
| | Crown | Wall Seam | Crown | Wall Seam | Crown | Wall Seam | Crown | Wall Seam | Crown | Wall Seam |
| Case-1 | 20 | 64 | 17.5 | 3 | 32 | 12 | 4 | 5 | 0 | 0 |
| Case-2 | 50 | 218 | 45 | 15 | 22.5 | 5 | 4 | 6 | 0 | 6 (left) 8 (Right) |
| Case-3 | 22 | 72 | 35 | 5 | 22.5 | 5 | 3.5 | 5.5 | 0 | 4 (Left) 6 (Right) |

From Table V, it is seen that the x-displacements in the shear seam are increased from 64 mm (Elastic Case-1) to 218 mm (Elastic-plastic Case-2 without supports) and are then reduced to 72 mm after installation of the support system in Case-3 and in the crown from 20 mm in Case-1 to 50 mm in Case -2, which is reduced to 22 mm in Case-3.

The wall convergence for Case -1 is about 0.48% of cavern width, which is increased to about 2% for Case-2 which is very high and unsafe and may pose problems related to stability. In order to arrest this wall convergence at seam location, the elaborate support system as described above was considered in the analysis. It is seen from the results of Table V, that for Case-3, the wall convergence is reduced to about 0.5%, which is well below the safe convergence limit of 1% of cavern dimension. The plastic zone in Case-2 is above 6 m in left wall and 8 m right wall seam location, which is also arrested to 4 m in left wall and 6 m in right wall after the installation of the support system in Case-3. The results of the displacement and convergence are well within the permissible range of 1% of cavern dimensions for Case-3. Hence the support system adopted for analysis is adequate and safe.

Accordingly, for treatment of shear zone support system following sequence of operation was adopted:

1. Consolidation grouting was carried out through 38 dia., 18m long holes drilled 1m away along the top edge of shear zone. Grouting of last 12m length was carried out in first phase.
2. Resin end anchored fully grouted 36 dia., 15m long rock bolts 'a' of grade Fe-500 were installed in next stage.
3. Shear zone material was removed through scrapping. Depth of cavity was kept more than the width of shear zone. After removing the material cavity was dried and cleaned with air jet.
4. 50mm thick layer of shotcrete was applied on the scooped surface and then resin end anchored fully

grouted 25dia., 3m long rock bolts 'e' were installed inclined vertically upward.

5. Cavity was filled with cement concrete having characteristic strength M15 in two layers. Shotcrete was filled as last layer.
6. Resin end anchored fully grouted 36dia., 20m long rock bolt 'b' & 'c' of grade Fe-500 were installed. One more row of rock bolts parallel to 'b' & 'c' in between rock bolts 'b' & 'c' was installed if vertical distance between these two rock bolts was found to be more than 1500mm. Rock bolts were installed after shotcrete/ cement concrete attained strength.
7. Then resin end anchored fully grouted 36dia., 15m long rock bolts 'd' of grade Fe-500 were installed.
8. Consolidation grouting was carried out at low pressure in the last 6m through grout holes.

Figs. 5,6 and 8 show details of concrete plug along with extra rock bolting in shear zone, front view of power house wall showing location shear zone along with rockbolts etc. and cross section of power house with shear zone on the both walls along support system respectively. Fig.7 shows the pictorial views of scooped/excavated shear zone area and its backfilling with concrete.

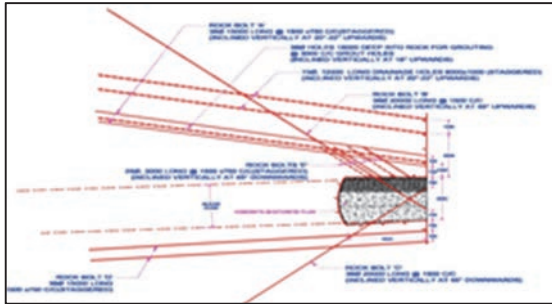


Fig.5. Concrete plug and Rock Bolt Arrangement for Shear zone Treatment

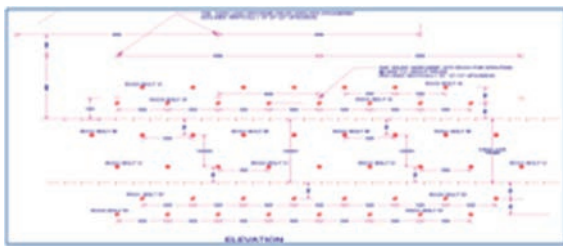


Fig.6. Front view of power house wall showing rock wall



Fig.7. Scooping and treatment

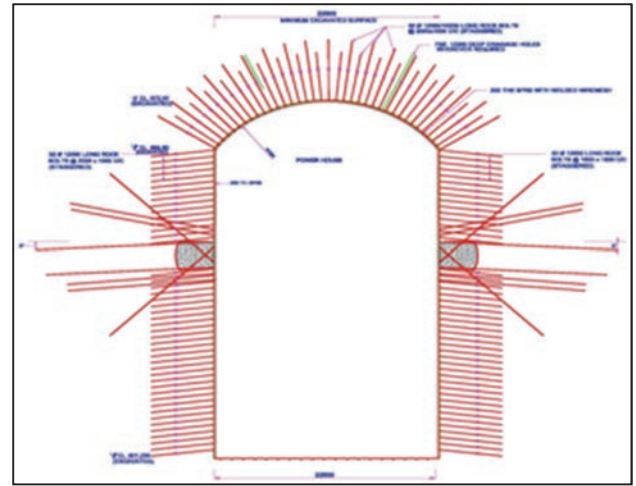


Fig.8. C/S of Power House with Shear Zone Treatment and Support System on Both Walls

III. CONCLUSION

Hydroelectric projects are mostly located in mountainous areas with disturbed fragile rock masses, where geological prediction, interpretation and treatment of adverse geological features play a vital role in development of projects. Himalayas are the youngest mountain range in the world and therefore adverse geological features cannot be ruled out, even if the detailed geological exploration is carried out during investigation and pre construction stages.

The present study concurred that thick shear zone in underground caverns poses threat to the stability due to extensive dilation due to unfavorable geology. Proper treatment on the basis of analytical analysis of the cavern taken due consideration of shear zone becomes necessary so as to achieve proper stability of the cavern. Power house cavern of Punatsangchhu-I H.E. Project shows that support system and shear zone treatment adopted for encountered shear zone in the form of concrete plug and its tying with surrounding rock mass was a sound technique to arrest excessive dilations and instabilities and thus improving overall stability of the cavern.

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