Selection of Suitable Location for Large Underground Openings in Complex Geology

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ABSTRACT

With the recent development in the construction technology, it is possible to implement any hydro power project, irrespective of its magnitude. However, this poses immense challenge for the right 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 any geological surprise during the construction stage. In view of the fact that the investigations are time consuming, it is prudent to accomplish them along with the preconstruction phase or even the construction of allied Main Civil works. The befitting example illustrating this is the extension of exploratory drift at powerhouse complex of PHEP-I along with construction of main access tunnel and construction adits to powerhouse and transformer hall caverns and interpretations of the geological information intercepted through the drift for suitably locating the caverns in the hill mass. This would ensure the accelerated implementation of hydropower project without sacrificing the precious time on elaborate investigations separately and thereby minimizing the uncertainty in such a huge project.

Keywords: Geotechnical investigation; Tunnels; Powerhouse cavern; Shear zone.

1. INTRODUCTION

Punatsangchhu-I Hydroelectric Project (PHEP-I), a run-of-the-river scheme is located about 70 km north of Thimphu, the Capital, in Wangdue district of Bhutan. The project envisages construction of a 136m 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 niches) has been constructed at powerhouse complex (Fig. 1). The geotechnical informations revealed on analyzing the rock strata intercepted in the drift have been of prime importance for ascertaining the location of caverns on geological considerations. The unfavorable geology may turn even the feasible location to a site which is not acceptable. Therefore, the regional geomorphological and geological appraisal gains significance in this context.

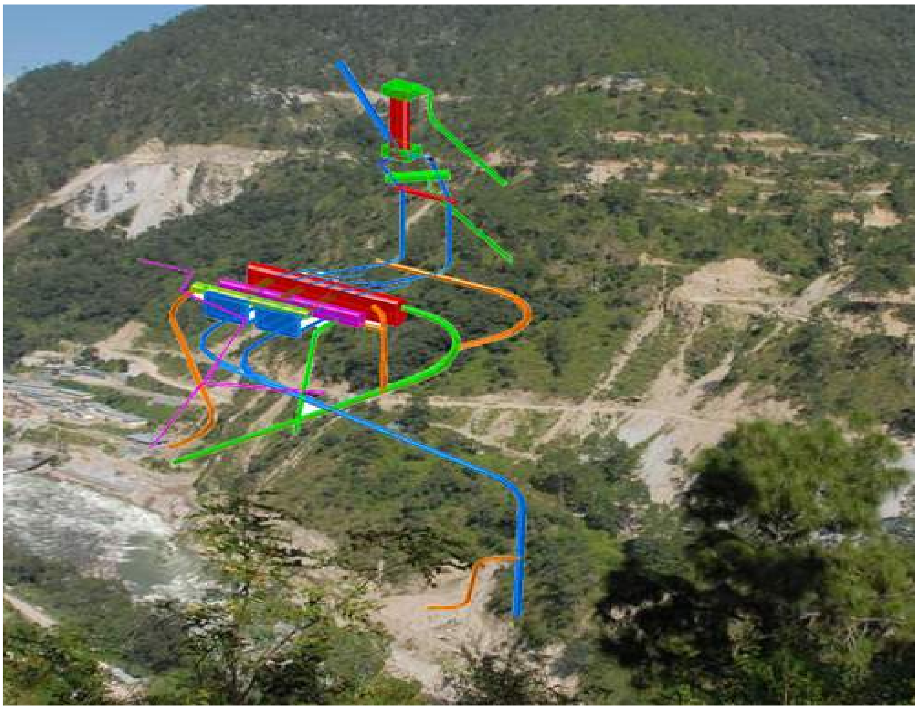

Fig.1 **-** Pictorial 3-D view (powerhouse complex)

2. REGIONAL GEOMORPHOLOGY

Bhutan is divided into a number of geomorphic regions by ravines created by major southerly flowing rivers like Amochhu, Wangchhu, Punatsangchhu, Mangdechhu and Manaschhu, within the Lesser and Central Himalayan tract in parts of Eastern Himalayas. These snow-fed rivers owe their origin to glacier and glacial lakes located to the North, near the Tibetan Plateau having elevations of 4000 m from the MSL.

Mochu and Phochu, the two major rivers, fed by glaciers and glacial lakes like Lunana, Rephsbeng originate from the northern boundary of Bhutan. These rivers flow southerly and meet at Punakha from where it is named as Punatsangchhu. Thereafter, Punatsangchhu river flows southward, more or less parallel with the 90°E longitude. However, from the downstream of confluence of Rurichhu it is flowing towards SE to SSE upto the confluence of Kisona Chhu and thereafter it is flowing more or less south. The main tributaries meeting the trunk stream in the area are Tabaynongchhu, Basochhu, Rurichhu, Pestochhu, Kamechhu on the right bank and Dangwechhu, Panjachhu, Haluchhu, Phandechhu and Dichhu on the left bank respectively. Towards further downstream of PHEP, in the southernmost region of Bhutan, this river is known as Sankosh, which flows towards plains of India and finally joins the river Brahmaputra.

Topographically, the Punatsangchhu basin, upstream of the dam site, upto Punakha, shows two major types of geomorphic landforms. From Punakha down to Wangdue-Phodrang bridge (~ 12 km), exhibits a matured river valley, characterised by gentle river gradient (1 in 368) with meanders and by thick alluvium deposit comprising mainly sand, pebbles, cobbles and boulders. The valley is significantly wide, as observed near Punakha, Kuruthang, Wangdue-Phodrang etc., mostly modified U-shaped with gentle abutment slopes on both sides. It appears to be a modified glacier valley. This terrain sharply changes from the confluence region with Dangwechhu, ~ 2 km downstream of the Wangdue-Phodrang bridge (near Wangdue Rapids), wherein the river exhibits steeper gradient (1in 8 ~ 1 in 78) towards downstream and flows with a number of rapids/cascades. This may indicate a neotectonic activity and the downstream block may have uplifted, as a result, the river gradient has been increased. This part of the river valley is characterized by rocky cliffs, mostly on the left bank and gentle abutment slopes covered with colluviums on the right bank. Since gneissocity dips along the slopes of the right bank, right abutment slope is much gentler. The right bank slopes are covered with colluviums consisting of large boulders/ rock blocks set in a sandy to clayey matrix, while the left bank is demarcated by steep rocky cliffs. In this part numbers of un-paired terraces are present all along the river course either on the left bank or on the right bank, which may be the manifestation of some neo-tectonic activity (Ghoshal and Gajbhiye, 2009).

3. GEOLOGY

Regionally the PHEP-I area is located within a part of the Tethyan Belt of Bhutan Himalayas and at the Dam site, 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 (reservoir and dam) is represented by garnetiferous, biotite bearing quartzofeldspathic gneiss showing a general foliation trend N10^{o}E to N40^{o}E and dips 20^{o} to 40^{o} towards ESE to SE. At places, the rocks exhibit broad warps as evident from the swing in foliation from N40^{o}E to N-S and even upto N 10^{o}W- S 10^{o}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 90^{o}E 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-tectonism in the area (Ghoshal and Gajbhiye, 2009).

3.1 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, Wangdue district. Garnetiferous quartzo-feldspathic gneiss and biotite gneiss with band of amphibolite are the country rock exposed in the area. Granite, pegmatite, quartz-tourmaline rocks 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.

3.2 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 1.

The details of the shear zones encountered in the exploratory drift are summarized in Table 2, and depicted in Fig. 2.

Table 1 - Details of joints

No	Strike direction	Dip amount	Dip direction	Spacing (cm)	Continuity (m)	Opening (m)	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-S50°W	55°-80°	N 75°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-S55W	45°-80°	N25°W-N60°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°	S15°E-S20°W	10-80	2-5	Tight	Rough planar, random
J6	N50°W-S50°E to N670°W-S60°E	35°-40°	N30°E-N40°E	Occasional	1-3	Tight	Rough undulating rare

Table 2 - Details of shear zone

No	Strike direction	Dip amount	Dip direction	Width (cm)	In filling
SZ1	N20°E-S20°W	30° to 32°	N110°	60 to 100	Sheared Gouge
SZ2	N35°W-S35°E	35°- 47°	N255°W	2 - 5	Main seepage zone
SZ3	N40°E-S40°W	30°	N130°	90 - 120	Clay Gouge

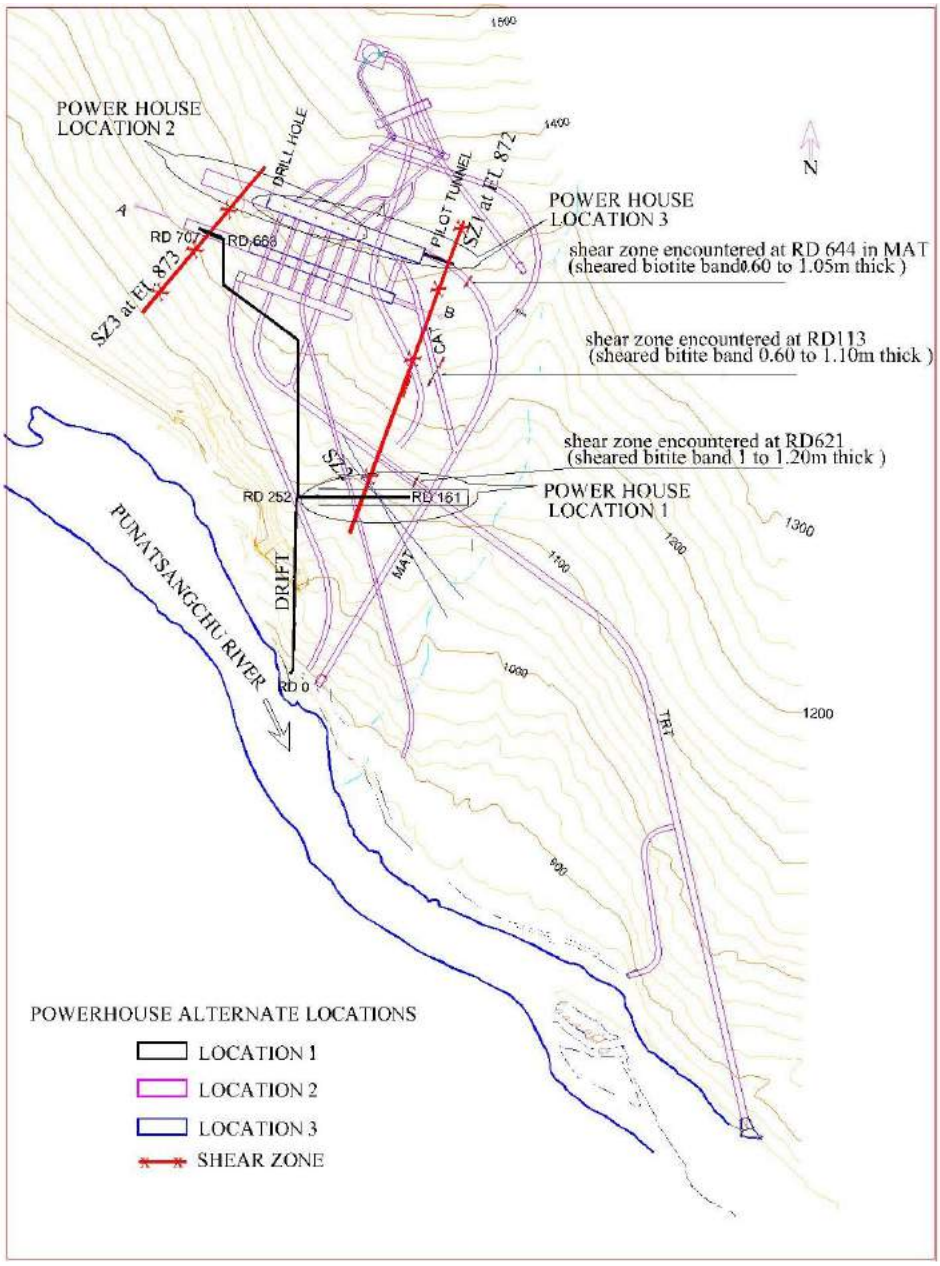

Fig. 2 – Location of shear zones and alternate locations of powerhouse cavern

4. 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 the suitable area for powerhouse and transformer caverns. It is worth mentioning that as on date (10th November 2010), the central gullet along the powerhouse cavern stands excavated in favourable geological conditions and the side slashing is under progress (Gupta et al., 2010).

The exploratory drift of size 1.8m (W) x 2.1m (H) started on 21st April 2007 with invert of portal at RL 872.56m to match with the crown of transformer / powerhouse cavern, which was completed on 10th July 2010, i.e. the total length of 960m (including niches) excavated in about three years. During the course of excavation of drift various alternate powerhouse locations have been considered feasible and weighed on the geological considerations. These alternate locations of powerhouse cavern are addressed to as powerhouse location-1, 2 and 3 in this paper. The alignment of drift towards various alternate locations of powerhouse cavern is also shown in Fig. 2. This case study focuses upon various alternate powerhouse locations considered feasible at various stages of selection and final suitable location (i.e. Location 3) identified for the purpose.

4.1 Power House Location 1

The drift had been excavated in N30^{o}E direction for the first RD 6m, and then in Northerly direction up to RD 252m. From RD. 252m the drift had been driven in the Easterly direction, partly through earlier proposed Powerhouse Location (at DPR stage) for 161m length. A shear zone (SZ1) of about 1m width with sheared gouge was encountered at RD 96m to 100m (RDs measured from Bend at 252m). This shear zone is envisaged to intercept the crown, all along both the walls and invert of the caverns resulting in severe construction difficulties and stability problems of the structure. The average ‘Q’ and ‘RMR’ values of rock mass where poor rock has been encountered i.e. from RD 96m to 100m is assessed as 1.5 to 2 and 22 to 30 respectively. Further another shear zone SZ2 of 2 to 5 cm width but the path of the main seepage zone has been encountered from RD 109m to 111m which had high ingress of water. The details of shear zones SZ1 and SZ2 are summarized in Table 2 and depicted in layout plan of power house complex plan in Fig. 2. In view of the presence of both the shear zones, the location of powerhouse in this area was not found suitable and therefore the extension of drift in eastern direction was abandoned. However, the main drift was continued to be extended towards north form RD 252m onwards.

4.2 Power House Location 2

The alternate location of powerhouse beyond the shear zone inducing seepage i.e. SZ2 has been located by continuing the drift for about 416m towards North into the hill. Further the orientation of powerhouse cavern has been determined by conducting in situ stress measurement by hydrofrac method using HTPF method (hydrofrac test in pre–existing fractures) inside 50m deep NX Size borehole at RD 28m and RD 455m inside the exploratory drift to powerhouse complex. The results of in situ stress test data is presented in Table 3.

The modulus of deformation of rock mass (E_d) and the modulus of Elasticity (E_e) are important engineering parameters required for the stability analysis and design of rock structures. Deformability measurements at two locations (i.e. at RD 400m & 476m) inside the exploratory drifts to powerhouse complex (each location consists of two sets) are conducted and results are presented in Table 4 (Sengupta et al., 2010).

Table 3 - In situ stress data

Principal Stress Tensors	RD 28m	RD 455m
Vertical Stress (σ_v) in MPa (Calculated with a rock cover of 177m and density of Rock=2700 kg/m^3)	6.01	8.65
Maximum Horizontal Principal Stress(σ_H) in MPa	08.24 +/- 0.3369	11.47 +/- 1.7739
Minimum Horizontal Principal Stress(σ_h) in MPa	5.49 +/- 0.2246	7.65 +/- 1.1826
Maximum Horizontal Principal Stress Direction	N120°	N120°
K= σ_H/σ_v	1.37	1.32

Table 4 - Deformability of rock mass

Parameters	Minimum value	Maximum value
Deformability modulus E_d (GPa)	1.15	1.94
Elasticity modulus E_e (GPa)	1.68	8.75

Accordingly, the long axis of powerhouse cavern is oriented almost along or sub-parallel to that of maximum principal stress as N70°W-S70°E. However, on continuation of drift along the centre line of oriented transformer cavern a major shear zone SZ3 of about 1m width having clay gouge was encountered at RD 694m. This shear zone is parallel to the foliation and sympathetic to SZ1. This shear zone is envisaged to intercept the crown, all along both the walls and invert of the caverns resulting in severe construction difficulties and stability problems of the structure. Therefore, this location was also not found suitable for caverns. Details of shear zone SZ3 are also summarized in Table 2 and depicted in layout plan of power house complex in Fig. 2.

4.3 Power House Location 3

In order to avoid encountering the shear zones to the minimal, the powerhouse has been shifted along the centre line by 98m towards Main Access Tunnel (MAT) side. Accordingly, the powerhouse and transformer hall caverns have been placed in between both the shear zones SZ1 towards service bay side and SZ3 towards far end side. The advantage of shifting caverns by 98m is presented in Table 5. The scenario has also been depicted in Figs. 3 & 4.

5. VERIFICATION OF LOCATION OF SHEAR ZONES

The shear zone SZ1 has been intercepted in various component presently under construction i.e. CAT, MAT and TRT at various elevations. The location of these shear zones encountered at various project components are depicted in Fig. 5. The continuity of Shear zone SZ1 has been verified as the same has been encountered in the MAT at RD 644m (RL 851m), in CAT at RD 113m (RL 866m) and in TRT at RD 621m (RL 830m).

Further, to ensure the location of this shear zone at powerhouse level, a pilot tunnel has been excavated from service bay side to intercept the shear zone. Having constructed pilot tunnel, it is confirmed that shear zone SZ1 exists at RD 45m at the same elevation of Powerhouse crown.

Table 5 - Shifting of powerhouse

Location		At crown (RD)	Elevation (m)	At bottom (RD)	Elevation (m)	Affected zone (m)
Location 2	Power House	169.45	872.5	76.74	879.5	92.71
	Transformer	182.41	874.5	137.45	848	44.96
Location 3	Power House	231.4	851	174.74	819.5	56.66
	Transformer	Nil		Nil		Nil

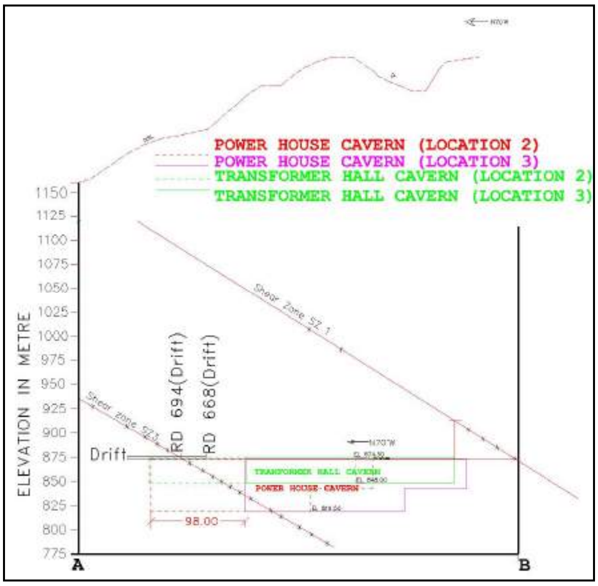

Fig. 3 - Shear zones projected at power house cavern

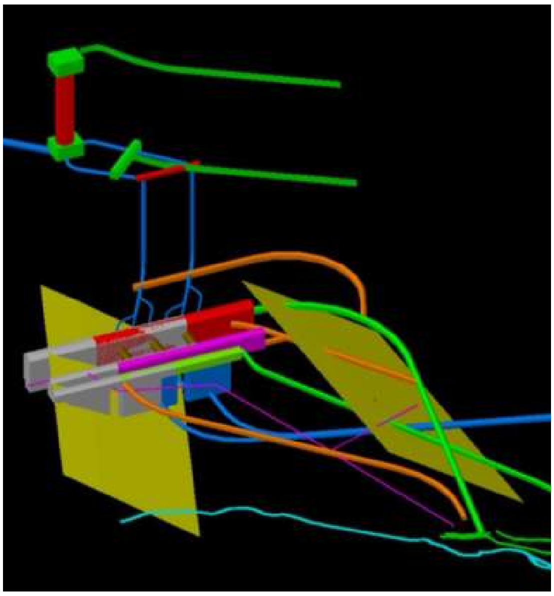

Fig. 4 - Shear zones projected in cavern (3-D View)

However, to confirm the location of shear zone SZ3 at far end of powerhouse cavern a NX size 50m drillhole has been drilled from central gullet of cavern with collar elevation of EL 865m up to 815m (i.e. 4m below deepest invert level of powerhouse cavern). The drillhole reveals the existence of shear zone at 11.5m depth and shattered zone at 21.5m depth with almost 100% core recovery in the remaining reaches. This confirms the presence of shear zone SZ3 near far end of the powerhouse.

As evident from Figs. 3 and 4, the powerhouse and transformer hall caverns are placed in geologically most suitable area (Fig. 6) bounded by two major shear zones at both the ends of caverns.

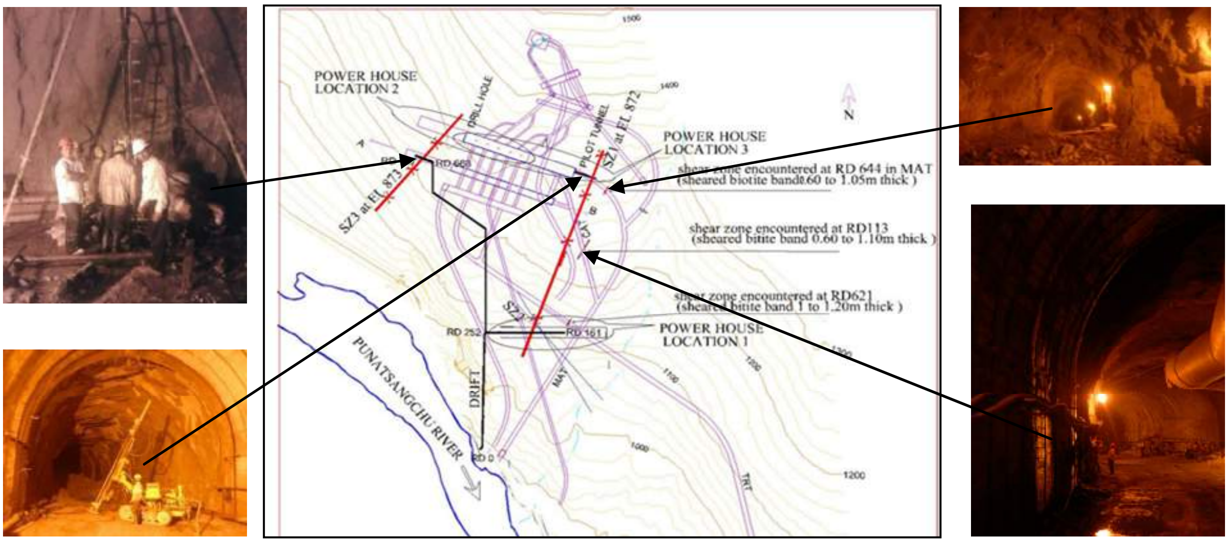

Fig. 5 -Verification of location of shear zones

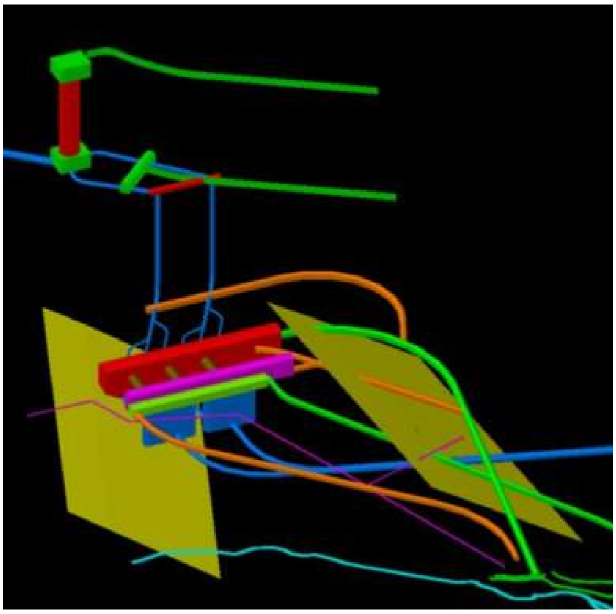

Fig. 6 - Optimal location of underground powerhouse (location 3)

6. CONCLUSIONS

The powerhouse and transformer hall caverns are placed in geologically most suitable area bounded by two major shear zones at both the ends of caverns. The entire area has been explored in detail and the locations of both the shear zones have been verified by conducting drifting and drilling towards far end and pilot tunnel towards service bay end. The optimized timely investigations play a significant role for suitably locating the major underground structures and thereby minimising the uncertainties involved in construction such a huge caverns.

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References

Ghoshal, T.B. and Gajbhiye, P.K. (2009). Report on the Geotechnical Investigations of Punatsangchhu-I Hydroelectric Project, Bhutan, Geological Survey of India, November, 2009.

Gupta, Amit, Bhatt, Aditya K. and Dhir, Y. K. (2010). Optimization studies for finalization of suitable location of powerhouse and transformer hall caverns, International Conference on Accelerated Development of Hydropower in Bhutan - Opportunities and Challenges, by CBIP at Thimpu, Bhutan.

Sengupta, S., Subrahmanyam, S., Joseph, Sinha, R.K. and Shyam, G. (2010). Report on Determination of In situ Permeability, In Situ Stress and Deformability Parameters of Rock Mass for the Design of Underground Powerhouse Complex at Punatsangchhu Stage-I H.E. Project, Bhutan, National Institute of Rock Mechanics, May, 2010.