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Optimal Orientation of Power House Cavern in Upper Himalaya

Hari Dev, Senthil P., Sukhdev Singh, D. V. Sarwade*

Central Soil and Materials Research Station, New Delhi, India

**E-mail: haridev65@gmail.com*

ABSTRACT

The orientation of caverns is influenced by several factors like geology, ground water conditions, in-situ stresses, intended objective etc. To be precise, number and orientation of joints play a key role in finalising the orientation apart from other factors like fault/shear/weak zones. Direction and magnitude of principal stresses is also one of the primary parameters influencing the stability of underground structures. Hydropower development requires use of underground space for hosting the major appurtenant structures like desilting chambers for exclusion of silt particles, tunnels for minimizing the length of water conveyance system, surge shafts/chambers and power house/transformer caverns. This paper deals with finalisation of optimal orientation of large sized underground power house and transformer cavern. Different options based on hydraulic, geological, stresses criteria have been discussed in this paper.

Keywords: *In*-situ stress; Wedge analysis; Horizontal stress; Vertical stress; 2-D Numerical modelling

1. INTRODUCTION

Design and construction of underground tunnels and caverns requires thorough knowledge of the site geology including number of joint sets, their orientation, joint properties, joint infilling material, shear or weak zones and their orientations in relation to the structure, in-situ stress state, stress-deformation behaviour of the rock and rock mass etc. Stability of the structure is of primary importance besides cost economics. While excavating or creating any opening in rock mass like a tunnel or a cavern, in-situ state of stress gets disturbed and redistribution of stresses take place. The response of the rock to the excavation activity mainly depends on many factors viz. primary or induced stresses; geometry, size and orientation of the excavation; vertical and lateral rock cover; geological discontinuities; excavation methodology and sequence etc. Apart from the primary and induced stresses, convergence mainly depends on the strength and stress-deformation properties of rock mass; orientation of discontinuities in relation to the shape, size and orientation of cavern/tunnel. Convergence in competent rock is lesser as compared to soft or weak rocks. Geological variations, geometry of joints in relation to cavern orientation and dimensions, presence of weak zones and shears may cause stress concentrations and may lead to failures if not addressed properly. Artificial support is provided to limit convergences, to prevent stress concentrations and distribute the rock loads on a larger area.

In the present study, stability analysis is carried out for exploring all the options to arrive at the final design. This case study elaborates the criteria of fixing of alignment of powerhouse cavern based on in-situ stresses, geological and hydraulic flow considerations supported with numerical modelling.

2. THE PROJECT

In the present study, hydraulic fracturing (HF) test was adopted for the evaluation of in-situ stresses in rock mass in a drift for a proposed underground power house complex comprising machine hall cavern of 100.0 m (L) x 18.0 m (W) x 41.00 m (H) size to house 4 vertical Francis type turbine units each of 42 MW installed capacity and transformer hall of 80.0m (L) x 16.0 m (W) x 28.0 m (H) size for the hydropower development in Upper Himalayas. Tests were conducted in EX size (38 mm diameter) in vertically downward drillholes to determine the horizontal stresses. Vertical stress was estimated from the depth of rock cover. Surface geological map highlighting the project components is shown in Figure 1.

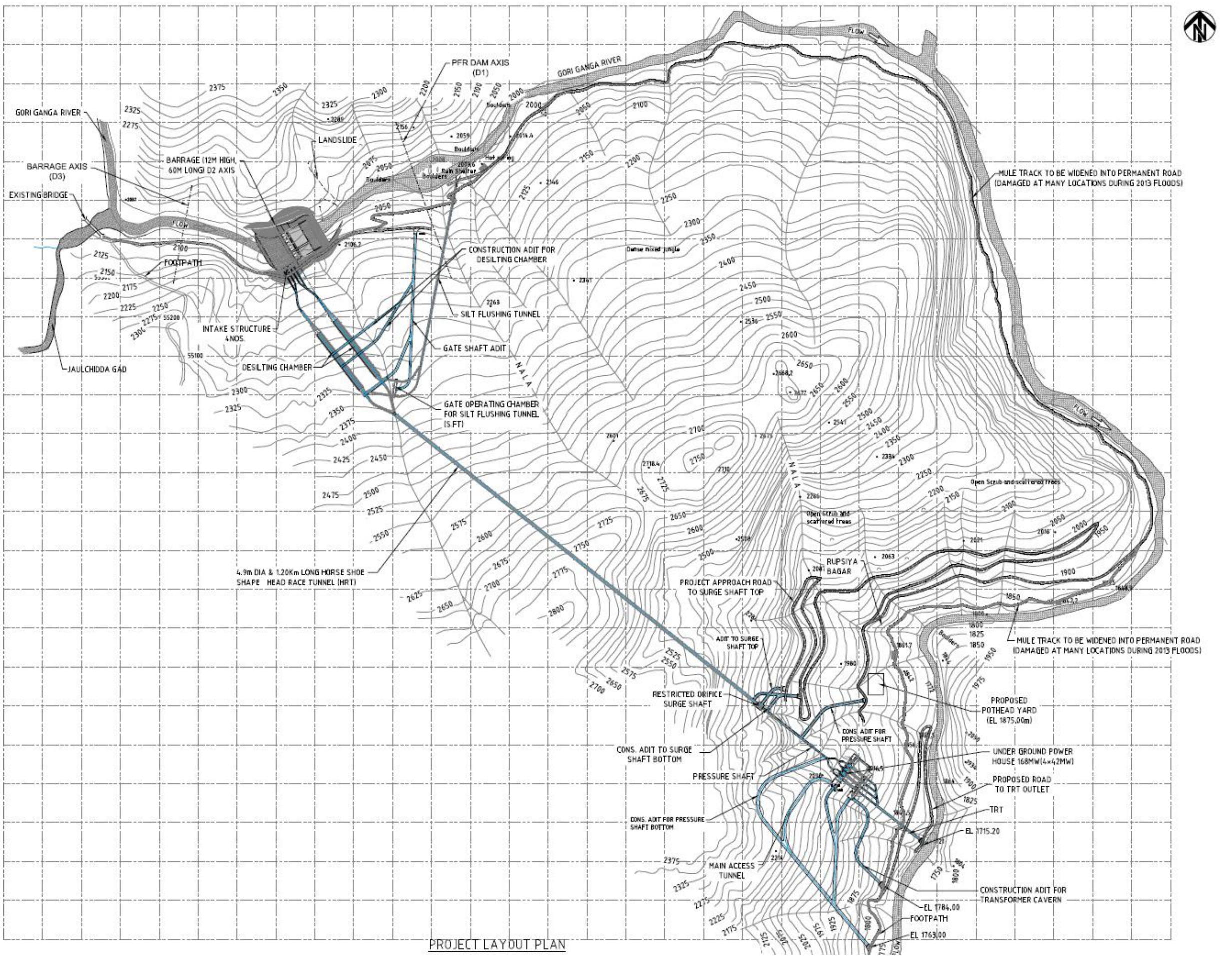


Fig. 1 - Lay out plan of the project

3. GEOLOGY

The caverns have been proposed in hard and intact gneisses, mica schist, banded quartzitic gneisses of Pandukeshwar Formation The rock mass is foliated, jointed and fresh to slightly weathered. The rock mass dips in N350°/50° (Foliation). Three sets of joints and some random joints other than foliation have been recorded, viz. J2: N100°/60°, J3: N200°/60° and J4: N155°/50°. Systematic discontinuity surveys in the powerhouse area have revealed volumetric joint counts (Jv) ranging between 4 and 12 which indicate degree of jointing from moderate to high range (Palmstrom 2005). The corresponding RQD, therefore, is estimated to be between 75% and 100%. Shearing has been noticed at places mostly along the weak schist bands. Rock mass in general has been classified as Class-II with RMR ranging from 70-75 and Q values varying from 9 to 14. Joint set properties are detailed in Table 1. The stereographic plot of all the four prominent joint sets is shown as Figure 2. Foliated gneisses in the foot track close to powerhouse area are shown in Figure 3.

Table 1 - Joint sets and their engineering properties in project area

Set No.	Dip Direction/ Amount	Feature	Persistence (m)	Joint Roughness	Aperture (mm)	Filling	Spacing (cm)
J1	N350^0/50^0	Foliation	15-20	Rough, Undulating	Tight to 1-2	Unfilled	10-250
J2	N170^0/65^0	Joint	20-25	Rough, Planar	Tight to 2-3	Unfilled	20-200
J3	N110^0/60^0	Joint	10-15	Rough, Planar	Tight to 2-5	Unfilled	15-250
J4	N225^0/55^0	Joint	3-5	Rough, Planar	1-3	Partially filled	20-300

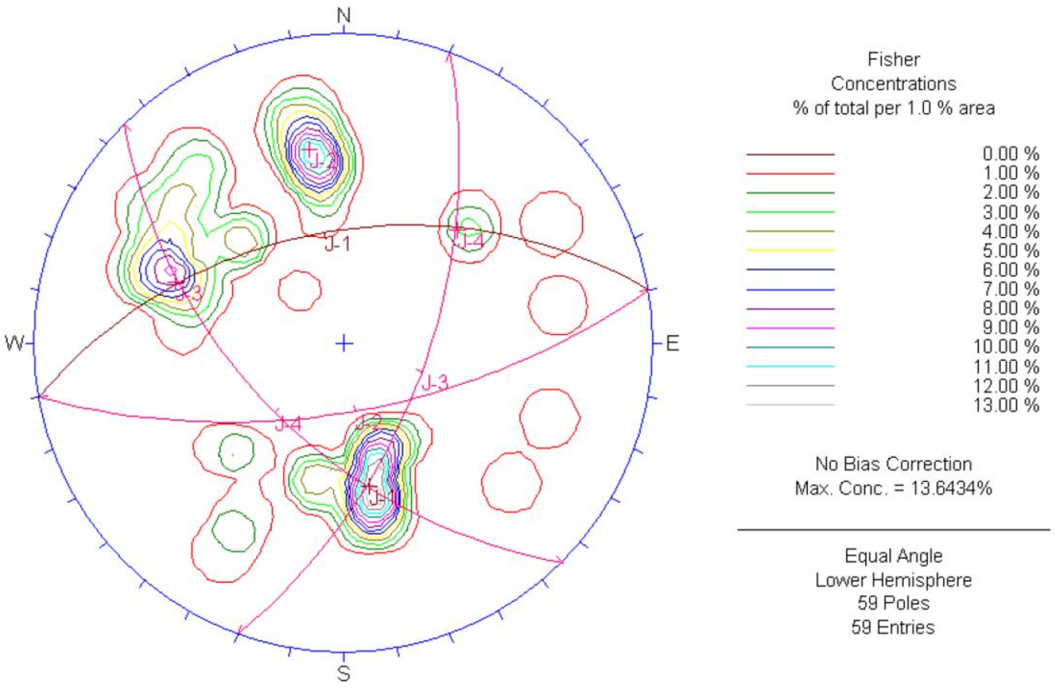


Fig. 2 - Stereo plot of joint sets

Fig. 3 - Foliated gneisses close to powerhouse area

4. IN-SITU STRESSES

Hydraulic fracturing method was used for stress measurements in the power house drift. Double packer system is used on short intervals devoid of natural fractures (Haimson and Fairhurst 1967). Classical method of hydraulic fracturing was followed and double tangent method (Enever and Walton 1987) was followed for calculating the shut-in pressure (S_i). The fundamental assumptions underlying the application of hydraulic fracturing are that:

i) One of the principal stress components is co-axial with the test hole,
ii) The long-term shut-in pressure is approximated as the magnitude of the smaller horizontal stress component.
iii) The crack will generally tend to initiate in a plane normal to minimum stress (i.e., along the maximum stress).

The recommended values of maximum and minimum horizontal stresses (σ_H and σ_h) were 4.8 MPa and 3.4 MPa, respectively. Vertical stress (σ_v) estimated from the rock cover above the test locations comes out to be 7.6 MPa which is higher than both the horizontal stresses. Stress ratios σ_H/σ_v and σ_h/σ_v were found to be 0.62 and 0.44, respectively. Direction of maximum horizontal stress was determined as N40^{0}W - S40^{0}E.

Normally, horizontal stresses are found to be higher at shallow depths as compared with vertical stress (Hast 1958, Dewey 1972, Mckenzie and Sclater 1973, Courtillot and Vink 1983. Sheorey 1994). Both the stress ratios in the present case are less than 1.

Figure 1 shows that river traverse takes a U-turn between proposed barrage and power house locations, thereby isolating the hill. Low magnitude of horizontal stresses compared with the estimated vertical stress may be attributed mainly to phenomenon of stress relief due to topography. Number of cross drains in the area also contributes to the stress relief phenomenon.

Stress measurement tests have been performed in drillholes at depth of 6 m to 16 m, since, the size of the drift is 1.8 x 2.1 m, the results are not influenced. The tests have been performed beyond the disturbed zone, thus eliminating the excavation effect. The reason for lesser magnitude of horizontal stress compared with vertical stress is mainly because of the local topography resulting in the stress release. Although, normally, horizontal stresses are greater than vertical stress at shallow depth, but exceptions can be there. No correction factor has been applied and it is not required.

5. CRITERIA FOR ORIENTATION OF UNDERGROUND CAVERNS

Stability of underground caverns can be attained with suitable artificial support measures. Size, shape, orientation and width of rock pillars in case of multiple caverns are critical design elements. For economy, support systems should be optimised by aligning the caverns favourably. Berg-Christensen and Dannevig (1971) proposed the criteria for aligning the unlined pressure tunnels in the preliminary design based on vertical and lateral rock cover. Hari Dev et al. (2016 and 2019) has discussed the orientation of long axis of the cavern/tunnels considering geological and in-situ stresses.

As far as water conveyance tunnels in hydropower project are concerned, there is little scope of changing the alignment, however, large caverns like power house complexes can be suitably aligned to satisfy the stability requirements. The following criteria can be adopted for aligning the large caverns:

- Usually, the underground caverns and large sized tunnels can be aligned in a direction perpendicular to the minimum horizontal stress. In such cases, the minimum stress acts on the walls of the cavern which of course will minimise the deformations or convergences and ultimately need least artificial support system. In high stress regions, orientation of caverns at an inclination to maximum horizontal stress attracts buckling deflection in walls (Bahram Salehi 2017). Adequacy of rock cover is another major concern while deciding orientation of large caverns and tunnels (Sharma 1994).
- The caverns may be oriented in a direction normal to the strike of the bedding joint. The weak/fractured/shear zones should be avoided. For long and high walls, it is important to have an angle of at least 25^0 to steeply dipping smooth planes or clay-filled joints (Olson et al., 1977). Further, if the direction of the principal stress is close to the direction of bedding or filiation planes in highly anisotropic rocks, the length axis of the opening be aligned by 35^0 absolute minimum to the strike of the foliation plane.
- Intersection of joints result in formation of wedges either in walls or in the crown of the caverns or tunnels. Hence, the direction should be chosen such that the wedges formed are least. In preliminary or pre-feasibility stages, the joints seen as outcrop at the exposed rock faces can be used for wedge analysis. Since, there is possibility of variation in characteristics of joints inside rock at proposed location of the underground structure, therefore, it is advisable to update geological inputs and redraw the stereonet diagram for refinement. The cavern orientation may be decided based on the geological wedge analysis at the actual location (Hari Dev et al., 2016).
- Due weightage should be given to major discontinuities like fault plane, major shears, fractured rock mass, karst or probable solution cavities etc. and it is imperative to study their impact on the

stability of the proposed structure. In case of major stability issues, deviations in the orientation and locations can be considered.

- In case of low magnitude of horizontal stresses, the bedding joint can be given priority. In zones of high stresses, the orientation should be strictly based on the in-situ stresses.
- The above criteria may also lead to conflicts as all the criterion may not merge at single solution, therefore, in such cases the numerical tools can be used to model the stress induced deformations, assess the stress distribution, stress concentrations and deformations. The numerical tools require reliable input parameters.
- Apart from above, in hydro power projects, the orientation is also guided by hydraulic considerations too. The pressure shaft or penstocks should strike normal to the generating units. In order to satisfy the criteria of stability of cavern, the curvature in penstocks may be needed which will result in change in length of water conductor system. This may lead to head loss and ultimately continuous loss in power generation.
- Cost-benefit economic studies can be done comparing the additional support requirements to keep the length of water conductor system to be shortest as compared with orientation favouring criteria of stresses in which the support requirements may be least but length of water conductor system may be greater.

In all the cases, stability of the cavern should be of supreme importance.

Four different orientations of the cavern suiting the geological and hydraulic requirements were analysed. Numerical analysis was carried out considering all the options using 2D numerical programme. Compared with 3D modelling, results of 2D analysis is conservative especially at the ends of the cavern. All the options have been discussed as under:

Case 1 - The orientation of the power house cavern may be aligned in N61^{0}E –S39^{0}W suiting the favourable orientation considering hydraulic requirements. The length of water conveyance system is least and it strike more or less perpendicular long axis of cavern.

Case 2 – The orientation of the power house cavern has been oriented perpendicular to the strike of foliation joint i.e. N170^0. This orientation is suitable from geological point of view. Aligning the cavern in this orientation shall result in curvature in penstocks as well as in outflow structure, thus leading to increase in length of water conveyance system apart from head loss.

Case 3 - Stress measurements in the exploratory drift confirmed the direction of maximum horizontal stress to be N40^{0}W-S40^{0}E. Therefore, the cavern can be oriented in N40^{0}W-S40^{0}E favouring the in-situ stress state consideration.

Case 4 – Cavern orientation can be kept oblique to the pressure shaft alignment, thus partially favouring hydraulic, geological and in-situ stress requirements, the orientation of cavern may be kept in N10^{0}E-S10^{0}W.

Initially, proposed alignment suiting the hydraulic flow requirements is shown in Figure 4. All the possible orientations suiting various criteria, are shown in Figure 5.

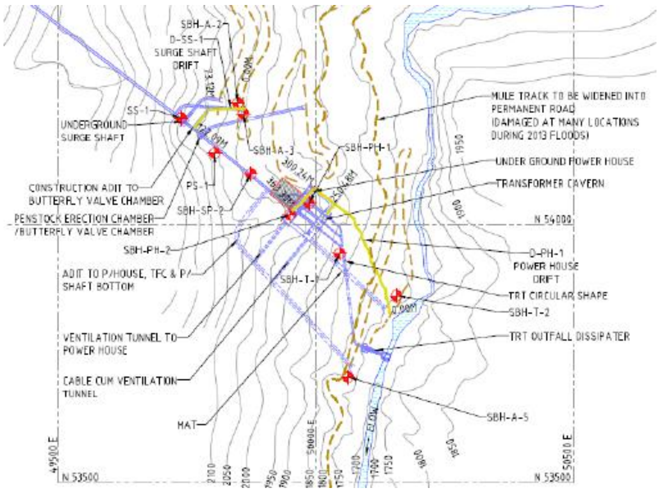


Fig. 4 - Proposed alignment favouring hydraulic flow requirements (Case 1)

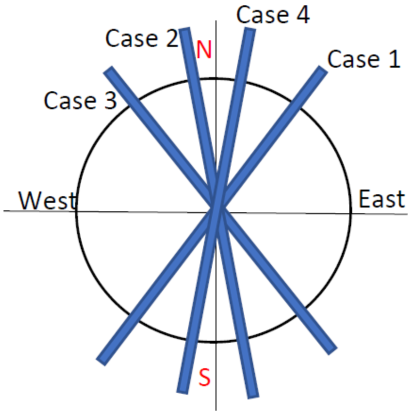


Fig. 5 - Alignment options suiting various criteria

6. ALIGNMENT OF POWER HOUSE CAVERN – 2D NUMERICAL MODELING

Since, above criteria suggest different orientations of the cavern (Figure 5), therefore, compromising orientation of cavern primarily suiting the stability and hydraulic requirements can be opted. Numerical modelling of the power house and transformer caverns (35 m apart) in all the tentative alignments was carried out using of the RS2 software. The artificial support systems viz. rock bolts and shotcrete as per details given below were considered in the model:

- 32 mm dia. 9 m long rock bolt @ 2 m c/c for power house cavern
- 32 mm dia. 6 m long rock bolt @ 2 m c/c for Transformer cavern
- 200 mm thick wire mesh reinforced shotcrete.

The cavern analysis has been done by adopting these support systems. Different combinations of support systems were modelled and analysis presented here is based on the above support systems. The following properties of rock and rock mass were considered in the model:

Unit weight	: 26 kN/m^3
Poisson ratio	: 0.3
Modulus of rock mass	: 7 GPa
Cohesion	: 1.5 MPa
Friction Angle	: 45^o

The rock material is considered as elastic perfectly plastic, i.e., peak and residual values of cohesion and friction angle are same. The magnitude and direction of in-situ stresses were considered as follows (CSMRS 2020):

In-situ stress in vertical direction	: 7.6 MPa
In-situ stress in Horizontal direction	: 4.8 MPa (N40^{o}W-S40^{0}E)
In-situ stress in longitudinal direction	: 3.4 MPa

The results obtained from the numerical analysis are presented in Table 2.

Table 2 - Results of numerical studies

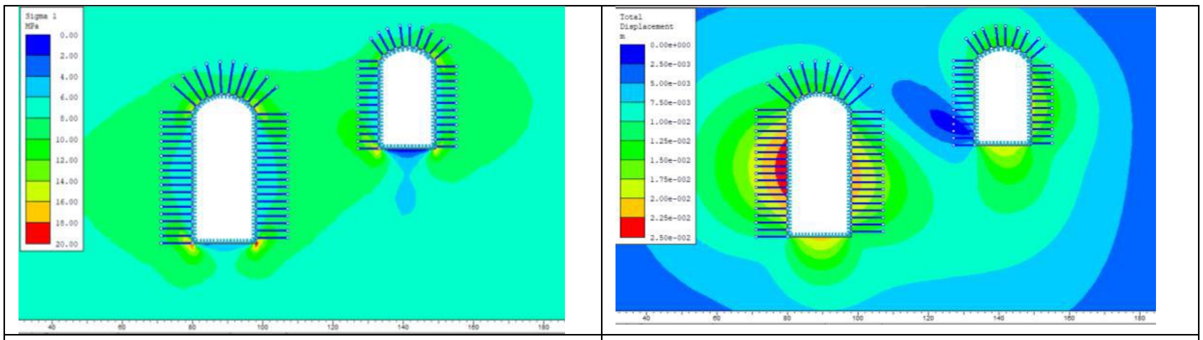
Sl. No.	Parameters	Case 1 N61^{0}E –S39^{0}W	Case 2 N10^{0}W-S10^{0}E	Case 3 N40^{0}W-S40^{0}E	Case 4 N10^{0}E-S10^{0}W
1	PH-Wall displ. (mm)	25	25	15	27
2	PH-roof displ. (mm)	15	15	17	15
3	PH-Invert disp. Upward (mm)	21	20	22	21
4	Plastic zone thickness on walls of PH (m)	7.0	6.0	7.5	7.0
5	Plastic zone thickness on walls of TC	6.0	5.5	6.0	6.0
6	Max. stress encountered (MPa)	17.9	18.6	14.6	18.4
7	Force on rockbolt (kN)	150	130	120	160
8	Axial force on shotcrete (x10^3 kN)	6.7	6.6	5.6	6.8
9	Remarks	Displacement within limits Supports are not yielding Length of Bolts > Plastic Zone.	Displacement within limits Supports are not yielding Length of Bolts > Plastic Zone.	Displacement within limits Supports are not yielding Length of Bolts > Plastic Zone.	Displacement within limits Supports are not yielding Length of Bolts > Plastic Zone.
10	Optimisation	Length of Bolts in roof can be reduced to 6 m. Side wall – No change	Length of Bolts Roof - Can be reduced to 6 m. Walls – Can be upto 7.5 m	Length of Bolts Roof: Can be reduced to 6 m. Side walls – No change	Length of Bolts Roof - Can be reduced to 6 m. Side walls – No change
11	Transformer Cavern	Length of Bolt on U/s and D/s walls considered to be 7.5 m and 6 m in all cases.			

For all the orientation options (Case-1 to Case-4); expected major stress, minor stress, total displacements and yield zone from the numerical studies are presented in Figures 6 to 9.

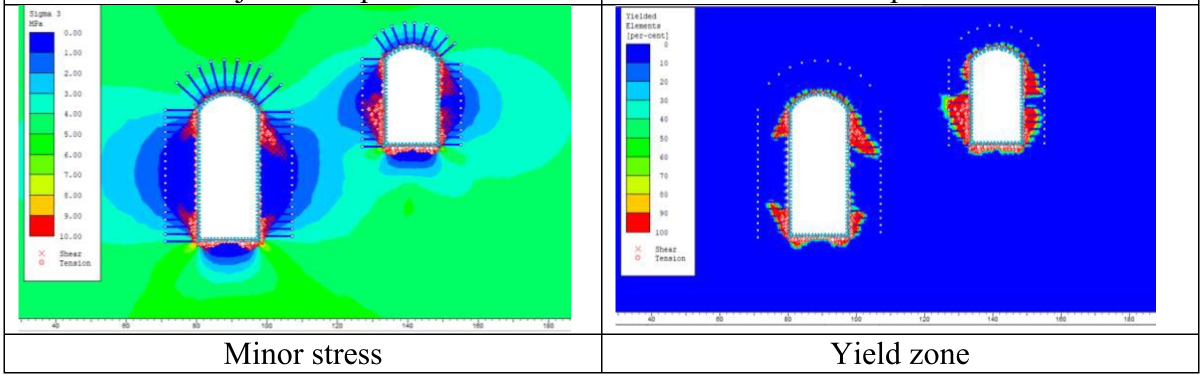
7. RESULTS AND DISCUSSIONS

Due to higher vertical stress than horizontal stress, the alignment selected as per in-situ stress measurement i.e., N40^{o}W-S40^{0}E (Case 3) requires more artificial support than rotating by 30^o clockwise from the major horizontal stress axis in N10^{o}W-S10^{0}E direction. The ratio of horizontal to vertical stress i.e, $K < 1$; in such cases, the powerhouse alignment shall be based on geologically favourable orientations and supported by numerical modelling results. Numerical studies also confirm the orientation favouring geology.

Numerical studies indicated minimum depth of plastic zone of the order of 6 m in walls of powerhouse with alignment favouring geological conditions (Case 2) whereas the remaining three alignments suggest extent of plastic zone as 7 -7.5 m. Alignment favouring in-situ stresses suggest minimum wall convergence of the order of 15 mm and roof displacement of 15-17 mm. Expected invert upheaval of the of the order of 20 -22 mm can be attributed to the stress ratio k being less than 1 (0.64 in this case).

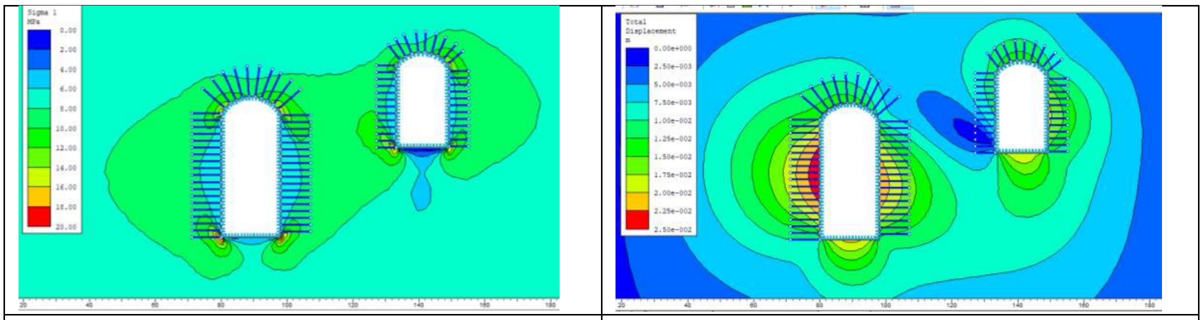


Major stress plot | Total displacement

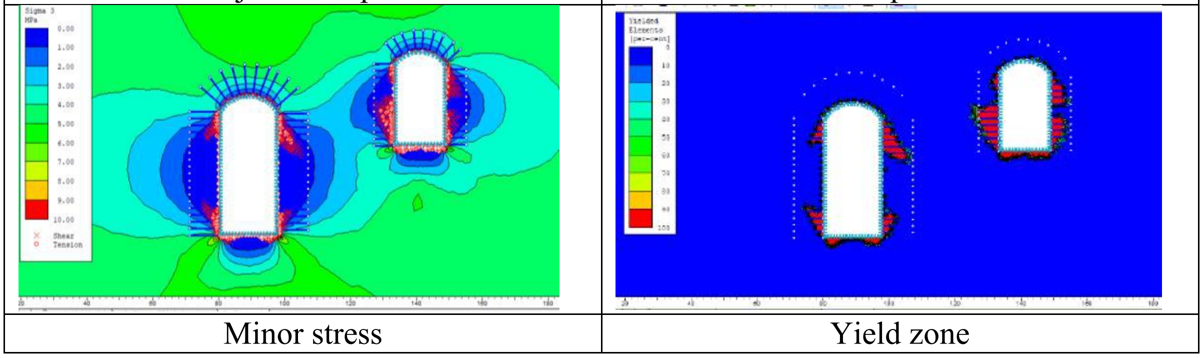


Minor stress | Yield zone

Fig. 6 - Results of model studies for cavern alignment in N61^{0}E-S39^{0}W direction (Case-1)

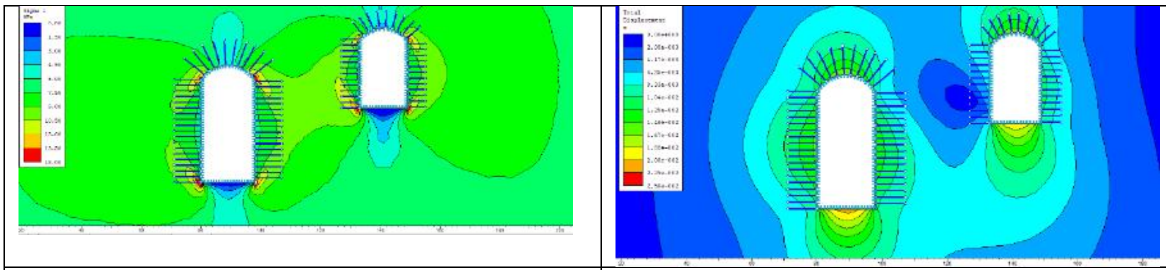


Major stress plot | Total displacement



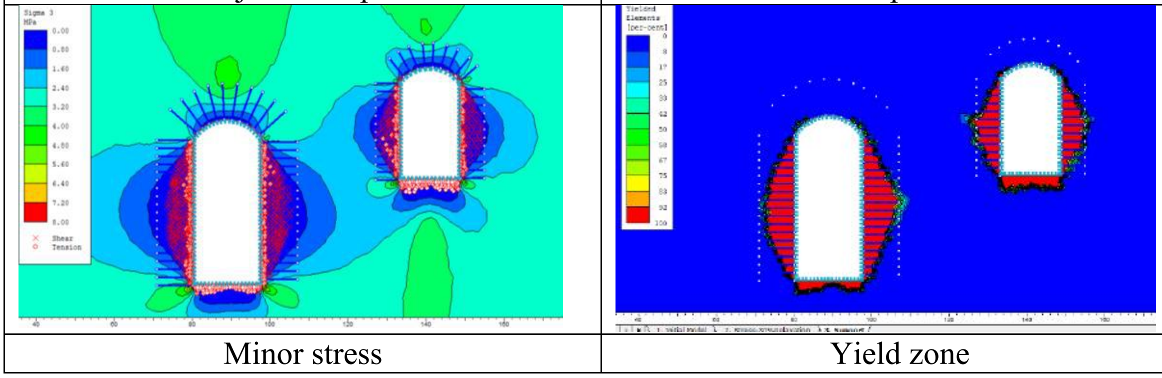
Minor stress | Yield zone

Fig. 7 - Results of model studies for cavern alignment in N10^{0}W-S10^{0}E direction (Case-2)



Major stress plot

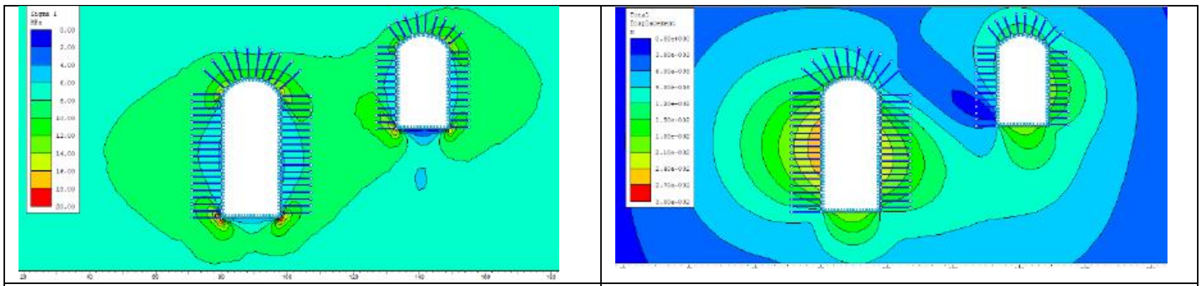
Total displacement



Minor stress

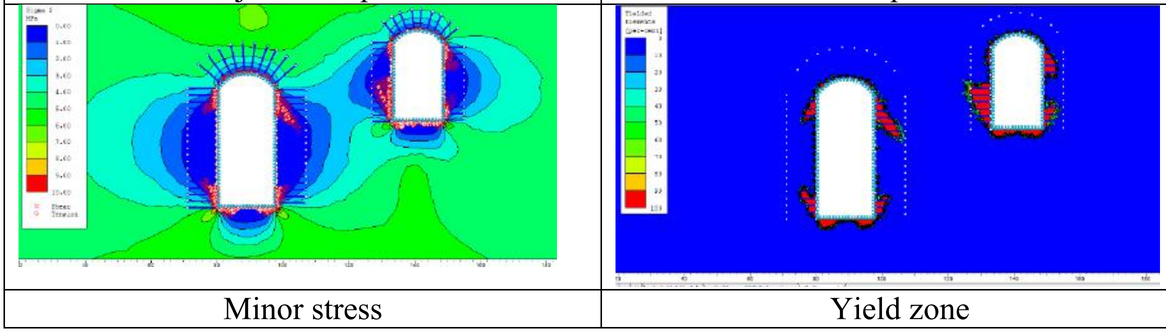
Yield zone

Fig. 8 - Results of model studies for cavern alignment in N40^{0}W-S40^{0}E direction (Case-3)



Major stress plot

Total displacement



Minor stress

Yield zone

Fig. 9 - Results of Model Studies for Cavern Alignment in N10^{0}E-S10^{0}W direction (Case-4)

Further, aligning the cavern in N10°W-S10^{0}E disfavours the hydraulic considerations. Therefore, numerical analysis was carried out by rotating the cavern 20^0 in clockwise direction i.e., in N10°E-S10^{0}W partially favouring the geological and hydraulic flow considerations. Numerical modelling results showed no significant variation in rock supports and resultant deformations.

As per Numerical modelling, the most favourable orientation of the power house cavern is N10°W-S10^{0}E (Case 2). Hence, based on the criteria, the optimal orientation of power house cavern is suggested as N10^{0}E-S10^{0}W (Case 4). This requires some alterations in water conveyance arrangement, but these can be manageable. The wall and roof convergences of the order of 27 mm and 15 mm, respectively are expected. The model suggests 7 m depth of plastic zone around the cavern. The power house cavern requires 9 m long rock bolts both ways at centre to centre spacing of 2 m to cater to maximum stress with mesh reinforced shotcrete 200 mm thick all along the cavern roof. Further, based on the stress distribution pattern, the length of the rock bolt can be optimised to 6m in roof whereas walls can be supported with minimum of 7.5 m long rock bolts at different elevations/cross sections. For transformer cavern, length of rock bolts can be kept as 6 m long on downstream wall and 7.5 m on the upstream wall.

8. CONCLUSIONS

Primarily, the orientation of any cavern primarily depends on bedding joint and stresses with regard to stability issues as well as optimal design. Underground caverns for hydropower development are guided by hydraulic flow considerations too. Sometimes, mid-way path may be required for aligning the caverns for hydropower development as too much rotation in water conveyance system leads to complexities in hydraulic flow apart from economic considerations.

Numerical modelling tools are suggested in case of indecisions arising out of the various criteria. In all the cases, the stability of the underground cavern should be given top priority. In extreme cases where stability issues are not getting addressed, the cavern can be relocated.

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