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Design of support system for surge shaft and powerhouse complex using *FLAC3D*

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1 INTRODUCTION

Hydroelectric projects in hilly terrains mainly consist of excavation of tunnels, shafts and caverns for the generation of electricity. In this study, the design of support system and the behavior of the underground surge shaft, machine hall cavern, transformer hall cavern and associated tunnels for an upcoming hydroelectric project in India are examined using 3D continuum analysis. The three-dimensional analysis of the surge shaft and the caverns were carried out by using *FLAC3D* (Itasca 2017) software.

Underground surge shaft has a diameter of 20 m and a height of 67.5 m. The size of the machine hall cavern is 58 m (L) × 18.8 m (W) × 33.70 m (H) and transformer hall cavern is 73.11 m (L) × 12.2 m (W) × 13.65 m (H). Machine hall cavern and transformer hall cavern are separated by rock pillar having a thickness of 35 m. Maximum rock cover of about 165 m was present above the powerhouse complex. The water is conveyed from surge shaft to powerhouse through two numbers of pressure shafts having a diameter of 4 m and each having a length of about 154 m.

2 GEOLOGY

The rock mass in the surge shaft and powerhouse complex consists of mainly metamorphic rock variants i.e. Porphyroblastic Gneiss, Biotite Gneiss, Quartzite Biotite Schist and Basic Rock. The rock mass in general is highly foliated and sheared. A drift having a length of about 327 m reaching crown of powerhouse has been excavated. The drift of the powerhouse area was encountered with shear and fractured zone and the same is expected in powerhouse walls also. The Pegmatite intrusion is also observed at the center of the excavated drift area. The geology incorporated in the model is based on the available information of two borehole logs and drift to powerhouse.

3 GEOTECHNICAL DATA

The rock mass properties for the model are arrived based on the empirical estimates given by Hoek & Diederichs (2006) using the intact rock parameters like Uniaxial compressive strength, GSI, elastic Young's modulus and mi. Intact rock properties were available for the four rock variants namely Porphyroblastic Gneiss, Biotite Gneiss, Quartzite Biotite Schist and Basic Rock. Properties with disturbance factor (D) value zero was used for arriving at the rock mass parameters. A blasting zone of 2 m all around the excavation of surge shaft, machine hall cavern and transformer hall were considered in the model. Properties with disturbance factor of 0.8 were assigned to the blasting zone. The material properties considered for different rock variants are given below in Table 1.

Table 1. Material properties considered in the analysis.

Parameters		Units	Porphyr-oblastic Gneiss	Biotite Gneiss	Biotite Schist	Basic Rock	Fractured Rock	Shear
Uni-axial compressive strength	UCS	MPa	50	42.24	61.44	40.32	40.32	40.32
Geological strength index	GSI		52	45	51	36	32	20
Elastic Young’s modulus of intact rock	Ei	GPa	22.85	21.24	24.75	18.54	18.54	18.54
Poisson’s ratio	ν		0.24	0.26	0.27	0.21	0.21	0.21
Density	γ	kg/m^3	2750	2600	2600	2600	2200	1800
Average overburden depth	z	m	120	120	120	120	120	120
m_i			20	28	12	12	12	12
Disturbance Factor D=0								
Elastic Young's modulus of rock mass	E_{rm}	GPa	7.9	4.7	8	2.2	1.7	0.7
Cohesion	c	MPa	0.829	0.725	0.839	0.483	0.44	0.253
Friction angle	φ	Deg	53.64	53.25	50.69	43.31	41.9	39.89
Tensile strength	σ_t	MPa	0.067	0.023	0.127	0.026	0.019	0.008
Disturbance Factor D=0.8								
Elastic Young's modulus of rock mass	E_{rm}	GPa	2.37	1.43	2.41	0.7	0.65	0.47
Cohesion	c	MPa	0.540	0.466	0.509	0.27	0.24	0.11
Friction angle	φ	Deg	44.83	42.83	41.55	30.42	28.19	23.31
Tensile strength	σ_t	MPa	0.03	0.009	0.05	0.009	0.006	0.0021

4 IN-SITU STRESS DATA

Hydraulic fracturing tests were carried out in the drift to powerhouse cavern by NIRM to ascertain the direction and magnitude of principal stresses. Maximum horizontal principal stress direction was found to be N40° and the longitudinal axis of the powerhouse cavern is N45°, accordingly the stresses are resolved and applied in the model. Vertical stress is calculated based on the overburden depth of 164.5 m. The ratio of major horizontal principal stress to vertical stress is found to be 1.237 and ratio of minor horizontal principal stress to vertical stress is 0.618. These in-situ stresses are applied in the model initially before the start of any excavations in the model.

5 NUMERICAL MODELLING OF THE EXCAVATIONS USING *FLAC3D*

A 3D continuum model was constructed in *FLAC3D* with the actual geometry of the underground surge shaft, machine hall cavern, transformer hall cavern, penstock manifolds and draft tubes. The boundaries are placed at sufficient distance away from the excavation in order to prevent the end constraint effect. In the 3D model the actual topography has been modelled based on the contour plan. The 3D model showing topography and various components for excavations along with the geology are shown in Figure 1. Mohr-Coulomb material model was utilized to simulate the behavior of rock mass due to excavation. In the model excavation was carried as per the planned sequence of excavation.

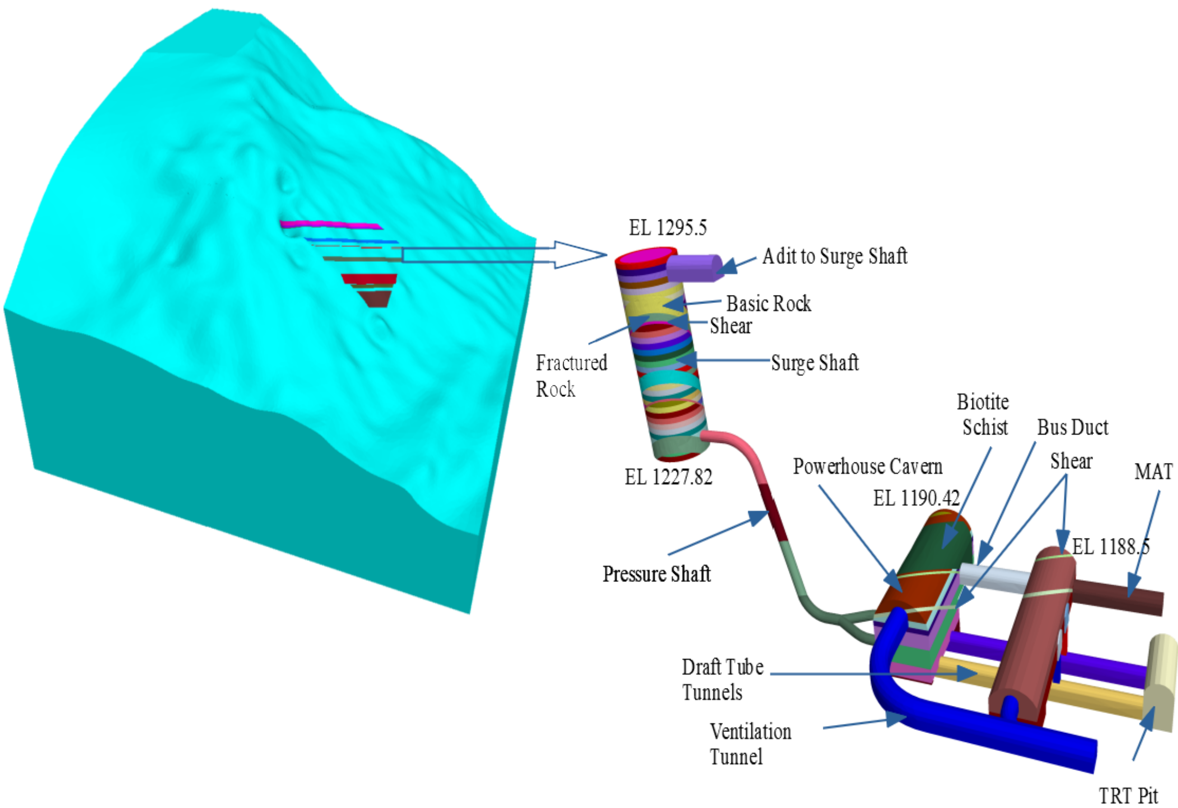

Figure 1. 3D View of the topography and geometry of the excavations along with geology modelled in *FLAC3D*.

6 SUPPORT SYSTEM

The following support system was considered for different excavations as given in Table 2.

Table 2. Support system considered in modelling for different excavations

Surge shaft	8 m long 32 mm dia. Fe500 rock bolts at 1.5 m center to center (staggered) 100 mm thick steel fiber reinforced shotcrete (SFRS)
Powerhouse crown	6.5 m long 32 mm dia. Fe500 rock bolts at 1.7 m center to center (staggered) 150 mm thick SFRS
Powerhouse walls	6.5 m long 32 mm dia. Fe500 rock bolts at 1.7 m center to center alternatively 10 m long 32 mm dia. Fe500 rock bolts at 1.7 m center to center (staggered) 150 mm thick SFRS
Transformer hall crown & walls	5 m long 32 mm dia. Fe500 rock bolts at 1.5 m center to center (staggered) 150 mm thick SFRS
Penstocks, draft tubes, ventilation tunnels & Main access tunnels	3 m long 25 mm dia. Fe500 rock bolts at 1.5 m center to center (staggered) 100 mm thick SFRS
TRT pit	4.5 m long 32 mm dia. Fe500 rock bolts at 1.5 m center to center (staggered) 100 mm thick SFRS

7 RESULT AND DISCUSSION

The results in the form of displacements, yield zones, stresses, strength to stress ratios and forces in the support system are analyzed for assessing the stability of the surge shaft, machine hall cavern, transformer hall cavern and other associated tunnels.

7.1 *Displacement*

Maximum displacement of about 36 mm was observed at EL 1254 in surge shaft where fractured rock mass intersects the excavation. The fractured rock has a thickness of 4.5 m at this location. Maximum displacement observed in powerhouse crown is 32 mm, on the upstream wall is 48 mm at RD 27 m and at EL 1167.8 m and on the downstream wall is 36 mm at RD 21 m and at EL 1178.2 m. The displacement magnitudes are largely influenced where the excavations intersect fractured rock mass and shear zones. The displacement contours on upstream and downstream wall of powerhouse cavern is shown in Figure 2.

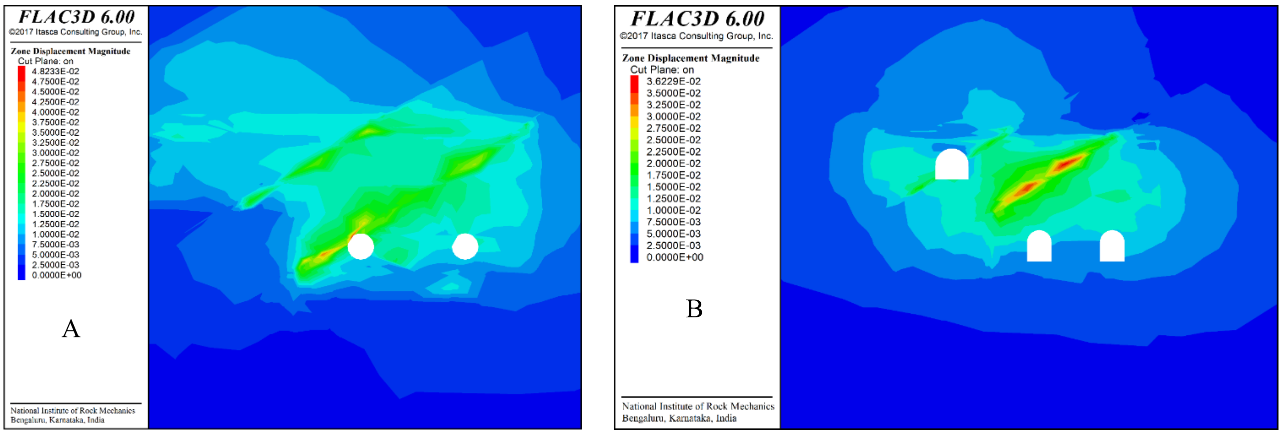

Figure 2. Displacement contours of powerhouse cavern (A) Upstream wall and (B) Downstream wall.

7.2 *Stress distribution*

Stresses in the rock mass gets redistributed due to the excavation activity. Stresses are analyzed based on the magnitude of maximum and minimum principal stresses. Major principal stress of the order of 2 MPa to 10 MPa and minor principal stress of magnitude 0.005 MPa to 0.05 MPa was observed in the surge shaft. Similarly, in machine hall cavern, major principal stress of the order of 2 MPa to 9 MPa is observed, however higher magnitude of stress i.e. 21 MPa is observed at the junction of powerhouse cavern downstream wall with draft tube tunnel. Minor principal stress of magnitude 0.01 to 0.1 MPa was observed in the powerhouse complex. These stress values are well within the strength of the rock mass indicating the stability of the excavations. The maximum and minimum principal stress tensors at an RD of 30 m from the powerhouse cavern is shown in Figure 3.

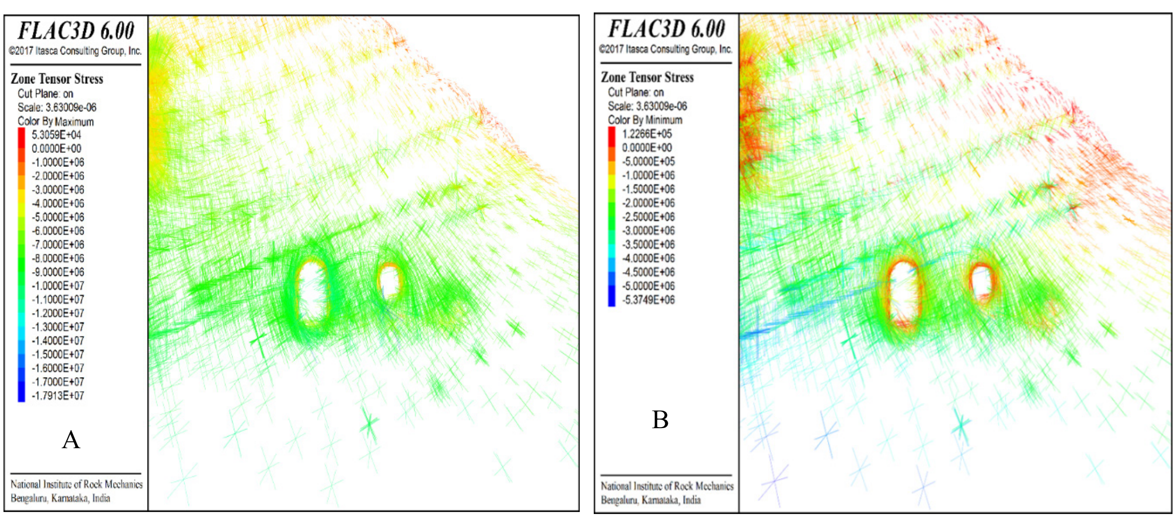

Figure 3. Principal stress tensors at RD 30 m from machine hall cavern (A) Maximum principal stress and (B) Minimum principal stress.

7.3 *Performance of support system*

It can be seen that the length of rock bolts is sufficient to restrict the displacements and yield zone at most of the locations of surge shaft and powerhouse cavern complex. It is observed that the axial force in rock bolts had attained their yield capacity where fractured rock mass and shear zone intersects the surge shaft and powerhouse cavern excavations indicating the failure of bolts. Hence, at these locations it is suggested to carry out consolidation grouting for a depth of about 8-10 m to improve the rock mass conditions. No breaking of bond is observed between the liner and the excavations. The extent of yield zone around the powerhouse cavern after complete excavation is given in Table 3.

Table 3. Extent of yield zone around the powerhouse cavern.

RD	Upstream (m)	Crown (m)	Downstream (m)	Floor (m)	Remarks
0	2.2	2	2	2.92	
5m	6.73	2	2.5	3.44	
10m	10	3.1	5.33	2.87	Draft tube and unit penstock intersection area on d/s and u/s wall
15m	12	5.03	6	3.93	
20m	11.8	5.5	6.9	7.09	
25m	8.2	5	8.7	2.23	
30m	8.4	3.27	7.7	3.34	
35m	5.6	2	4.2	-	
40m	6.2	2.7	2.4	8.8	
45m	3.2	3.5	4	3.81	
50m	3.2	2.54	5	2.9	
55m	3.2	3.8	2	4	
60m	3.2	2	4	-	

8 CONCLUSIONS AND RECOMMENDATIONS

- The support system considered for the excavations is found to be satisfactory.
- Fractured rock and shear zone material bands had considerable influence on the displacement pattern of surge shaft and on the crown and walls of machine hall cavern. Higher displacements of the magnitude 36 to 48 mm are observed at these locations.
- At intersections where surge shaft and machine hall cavern excavation fall in fractured rock and shear zone, the spread of yield zone is more. At these locations' consolidation grouting may be carried out to a depth of about 8-10m, to improve the rock mass parameters.
- The length of rock bolts needs to be increased to 8 m near the junctions of unit penstocks, draft tube tunnels and at other tunnel junctions.
- The orientation of the rock bolts must be decided based on the actual field conditions.
- Proper instrumentation plan needs to be implemented to capture the behavior of the rock mass surrounding the surge shaft, powerhouse complex and also to quantify the performance of the support system. Back analysis of the model has to be carried out if the displacement values differ from the predicted value during the excavation stage.
- In addition to regular instruments for measuring the displacement and loads, crack meters may be installed across shear joints and monitored regularly in order to assess the behavior of the shear joints.
- Further optimization of the supports can be done during the construction stage based on the instrument observations of parameters like wall displacements, convergence and load on the rock bolts etc.

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