Indian Society of Engineering Geology

Jour. Engg. Geol., Vol. XXXVII, Nos. 1-4

Stability Analysis of Underground Powerhouse of Malshej Ghat PSS Project, Maharashtra, India

P.C. Nawani, A.K. Naithani and Sripad R. Naik

Abstract

The proposed underground powerhouse complex of Malshej Ghat Pump Storage Scheme (700 MW) comprises a Machine-hall cavern and a Transformer cavern. The powerhouse is situated sufficiently away from the cliff of Malshej Ghat so as to have sufficient top and lateral covers. The proposed powerhouse area is located below the flat topography of the basaltic traps on the surface. The area was investigated through detailed engineering geological mapping on 1:1000 scale, exploratory drilling, laboratory core samples analysis and in-situ testing for stress measurements. Drill hole BHTC was drilled from the top of transformer cavern up to a total depth of 450 m while two deep drill holes BHPH-1 and BHPH-2 were drilled to explore the machine hall. In-situ stress measurements by hydrofrac method have been attempted in transformer hall and machine-hall areas. From the available surface and subsurface geological information, it has been interpreted that the rock types to be encountered in the powerhouse cavity will be grey fine grained compact basalts with laths of plagioclase, amygdaloidal basalts and volcanic breccia. The assessment of RMR and Q, for basaltic rock mass, based on the information available of the rock joints and their nature and drill holes core has been made. The basaltic rocks are falling under 'fair' to 'good' rock category. In this paper attempt has been made to analyse the stability of U/G powerhouse through 3D discontinuum model using 3DEC- incorporating the joint parameters, in-situ stress parameters and laboratory test data. The required support design for the safe construction was done and was evaluated using the 3D model so that optimum support requirement was emphasized in the study.

Introduction

The proposed Malshej Ghat Pumped Storage Scheme (PSS) for generation of 700 MW hydropower is located in Thane and Pune Districts of Maharashtra and envisages important structures such as concrete dams (upper and lower dam), spillways, head race tunnel (HRT), pressure shaft, underground power house and tail race tunnel. The underground powerhouse comprises a Machine-hall and a Transformer caverns. The size of machine-hall cavern is 119.4m (length) x 21m (width) x 46.0 m (height) and that transformer cavern is 90m (length) x 22m (width) x 23.5m (height). An underground powerhouse is considered suitable for the PSS due to large submergence required below MDDL at RL 263m. The centerline of the runner will be at RL 203m that is sufficiently below the MDDL in the lower reservoir, for the satisfactory operation of the pump-turbine. The corresponding level of bottom of draft tube will be at around RL 195.10 m and the deepest foundation level at RL 191.00m. The powerhouse is situated sufficiently away from the cliff of Malshej Ghat so as to have sufficient top and lateral covers.

In this paper, an attempt has been made to bring out the rock mass condition of power house and transform caverns of the proposed scheme on the basis of detailed engineering geological mapping, geological logging of drill holes, laboratory test result and *in-situ* stress measurement and to analyse the stability of U/G powerhouse through 3D discontinuum model using 3DEC- incorporating the above mentioned

National Institute of Rock Mechanics, KGF, 563117, Karnataka

parameters. The basic purpose of geotechnical investigations was to identify/ map different rocks and structures like joints, shear zones, faults, fracture zones, etc. and to determine engineering properties of rocks by lab testing. In order to forecast the geology of power house and transformer caverns and to estimate the rock mass characteristics, detailed engineering geological mapping has been carried out on 1:1000 scale with 2m contour intervals by deploying Total Station. The maps prepared during detailed investigation depict the boundaries of different geological units with structural data, areas covered by thin veneer of soil (from 0.2 to 3.0 m thick), vegetations, boulders, river and streams at the power house site. This area has been explored by core drilling with three vertical holes and their details are given in Table 1. Core samples from the borehole BHTC were tested for physico-mechanical properties of rocks in the laboratory. *In-situ* testing for stress measurement inside the bore holes BHPS-1 and BHTC in the power house area has been done. Rock mass classification using Q-system (Barton et.al. 1974) and Rock Mass Rating (RMR) system (Bieniawski, 1979, 1989) was attempted. Finally, through 3D discontinuum model using 3DEC, the required support design for the safe construction was done and was evaluated using the 3D model so that optimum support requirement was emphasized in the study.

Geology of the Area

The Malshej Ghat PSS project lies in the northern part of Western Ghats of Deccan Trap, within the Maharashtra Volcanic Provenance. This area is covered almost entirely by Deccan basalt (of Upper Cretaceous to Palaeogene age) except for a few patches of alluvium occurring in the valley portions. The rocks of the power house area fall under Salher/ Jawhar Formation of the Kalsubai sub-group separated from Lower Ratangarh / Igatpuri Formation by a giant plagioclase phenocrysts horizon at or near the formation boundary (Godbole *et al.*, 1996; Bodas *et al.*, 1988, 1985; Beane *et al.*, 1986; Hopper *et al.*, 1988). The Jawhar Formation contains aphyric to microphyric to giant plagioclase basalt (GPB) through porphyritic types with occasional flow top breccia. It comprises pahoehoe and simple flows (a'a). In this area in the compound flow joints are random and irregular with multiple scarps and at the bottom of flow pipe vesicles were reported. The compound flows contain several units, which vary in thickness from less than a meter to several meters and are normally aphyric to feldspar phyric. The contact zones between the successive lava flows are moderately to highly weathered and marked by the presence of flow breccia, predominance of amygdules at the top of the lava flow, pipe amygdalues at the bottom of the upper flow or red-bole bed. Flow breccia

Table 1: Results of drill holes data in the power house area.

1	2	3	4	5	6	7	8	9	10
BHPH-1	677.07	Vertical	450.0	1.25	86-100	44-100	75.5	W-I to W-III	Compact basalt, amygdaloidal basalt, volcanic breccia, red bole and porphyritic basalt with laths of plagioclase
BHPH-2	674.6	Vertical	450.0	0.25	87-100	59-100	131.0	W-I to W-III	Compact basalt, amygdaloidal basalt, volcanic breccia, red bole and porphyritic basalt with laths of plagioclase
BHTC	674.578	Vertical	450.0	3.0	96-100	75-100	-	W-I to W-III	Compact basalt, amygdaloidal basalt, volcanic breccia, red bole and porphyritic basalt with laths of plagioclase

1- Borehole number, 2- Ground elevation, 3- Angle with horizontal, 4-Total depth (m), 5- Thickness of overburden (m), 6- Core recovery (%), 7- RQD (%), 8- Depth of water table, 9- Weathering grade, 10- Rock types contains angular, sub-angular rock fragment of older flow. Drilling at this site has confirmed that excavation of power house and transformer caverns will be through grey fine compact basalts with laths of plagioclase, volcanic breccia, grey amygdaloidal basalts and coarse grained compact basalts. In this area traps show two and more sets of vertical joints. Horizontal joints are parallel to the top or bottom surfaces. Two sets of columnar joints are reported in thicker flows. Fractures are reported and they are generally parallel to the prominent joint directions. Conchoidal fracturing of the rock mass is a common feature. No curviplanar (fold) structure has been reported from this area. Some of the joints and micro fracture are developed due to cooling of hot lava while some are tectonic in origin. Mafic dykes are very prominent along the Kalu river and its tributaries. The width of dykes varies from ~32cm to ~3.5m and the length of the dykes varies from ~ 3.5 km to ~4 km. The mafic basaltic dykes show prominent columnar joints (horizontal and vertical sections). A suspected fault, trending N-S along the nala and disposed very close to MTDC Guest House, was mapped. It is a vertical fault and a displacement of about 1.4m was recorded in the field. This fault is likely to intersect the proposed penstock alignment and it may intersect at 40m and 100m away from the locations of underground power house and transformer cavities respectively. This fault needs to be verified during construction of main drift to power house. No significant shear zone was noticed in the area.

Geotechnical Investigations

Initially the powerhouse cavern was located to the north of the present location oriented in a general north-south direction and based on the preliminary investigations the Geological Survey of India, had commented that layout of the powerhouse being closer to the lower reservoir rim was apprehended to result in heavy seepage into the powerhouse cavity due to jointed nature of rocks. Taking this into consideration and also existence of topographic depressions, the powerhouse cavern was recommended to be located southward by about 500m below the steep rock slopes. The power house is located U/G on considerations as enumerated below:

a) The topography of the region is not suitable for surface penstocks and power house as the hill slopes are nearly vertical.

b) In the design of steel lining for the pressure shafts 50% of load due to internal pressure is assumed to be taken by surrounding rock. This benefit is not available in case of surface penstocks. Moreover, the length required for surface penstock is also likely to be more.

a) The geological and topographical conditions of this region are quite similar to Vaitarna and Koyna HE projects which have underground powerhouses.

Geological Mapping and Exploration

The proposed powerhouse is located below the flat topography of the traps on the surface. Geological mapping has been carried out on 1:1000 scale from dam site to the Malshej Ghat rock scarp up to the west of powerhouse area. At the surface on the top of powerhouse cavern, grayish black fine grained compact basalts and amygdaloidal basalts with thin cover of soil (from 0.2 to 3.0 m) are present along with isolated patches of sparse forest cover. On the surface, compact basalts are highly (W-IV) to moderately (W-III) weathered and three sets of joints are prominent. Along the nala, 40m upstream of powerhouse, which is controlled by suspected N-S trending fault, compact basalts are exposed. The prominent sets of joints recorded in the compact basalts and amygdaloidal basalt at the top of power house area are given in Table 2 and 3. The power house area was explored by core drilling with three vertical holes each upto a depth of 450m, two on the top of machine hall (BHPH-1, BHPH-2) and one at the top of transformer cavern (BHTC-1). Above the powerhouse cavity, bed rock comprising of grey fine compact basalts with laths of plagioclase, volcanic breccia and coarse grained compact basalts have been met. The general core recovery in this zone is varying from 96% to 100% and RQD is 56% to 100%. It has been interpreted on the basis of drilling data that the rock types to be encountered in the power house and transformer hall will be grey fine grained compact basalts with laths of plagioclase. The prominent sets of joints recorded from drill core data in the compact basalts with laths of plagioclase have the following characteristics: 10° (dip amount)/ joint surface smooth-planar, 20°/ smooth-planar, 30°/smooth-planar, 50°/ smooth-planar, 65°/smooth-planar, 65°/ smooth-undulating, 70°/smooth-planar, 80°/ smooth-planar, vertical/smooth-planar. The rocks are fresh (W-I). Depth of water table measured at the time of drilling of BHPH-1 and BHPH-2 was at 75.5m and 131m respectively. One drift of 1035 m long from TRT portal upto power house grade was recommended to explore the actual geological conditions at the underground power house location by identifying rock types, structural discontinuities, shear zones, faults, weak zones and other adverse geological features. This drift will also be used for *in-situ* stress measurement and deformation modulus of rock mass.

On the basis of exploratory drill holes data, assessment of rock masses expected to be encountered during the excavation of the machine hall and transformer caverns is given in Table 4 and shown in geological section (Fig. 1).

Laboratory Testing

Triaxial compression tests under dry and water saturation conditions on core samples from the borehole BHTC and estimation of cohesion (shear strength) and friction angle were carried out at NIRM lab and the test results are summarized in Table 5.

Table 2: Prominent joint sets developed in compact basalts at the power house area

Type of Joint	Strike or Dip Direction/ Dip	Spacing (Cm)	Persistence (m)	Roughness	Aperture (mm)	Infilling	GW
Vertical	NW-SE	10-80	2-5	RP, RU	2	Calcite	Dry
Vertical	ENE-WSW	50	>5	RU	Closed	None	Dry
Vertical	NNW-SSE	50	5-6	RU	Closed	None	Dry
Vertical	NE-SW	25-60	3-5	RU	Closed	None	Dry
Vertical	WNW-ESE	30-60	2-5	RU	Closed	None	Dry
Vertical	N-S	30-40	2	RU	Closed	None	Dry
Sheet Joint	-	20-60	>20	RU	Closed	None	Dry
Inclined	S/45°	60	>5	RP	Closed	None	

Table 3: Prominent joint sets developed in amygdaloidal basalts at the power house area

Type of joint	Strike or Dip Direction/ Dip	Spacing (cm)	Persistence (m)	Roughness	Aperture (mm)	Infilling	GW
Vertical	WNW-ESE	5-40	10-20	RU	Closed	None	Dry
Vertical	NW-SE	10-60	5-10	RU, RP	Closed	None	Dry
Vertical	NNE-SSW	10-50	2-5	RU, SP	1-2	Soil material	Dry
Vertical	NNW-SSE	20-60	3-5	RU, SP	1	None	Dry
Vertical	ENE-WSW	25-60	1-20	RU, RP, SP	5	None	Dry
Vertical	NE-SW	25-50	1-5	RU	0.5	None	Dry
Inclined	SE/50°	25	3	RU	Closed	None	Dry

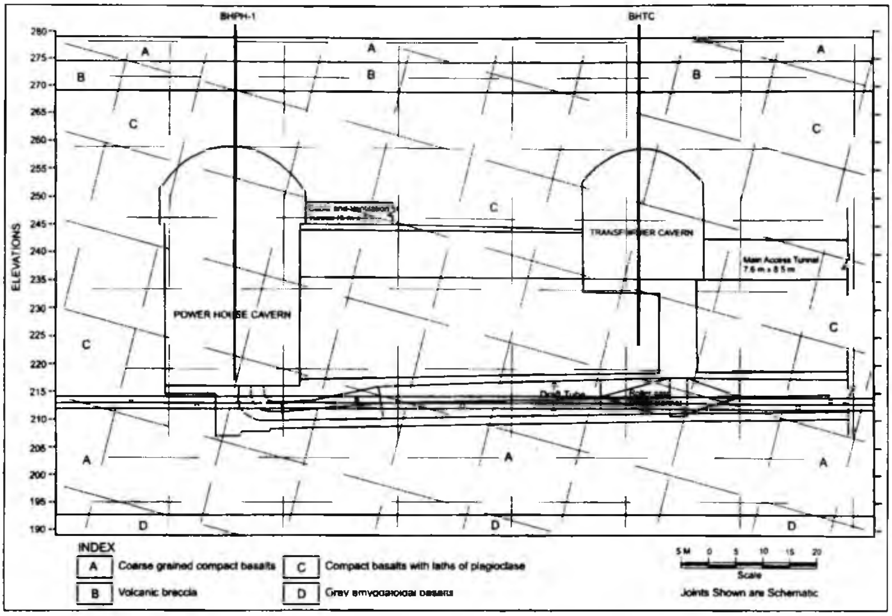

Fig. 1: Geological section of the power house and transformer caverns

Table 4: Assessment of the rock masses expected in power house area.

Elevation (m)	Rock type	Number of joint sets	Weathering grade	RQD (%)	RMR	Q	GSI (From RMR_{89})
275.0 to 269.0	Volcanic breccia	One plus random	W-I	100	55-60	12	50-55
269.0 to 214.0	Grey fine grained basalts with laths of plagioclase basalt	Three	W-I	83 -100	60-65	13	55-60
214.0 to 213.0	Volcanic breccia	One plus random	W-II	100	55-60	12	50-55
213.0 to 212.0	Grey amygdaloidai basalt	Two	W-II	94-100	60-65	14	55-60
212.0 to 192.5	Coarse grained compact basalts	Three	W-I to W-II	89-100	65-70	17	60-65
192.5 to 187.5	Grey amygdaloidal basalt	One plus random	W-I	96-99	60-65	14	55-60
Based on drill holes BHPS-1, BHTC and BHTR-2							

Table 5: Results of lab tests to rock samples – power house area

Rock Type	Location	Depth (M)		Cohesion, MPa		Friction angle, Deg	
		From	To	Dry	Saturated	Dry	Saturated
Volcanic breccia	BHTC	27.45	27.95	25.07	19.12	27.07	26.14
Compact basalt	BHTC	89.52	89.89	32.98	32.37	26.00	25.24
Compact porphyritic basalt	BHTC	271.33	271.59	28.52	29.14	32.00	25.61

Hydrofrac Test

Hydrofrac stress measurements inside the boreholes BHTC and BHPS-1 which were drilled on the top of transformer cavern and along the alignment of pressure shaft have been carried out. The stress regime evaluated is given in the Table 6.

Table 6: Stress regime at the proposed powerhouse of Malshej Ghat PSS project

Maximum horizontal principal stress (σ_H)	6.24 + 0.929 MPa
Minimum horizontal principal stress (σ_h)	2.08 $\pm$ 0.3099 MPa
Vertical Stress (σ_v)	3.40 MPa
Orientation of the maximum horizontal principal stress (σ_H)	N140°

Numerical Modeling of Powerhouse

In order to access the stability of the powerhouse complex, three dimensional numerical analysis was conducted by modeling the machine hall, transformer hall and bus ducts. Surrounding rock mass along with the joint characteristics was simulated in the model. The geometrical, geological and geotechnical details described in the previous sections were incorporated in the stability analysis. Three dimensional distinct element code (3DEC) was utilized for the analysis. A disturbance zone of 3m was created around the caverns in order to simulate the conditions due to blasting. The perspective view of powerhouse complex is shown in Fig. 2. The stability analysis was performed on the model without supports based on the displacement profiles obtained after complete excavation.

Numerical modeling studies revealed maximum displacements were occurring on the crown of both machine hall and transformer hall as shown in Fig. 3. The displacements in machine hall were found to be higher than the transformer hall. The bus ducts also experienced significant displacements due to the excavation. Maximum displacement of 0.165m between RD 70 and RD 90 were predicted in the crown of machine hall. Similarly, maximum displacement of 0.14m between RD80 and 100 has been estimated in the transformer hall and in bus ducts it is 70mm. The stability analysis was carried out using Mohr Coulomb yield criteria. Results indicated that the rock mass surrounding the machine hall and transformer hall have low factor of safety (<1.5) (Fig. 4). This may be attributed to the disturbance zone created due to the blasting of the rock mass during excavation which was simulated in the model. Similar results were found in the rock mass around the bus ducts. However, rock mass up to a distance of 10m-12m around the bus ducts was found to be affected due the excavation. Suitable designed support system having a combination of rock bolts and shortcrete

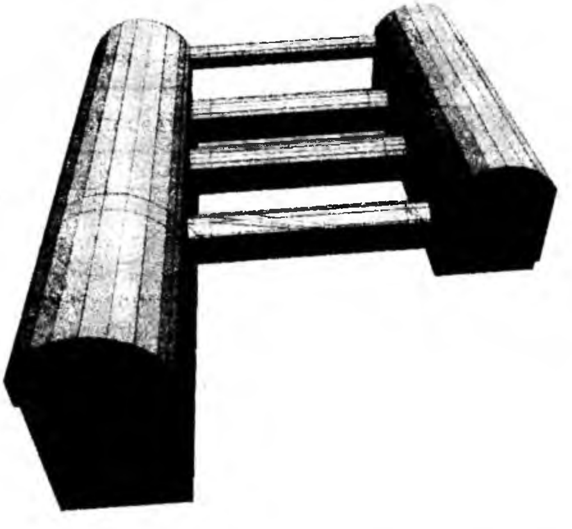

Fig. 2 Perspective view of the modeled powerhouse complex

lining was found necessary in order to improve the stability of powerhouse complex.

Conclusions

Based on above studies, the following inferences and recommendations have been made.

a) The irregular lava flows consisting of porphyritic compact basalts, amygdaloidal basalts, volcanic breccia and coarse grained compact basalts occur at the proposed power house location. Porphyritic basalt is grey and fresh and phenocrysts of feldspars are common. It is sparsely amygdaloidal in structure and least jointed at lower levels. Compact basalt with specks of feldspar is grey and fresh to slightly weathered. Joints are very common in the compact basalt. Amygdaloidal basalt is grey and fresh to slightly weathered. Volcanic breccia consists of fragments of amygdaloidal basalt and rarely jointed.

b) Flows of porphyritic / compact and amygdaloidal basalt are alternately occurring. The flow contacts seen during the logging have indicated that alternate thin and thick lava flows and thickness of the flows are generally increasing with depth.

c) As the lava flows have spread over extensive areas as horizontal sheets, the same lava flows are expected to occur at the same level.

d) In view of thick lava flows and less jointed fresh porphyritic basalts over the crown, no major geotechnical problems may arise during the excavation of the proposed underground power house. However, the horizontal disposition of the flow layers may cause separation of layers in the crown portion which need to be tackled by installing long rock bolts for ensuring effective stitching of flows.

e) Moreover, combination of vertical joints and horizontal joints may at places result into block falls at the crown level, which also need to be tackled by rock bolting and reinforced shotcreting.

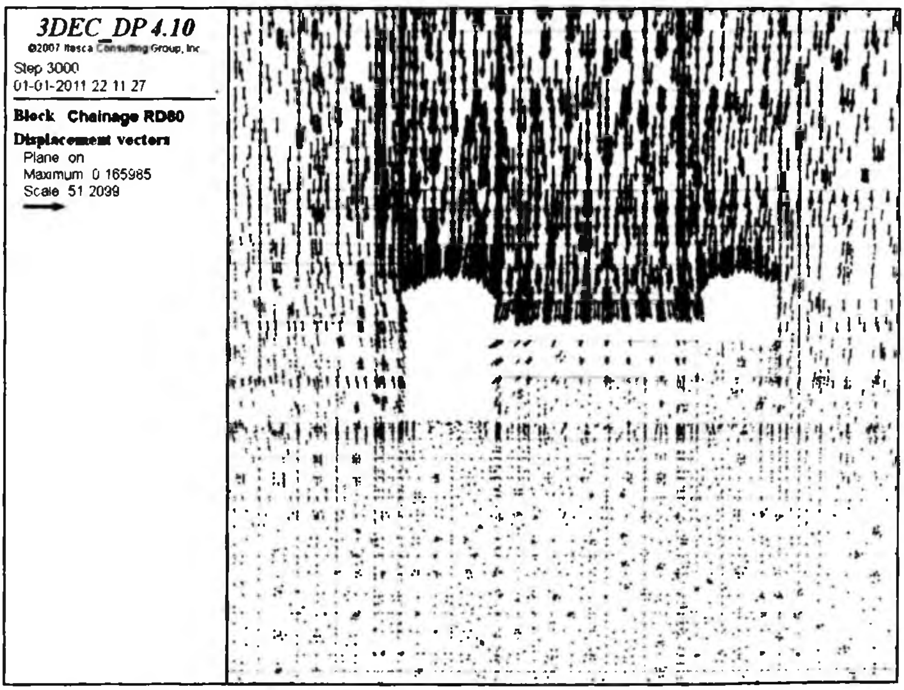

Fig. 3: Displacements in powerhouse complex at RD80

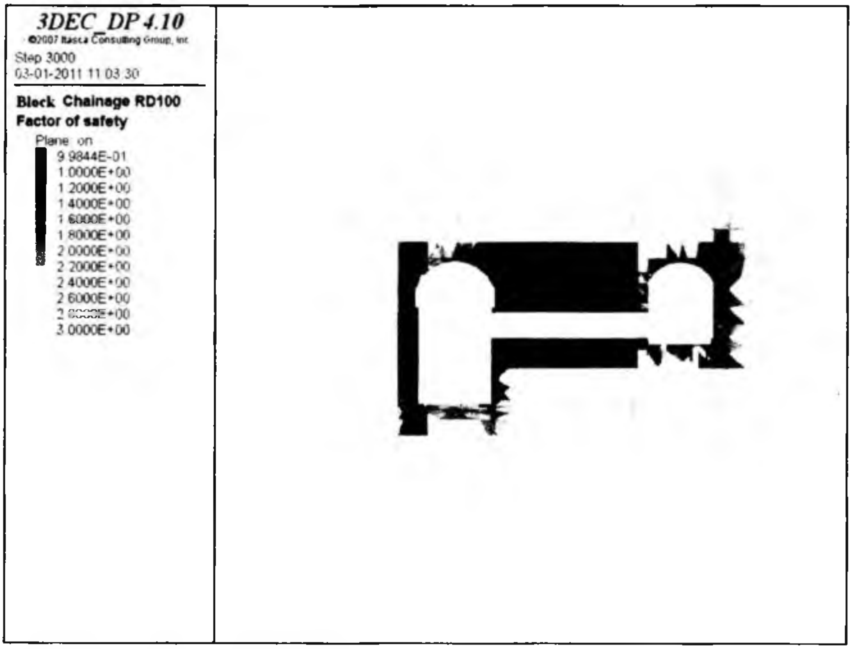

Fig. 4: Factor of safety contour at RD100

f) The vertical joints on the walls of caverns might at times also pose some problem related to convergence or bulging during benching down which ought to be arrested by rock bolting.

g) The alignment of the longer axis of the power house on the basis of orientation of the major principal axis of *in-situ* stress can be fixed at N40°W direction for maximum stability.

h) The water table is expected to play a role during excavation of the power house and water seepage cannot be ruled out in the powerhouse area. Provision for drainage gallery should be incorporated in the design.

i) Numerical modeling studies revealed that the maximum displacement of 0.165m and 0.14m can be expected in machine hall and transformer hall caverns respectively.

j) Factor of safety values were found lower than 1.5 in rock mass surrounding the caverns and bus ducts. Hence suitable support system should be designed for restricting the displacement and increasing the stability of the rock mass

Acknowledgements

The part of this paper is prepared from the DPR report of Malshej Ghat PSS Project, which was sponsored by NPCIL, Mumbai, so we sincerely thank the Management of NPCIL for the same. We also sincerely acknowledge the support extended by Mr. N. Madhusudhana Rao, Addl. Chief Engineer (Civil) and Mr. S. K. Tiwary, Addl. Chief Engineer, M/S NPCIL during the field investigations at the MGPSS site. We also sincerely acknowledge the co-ordination and support rendered by Mr. G. S. Choudhary, DGM, THDC India Ltd. We thank Mr. D.N. Krishna, Project Engineer (Civil) and Mr. K.S. Krishnamurthy, Consultant Geologist, TCE for technical interactions throughout the project period. Dr. Roshan Nair, Scientist at NIRM is thankfully acknowledged for help in numerical modeling.

References

Anon, 2010: A detailed report on engineering geological, geophysical and geotechnical investigations of Malshej Ghat PSS project (700 MW) Maharashtra, NIRM Report No. NIRM/TSD/NPCIL/PP-02/2007, 422p (Unpublished).

Barton, N.; Lien, R. and Lunde, J. 1974: Engineering classification of rock masses for the design of tunnel support. Rock Mechanics, vol. 6(4), pp 189-236.

Beane, J.E.; Turner, C.A.; Hopper, P.R.; Subbarao, V.K. and Walsh, J.N. 1986: Stratigraphy, composition and form of the Deccan Basalts, Western Ghats, India. Bull. Volcanol., vol. 48, pp 61-83.

Bieniawski, Z.T. 1979: The geomechanics classification in rock engineering application. Proc. 4th Internatl. Congress on Rock Mechanics, ISRM, Montreux, Balkema, Rotterdam, vol. 2, pp 41-48.

Bieniawski, Z.T. 1989: Engineering rock mass classification. John Willey & Sons, New York, 251p.

Bodas, M.S.; Khadri, S.F.R.; Subbarao, K.V.; Hooper, P.R. and Walsh, J.N. 1985: Flow stratigraphy of a part of the Western Deccan basalt Province: A preliminary study. Proc. of Fifth Session Indian Geol. Congr., pp 339-347.

Bodas, M.S., Khadri, S.F.R. and Subbarao, K.V. 1988: Stratigraphy of the Jawhar and Igatpuri Formations, Western Ghat lava pile, India. In Subbarao, K.V. (Ed.), Deccan Flood Basalts. Mem. Geological Society of India, No. 10; pp 235-252.

Godbole, S.M.; Rana, R.S. and Natu, S.R. 1996: Lava stratigraphy of Deccan Basalts of Western Maharashtra. Gondwana Geol. Mag. Spl. vol. No. 2, pp 125-134.

Hooper, P.R.; Subbarao, K.V. and Beane, J.E. 1988: The giant plagioclase basalts (GPBs) of the Western Ghats, Deccan Traps. Memoir Geological Society of India, No. 10.