Stability analysis of underground powerhouse caverns using discontinuum numerical modelling

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Abstract

In this paper, three dimentional modeling studies of power house and desilting chambers of Tala Hydroelectric Project, Bhutan and Nathap Jhakri Project and Tapovan Vishnugad Project in Himalayan conditions and the cases of Sardar Sarovar, Pykara, Srisailam, Ghatgar Pumped Storage in Peninsular India have been discussed. The paper presents important observations and recommendations from the numerical modeling of the underground caverns. In some cases, instrument data was available for back analysis and caliberation of the model. The numerical modeling results were used for substantiating the design in most of the projects.

Introduction

India is world's 5th largest energy producer, accounting for 4 per cent of global energy production (Anon, 2010). Energy resources of the country are unevenly distributed with bulk of the hydro resources in the northern and north-eastern part (Himalayan region), and fossil fuel resources in the central and western parts. Energy security is one of the major concerns in Indian scenario. About 75 per cent of the electricity consumed in India, is generated by thermal power plants, 21 per cent by hydroelectric power plants and 4 per cent by nuclear power plants

A large part of hydroelectric potential lies in Himalayan region which still young and extremely unstable with regards to its structure. The concerns regarding energy security can be satisfactorily met by detailed research and development (R&D) in the hydropower sector. A hydroelectric power plant consists of various components like the dam, reservoir, head race tunnels, powerhouse complex etc. The stability of these structures with respect to geology of the area is of utmost importance. Powerhouse complex consists of large underground caverns used for a variety of purposes including caverns housing turbines, generators and transformers. It comprises of machine hall, transformer hall, bus ducts, escape ducts etc. These caverns are constructed in close proximity to each other and their interaction plays a vital role with the stress and displacement during the construction.

Construction of underground excavations for hydroelectric projects is a challenging task due to complex hydro-geological conditions and tectonic influences. These complexities could be further aggravated by the non-homogeneity and anisotropic nature of rock mass, and their time dependent behaviour and *in situ* stress. Rock mass is seldom free of faults, joints or any other discontinuities. The stability of underground structures depends significantly on the jointing pattern and the properties of infilling. Their design is usually based on the prediction of redistributed stress around the opening and subsequent movements by considering these geological features. The high capital costs and risks associated to these facilities, design of the caverns must ensure minimum potential hazards and cost effective and practical engineering solutions.

The design of underground excavations is dependent on the material itself, the imposed disturbance due to excavations, state of stresses and rock properties. The

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disturbance caused during the excavation process generates deformation and development of fractures in rock mass. It may result into instability problem leading to failure or even collapse of the excavation.

Numerical methods can simulate different phases of excavation in caverns and identify critical situations at the design stage. As the excavation proceed, surrounding rock mass may fail leading to collapse in the opening, unless the walls of cavern are not supported. Prior knowledge of impending deformations can help in considering preemptive solutions. This paper addresses stability aspects of underground caverns analysed using 3DEC, a three dimensional discrete element code. Critical review of various cavern projects undertaken at National Institute of Rock Mechanics (NIRM) is presented and discussed.

Numerical modelling case studies

Three dimensional models with sequential excavations and support system have been analysed. The projects, which are discussed in this paper, are given below.

a. Ghatghar pumped storage project

b. Nathpa Jhakri hydroelectric power project

c. Pancheshwar multipurpose hydroelectric power project

d. Sardar Sarovar project

e. Tala hydroelectric project

f. Tapovan Vishnugad hydroelectric project

The 3DEC analysis included study of displacements, stress and factor of safety during excavation of the caverns and subsequent implementation of support system.

a. Ghatghar pumped storage project

Ghatghar Hydroelectric Project was first ever Roller Compacted Concrete (RCC) dam in India implemented by Irrigation Department of Government of Maharashtra (Gaikwad et al., 2003). It was constructed by creating two reservoirs and underground powerhouse near village Ghatghar in Ahmednagar District of Maharashtra. It provides for an installation of two reversible pump turbines/generator motor units each of 125 MW in an underground powerhouse complex. The underground

Fig. 1: Plan of numerical model developed for Ghatghar powerhouse complex

powerhouse consisted of two major caverns namely machine hall of 94m long, 23.4m wide and 47m high and transformer cavern of 77m long, 20m wide and 30m high and connecting tunnels (Rao and Gupta, 2001a). The caverns are parallel to each other and separated by a 43m pillar. The caverns are located at a depth of 290m below the surface. Excavations were done in compact basalt with rock mass classification as per Geological Strength Index (GSI) estimated as 70. There existed a fracture zone above the caverns at distance of 3m from the crown of transformer cavern. Modeling studies were conducted to analyse the efficacy of the support system and the stability of powerhouse as shown in Fig. 1 (Rao and Gupta, 2001).

Based on the modeling studies, it was concluded that powerhouse cavern experienced maximum horizontal displacements of 21mm in the upstream wall of powerhouse, whereas maximum deformations in the downstream wall were of the order of 10mm (Rao and Gupta, 2001). The maximum roof deformations in the powerhouse were 16mm. The factor of safety values were computed using Hoek and Brown failure criterion. During the sequence of excavation, rock mass failure was observed to a maximum extent of 10m on the upstream wall of the powerhouse. The remaining portions of powerhouse experienced failure up to 5-6m in the cavern wall. Results indicated that in case of transformer cavern, the failure extended to couple of meters only. The support system implemented in the caverns included system of rock bolts and 75mm shortcrete (Rao and Gupta, 2001). The support system was found to reduce the deformations by 30 to 40 per cent in the roof and 20 to 30 per cent in the walls. However, modeling studies revealed that there was some increase in the surface deformations of the walls in spite of 75mm thick shortcrete. Hence it was recommended to increase the thickness of shortcrete to 150mm. Further, it was concluded that rock bolts of 32mm diameter and 12m length should be provided between the bus ducts on the downstream wall of the powerhouse in the middle one third and 10m long bolts in the remaining portion at 1.5m spacing in order to strengthen the pillar between the two caverns.

b. Nathpa Jhakri hydroelectric power project

The 1500 MW Nathpa Jhakri Hydroelectric Project (NJHP) is one of the largest run of the river schemes in the world. It consists of a 60.5 m high concrete gravity dam, four intakes and four underground desilting chambers, a 10.15m diameter head race tunnel (HRT) of 27km length and 21m diameter surge shaft. Three pressure shafts, each 4.9m diameter, taking off from the surge shaft, feeds the discharge to six generating units of 250 MW each housed in an underground powerhouse utilizing a design head of 425 m. It has four egg shaped desilting chambers of 525m length, 16.31m wide and 27.5m height (Sharma, 2006). Desilting chambers, lying parallel to each other aligned N32°E–S32°W at 45.60 m c/c, are housed within augen gneiss under a rock cover of 150m to 490m. The rock mass was heavily disturbed with five joint sets. The average GSI of rock mass was found to be 63 with unconfined compressive stress of 52.89MPa.

The excavation in desiliting chamber was studied using 3DEC and adequacy of support system was analysed (Rao et al., 2003). The desilting chambers were analysed in two parts, i.e. without support system and with support system consisting of shotcrete of 150mm and rock bolts of 32mm diameter of 6m length at 1.5m spacing. Cable anchors of 20m long and 50t capacity at 3.75m spacing were also simulated along with the other support system. The effect of joint trace length was also analysed in the study. The results indicated that maximum displacements of 83mm were observed in the walls of the chambers with no support condition (Fig. 2). The entire rock mass between the chambers 2 and 3 near the Adit-II failed. There was a marginal reduction of displacements (10 per cent) by introducing

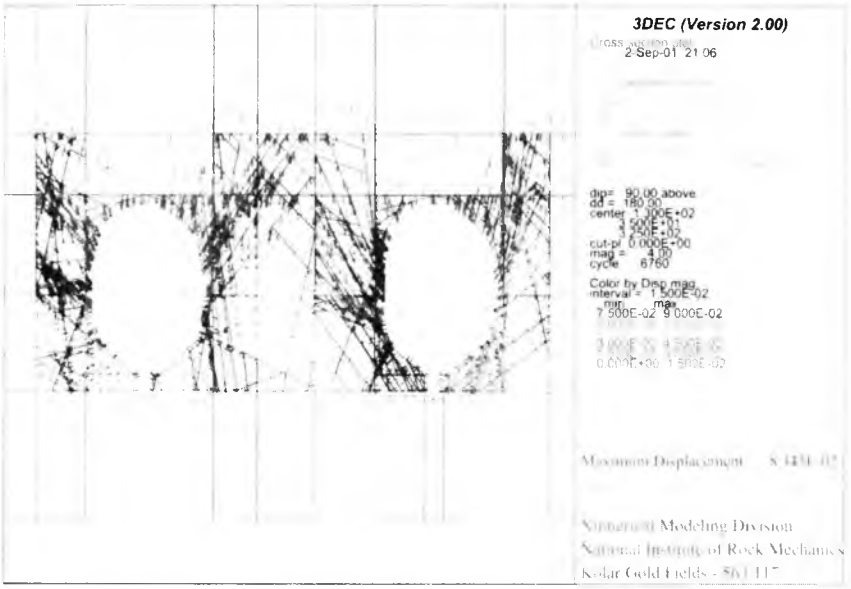

Fig. 2: Typical section of displacement predicted in desilting chamber at NJHP

support system. However, there was no improvement in the failed condition of rock mass between chamber 2 and 3. Cable anchors had insignificant effect in improving the condition of the rock mass (Rao et al., 2003). They also concluded that varying the trace length of the joints, affect the extents of rock mass failure and increase in trace length increase the extents of failure.

c. Pancheshwar Multipurpose Hydroelectric Power Project

The Pancheshwar Dam is located on the river Kali bordering northern India and Nepal. The project envisages to generate 5600MW of electricity by constructing 315m high rock fill dam which would constitute world's highest dam (Everard and Kataria, 2010 and Anon, 2007). The site is located about 70 km upstream of Tanakpur Barrage. Dam site is in the highly seismic Himalayan tectonic belt bounded by the Main Boundary Fault and Main Central Thrust. The project area lies within Almora Crystallines/Kalikot Formation (Dadeldhura Group) forming a part of lesser Himalayan belt. It consists of low to high grade metamorphic rocks of quartz-mica schist and augen gneiss (Kumar et al., 2003).

Powerhouse complex constitutes two underground caverns consisting of machine hall of 270 long, 23 to 27m wide and 45m high and transformer cavern of 270m long, 20m wide and 22m high with a rock cover of 220m. Various structural and geotechnical aspects pertaining to powerhouse complex were studied by using 3DEC as given in Fig. 3 (Rao et al., 2002):

a. Displacement around the excavations

b. Adequacy of the proposed support system

c. Increase of width of machine hall from 23m to 27m

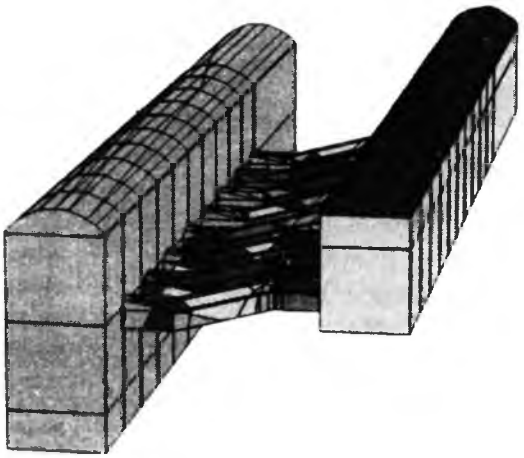

Fig. 3: Model developed for Pancheshwar power-house complex

The study predicted deformations of 100mm in case of 23m width of machine hall walls in Indian side (Rao et al., 2002). Introduction of support system reduced the deformations by 20 to 30 per cent. However in case of machine hall situated in Nepal side, deformations were found to be 250mm and 193mm with regards to model without supports and with supports, respectively. The study also revealed that increase of width to 27m causes severe deterioration of the structure. The entire pillar between bus galleries was predicted to fail in case of powerhouse on Nepal side.

d. Sardar Sarovar Project

It is a major dam on the river Narmada located at Navagam about 100 km south east of Vadodara in Gujarat. Sardar Sarovar roject consists of 121.92m high dam, 1200MW river bed powerhouse, 250MW canal head powerhouse and other water conducting system for canal and water supply (Anon, 2008). The river bed powerhouse complex consists of 23m wide, 57m high and 210 m long cavern, six pressure shafts of 9m diameter for intake of water from the reservoir to the powerhouse and six draft tubes of 16m wide double D shaped for drawing out water to collection pool.

Numerical studies were conducted on the effects of excavation of caverns, efficacy of support system and effect of dam loading on displacements and factor of safety of the rock mass as shown in Fig. 4 (Rao and Gupta, 2001b). Rock mass in the caverns consisted of layers of basalt separated by pockets of agglomerate. Intrusion of ENE-WSW trending dykes on the southern end of the cavern, and another dyke, which is vertically located beyond the northern end of the cavern. The major joint systems consist of three joint sets. In addition to the joint system, the major discontinuities consist of seven shear zones occurring in the cavern area. It was concluded that large movements of 50mm existed on the upstream wall near the pressure shaft 3 (Rao and Gupta, 2001b). Similarly, horizontal displacements of nearly 40mm were observed on the downstream wall between the bus galleries 2 and 3. Ramp removal increased horizontal displacements up to 20mm on the downstream side.

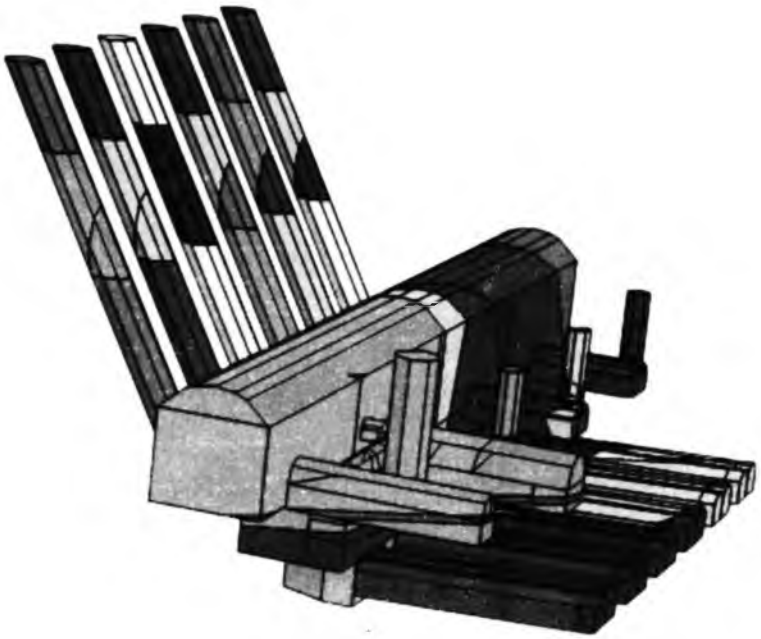

Fig. 4: Model of Sardar Sarovar powerhouse project

Deformations at the roof of cavern were found to be lesser in comparison to the walls of cavern due to high horizontal in situ stresses (Rao and Gupta, 2001b). The installed support system was found to be effective in reducing the horizontal movement of the walls in powerhouse. Zones of failure in the rock mass were also confined to the wedges formed in the upstream wall and downstream wall. As the extent of failure zones in the wedge regions are less than 20m, the support system consisting of 25m cable bolts on the downstream side, was found adequate. The impounding of dam caused insignificant increase in deformation. The numerical modeling studies were facilitated with field instrumentation and results were found in close relation.

e. Tala Hydroelectric Project

Tala Hydroelectric Project, the biggest joint project between India and Bhutan, is 1020MW run of the river project on the Wangchu river in Chukha Dzongkhag of western Bhutan. It is the region's largest high-head project with 92m concrete dam and underground complex consisting of 206m long, 20.4m wide and 44.5m high powerhouse and transformer hall of 191m long, 16m wide and 24.5m high. Rock formation at the site of powerhouse complex mainly comprised of nearly 67 per cent of poor to very poor rocks (ranging from class IV to VI) and 33 per cent of class II and III, according to Q system classification. Numerical model studies were conducted to estimate the stress distribution around the cavern and to analyse the adequacy of the support system installed in the powerhouse complex (Rao et al., 2005). Sequential excavation of powerhouse complex was simulated in 3DEC software and the displacements and factor of safety were analysed. Analysis revealed that maximum horizontal displacement of 360mm occurred on the downstream wall. The rock mass failure was predicted up to 10m on either side of machine hall whereas the roof of bus ducts experienced failure upto 7m (Fig. 5).

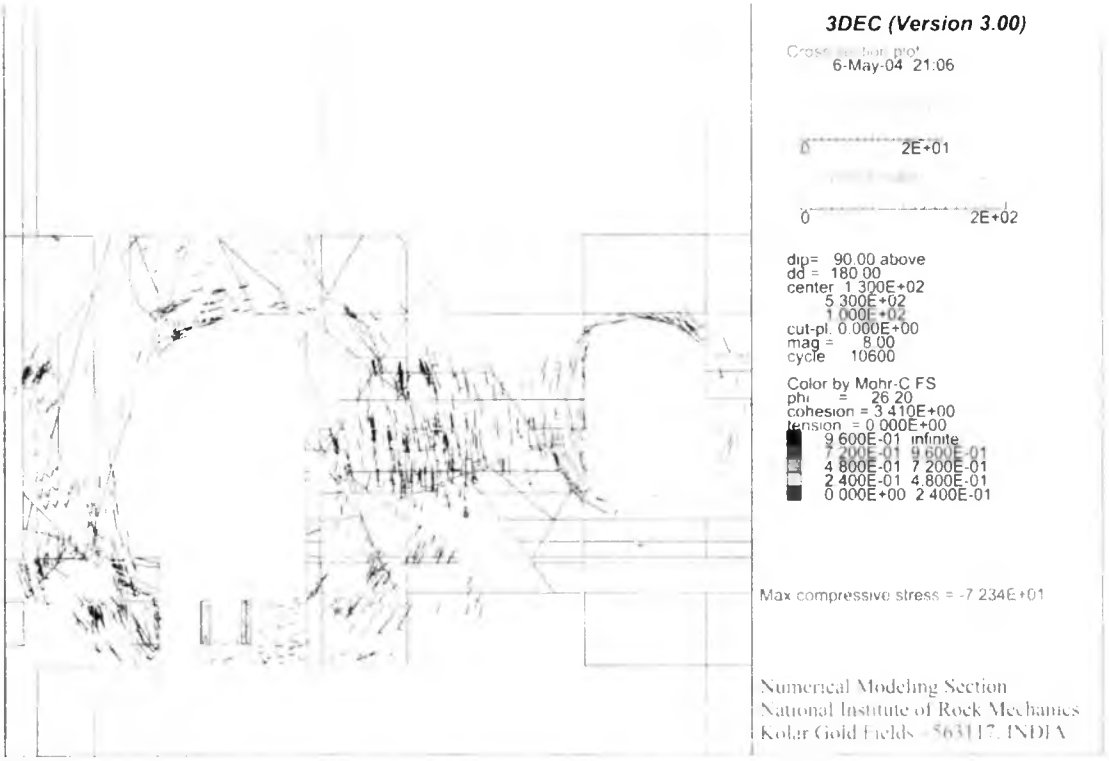

Fig. 5: Factor of safety along a section across powerhouse and machine hall

Maximum floor heave of 40mm was predicted at the turbine pit. Rock mass failure was found to be affected up to 15m around pressure shaft manifolds 1 to 4. The results also indicated 2.4 per cent failure of rock bolts in the upstream wall and 3.0 per cent in the downstream wall.

f. Tapovan Vishnugad Hydroelectric Project

Tapovan Vishnugad Hydroelectric Project (4 x 130MW) is a run-of-the-river project on river Alakananda, a tributary of Ganga situated in the state of Uttarakhand. The project area falls in the Uttarakhand Himalayas and is located within the Higher Himalayan Belt, north of the Main Central Thrust (MCT) - a low angle northernly dipping tectonic plane. The power house is located on the left bank of Alakananda river, near Joshimath. This scheme will generate 520MW of hydroelectric power. Dhauliganga river flows from higher altitudes in a southwest direction upto Tapovan. The river at barrage site flows in a NW course for a distance of about 400m, before its confluence with Alakananda river. The river flows closer to right bank and left bank is occupied by shoal material. The powerhouse area is bounded by ridge and stream to the north of Shelong village and Animath nala on the southern side, on the left bank of river Alaknanda. The powerhouse complex consists of three main underground excavations consisting of machine hall (158.5m x 22.3m x 48.6m), transformer hall (147.75m x 18.3m x 27.8m) and two bus ducts and other tunnels. Numerical analysis was conducted to ascertain deformations in powerhouse complex during excavation stages and adequacy of support system as shown in Fig. 6 (Sripad et al., 2010). The caverns are separated by 55m thick rock-pillar in between. The project area consisted of rock mass grouped as Central Himalayan crystallines and composed mainly of medium to high grade metamorphic rocks. It consist of mica schists, quartzite, fine grained quartz mica gneisses and augen gneisses belonging to Helong Formation of Central Crystalline

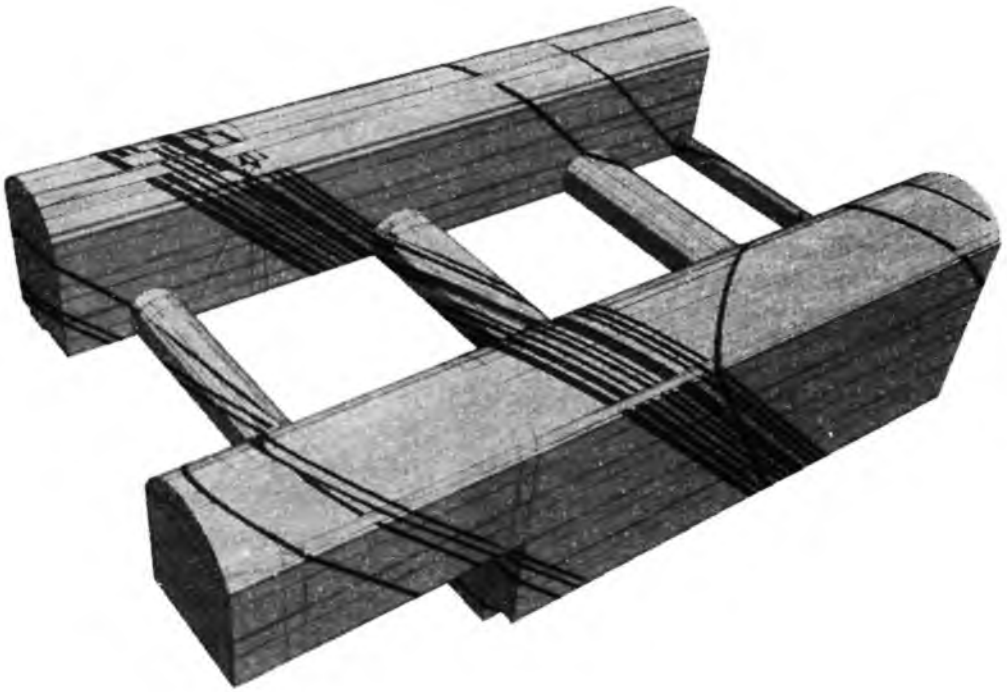

Fig. 6: Numerical model of Tapovan Vishnugad Hydroelectric Project

logged in exploratory drift excavated for reaching powerhouse location within quartzites. Foliation of rock mass in the area varied from N70°W-S70°E to NW-SE with dips of 40° to 60° towards NE. The rock mass included quartzite which were massive, jointed and highly jointed types at different locations, based on the joints and their spacing. The shear zones were found to be weak and consisted of clay infillings. Besides shear zones, there existed bands of biotite schist (10-15cm thick) along the foliation joint cutting powerhouse between 75m and 110m chainage and transformer hall between 14m to 33m chainage.

The results indicated that large displacements occurred at walls of cavern as compared to the crown due to higher horizontal in situ stress in case of caverns without support. The displacements were not uniform along the length of cavern due to geological and geometrical discontinuities. The faces of powerhouse experienced higher displacements where the biotite schist seams and shear zone are encountered. Maximum displacements were predicted to be 2.93m in powerhouse and 1.4m in transformer hall caverns. The higher displacement magnitudes were due to sharp contrast in strength properties as disturbance factor was changed from 0.8 to 0 after 3m depth. The displacements reduced to 59mm in powerhouse cavern, whereas it was found to be around 22mm in the transformer hall cavern by introduction of support system. Displacements were found to be evenly distributed along the cavern due to shortcrete and steel ribs support. Nearly 16.5m of rock mass (out of 55m) lying between powerhouse and transformer hall was found to be having factor of safety less than 1.2. Hence application of cable anchors was recommended in the above zone.

Conclusions

Numerical analysis is effective tool in analysing the stability of underground caverns. The review of various projects revealed that the geology and geotechnical parameters of the rock mass govern displacements and deformations in caverns. Decision about the adequacy of support system can be reviewed by modelling the existing/ designed support system during the sequence of excavation. Weak zones in rock mass can be identified and suitable remedial measures can be taken on the basis of the analysis.

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