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ABSTRACT

Support requirements for two caverns are worked out by empirical and the numerical approaches. The adequacy of the shotcrete-rock bolt support system is monitored by measuring the deformations of caverns walls and roof. The measurements are compared with the results obtained from the numerical approach. Brief geology, the supports, and the results of performance monitoring are presented in the paper.

KEY WORDS

Support Design, Cavern, Empirical Approach, Numerical Approach, Roof Support, Wall Support, Rock Bolt, and Shotcrete

INTRODUCTION

Two underground powerhouse cavities are in the final phase of construction. These are planned for housing underground hydro-power stations of the Sardar Sarovar Project in Gujrat State and the Koyna Stage IV Project in Maharashtra State of India. The Sardar Sarovar powerhouse cavern is 23m wide, 57m high and 210 m long and the Koyna powerhouse cavern is 20 m wide, 50 m high and 145 m long.

The support requirements were initially worked out by the empirical approach of Barton et al. (1974). As the excavation work progressed and more reliable input data became available, a 3D numerical analysis was performed by Central Mining Research Institute (CMRI), Dhanbad, India for both the caverns. The support requirements worked out from the numerical analysis corroborated with those obtained from the empirical approach. The adequacy of shotcrete-rock bolt support system was further established by continuous monitoring of the roof support behaviour by instrumentation. The estimation of the support requirements by empirical and numerical approaches, the support system used, and the performance monitoring are given in the paper along with brief geology of both the caverns.

GEOLOGY

Sardar Sarovar Cavern

The rock masses in the area are of Deccan trap group under a thin soil cover of about 30 cm. These consist of different lava flows viz. porphyritic basalt, amygdaloidal basalts and agglomerates. The basalts are intruded by two dolerite dykes, varying in width from 40 to 50m. The first southern dolerite dyke trends in N 70°E with dip of 60° - 65° towards river side. Its two contacts with adjacent basalt are sheared. The first shear contact is thin and does not intersect the cavern whereas the second sheared contact is 1 - 2m wide and intersects the cavern roof at Chainage 1492m. This shear zone is traversed by one set of closely spaced strike joints which are almost parallel to the dolerite dyke. Another near vertical dyke at the right end of the cavern trends in N 55°E. Its southern contact with basalts is calcified while the northern one has not been ascertained.

An agglomerate band, which is about 40m long and 2 - 3m thick and dipping at 8° towards hill side, is present about 1m above the roof of the cavern between chainage 1501 and 1541m. Because of the anticipated roof stability problems in the vicinity of agglomerate band, the behaviour of the band was monitored using multipoint borehole extensometer

(MPBX). The MPBX has given interesting results as discussed under 'Performance Monitoring'.

Koyna Powerhouse Cavern

The Koyna valley and all the principal elements of the project are located in the Deccan traps. These rock masses consist primarily of a succession of basaltic lava flows, as mentioned above, covering 5,00,000 sq. km. or more.

The Deccan traps lie in nearly horizontal flows showing a slightly easterly dip of about 30 minutes. There are no faults visible in the region.

The cavern is excavated through a variety of rock masses with diverse engineering characteristics. These rocks are the compact or non-vasicular basalts and the amygdaloidal basalts with gas cavities filled with secondary minerals which give them the spotted appearance. The common cavity fillings are zeolites and chlorophites. The compact basalts have occasional and random joints. Apart from the compact basalts and the amygdaloidal basalts, the volcanic breccias are also found at the lower level (between RL. 130 and 122m). The volcanic breccias with random joints are weak in strength (Table 1). In general, the rock masses except the volcanic breccia are considered good for underground construction.

SUPPORT REQUIREMENTS

Empirical Approach

The classification system of Barton et al. (1974) was employed for initial design of the support systems for both the caverns. The supports thus obtained are given in Table 1.

The designed support in columns 3 and 4, Table 1 will be read as follows :

B(tg) 1.75 + S(mr)12.5cm (7T) - Rockbolts with pre-tension of 7 tonnes at a spacing of 1.75m Centre to Centre alongwith 12.5cm thick mesh reinforced shotcrete.

Numerical Approach

The finite element method is a powerful technique where the effects of various parameters on the overall design may be studied.

Practical applications of the numercial methods are particularly directed to modelling the effects of different geological features and to determining the potential fracture zones around excavations at depth (Hoek and Brown, 1980). By using a suitable rock failure criterion, it is possible to identify weakness zones around excavations for selection of rock support. In addition, the effect of inter-sections and stresses around a cavern can be assessed by means of three dimensional finite-element (3D-FEM) analysis.

The 3D-FEM analysis was conducted at CMRI, Dhanbad, India using the BMINES computer programme obtained from the USBM. The CMRI failure criterion developed by Sheorey et al. (1989) was used to obtain the maximum boundary stress and to plot the safety factor contours from the principal stress. The safety factor is defined as the ratio of the major principal stress at failure to the major principal stress induced in the rock mass at any point (Sheorey et al., 1993). The results of analysis are given in the following paragraphs :

Table 1 - Support Requirements from the empirical approach

S. No.	Rock Type	Designed Support		Bolt Length (m)	
		Roof	Wall	Roof	Wall
(1)	(2)	(3)	(4)	(5)	(6)
A.	SARDAR SAROVAR CAVERN				
1.	Basalts or Dolerites (Q = 10)	B(tg) 2 + S(mr) 8.5cm (7T)	B(tg) 1.75 + S(mr) 8.5cm (9T)	5.5	10.5
2.	Shear Zone (Q = 1.25)	B(tg) 1.75 + S(mr) 12.5cm (7T)	B(tg) 1.6 + S(mr) 8.5cm (9T)	5.5	10.5
B.	KOYNA POWERHOUSE CAVERN				
3.	Compact Basalts (σ_c = 40 MPa; Q = 13.2)	B(tg) 1.5-2 + S(mr) 5 - 10cm (8T)	B(tg) 1.5 - 2 + S(mr) 2-3cm (8T)	5.5	9.5
4.	Vesicular Basalts (σ_c = 20 MPa; Q = 3.21)	B(tg) 1-1.5 + S(mr)10-15cm (8T)	B(tg) 1-2 + S(mr) 10-15cm (8T)	5.5	9.5
5.	Volcanic Breccia (σ_c = 15 MPa; Q = 1.5)	B(tg) 1-1.5 + S(mr) 10-15cm (8T)	B(tg) 1-1.5 + S(mr) 10 -15cm (8T)	5.5	9.5

Notations: σ_c = crushing strength of rock mass; Q = Barton's rock mass quality; B (tg) = tensioned rock bolts ; S(mr) = mesh reinforced shotcrete; S = plain shotcrete and; (8T), (7T) etc. = pretension in rockbolts in tonnes

a. Sardar Sarovar Cavern: The model was run considering two conditions - i.e., with dam loading and without dam loading. The insitu stress values determined by National Geophysical Research Institute (NGRI), Hyderabad, India were used. The modulus of deformation of 18 GPa and Poisson's ratio of 0.2 was selected for Basalts and Dolerites. The analysis of Sheorey et al. (1993) suggests that

(i) No roof deformation is obtained. On the contrary, upheaval of roof is obtained which vanishes on dam loading.
(ii) Overall wall displacements in the excavation are likely to be small, the maximum value being 7.6mm.
(iii) Failure in both walls is indicated in the areas affected by shear zones, the probability being higher in the upstream wall.
(iv) Failure in the upstream wall between the pressure shaft is due to the occurrence of major compressive and minor tensile stress.
(v) Dam loading has little to no influence on the stability of the powerhouse cavern.

b. Koyna Powerhouse Cavern: The in-situ stress values were determined by CMRI using hydrofrac technique. The modulus of deformation of the rock mass was taken as 19.3 GPa, and Poisson's ratio as 0.15. Analysis of Sheorey et al. (1993b) suggested the following:

(i) No major problems of stability are anticipated due to low stresses and good rock types, i.e., Vasicular basalt and compact basalt.
(ii) The roof deformation is obtained as 6.0 mm
(iii) Overall wall deformations in the cavern are likely to be small, the maximum value being 13 mm.

Safety factor contours were plotted for obtaining the bolt length. The contour of safety factor 1.5 (considering long-term stability) is recommended for deciding the bolt length. The bolt lengths, thus obtained, for various rock types for Sardar Sarovar and Koyna powerhouse caverns are given in Table 2.

Table 2 : Bolt length from numerical approach

Cavern Name	Rock Type	Bolt Length (m)	
		Wall	Roof
(1)	(2)	(3)	(4)
Sardar Sarovar	Basalts	6	6
	Dolerites	6	6
	Shear zone	25*	6
Koyna Cavern	Compact Basalt	6	6
	Vesicular Basalt	10	6
	Breccia	12	-

(* - Pre-stressed cable anchors)

EMPIRICAL Vs NUMERICAL APPROACHES

It is seen from the above two approaches that the empirical approach provides the support pressure and the support requirements in terms of rock bolt spacing, pretension and length and the thickness of shotcrete with or without wire-mesh (Table 1). Numerical approach, on the other hand, provides the stress zone and the safety contours. Using the safety factor contours, rock bolt length is worked out as given in Table 2.

The bolt length, obtained from the empirical approach is independent of the quality of the rock mass (Table 1). Hence for a given span or height the bolt length will remain the same whether the rock mass is poor or good (column 6, Table 1) which seems to be unrealistic. The numerical approach, which considers the crushing strength of the rock mass, provides the bolt length based on the quality of the rock mass. Because the crushing strength varies with rock mass quality. The wall bolt length from numerical approach varies between 6m and 25m in case of the Sardar Sarovar cavern and between 6 and 12m in case of the Koyna cavern (Column 3, Table 2) in comparison of the bolt length of 10.5m for Sardar Sarovar Cavern and 9.5m for Koyna Cavern from empirical approach (column 6, Table 1).

The bolt length for the roof supports from the two approaches are comparable (Column 5, Table 1 and Column 4, Table 2).

The above discussion shows that there is a need for a rational empirical approach for obtaining the length of the rock bolt considering the rock mass quality and insitu stress.

PERFORMANCE MONITORING

The adequacy of shotcrete-rock bolt support systems for the roof has been checked by monitoring the Sardar Sarovar cavern for 7 years and the Koyna cavern for 4 years. Multipoint borehole extensometers (MPBX) and the closure studs for tape extensometer were installed to monitor deformations of the cavern roof and walls.

The maximum measured roof convergence for the Sardar Sarovar cavern is 10mm for the shear zone area and 6 to 8mm for basalts and Dolerites, whereas the wall deformations are between 5 and 10mm.

A typical MPBX plot of monitoring the agglomerate band area of Sardar Sarovar Cavern is shown in Fig. 1. Continuous monitoring of agglomerate band has helped in ascertaining the widening of one of the contacts of agglomerate band with surrounding basalts. Though the rate of widening/opening of contact was only 0.024mm/month, but considering the life of the cavern, this rate may be disastrous. Therefore, after about 40 months of monitoring, it was decided to install longer rock bolts to stitch both the contacts. Subsequent monitoring has shown that the cavern roof around agglomerate band is stable.

The maximum observed roof convergence in the Koyna cavern, on the other hand, is between 5 and 7.2mm which is quite close to the value (6mm) obtained from 3D-FEM analysis. Though the roof convergence values at Sardar Sarovar cavern are not comparable to the values of 3D-FEM analysis, the overall results from the study of two caverns has generated confidence among the engineers on its utility.

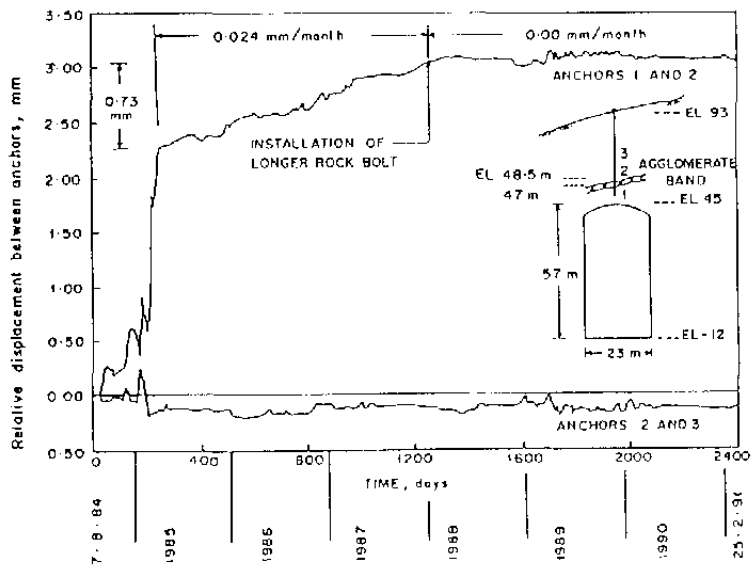

Fig. 1 - Monitoring of Agglomerate band by MPBX in powerhouse cavern of Sardar Sarovar Project, Gujrat, India

CONCLUSIONS

From the study of the two caverns it is concluded that

(i) The two approaches, empirical and the numerical, are complimentary to each other. The bolt length can be ascertained by numerical approach whereas the other details like bolt spacing, bolt pretension, shotcrete thickness etc. can be obtained from the empirical approach.

(ii) There is a need to develop an empirical approach for obtaining the bolt length considering the quality of the rock mass and the insitu stress.

(iii) The shotcrete-rockbolt support is an efficient and fast support system for caverns.

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