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Parametric Study of Cavern Stability: A Case of Underground Powerhouse Cavern of Middle Mewa Hydropower Project, Nepal

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Abstract

The parametric study of geomechanical factors must be understood in order to analyze the stability of underground rock structures. A parametric study was performed on a underground cavern with varying rock mass quality according to Geological strength index (GSI) using RS2 to investigate the importance of these geomechanical parameters in the stability of underground cavern. The planned powerhouse cavern has a dimension of 61 m length, 15 m width, and 31 m height.The cavern lies in moderately strong schistose gneiss rockmass. The stability of a cavern has been studied by investigating the yielded elements and maximum total displacement. Best estimate values and worst-case values from laboratory data are used for sensitivity analysis. Rockmass parameters are calculated using Generalized Hoek-Brown criterion in RS2 model. Residual parameters in plastic analysis are calculated from strength parameters using GSI-dependent equations. In elastic analysis, the most sensitive property is young's modulus and the parameters of the Hoek-Brown criterion have little significance. But in plastic analysis, the parameters of the Hoek–Brown criterion affect the deformability, which becomes more remarkable with increasing plastic area. Similarly, Young's modulus, Uniaxial compressive strength, and Geolgical strength index also have major significance in parametric study. Best fit model with actual ground deformation is also found by doing back analysis.

Keywords

Parametric Study, Cavern Stability, Numerical modelling.

1. Introduction

Instabilities caused by excessive deformation in rock mass around an underground opening periphery is a significant challenge in Himalayan tunneling. Because of the young tectonic setting, the rock mass in this region is broken, weathered, faulted, and sheared [1]. Rock mass quality also varies frequently along the length of tunnels or height of caverns. Investigations are often limited to rock samples obtained for rock mechanical tests, which may not be representative. Moreover, in-situ rock stresses are either not available, estimated or referred to from other locations. Thus, there are uncertainties in the estimation of input parameters in evaluating the stability of underground structures. In order to evaluate the stability of underground structures realistically, parametric assessment of input parameters, such as rock mass properties and in-situ stress, must be made. The best method for doing this is through sensitivity analysis. The assessment of underground construction are highly sensitive to the accuracy and reliability of the estimated input parameters [1].

Many authors have used numerical methods to perform sensitivity analyses on parameters influencing the stability of underground openings [2]. The extent of the total deformation is heavily influenced by the deformability properties of the rock mass and the in-situ stress conditions in the area. If the in-situ stress is not isotropic, the magnitude of deformation varies not only along the longitudinal alignment but also along the tunnel wall's periphery [3]. Shuangjian et al. investigated the sensitivity of factors influencing jointed rock strength [4]. Starzeca and Andersson investigated the sensitivity of geometric parameters of possible blocks in underground openings [5]. Bhasin and Hoeg investigated the sensitivity of joint parameters in a large Himalayan cavern. The sensitivity studies involving changes in joint spacings (block size) revealed that the deformations around an opening are dependent on the size or the number of blocks adjacent to the excavation [6]. In addition to the existing empirical and analytical approaches for the design and stability analysis of underground structures in weak geology, numerical modeling would provide a clear understanding of rock support design [7]. Beiki et al. used neural network sensitivity analysis to estimate the deformation modulus of rock mass [8]. The sophisticated empirical Hoek-Brown formula is sensitive to the GSI and disturbance parameter (D) [9]. The relative sensitivity of the Hoek-Brown formula can be significantly reduced with more precise measurements and GSI determination at high GSI values and disturbance factor determination at low GSI values [9]. The sensitivity of these parameters varies depending on the situation, whether the rock mass is intact or jointed. A change in the properties of the rock mass, or a transition from elastic to elastoplastic behavior, causes a shift in the priority of parameter sensitivity. This paper attempts to prioritize sensitive parameters influencing the stability of underground opening.

2. The Case

The Underground Powerhouse Cavern of the Middle Mewa Hydropower Project is located in Taplejung District in the eastern part of Nepal. Physiographically, the project area lies in the higher Himalayan zone. The layout of the project is shown in Figure 1. The rock mass in the powerhouse cavern is primarily schistose gneiss with biotite as the dominant mineral. The powerhouse cavern is aligned N03 azimuth. The foliation plane of the rockmass is mainly dipping towards the north, having foliation joints' dip and dip direction ranging about 35°to 50°/ 25°to 60°respectively. Geophysical investigations showed that the rock mass would have shear velocities of 250 m/s to 1500 m/s. Core drilling near the powerhouse from the top revealed that the joints in the rocks are planar smooth. Mostly, the joints are filled with sand and mica. The foliation angle is 30°. The core recovery is above 90 percent on average in the bed rock and the RQD is very poor quality to very good quality, ranging from 0 to 91 percent. Altogether, 11 lugeon tests were carried out, commencing from 3.00 m up to a depth of 49.00 m. The lugeon value ranged from 0.49 to 19.98 following dilation, void filling, and laminar type of flow [10].

The cavern is currently under construction. The initial design of the cavern rock support was based on the laboratory rock mechanical test data, assumed rock mass quality, and estimated in-situ stresses. As the cavern is excavated, rock mass quality is better known, supports have been installed, multipoint bore hole extensometers have been installed, and converences of the rock mass have been recorded, an update on the cavern stability with updated input parameters is sought. An excavated cavern photograph and plan of powerhouse area are presented in Figure 2 and Figure 3 respectively.

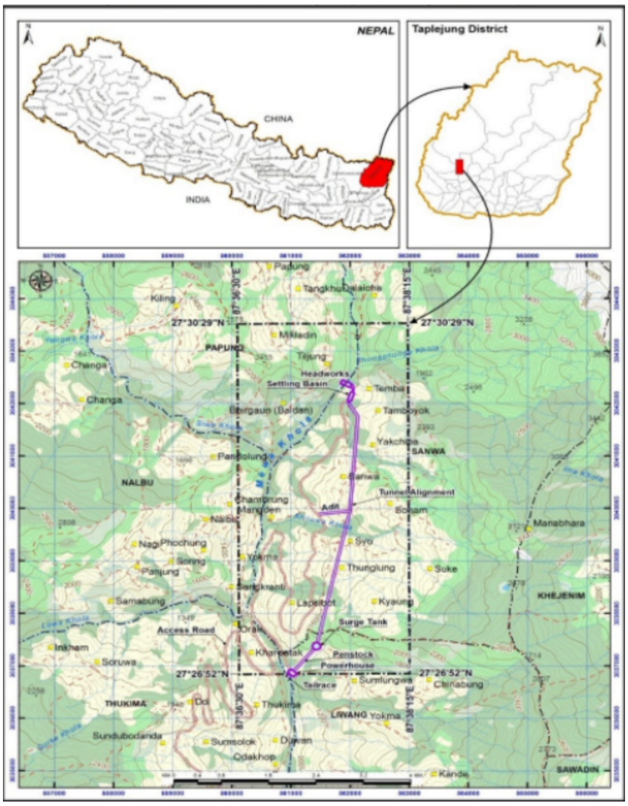

Figure 1: Layout Map of Middle Mewa Hydropower Project

Figure 2: Powerhouse cavern of MMHPP

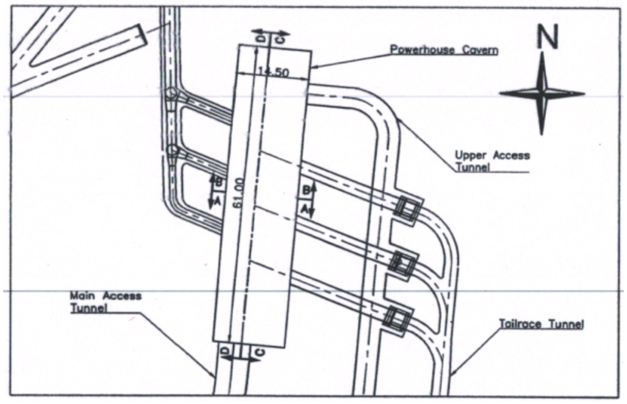

Figure 3: Plan of Powerhouse Cavern [10]

3. Basics of Generalized Hoek-Brown Criterion

The Hoek-Brown criterion is one of the most popular failure criterions for determining the failure envelope of the rock mass. For jointed rock masses it is given by the following generalized formula [11]:

$$\sigma_1' = \sigma_3' + \sigma_{ci}\left[m_b \frac{\sigma_3'}{\sigma_1'}\right]^a \tag{1}$$

$$m_b = m_i\, exp\left(\frac{GSI - 100}{28 - 14D}\right) \tag{2}$$

$$s = exp\left(\frac{GSI - 100}{9 - 3D}\right) \tag{3}$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{\frac{GSI}{15}} - e^{-\frac{20}{3}}\right) \tag{4}$$

Where, m_b, s and a are the rock mass material constants. D is disturbance factor, GSI is geological strength index and mi is material constant for intact rock.

The Hoek-Brown equation is suggested by ISRM for using as failure criterion of jointed rock mass [12]. Since the rock mass of the Underground Powerhouse can be assumed to be homogenous and heavily jointed, it is believed that the Hoek-Brown failure criterion can be used for stability evaluation by numerical method.

4. Computational model

RS2 is used for 2-dimensional analysis and design of underground tunnels in hard rock, weak rock, jointed rock, and soft ground, and other geotechnical work. Multi-stage analysis and advanced support design tools simplify the design of tunnel lining systems that use Mohr-Coulomb and generalized Hoek-Brown failure criteria and others for material modelling [13]. Figure 4 shows the cross section of the cavern that is used in the numerical analysis. Elastic analysis is carried out first, and after that, plastic analysis is done, varying different rock mass parameters to access the collapse behavior of the structure on the basis of yielding of cross section.

The stability of the underground powerhouse cavern is reflected by the maximum total displacement and yielded elements of the cavern. The parameters used for the study include Young's modulus, Poisson's ratio, parameters of Hoek–Brown criterion for uniaxial compressive strength (UCS), and GSI value.

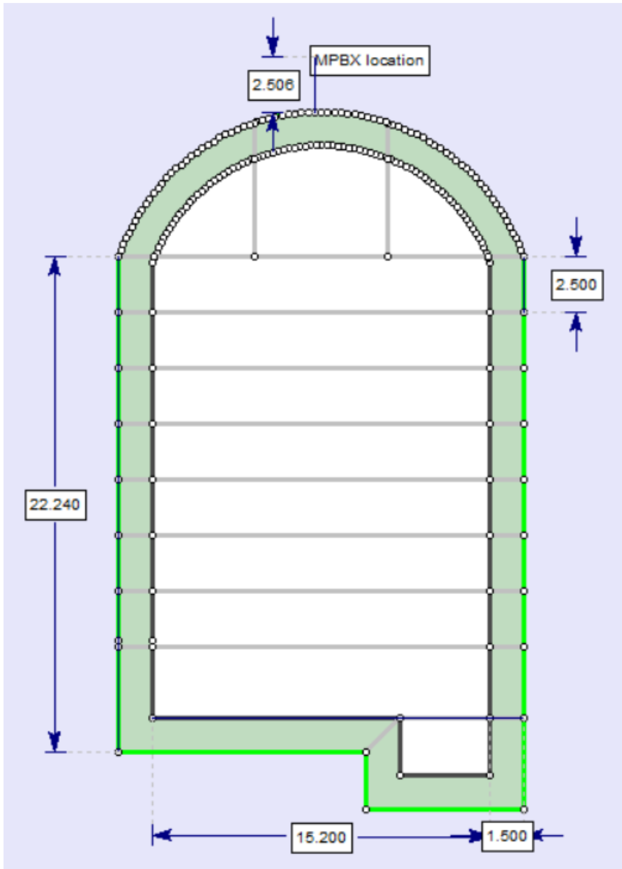

Figure 4: Cross section of powerhouse cavern used for modelling along with location of MPBX

5. Method of parametric study:

With all of the uncertainties in the values, it is worthwhile to investigate the situation with worse parameters, and the best way to do so is through parametric study. Table 1 shows values for best estimate model and worst case model.

Table 1: Input for parametric study

Parameters	Best Estimate	Worst case
GSI	45	35
UCS (Mpa)	28	12
E-Modulus (Gpa)	25.02	15.41
Poisson's ratio	0.16	0.25
mi	24	16

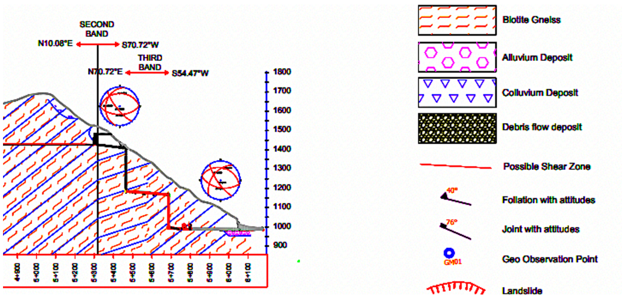

Figure 5: Geological profile of powerhouse cavern area [10]

The Himalaya has tectonic stress due to the plate tectonic movement of the Indian Plate into the Eurasian Plate [14]. There are no in-situ stress measurement carried out for the Project or near the Project. Shrestha and Panthi state that tectonic stress in schistose rock mass may be assumed 4-5 MPa [1]. World stress map indicate that tetonic stress may be oriented to the North or North-West at the eastern Himalaya [15].

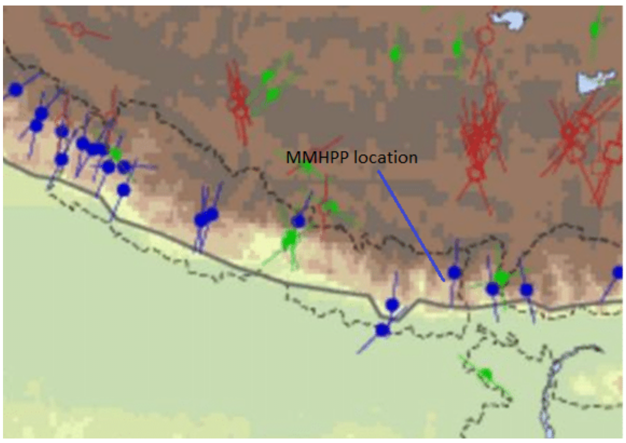

Figure 6: Stress map of the Himalaya and adjacent region (World Stress Map, 2008)

The Cavern has an overburden of 190 m, which was calculated from the geological profile of powerhouse cavern area shown in Figure 5. Assuming 5 MPa tectonic stress according to Panthi, the tectonic stress value based on the Nepal geographical location is assumed to be 5 MPa along the direction of 5°North-West [15]. Insitu stress condition values used for sensitivity analysis are shown in Table 2.

Table 2: Estimated stress situation

σ_1(MPa)	σ_3(MPa)	σ_z(MPa)
5.4	1.5	6.45

The range of rock mechanical values obtained from laboratory tests is summarized in Table 3. Using this data for analysis helps us to analyze both cases and the significance of the rock mass parameters on the stability of a cavern.

Table 3: Laboratory test results

Test		Values
MPER Test	MOE(Gpa)	25.02-15.41
	Poisson's ratio	0.25-0.18
Brazilian test	Tensile Strength(Mpa)	2.94-9.12
UCS	(Mpa)	12-28

Parametric analysis without a support system is carried out in order to see which parameters influence stability the most using the data in Table 1. A best-estimate model and a worst-case model are prepared. Each parameter is set to the worst value one by one in the best model, and the sensitivity of the model is measured by the increase of yielded mesh elements from the best estimate in percent and maximum total displacement for an unsupported state. Then, again, each parameter is set to its best value, one by one, in the worst model.

Best fit model with actual ground condition is also found by doing back analysis with the deformation data measured by MPBX, located at 2.5 m above the crown of powerhouse cavern. The new MPBX deformation data obtained from the site for which back analysis was done to determine rock mass parameters precisely and to validate the 2D model.

6. Results And Discussion:

All the parameters have been analyzed one by one using the method mentioned above. Hoek-Brown criteria parameters doesnot affect elastic analysis. The maximum total displacement in the best estimate model is 3.81 mm and in the worst-case model is 6.40 mm. The influence of other parameters is also negligible. But, in the case of plastic analysis, parameters of Hoek-Brown criteria have a significant effect on the model. Young's model and UCS also have a considerable effect on both the increase in yielded elements and maximum displacement. The stress is constant during the analysis while other parameters (E-modulus, UCS, GSI, mi, Poisson's ratio, disturbance factor) are varied.

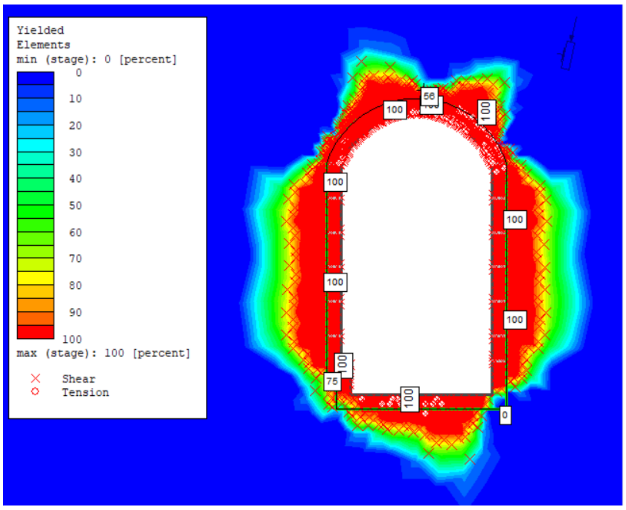

Figure 7: Best case model with yielded elements

Table 4: Parametric analysis. Yielded mesh elements and increase of yielded mesh elements from the best estimate model

Description	Yielded (%)	Max dis(mm)
Best estimate	1192	4.97
Worst case	1758(47)	19.1
1.Worst value on best model		
UCS	1536(29)	6.12
E-Modulus	1376(15)	9.4
E-Modulus(res)	1205(1)	4.98
GSI	1415(18)	5.43
mi	1340(12)	5.01
Poisson's ratio	1178(0)	5.12
Disturbance factor	1281(7)	5.63
2. Best value on Worst mode		
UCS	1538(29)	11.8
E-modulus	1764(42)	15.1
GSI	1645(38)	14.4
mi	1665(39)	15.5

Stress levels are constant, so the influence due to stress is minimal. In the first model, UCS, GSI and E-modulus show little effect on yielded elements, but the influence of E-modulus on the amount of total displacement is more compared to UCS and GSI. Poisson's ratio have no effect in total displacement and yielded elements. mi, and disturbance factor have a negligible effect on total displacement but a significant effect on the yielded mesh elements.

On the second model, the value of displacement has decreased significantly after using the best values of UCS, E-modulus, and GSI, while mi value has almost no effect on displacement. E-modulus value has more significance in yielded mesh elements compared to GSI, UCS and mi.

The RS2 program provides the option of providing the residual Young's modulus for plastic analysis; however, it can only be used in analysis if the rock mass has yielded and Young's modulus is used in the worst-case scenario, the results are more severe.

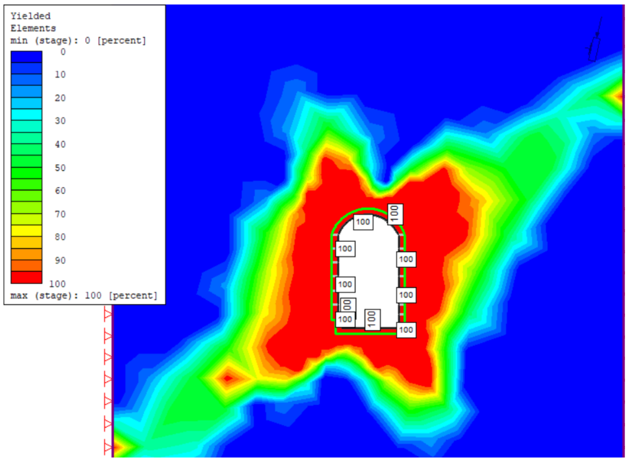

Figure 8: Worst case model with yielded elements

Table 5: Best fit model input parameters

Parameters	Undisturbed zone	Disturbed zone
mb	2.394	1.2
s	0.0015893	0.000438
a	0.5099	0.5099
mr	2.394	1.2
sr	0.0015893	0.000438
ar	0.5099	0.5099
Erm(Mpa)	3329	1587
GSI	42	42
mi	19	19
UCS	24	24
D	0	0.5
Ei (Mpa)	18.2	18.2

From Figure 7 and Figure 8, the plastic zone has increased significantly in the worst-case model, while in the best-estimate model it is only around the periphery of the cavern. The amount of total displacement also increases significantly in the worst-case model to 19.1 mm. Also, best fit model with actual ground deformation was found by doing back analysis.

Table 6: Input parameters for support system used

Shotcrete	
Thickness	0.3 m
Young's modulus	30000 MPa
Poisson ratio	0.15
Compressive strength	40MPa
Tensile strength	3 MPa
Rock bolt	
Young's modulus	20000 MPa
Bolt Diameter	25mm
Bolt Length	6m
Tensile strength	0.12 MN
Rock Anchorage	
Young's modulus	20000 MPa
Bolt Diameter	32mm
Bolt Length	8m in roof 12m in wall
Tensile strength	0.15 MN

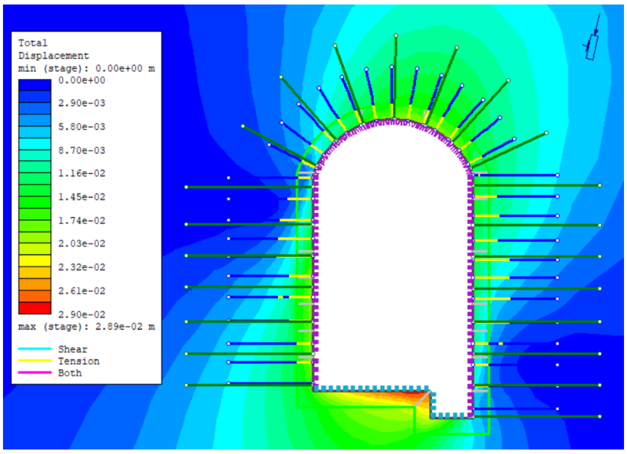

Figure 9: Best fit model

Rock support applied in the roof and walls of the powerhouse cavern are shotcrete, fully grouted rock bolts and rock anchorage with properties shown in Table 6. The maximum displacement of the powerhouse cavern at final stage was 14 mm as shown in figure 10, which is similar to the deformation data obtained from instrumentation at site where MPBX is located 2.5 m from the crown portion. To obtain this value of deformation in RS2, back analysis was done

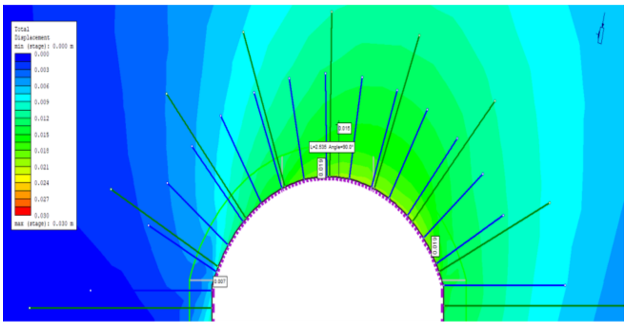

Figure 10: Displacement at 2.5m above crown

many times changing different parameters which lead to similar result as actual ground condition which is shown in figure 11.

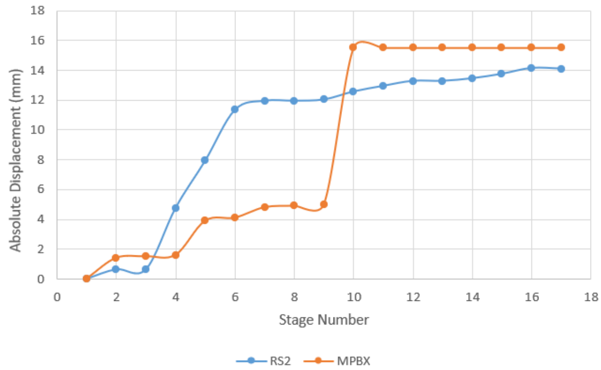

Figure 11: Plot of Stage Vs Absolute displacement

Table 7: Result of model with varying tectonic stress

Tectonic stress(Mpa)	4	5	6
Yielded elements	1938	1981	2043
Yielded bolts	49	65	71
Max. displacement(mm)	14	15	16

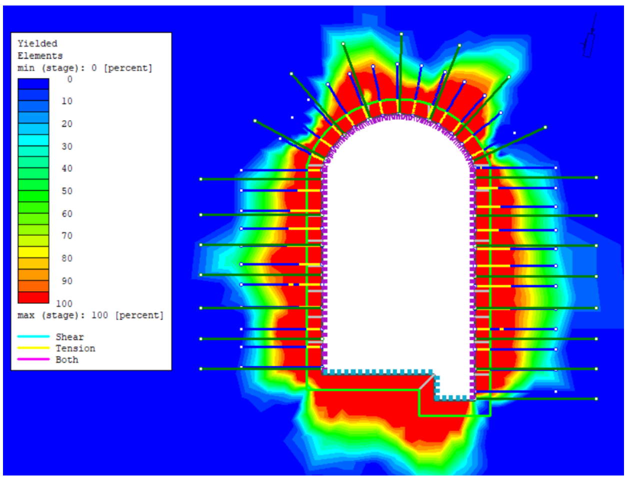

Figure 12: Yielded elements along with yielded bolts at 5 MPa tectonic stress

The value of tectonic stress was also differed in the model to see the effects. The result of the models with varying tectonic stress is shown in Table 7. The result showed that with increasing tectonic stress the maximum displacement and yielded elements both increase along with yielded bolts. But comparing the displacement with the monitoring data and analyzing the stress situation of the area as suggested by Shrestha and Panthi, applying tectonic stress of 5 Mpa is correct decision [1]. By using the tectonic stress, inplane stress and outplane stress were found to be 0.86 MPa and 4.92 MPa respectively.

7. Conclusion

The parametric study of the powerhouse cavern of the Middle Mewa Hydropower project by varying the rock mass parameters to best value and worst value was carried out by numerical modelling using RS2 and the results were compared with the best estimate model. The accuracy of numerical model-based stability analysis is dependent on the quality of input parameters. As a result, it is crucial to recognize that uncertainties in input parameters will result in inaccurate numerical model results. UCS and Hoek-Brown criterion parameters have no sensitivity in an elastic state and gradually affect stability when plastic area occurs in the rock mass surrounding the cavern. In an elastic state, the most important parameter is Young's modulus. In a plastic state, the main parameters concerning cavern stability are Young's modulus and UCS, respectively. Therefore, for a perfect model to replicate the actual ground conditions, the rock mass parameters must be wisely selected to match the ground conditions and decrease the uncertainties by doing parametric study followed by back analysis with actual deformation data of site.

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References

[1] PK Shrestha and KK Panthi. Analysis of the plastic deformation behavior of schist and schistose mica gneiss at khimti headrace tunnel, nepal. *Bulletin of Engineering Geology and the Environment*, 73(3):759–773, 2014.

[2] WR Abdellah, MA Ali, and Hyung-Sik Yang. Studying the effect of some parameters on the stability of shallow tunnels. *Journal of Sustainable Mining*, 17(1):20–33, 2018.

[3] KK Panthi and PK Shrestha. Estimating tunnel strain in the weak and schistose rock mass influenced by stress anisotropy: An evaluation based on three tunnel cases from nepal. *Rock mechanics and rock engineering*, 51(6):1823–1838, 2018.

[4] Niu Shuangjian, Jing Hongwen, HU Kun, and Yang Dafang. Numerical investigation on the sensitivity of jointed rock mass strength to various factors. *Mining Science and Technology (China)*, 20(4):530–534, 2010.

[5] P Starzec and J Andersson. Application of two-level factorial design to sensitivity analysis of keyblock statistics from fracture geometry. *International Journal of Rock Mechanics and Mining Sciences*, 39(2):243–255, 2002.

[6] R Bhasin and K Høeg. Parametric study for a large cavern in jointed rock using a distinct element model (udec—bb). *International Journal of Rock Mechanics and Mining Sciences*, 35(1):17–29, 1998.

[7] SS Khadka and RK Maskey. Stability analysis and design of rock support for tunnel and cavern of kathmandu university geo-lab. *Kathmandu University Journal of Science, Engineering and Technology*, 13(1):1–19, 2017.

[8] Morteza Beiki, Ali Bashari, and Abbas Majdi. Genetic programming approach for estimating the deformation modulus of rock mass using sensitivity analysis by neural network. *International journal of rock mechanics and mining sciences*, 47(7):1091–1103, 2010.

[9] Péter Ván and Balázs Vásárhelyi. Sensitivity analysis of gsi based mechanical characterization of rock mass. *arXiv preprint arXiv:1210.3024*, 2012.

[10] Mewa Developers Ltd. Detailed project report of mmhpp, 2020.

[11] Evert Hoek, Carlos Carranza-Torres, Brent Corkum, et al. Hoek-brown failure criterion-2002 edition. *Proceedings of NARMS-Tac*, 1(1):267–273, 2002.

[12] E Eberhardt. The hoek–brown failure criterion. In *The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014*, pages 233–240. Springer, 2012.

[13] Rocscience. 2d finite element analysis. version: 9.008, user manual. 2016.

[14] KK Panthi. Analysis of engineering geological uncertainties related to tunnelling in himalayan rock mass conditions. 2006.

[15] CB Basnet and KK Panthi. 3d in-situ stress model of upper tamakoshi hydroelectric project area. 2017.