Applied Numerical Modeling in Geomechanics – 2020 – Billaux, Hazzard, Nelson & Schöpfer (eds.) *Paper: 01-03*
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Method of determining grading deformation alert index of underground cavern complex and its application

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1 INTRODUCTION

Deformation of surrounding rock mass has always been a key problem during construction of underground caverns. The critical strain of rock mass suggested by Sakurai (1981) can be used as a hazard warning level for monitoring the stability of tunnels and classified into three stages based on the monitoring value and the response of rock mass during excavation. Following the suggestions of Sakurai (1983), an analysis was carried out by Duncan-Fama (1993), Carranza-Torres & Fairhurst (1999) to determine the relationship between σ_{cm}/p_0 (σ_{cm} is the uniaxial compressive strength of the rock mass, p_0 is the in-situ stress) and the percentage "strain" of the tunnel (the percentage "strain" is defined as the 100× the ratio of tunnel closure to tunnel diameter), and according to the value of the "strain", Hoek (2000) classify it into five grades to assessing the squeezing and the difficulty with tunneling in weak rock. The deformation of underground caverns depends on the strength of the rock mass, the in-situ condition, and the size of the caverns, excavation effect of cavern group, etc. Establishing the grading deformation alert index before construction, and dynamic adjustment of the index according to monitor data on site, the inversion analysis, and the excavation response of rock mass is very important to the stability of the underground caverns and optimize the excavation and support design during excavation. Therefore, the method generally used in single tunnels to determine the deformation alert value is not suitable for large caverns complex, such as underground powerhouse complex which with larger height and span, stratified excavation method and with the influence of the other caverns surrounding the main powerhouse. According to the geological strength index (GSI) of rock mass, considering the variation characteristics of actual rock mass quality, a method for determining the grading deformation alert index of underground cavern complex is established, with different rock mass quality, different monitor position, etc. And the method is applied to the underground powerhouse complex in a Middle East pumped storage project.

2 METHOD FOR DETERMINING GRADING DEFORMATION ALERT VALUE

The Mohr-Coulomb (MC) constitutive model is one of the commonly used constitutive models for rock mass in underground caverns. The young's modulus and the shear strength index: cohesion and friction angle, are the key parameters to evaluating the deformation and the plastic zone of underground caverns in a numerical model. According to Hoek-Brown Criterion (2002), the parameters of the MC model can be obtained with GSI, UCS (uniaxial compressive strength of intact rock) and mi (the material constant). For the same lithology, GSI is one of the most important indicators for determining the mechanical parameters of the rock mass.

Rock Mass Rating (RMR) is the most widely used engineering classification system for rock mass, which is developed by Bieniawski in 1973. The rock mass can be classified to five grades according to RMR value. For the same grade rock mass, take fair rock for an example, the RMR is 41-60. According the correlation between the RMR and GSI, the GSI value will be in the range of 36-55. Therefore, for the same class of rock mass, the geotechnical parameters of rock mass with the same cover depth, lithology and class would be changed greatly.

When designing the support system of a large span of underground caverns such as underground powerhouse of hydropower stations before construction (excavation), the support scheme will vary depending on the rock mass quality and the location of the caverns (roof, sidewall or intersections), according to the rock mass classification and geology investigation information on site. The average value or the median value of statistical results of GSI generally will be used to verify the support design in numerical model.

The uncertainty of the rock mass quality of underground caverns during the construction stage exists objectively. Considering the statistical results of GSI of geological boreholes and adit tunnels before excavation cavern complex, using the average and the low limits value of GSI to calculate the displacement in numerical model, total deformation and deformation increments in each excavation stage of typical monitoring points in different locations can be obtained in different rock mass quality. Grading deformation alert index can be established by the deformation characteristics of each monitoring point under two different GSI values. See details in Figures 1 & 2.

3 APPLICATION IN KHPSP IN MIDDLE EAST

3.1 *Project introduction*

The Kokhav Hayarden pumped storage power station project (hereinafter referred to as the KHPSP) is located near the village of Gesher in northern Israel, near the Jordan River Valley, 120 km from Tel Aviv, the second largest city of Israel. The underground powerhouse complex including main powerhouse, auxiliary powerhouse, transformer hall, Busbar tunnel, main access tunnel, emergency cable tunnel, and construction adit. The size of the powerhouse is 82.2m×18.0m×43m (length×width×height).

3.2 *Geology condition*

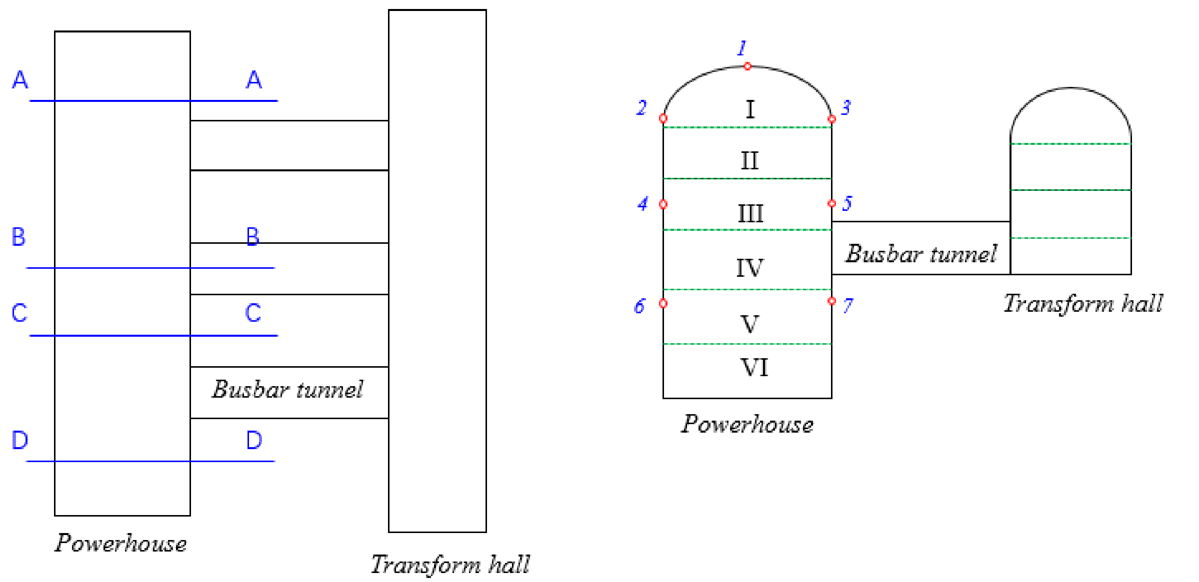
According to the geological model shown in Figure 3, in the Powerhouse complex, mostly of basalt lithology were strong basalt, vesicular basalt (bs-weak), and pyroclastic including tuff and breccia, which is a mixture of basalt clastic and clay or volcanic ash. Fault f18, f22 are intersected with the main powerhouse. The rock mass classification is class III and locally class IV. The stress regime is strike-slip regime with stress situation of $S_{Hmax}>S_v>S_h$, S_{Hmax} Direction is N11°W, and the maximum horizontal principal stress is 1.5 of the vertical stress, which is in the range of 12-15 MPa.

3.3 *Monitoring sections*

There are 6 monitor sections along the powerhouse axial. The monitor devices include extensometers, rock dowel stress meters, convergence monitoring, etc. Displacement monitoring is arranged in both crown and sidewall of the powerhouse, as shown in Figure 4. The extensometers are planned to install after the tunnel face passes through the position of the monitor device.

3.4 *Numerical model*

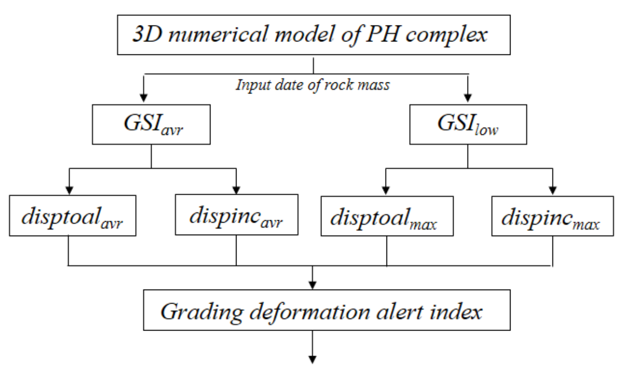
The Mohr-Coulomb Constitutive Model is used for rock mass with *FLAC3D* (Itasca 2017). The numerical model is shown in Figure 5. The main powerhouse excavation is divided into 6 main layers with 12 substeps. Shotcrete and rock dowel tendons are simulated by liner and cable structural element in *FLAC3D*.



a. Layout of powerhouse complex *b. Monitor point in Typical section B-B of PH*

1. *A-A, B-B, C-C, D-D are 4 typical monitoring section of PH;*
2. *point 1-7 are the seven displacement monitor point in section B-B;*
3. *The powerhouse are excavated in 6 stages which is from layer I to layer III.*

Figure 1. Typical displacement monitor layout of underground cavern complex.



	Safety level	Alert level 1	Alert level 2
The monitor device pre-installed before excavation, the monitoring results is obtained the total displacement	$disp_{mon}^{*} < disptoal_{avr}$	$disptoal_{avr} < disp_{mon} < disptoal_{max}$	$disp_{mon} > disptoal_{max}$
The monitor device installed delayed, the monitoring results is obtained the displacement increment	$disp_{mon} < dispinc_{avr}$	$dispinc_{avr} < disp_{mon} < dispinc_{max}$	$disp_{mon} > dispinc_{max}$
Stability judgment of rock mass and the engineering countermeasures	*the cavern deformation meets expectations, and surrounding rock is stable*	*should be paid attention to the deformation of the cavern. It also needs to carry out denser monitoring and analyze the reason, study the additional support*	*the deformation of the cavern is too large, and the additional reinforcement should be performed in time*

Note: $disp_{mon}$ is the displacement monitoring results of extensometers installing in the rock mass of caverns on-site.*

Figure 2. Technical route of establishing grading deformation alert index of underground cavern complex.

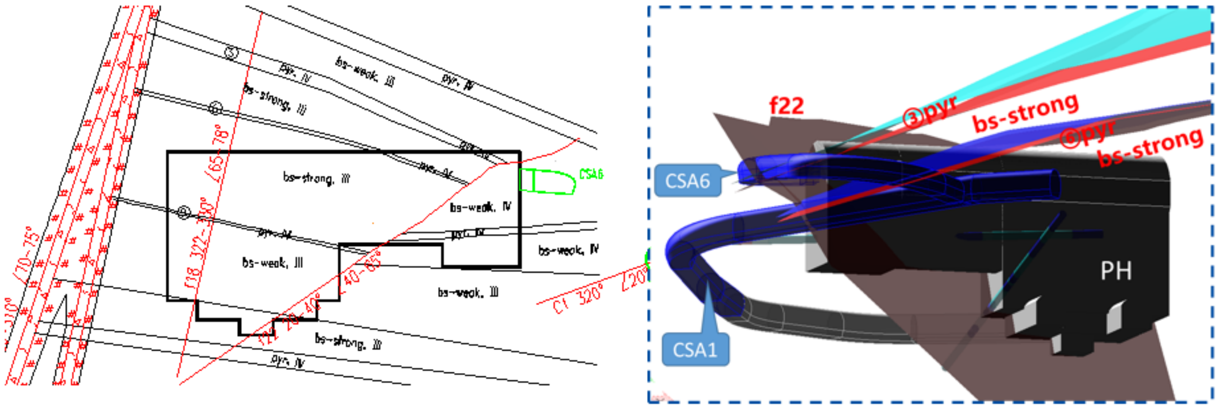
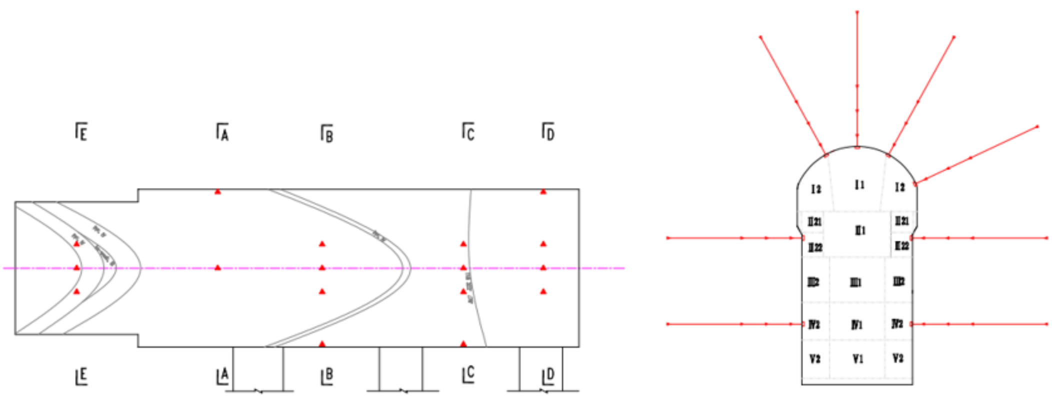
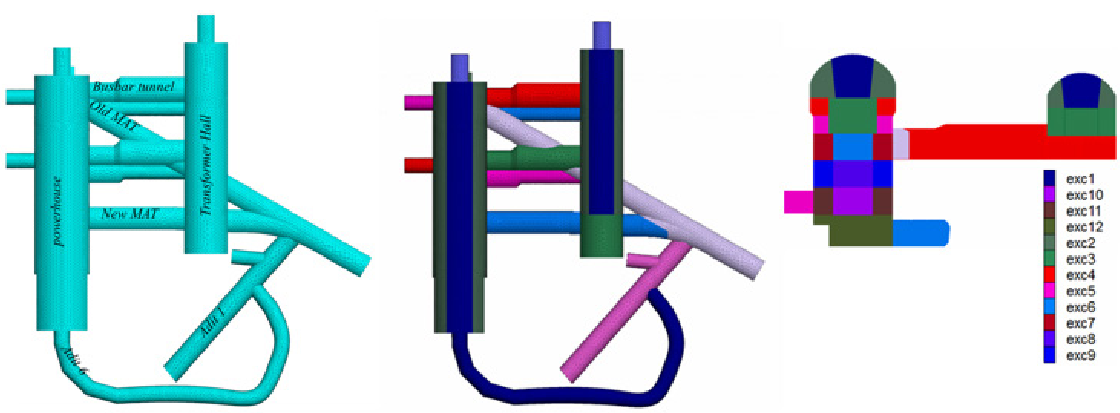


Figure 3. Geological model of underground powerhouse.



a. Layout of monitor of powerhouse *b. Extensometer of typical section B-B*

Figure 4. The layout of the extensometer arrangement in the powerhouse.



3 parts of backfill concrete of olad mat Excavation parts of PH complex(top view) 12 excavation substeps of PH

Figure 5. Numerical model of powerhouse complex.

4 RESULTS AND DISCUSSION

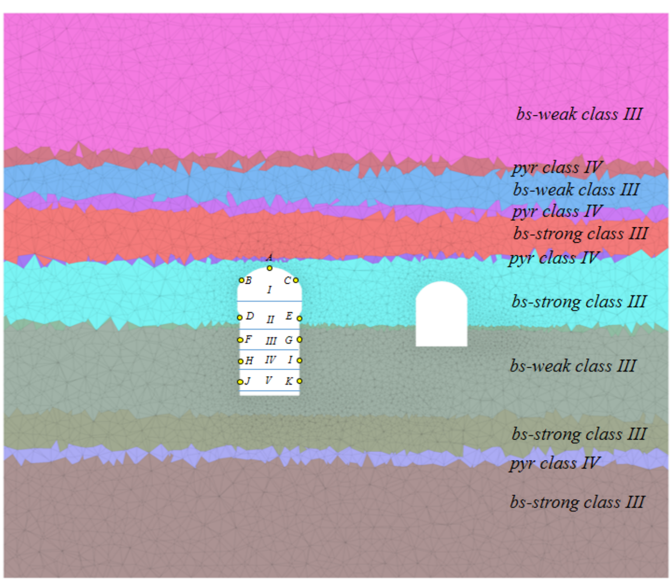
4.1 *Results*

Figure 6 shows a typical section of the 3D numerical model and the suggested parameters of different rock mass units. According to the technical route map, using the average GSI of the same classification of each lithology in the numerical model, the $dispinc_{avr}$ of typical monitor points can be obtained and when using the minimum GSI of rock mass, the $dispinc_{max}$ can be obtained. The grading deformation alert value for one point in a typical monitor section of the main powerhouse is shown in Table 1.

Table 1. Grading deformation increment alert value of the typical section B-B in the powerhouse.

Exaction stage	deformation increment δ in the crown of section B-B(unit/mm)		
	Safety level	Alert level 1	Alert level 2
I	δ≤14	14<δ<18	≥18
II	δ≤20	20<δ<26	≥26
III	δ≤25	25<δ<32	≥32
IV	δ≤26	26<δ<33	≥33
V	δ≤27	27<δ<34	≥34
VI	δ≤28	28<δ<36	≥36
Stability judgment of rock mass and the engineering countermeasures	The cavern deformation meets expectations, and surrounding rock is stable.	Should be paid attention to the deformation of the cavern. It also needs to carry out denser monitoring and analyze the reason, study the additional support.	The deformation of the cavern is too large, and the additional reinforcement should be performed in time.

Note: the monitor device in Project KHPSP are lagging installed after the explosion of the monitor position.



Lithology	*Rock classification*	$\sigma_{ci(MPa)}$	m_i	*average value of GSI*	*minimum value of GSI*
bs-strong	*III*	*101.3*	*12*	*55*	*50*
bs-weak	*III*	*50.81*	*12*	*50*	*45*
	IV	*33.90*	*9*	*40*	*35*
pyroclastic	*IV*	*8.80*	*12*	*35*	*30*
	V	*5.30*	*3*	*20*	*15*

Take monitor point A for an example. For all the 11 lithology in the left figure:

1. *take the average value of GSI in above table,* $dispinc_{avr}$ *can be obtained, which is means the upper limit value of alert level 1 for each sub-excavation stage;*
2. *take the minimum value of GSI in above table,* $dispinc_{max}$ *can be obtained, which is means the lower limit value of alert level 2 for each sub-excavation stage.*

Figure 6. The monitor points arrangement of the powerhouse and the parameters of rock mass.

4.2 *Discussion*

The deformation characteristics is one of the most important ways to judge the stability of the underground caverns during construction and using the grading deformation alert index is suitable for guiding construction and ensure construction safety. Besides the alert index of deformation, stress of rock dowels, axial load of tendons, the depth of EDZ also should be considered together as a system to judge the stability characteristics of the cavern and the safety margin of the support system comprehensively.

Due to variation of the lithological and the existing of the faults, in-situ stress may have abnormal features locally, therefore, the application of deformation alert index needs to consider the impact of this factor according to specific conditions.

5 CONCLUSIONS

With the numerical model, the grading deformation alert value can be obtained according to GSI value of the rock mass in the underground cavern complex. Cavern group effect, excavation support scheme, time of installing the monitoring instrument, etc., can be reflected with this method.

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