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Application of temporal and spatial characteristics of shotcrete mechanics in Middle East pumping storage project

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1 INTRODUCTION

Through the study of the actual force mechanism of the shotcrete and response characteristics of a tunnel during construction, it can be seen that the stress adjustment of the shotcrete during construction has a very complicated time and space effect. The results show that the force of shotcrete support structure will increase when advancing the tunnel face, and the deformation and strength mechanical properties of shotcrete will change with the advance of the tunnel face until the design strength is reached. The mechanical properties of the contact surface between the shotcrete and the rock mass also change gradually with the advance of the tunnel face. In the design and analysis of the support structure, if the time and space effect of shotcrete construction and mechanical properties are not taken into account, the actual stress of the shotcrete will be overestimated. Through the practical application of the shotcrete design of the adit tunnel in the Kokhav Hayarden pumped storage project in Israel, it was shown that it is necessary to consider time and space effect in verifying the design of shotcrete support in a tunnel; otherwise, its actual force will be overestimated .

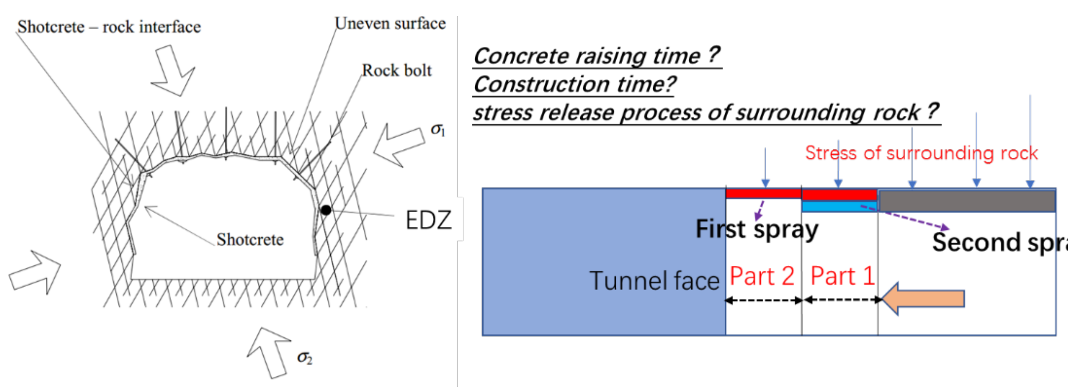

Figure 1. The interaction mechanism between shotcrete and surrounding rock and the relationship between time and space.

2 DESIGN AND ANALYSIS

In this paper, the software *FLAC3D* (Itasca 2017) is used to verify the shotcrete design. The software has good operability, and the time effect of shotcrete, EDZ of rock mass and other factors of mechanical parameters of the shotcrete can be considered in the analysis.

2.1 *Mechanical parameters of shotcrete*

Through the whole construction process of underground tunnels, the interaction between surrounding rock and shotcrete has a time effect. On the one hand, it takes time for the connection between blasting, mucking and supporting, etc.; on the other hand, it takes time for the strength of the shotcrete to increase from zero to the design value.

Oreste (2003) suggested that equation (1) could be used to calculate the relationship between mechanical parameters of shotcrete and time.

$$M_{shot,t} = M_{shot,0} \cdot (1 - e^{-\alpha t}) \tag{1}$$

Where $M_{shot,t}$ is the parameter of the spray layer at time t (elastic modulus E, uniaxial compressive strength σ_c); $M_{shot,0}$ is the parameters of the spray layer at the time $t = \infty$ (elastic modulus E, uniaxial compressive strength σ_c); α and β are constant.

Gyu-jin Base (2004) has done a lot of experiments on the parameters of the contact between the shotcrete and the surrounding rock and got the correlation between the mechanical parameters of the shotcrete itself (elastic modulus E and uniaxial compressive strength σ_c) and the mechanical parameters of the contact between the surrounding rock and the shotcrete (K_n, K_s, c, f) and time-effect. See equation (2) to equation (8).

$$\sigma_{c,shot} = 13.301 + 3.08 \cdot \ln(t - 0.025)(R^2 = 0.999) \tag{2}$$

$$E_{shot} = -0.829 + 4.483 \cdot \ln(t + 1.289)(R^2 = 0.99) \tag{3}$$

$$C_{inter} = 0.797 \cdot (1 - e^{-0.112t})\ (R^2 = 0.987) \tag{4}$$

$$f_{inter} = 42.672 \cdot (1 - e^{-1.553t})\ (R^2 = 0.959) \tag{5}$$

$$\sigma_{t,inter} = 0.336 \cdot (1 - e^{-0.122t})\ (R^2 = 0.989) \tag{6}$$

$$K_{s,inter} = 3.559 \cdot (1 - e^{-1.125t})\ (R^2 = 0.965) \tag{7}$$

$$K_{n,inter} = 3.495 \cdot (1 - e^{-0.186t})\ (R^2 = 0.982) \tag{8}$$

Where $\sigma_{c,shot}$ is the uniaxial compressive strength of the shotcrete, MPa; E_{shot} is the modulus of elastic of the shotcrete, GPa; C_{inter} is the cohesion of the contact surface , MPa; f_{inter} is the friction angle of the contact surface; $\sigma_{t,inter}$ is the tensile strength of the contact surface, MPa; $K_{s,inter}$ is the tangential stiffness of the contact surface; $K_{n,inter}$ is the normal stiffness of the contact surface.

Saiang et al. (2005) also conducted laboratory tests on the contact surfaces with different roughness and obtained the mechanical parameters of the contact surfaces with different roughness.

Table 1. Laboratory test results of mechanical parameters of the contact surface between shotcrete and surrounding rock.

parameters	JRC=1-3	JRC=9-13
f_{inter}	Peak value：40°；residual value35°	Peak value：47°；residual value 39°
c_{inter}	0.56MPa	/
$K_{s,\text{inter}}$	251MPa/mm	/
$K_{n,\text{inter}}$	0.94MPa/mm	1.3MPa/mm

note：JRC is roughness grade divided according to Barton (1977).

2.2 *The evaluation of the internal force of shotcrete*

The force analysis of shotcrete mainly needs to consider two cases:

- Case (1) spray shotcrete and anchor support. In this case, the force generated by surrounding rock deformation is mainly borne by the shotcrete.
- Case (2) combined support of spray shotcrete, anchor, and steel arch. In this case, the deformation force of surrounding rock will be shared by shotcrete and steel arch.

Carranza-Torres & Diederichs (2009) made a detailed analysis of the internal forces of shotcrete and steel arch of the two cases, and proposed the strength envelope of compression, tension and shear force. Based on the theory of literature, the stress of each unit of the liner structure in the numerical calculation can be extracted and the stress state can be evaluated. The main formula is:

(1) Spray anchor support (shotcrete + anchor)

$$\begin{cases} \sigma_c^t = \frac{N}{A} \pm \frac{M}{I} t/2 \\ \tau_{max} = \frac{3}{2}\frac{Q}{A} \\ \sigma_c^t = \frac{\sigma_{max}}{2} \pm \sqrt{(\frac{\sigma_{max}}{2})^2 + \tau_{max}^2} \ ; \sigma_{max} = \frac{N}{A} \end{cases} \tag{9}$$

Where σ_t is the compressive strength of the material; σ_c is the tensile strength of the material; A is the cross-sectional area of the material; I is the moment of intertia of the material; M and N is are the bending moment and axial force respectively; t is the height (thickness) of the section; Q is shear force.

$$\begin{cases} N_c = -\frac{|M|At}{2I} + \sigma_c A \\ N_t = -\frac{|M|At}{2I} + \sigma_t A \end{cases} \tag{10}$$

$$\begin{cases} N_c = -\frac{9}{4}\frac{Q^2}{\sigma_c A} + \sigma_c A \\ N_t = -\frac{9}{4}\frac{Q^2}{\sigma_t A} + \sigma_t A \end{cases} \tag{11}$$

Where N_c and N_t are the maximum axial and axial tensile forces that the material can withstand. The strength envelope of the sprayed layer can be obtained by the formulas (10) and (11).

(2) Combined support of spray anchor and steel arch (shotcrete + anchor + steel arch)

$$\begin{cases} M_1 = \frac{MK_1}{n(K_1+K_2)} \\ M_2 = \frac{MK_2}{n(K_1+K_2)} \end{cases} \tag{12}$$

$$\begin{cases} Q_1 = \frac{QK_1}{n(K_1+K_2)} \\ Q_2 = \frac{QK_2}{n(K_1+K_2)} \end{cases} \tag{13}$$

$$\begin{cases} N_1 = \frac{N}{n}\frac{D_1}{(D_1+D_2)} + \frac{M}{nR}\frac{D_2K_1-D_1K_2}{(D_1+D_2)(K_1+K_2)} \\ N_2 = \frac{N}{n}\frac{D_2}{(D_1+D_2)} - \frac{M}{nR}\frac{D_2K_1-D_1K_2}{(D_1+D_2)(K_1+K_2)} \end{cases} \tag{14}$$

Where "1" and "2" subscripts respectively represent the spray layer and the steel arch; $D = EA/(1 - v^2)$; $K = EI/(1 - v^2)$. The axial force N, the bending moment M and the shearing force Q of the sprayed layer and the steel arch can be obtained by the formula (14-16). And the material can be judged whether the force meets the requirements by the formulas (12) and (13).

3 RESULTS AND DISCUSSION

According to the above methods, *FLAC3D* is used to design and demonstrate the shotcrete supporting structure of the adit tunnel in Kokhav Hayarden pumped storage project in Israel. The time and space effect of shotcrete support were considered. The power station is located in northeast Israel, on the western side of the Dead Sea fault. The lithology of the project area is mainly in bs-strong class III (dense basalt III), bs-weak class III/IV (porosity, almond basalt III/IV), pyr class III/IV (breccia class III/IV/V) and clay class V. The supporting in three kinds of rock mass will be studied. Due to the limitation of space, this paper describes the shotcrete design results of one case: clay class V (clay) and bs-weak class III/IV rock mass. The numerical model is shown in Figure 2. The parameters of the rock mass are listed in Table 2. The clay V rock mass basically appears in the form of sandwich. And the thickness of clay V is about 0.7~0.8m. In the analysis, we assumed that the thickness of clay is 0.7 m, and the angle is about 15°.

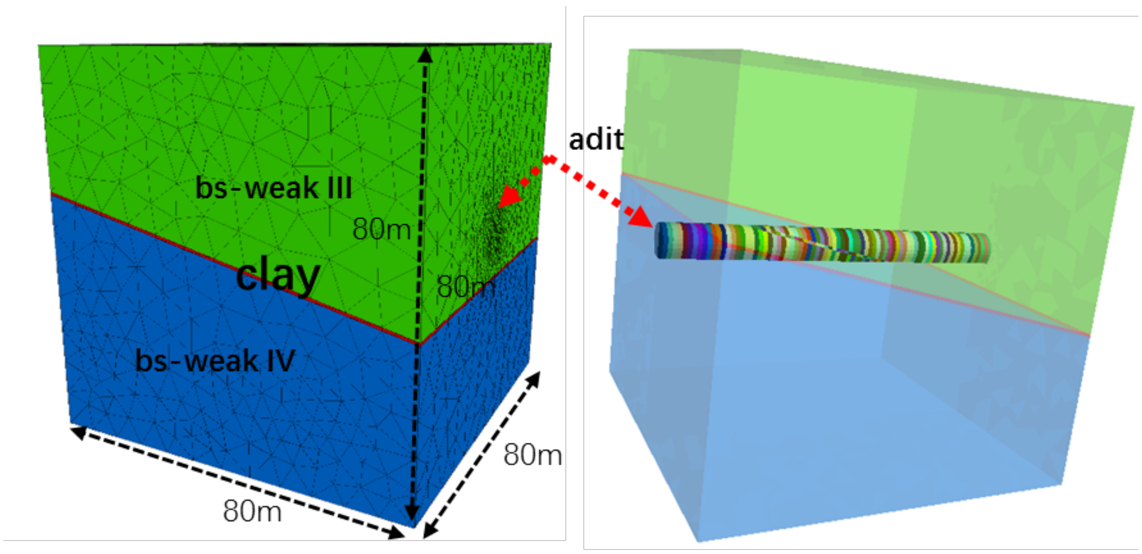

Figure 2. Calculation models for shotcrete design in clay class V rock mass.

Table 2. Mechanical parameters of rock mass in engineering area.

Rock lithology	Rock mass	density/kN▪m^3	σ_{ci} /MPa	GSI	mi	*u*
bs-weak	III	2.60	50	50.81	12	0.26
bs-weak	IV	2.35	40	31.34	9	0.285
Rock lithology	Rock mass	density/kN▪m^3	modulus/MPa	friction	cohesion/MPa	*u*
clay	V	1.9	300	0.25	0.03	0.33

The in-situ stress used in this numerical model is: $S_{Hmax}=1.5S_V$, $S_h=0.71S_V$; S_H Direction: N11°W; S_h Direction: N79°E; S_V is vertical.

According to the experimental results, the final elastic modulus of the spray layer was set at 30.6 GPa and poisson's ratio was 0.2. The time-space effect of elastic modulus of the spray layer mechanical parameters was considered in the calculation, and equation (4) was adopted for conversion. For example, when Part 1 (shown in Fig. 1) was excavated , the elastic modulus of the shotcrete of part 1 is calculated with equation (4) with time t_1 (assuming excavate one step need t_1 hour). Then, when part 2 is excavated , the elastic modulus of the spray layer of part 2 is calculated with equation (4) with time t_1. However, now the elastic modulus of the spray layer of part 1 is calculated with equation (4) with time $2t_1$.

3.1 *Results*

We considered whether or not to consider the time and space effect. Figure 3 shows the results of displacement, plastic zone and internal force of shotcrete.

3.2 *Discussion*

It can be seen that many points in the M-N and Q-N interaction diagram are out the envelope of the shotcrete when the the time and space effect is not considered. When time and space effect is considered, the bending moment and shear force of the shotcrete is decreased and all points are within the envelope. This means with the designed thickness of shotcrete, the internal force of the shotcrete meet the design requirement.

At the typical section, the roof arch displacement is 45.7mm, the side wall displacement is 38.5mm, the floor deformation is 138.0mm, and the maximum convergent strain is 3.83%. The depth of the plastic zone of the surrounding rock is 0.6-4.8m, which is less than the length of the bolt.

So, the time and space effect of shotcrete is very important in the simulation of the internal force of shotcrete and design of the type and thickness of shotcrete.

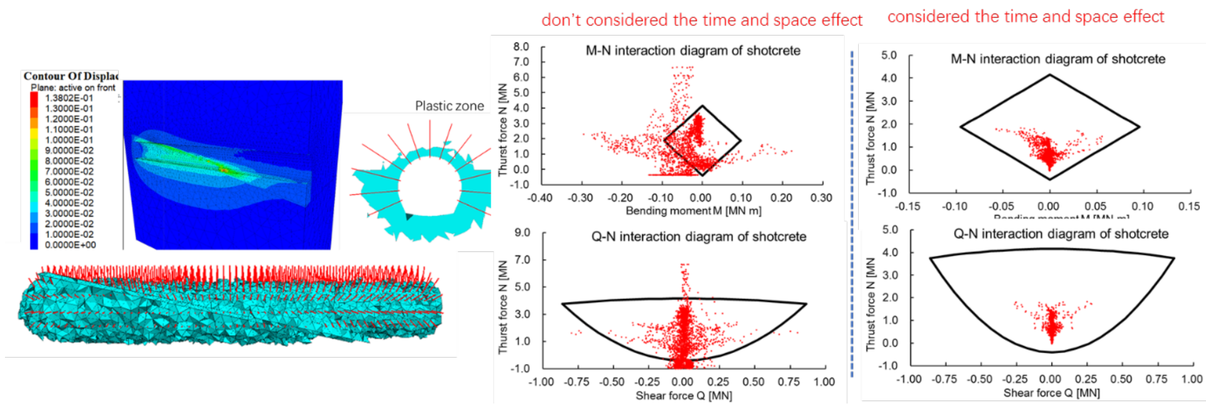

Figure 3. The results of displacement, plastic zone and the envelope of internal force of shotcrete in clay V rock mass with thickness t=25cm.

4 CONCLUSIONS

- As an important supporting type in underground caverns, the shotcrete has complex time and space effects in the process of construction, such as the mechanical properties of the shotcrete itself and the mechanical properties of the contact between the surrounding rock and the spray layer.
- It is necessary to consider the time and space effect imposed by the shotcrete in the support design and calculation, otherwise, the load borne by the shotcrete will be overestimated by 3-5 times.
- The axial force and bending moment of the envelope chart - shear force and axial force envelope diagram can be used to well evaluate the internal force of shotcrete layer, the calculation and practice verification.
- The practice of the tunnel support design of the Kokhav Hayarden pumping water storage power station in Israel indicates the rationality of the design calculation method considering the time and space effect imposed by the shotcrete. However, the time and space effects of the mechanical parameters of the contact surface between the surrounding rock and the shotcrete have not been taken into account in this study, which will be further explored in subsequent studies.

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