Calculating the GRC for tunnels supported by grouted rockbolts

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ABSTRACT: Obtaining Ground Response Curves (GRC) is a useful method in the design of support systems for underground excavations. Analytical methods have some limitations when modeling tunnels supported by grouted rockbolts. In this paper, by using numerical modeling 2D FLAC, the GRC are obtained for a tunnel supported by grouted rockbolts and are compared with the GRC for an unsupported tunnel. The tunnel's inner pressure is decreased step by step during the calculation using FISH language to simulate the advancement of the tunnel face. Rockbolts are modeled using CABLE elements with shear springs connected to them to simulate the grout surrounding them. In addition, the GRC calculated from two analytical methods are compared with the results obtained using the numerical method.

1 INTRODUCTION

There are various methods for designing support systems for underground excavations, and each one has advantages and disadvantages. The convergence-confinement method is a useful analytical method in which the interaction between the support and rock or soil media is investigated. In this method, two curves are plotted: Ground Response Curves (GRC) for the ground and Support Response Curves (SRC) for the support. The conjunction of these two curves is the equilibrium point which represents the displacement of a selected point on the tunnel perimeter.

The problem with using this method for grouted rockbolts is that the grout alters the ground properties and consequently affects the tunnel deformations; therefore, SRC and GRC cannot be divided into two independent curves. In other words, to represent the tunnels reinforced by grouted rockbolts, only the curve showing the combined behavior of the ground and rockbolts should be plotted. This new curve is then used for estimating (studying) other support systems such as shotcrete or concrete linings. In this paper, using a two dimensional numerical model, the GRC for a tunnel reinforced by grouted rockbolts is calculated and is compared with the GRC for a tunnel with no bolts.

2 METHODS FOR PLOTTING GRC

Attempts have been made to plot the GRC for tunnels supported by grouted rockbolts using analytical methods. In a model introduced by Indraranta-Kaiser (1990), only the final displacements of a tunnel supported by grouted rockbolts are calculated, and therefore no curve is plotted. In this solution, the relation between major stress components in the polar coordinates is presented in the following:

$$\sigma_\theta = m \cdot \sigma_r + s \cdot \sigma_c \tag{1}$$

Where $m = tg^2\left(\frac{\pi}{4} + \frac{\Phi}{2}\right)$, and $0 < s < 1$

The strength parameters of the rock (m, σ_c) are increased based on the following experimental equations reflecting the effect of grouted rockbolts where β represents the effect of bolts:

$$\begin{aligned} m^* &= m(1+\beta) \\ \sigma_c^* &= \sigma_c(1+\beta) \end{aligned} \tag{2}$$

β is calculated by the following where $\lambda =$ frictional factor of grout; $r =$ tunnel radius; $d_b =$ bolt diameter; and $C =$ spacing of the bolts:

$$\beta = \frac{\pi \cdot d_b \cdot \lambda \cdot r}{C} \tag{3}$$

In this approach, the GRC is not plotted, but only the final displacement of the tunnel perimeter is calculated based on increased strength parameters.

Zakariaee (2003) has introduced another analytical method in which the GRC is plotted using differential equations for the ground and rockbolts. In this solution, three zones are identified:

1. Rockbolts and rock are both plastic.
2. Rock is plastic but rockbolts are elastic.
3. Both rockbolt and rock are elastic.

In this method, the equilibrium equation is as follows:

$$\frac{\partial\sigma_r}{\partial r}+\frac{\sigma_r-\sigma_\theta}{r}=0 \tag{4}$$

The effect of grouted rockbolts is shown in the reduction of radial stress which is calculated as follows where T = bolt force, and C = spacing of the bolts:

$$\sigma'_r=\sigma_r-\frac{T}{C} \tag{5}$$

In this approach, the plastic zone radius is calculated through a trial and error method. Equation (4) can be solved using a stepwise calculation to obtain the GRC.

However, both Indraranta-Kaiser and Zakariaee method have certain assumptions which limit their applications; it is assumed that the rock is homogenous and isotropic, the tunnel cross section is circular (axisymmetric condition), and hydrostatic in-situ stress condition exists. In addition, the weight of the plastic zone is not taken into account.

On the other hand, approaches for plotting the GRC for tunnels supported by grouted rockbolts involving numerical methods do not make limiting assumptions that exist in analytical methods.

To plot the GRC for a section of a tunnel with a certain distance from the tunnel face, an inner pressure equal to the in-situ stresses is applied, and decreased step by step to simulate the advancement of the tunnel face. This gradual decrease in the inner pressure is referred to as "stress relaxation."

As Panet (1979) proposed, by relating the tunnel closure at a specific section of a tunnel to the face distance from that section, a proper relaxation factor for the section where the support is being installed can be identified. In order to do so, an axisymmetric model is used in this research. In the first step, the GRC for a tunnel supported by grouted rockbolts is plotted. Using this GRC and an appropriate relaxation factor, the effects of installing other supports such as shotcrete can be investigated.

3 MODELING PROCEDURE

The program used for modeling the excavation and support installation is 2D FLAC, which is a finite difference program widely used for modeling geotechnical problems. In our research, the Mohr-Coulomb constitutive model is used for modeling the rock behavior. The input parameters are shown in Table 1.

For modeling the rockbolts, cable elements are used. The length of the rockbolts is assumed to be large enough to completely cover the plastic zone. In order to estimate the plastic zone radius, the radius of the unsupported sections should be calculated first.

Table 1. Dimensions and properties for example tunnels.

Tunnel no.	Elastic modul. (MPa)	Poisson ratio	Fric. angle (Degree)	Cohes. (kPa)	Insitu stress (MPa)	Tunnel radius (m)
1*	5000	0.25	23	170	2.5	1.65
2*	1380	0.25	32	370	3.3	5.35
3	1600	0.2	30	240	2	3
4	1600	0.2	30	240	2	4
5	1600	0.2	30	240	2	5

*These two examples have been chosen from Kielder experimental tunnel (Freeman, 1978; Ward, 1976).

Table 2. Rockbolts and grout properties.

Tunnel no.	Area (cm^2)	Elastic modul. (GPa)	Spacing (m × m)	T_{max} (KN)	K_{bond} (MPa)	S_{bond} (MPa/m)
1&2	5	200	1 × 1	125	15000	0.8
3&4&5	5	200	1 × 1	550	15000	0.8

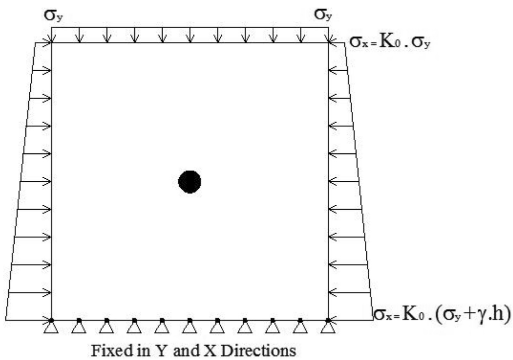

Figure 1. Boundary and stress conditions.

For modeling the grout, shear springs are placed at the nodal points of the cables and are attached to the rock elements. The properties for cable elements and grout are presented in Table 2. K_{bond} represents the grout shear stiffness and S_{bond} is the grout shear strength.

The mesh is generated radially. Because the model has to be large enough to ignore the boundary effects, the boundaries are set at a distance five times the diameter of the tunnel from each side of the tunnel. The bottom boundary is fixed in both horizontal and vertical directions. The in-situ stresses are applied to the top and side boundaries (Figure 1). After nullifying the excavation area, nodal forces which are equivalent to the inner pressures are applied. The inner pressure is equal to the in-situ stress at the start of the modeling procedure.

The nodal forces are decreased step by step until they reach zero. This research involved twenty steps; in the first step, the nodal forces are equivalent to the in-situ stresses, whereas in the last step the nodal forces are zero. This last step resembles the tunneling state in which the tunnel face has advanced far enough from the pertinent tunnel section that the tunnel face advancement does not affect the deformations of the tunnel section. The step by step calculations are performed by FISH programming language which is a part of FLAC program.

At each step, the closure of the tunnel perimeter is recorded by FISH. As nodal forces decrease in each step, which suggests that the tunnel face is advancing, more relaxation and closure occurs in the tunnel perimeter.

With a proper relaxation ratio, the cable elements and shear springs acting as grout are installed as the procedure continues so that the closure of the tunnel at each relaxation ratio is obtained; then the GRC is plotted. It is evident that the relaxation ratio at which the grouted rockbolts are installed must be within the elastic part of the GRC in order to make rockbolts more effective.

After plotting the GRC for the tunnel with grouted rockbolts, the effect of applying other types of supports such as shotcrete can be investigated by introducing them at proper relaxation factors. After installing other supports at proper steps of the solving, the modeling procedure should be continued to reach the final equilibrium.

4 INTERPRETATION OF THE OUTPUTS

The results of the modeling for the example tunnels are given in Table 3. For all the tunnels, the maximum radial displacement of the tunnel perimeter and the plastic zone radius are shown for both bolted and non-bolted cases. As expected, both plastic zone radius and maximum radial displacement are decreased when grouted rockbolts are used.

The GRC for tunnels 1 and 2 is plotted in Figures 2 and 3 respectively. As shown in the plots, installing the grouted rockbolts in the tunnel causes the GRC to move downward. In other words, with a specific relaxation factor and the same dimensions and properties, the displacement rate of a tunnel is lower when it is supported by grouted rockbolts than when it is not. The GRC consists of two parts: an elastic part and a plastic part. In the elastic part, the curve is linear and as the relaxation increases (the inner pressure decreases), the displacement, or the closure, increases linearly. In the plastic part, the GRC is concaved upward, and as the relaxation increases the displacement changes non-linearly, and finally the curve becomes almost flat. The installation of the grouted rockbolts only affects the plastic part of the curve and has no effect on the elastic part. According to these curves, the rockbolts have no effect on tunnel convergence until a section turns into plastic mode and displacements become high. At this point, the rockbolts restrict both plastic zone radius and tunnel convergence, thereby causing the GRC to move downward. This point can be recognized for both

Table 3. Results of modeling.

Tunnel no.	Tunnel radius (m)	Grouted rockbolts	Max. radial displacement (mm)	Plastic zone radius (m)
1	1.65	Yes	5	4
		No	7	5
2	5.35	Yes	28	8
		No	32	9
3	3	Yes	11	5
		No	14	6
4	4	Yes	15	7
		No	20	8
5	5	Yes	18	8
		No	27	10

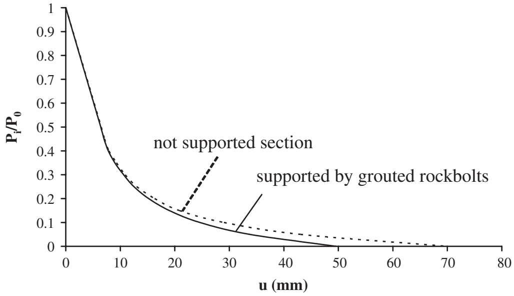

Figure 2. Ground Response Curve for tunnel 1. u is the maximum radial displacement of tunnel at inner pressure P_i. P_0 is the in-situ stress.

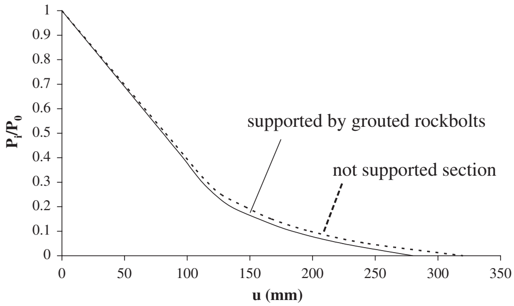

Figure 3. Ground Response Curve for tunnel 2. u is the maximum radial displacement of tunnel at inner pressure P_i. P_0 is the in-situ stress.

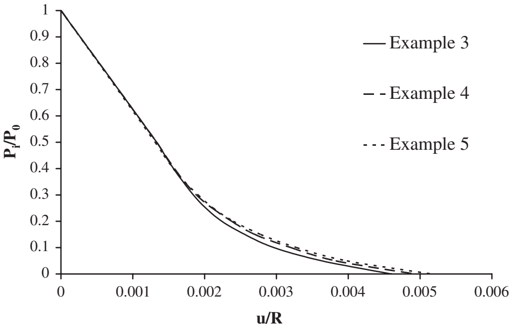

Figure 4a. Normalized Ground Response Curve for tunnels 3, 4 and 5; unsupported. u is the maximum radial displacement of tunnel at inner pressure P_i. P_0 is the in-situ stress. R is tunnel radius.

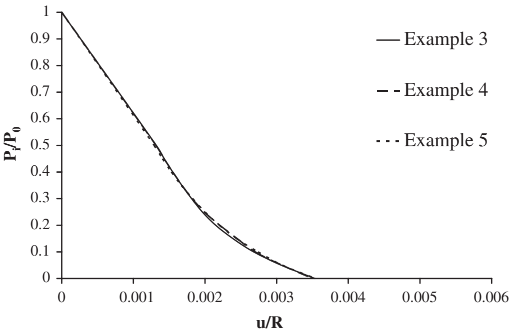

Figure 4b. Normalized Ground Response Curve for tunnels 3, 4 and 5; supported by grouted rockbolts. u is the maximum radial displacement of tunnel at inner pressure P_i. P_0 is the in-situ stress. R is tunnel radius.

tunnels: tunnel 1 at sixty percent (60%) of relaxation and tunnel 2 at seventy percent (70%) of relaxation.

The normalized GRCs for tunnels 3, 4 and 5 show minimal difference when the tunnels are not supported. This is shown in Figure 4. They are only different in their radius, and as the radius increases, the GRC moves slightly to the right. When these three sections are supported by grouted rockbolts of the same patterns and properties (see Table 2), the normalized Ground Response Curve is the same for all of them (Figure 4). This is due the fact that these tunnels are supported by high strength bolts which are not yielded in the calculation. It can be concluded that the pattern and properties of rockbolts have a greater effect on the GRC than the tunnel radius.

In Table 4, a comparison is made between the results from the numerical solution used in this research and the two analytical solutions introduced earlier in this paper. The properties of Tunnels 1 and 2 are applied here. As shown, the results of the numerical solution

Table 4. Comparison between different solutions for tunnels supported by grouted rockbolts.

	Numerical modeling		Zakariaee		Indraranta-Kaiser	
Tunnel number	Plastic zone r. (m)	Max. Disp. (mm)	Plastic zone r. (m)	Max. Disp. (mm)	Plastic zone r. (m)	Max. Disp. (mm)
1	4.4	0.5	5.5	0.5	–	0.4
2	8	2.8	8.3	2.9	–	3.7

are close to the results of Zakariaee analytical solution, while the results of Indraranta-Kaiser method are not close to these two methods.

In the numerical modeling and the Zakariaee method, the Mohr-Coulomb constitutive model is utilized, and the maximum displacement is calculated by solving the equilibrium equations. In FLAC, the finite difference method is used to solve the equations, whereas in the Zakariaee method the equations are solved using stepwise calculation. The Indraranta-Kaiser method is not based on the Mohr-Coulomb constitutive model, but it involves some empirical coefficients to simulate the behavior of the ground supported by grouted rockbolts. Therefore, the results from the Indraranta-Kaiser method are less compatible with the two other methods.

5 CONCLUSION

In this paper, a numerical modeling procedure was described to plot the Ground Response Curves (GRC) for the tunnels supported by grouted rockbolts. In this approach, there is no need to plot a separate Support Reaction Curve (SRC) for the rockbolts because the effects of the rockbolts are included in the GRC.

Using this numerical modeling, the GRC was obtained for tunnels supported by grouted rockbolts and was compared with the GRC for unsupported tunnels. The rockbolts were modeled using CABLE elements with shear springs connected to them to simulate the grout surrounding them.

Additionally, the GRC calculated from two analytical methods including Zakariaee method and Indraranta- Kaiser method were compared with the results obtained from the numerical modeling. It was shown that there is a rather good compatibility between these methods especially between Zakariaee method and the numerical simulation. The good compatibility between these two methods is due to their similar basic assumptions, whereas Indraranta- Kaiser method is an empirical method and it involves empirical coefficients to simulate the behavior of the ground supported by grouted rockbolts.

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