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Ground Characteristic Curve and Convergence Confinement Method - A case study

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ABSTRACT

Ground Characteristic Curve (GCC) describes the relationship between the initial stress of rock mass and the displacement of rock mass on the boundary of tunnels. Another way that indicates the relationship of support pressure and the level of Convergence Confinement of tunnels by percent. The using GCC to design supports in the underground construction has many advantages to ensure full utilization of the loading bearing capacity of rock mass, and release a part of initial stress in the rock mass around tunnels. However, this method is limited in the field of underground mines in Viet Nam. This article analyzed and applied GCC and Convergence Confinement Method (CCM) to design the supports of underground constructions and applied them to the geological conditions of the Nam Mau coal mine - Vinacomin. The research results show that at the geological conditions of the drift at level +125 in Nam Mau coal mine, TH section steel ribs with flange width 124 mm, section depth 108 mm, weight 21 kg/m, maximum support pressure 1.98 MPa, and spacing 700 mm were applied. Results of research in this method can be applied to design rock supports for deep roadways and other drifts in the underground mines in Quang Ninh province of Viet Nam. By a factor of safety, mobilized support pressure, wall displacement of roadways, and convergence of roadways the designation and selection of rock support around roadways will become clearer. Near future this method should be widely applied in the combined protection design in deep roadways in underground mines in Viet Nam. Although the method has great advantages, it is still necessary to have complete and detailed monitoring data of the geological and hydrogeological conditions in the area under consideration.

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1. Introduction

The rapid development of the economy in the world and Vietnam requires consuming bigger energy. Therefore, the shallow minerals are gradually exhausted and the mineral resources in the depth are required. Currently, coal mining countries have taken the steps of deep exploitation, the depth of exploitation under 1000m below the surface. Almost these exploitered depths existed in Russia, South Africa, Canada, the USA, India, Germany, and China. Rock mass types often change in the depth and have very strong alterations, so the design and structural selection are big challenges. Theories of analysis, and calculation of the structures in the roadways and drifts in case of exploiting shallow are not suitable for deep underground openings. Hence, they are inadequacies in the design (Hoek, 1980; Panet et al., 1995; Vrakas, 2014, 2016; Lee, 2014; Manuel et al., 2019; Naouz et al., 2019; Baklashov, 2002; Nguyen, 2007; Vo, 2006).

Deep mining is also accompanied by the difficult conditions on the ventilations in the roadways, the ventilated system will be more complicated, the fans must have a big capacity, the required amount of wind will be applied. Drainage also will become more complicated due to the increase of underground water. In Vietnam, at the Nam Mau coal mine in Quang Ninh province mines are often located near the sea, the sea level height and currently many mines are exploited under opencast mining, so the drainage and the stability for roadways and drifts are especially complicated and dangerous.

The varieties of geological conditions in the Quang Ninh area have been described in the documents (Dao et al., 2004; Nguyen, 2006).

The excavation of the deep roadways can be encountered by the soft and swelling rocks. When the water is present in the rocks, the pressure will be increased especially in the rock located in the tectonic regions. The initial stress will be changed, the pressure of rock mass also increased, the dimensions and cross-section of roadways will be reduced (Naouz et al., 2019; Vlachopoulos, 2009). The analytical theories are being applied in Viet Nam with the use of supports such as steel ribs, rock bolts, shotcrete and the combination of steel ribs with bolts, bolts with shotcrete are gradually become outdated, and not effective. Nowadays, the design trends of rock support basing on utilizing the combination working ability of rock mass (interaction of rock mass-supports) and support, releasing the initial stress in a rock mass (Do, 2011; Tran et al., 2018) will be more attention to maintaining stability and reduce the costs of roadway construction. This design in Viet Nam is still less concerned and focused on using the loading capacity of rock mass around roadways, which requires more in-depth researche and analysis in the future in the field of mining construction to ensure sustainable development of national energy.

In Vietnam the design and selection of rock supports on the GCC and CCM have been studied for a long time. (Nguyen, 2007) already gave the concepts and factors that have an influence on the calculation of the earth pressure in case of consideration to the GCC. Do (2011) analyzed the effects of the reliability when using the CCM to design the supports in underground construction. However, most of these authors are not related to the state of rock mass around roadways after installing supports. When the rock mass-support system will be worked together, at this stage, the second stress state in the rock mass around underground constructions tends to restore the original primary stress state and the actual conditions support must be carried loading from the recovered stress (the third stress state system of rock mass-support).

2. Theoretical basis of the Ground Characteristic Curve and Convergence Confinement Method

Derived from a circular tunnel with a radius of R_t in the homogeneous elastic rock mass or elasto-plastic environment. In the primary rock mass, the state of initial stress in the rock mass is not alternated $P = P_0$ (Figure 1), when the tunnel is excavated to the design cross-section with the excavated radius R_t the primary stress will be transformed. The displacement of rock mass on the tunnel boundary starts to increase (on the horizontal axis), at the same time initial stress will be released (initial stress decreased on the vertical axis). If the rock mass is elastic behavior, the tunnel boundary will be continuously transformed from R_s to the maximum

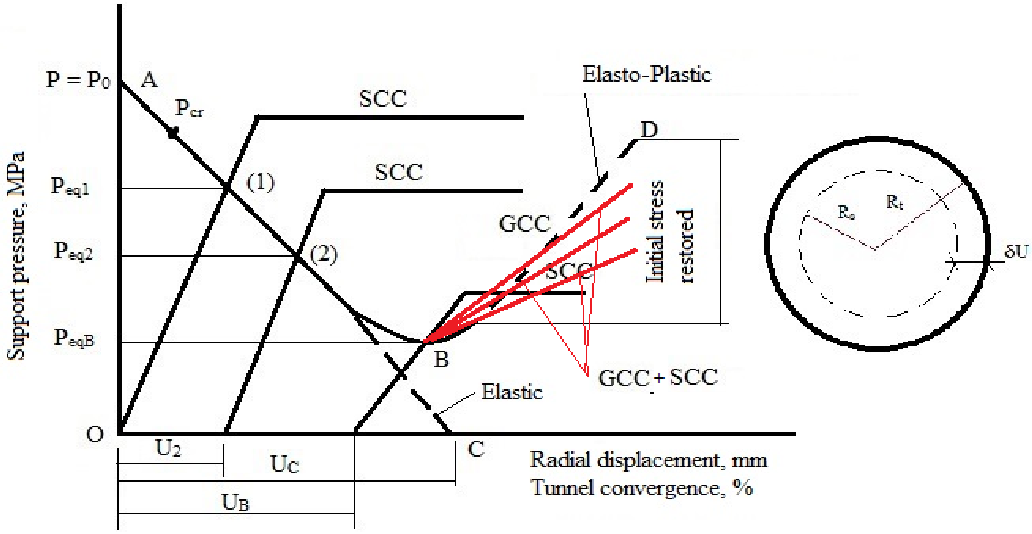


Figure 1. The Ground Characteristic Curve and Support.

displacement (U_c) at the point C on the horizontal axis (Figure 1), and rock mass on the boundary is limited deformed. In this case the tunnel will not need to use rock supports (natural stable tunnels - unsupported tunnels). In the elasto-plastic rock mass after the elastic stage, plastic deformation will appear, the graphic GCC also will go up tend (dotted lines).

The Support Characteristic Curve (SCC) described in (Figure 1) shows the values of durable pressures of support (these values can be received by the tests in the laboratories or the site of construction). The time of support installation in this method is an important parameter to reduce the thickness and the type of support. If after excavation tunnels supports are installed immediately, the system of rock mass-supports together work from the point (1) and the equivalent support pressure at this point P_{eq1}, in case of allowing the displacement of boundary an amount U_2 or (δU) as in the right of (Figure 1) the support pressure must be mobilized at the time durable support-rock mass working together is P_{eq2} ($P_{eq2} < P_{eq1} < P = P_0$). Effects of support systems and GCC are GCC + SCC (red line in Figure 1), this line can be linear or non-linear depending on the characteristics of GCC and flexibilities of supports. This case will be taken using the releasing of the initial stress. The optimal installing time can be selected by the displacement of tunnel boundary equations at U_B, the support must be carried pressure P_{eqB}, this point is optimal. However, because rock mass is elasto-plastic, from the B equivalent point, the system of support-rock mass together carries loading from rock mass. Rock mass outside of the plastic zone continues to be compressed from the rock mass in the elastic zone and because of the loss of rock mass volume in the massive rock (because of tunnel excavation R_t), rock mass in the elastic zone will be deformed, the support pressure will be continuously increased (dotted line in Figure 1). However, the finishing of the line only extends to the D point (unable to extend the height of point A) because of rock massive is reduced, initial stress has already been released.

Safety Factor (SF) will be applied in case of using GCC and CCM to design support in tunnels (Figure 2). SF can be calculated by the ratio between the mobilized support pressure Ps and equivalent pressure Peq (the time system of rock mass-support works together - intersection point GCC and SCC).

(Carranza-Torres, 2004) proposed the Ground Characteristic Curve with the sandstone by using the elasto-plastic solutions for circular tunnels with extremely initial stress of infinity. Formulas were written by (Carraza-Torress, 2000) as following:

$$m_b = m_i e^{\left(\frac{GSI-100}{28}\right)} \tag{1}$$

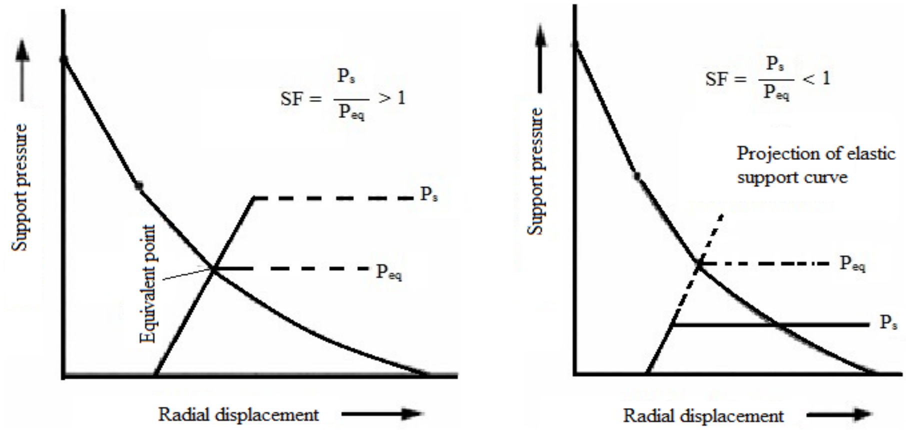


Figure 2. Defined the design of support according to Safety Factors (SF) (Carraza-Torress, 2004).

$$P_i = \frac{p_i}{m_b \sigma_{ci}} + \frac{s}{m_b^2} \tag{2}$$

$$S_0 = \frac{\sigma_0}{m_b \sigma_{ci}} + \frac{s}{m_b^2} \tag{3}$$

$$P_i^{cr} = \frac{1}{16}\left(1 - \sqrt{1 + 16 S_0}\right)^2 \tag{4}$$

$$p_i^{cr} = \left(P_i^{cr} - \frac{s}{m_b^2}\right) m_b \sigma_{ci} \tag{5}$$

$$s = e^{\frac{GSI - 100}{9}} \tag{6}$$

$$a = 0{,}65 - \left(\frac{GSI}{200}\right) \tag{7}$$

$$u_r^{el} = \left(\frac{\sigma_0 - p_i}{2G_{rm}}\right) R \tag{8}$$

$$G_{rm} = \frac{E_{rm}}{2(1 + v)} \tag{9}$$

$$E_{rm} = 1000 C(\sigma_{ci}) 10^{\left(\frac{GSI - 10}{40}\right)} \tag{10}$$

$$R_{pl} = \mathrm{Re}^{2\left(\sqrt{P_i^{cr}} - \sqrt{P_i}\right)} \tag{11}$$

$$K_\psi = \frac{1 + \sin\psi}{1 - \sin\psi} \tag{12}$$

$$\begin{aligned} \frac{u_r^{pl}}{R}\frac{2G_{rm}}{\sigma_0 - p_i^{cr}} &= \frac{K_\psi - 1}{K_\psi + 1} + \frac{2}{K_\psi + 1}\left(\frac{R_{pl}}{R}\right)^{K_\psi + 1} \\ &+ \frac{1 - 2v}{4\left(S_0 - P_i^{cr}\right)} \ln\left(\frac{R_{pl}}{R}\right)^2 \\ &- \left[\frac{1 - 2v}{K_\psi + 1}\frac{\sqrt{P_i^{cr}}}{S_0 - P_i^{cr}} + \frac{1 - v}{2}\frac{K_\psi - 1}{\left(K_\psi + 1\right)^2}\frac{1}{S_0 - P_i^{cr}}\right] \\ &\left[\left(K_\psi + 1\right)\ln\left(\frac{R_{pl}}{R}\right) - \left(\frac{R_{pl}}{R}\right)^{K_\psi + 1} + 1\right] \end{aligned} \tag{13}$$

$$\begin{aligned} \frac{u_r^{pl}}{R}\frac{2G_{rm}}{\sigma_0 - p_i^{cr}} &= \left[\frac{1 - 2v}{2}\frac{\sqrt{P_i^{cr}}}{S_0 - P_i^{cr}} + 1\right]\left(\frac{R_{pl}}{R}\right)^2 \\ &+ \frac{1 - 2v}{4\left(S_0 - P_i^{cr}\right)} \ln\left(\frac{R_{pl}}{R}\right)^2 \\ &- \frac{1 - 2v}{2}\frac{\sqrt{P_i^{cr}}}{S_0 - P_i^{cr}}\left[2\ln\left(\frac{R_{pl}}{R}\right) + 1\right] \end{aligned} \tag{14}$$

The meaning of these parameters in expressions from (1) to (14) can be explained in (Carranza-Torres, 2000, 2004).

2.1. Support Characteristic Curve for steel ribs

The maximum pressure (p_s^{max}) sustainable from the steel ribs and the elastic stiffness (K_s) of closed circular steel ribs is given by the following simplified expression after eliminating the effect of timber lagging (Carranza-Torres, 2000):

$$p_s^{\max} = \frac{3}{2}\frac{\sigma_{ys} A_s}{SR} \tag{15}$$

$$\frac{1}{K_s} = \frac{SR^2}{E_s A_s} \quad (16)$$

Where: p_s^{max} - maximum pressure of steel ribs (MPa); σ_{ys} - yield strength of the steel ribs (MPa); A_s - cross-sectional area of the section (m^2); S - steel set spacing along the tunnel axis (m); R - tunnel radius (m); K_s - elastic stiffness; E_s - Young's modulus of steel (MPa).

2.2. Support Characteristic Curve for shotcrete

The structural behavior of the lining system is calculated by using Equations (17), (18) to provide the maximum pressure that the shotcrete can sustain before collapse (P_s^{max}) and the elastic stiffness (K_s), they can be written as (Carranza-Torres, 2000):

$$p_s^{max} = \frac{\sigma_{cc}}{2}\left[1 - \frac{(R-t_c)^2}{R^2}\right] \quad (17)$$

$$K_s = \frac{E_c}{(1-v_c)R}\frac{R^2-(R-t_c)^2}{(1-2v_c)R^2+(R-t_c)^2} \quad (18)$$

Where: σ_{cc} - unconfined compressive strength of the shotcrete (MPa); E_c - Young's modulus of shotcrete (MPa); v_c - Poisson's ratio the shotcrete; t_c - thickness of shotcrete lining (m); R - radius of the tunnel (m).

2.3. Support Characteristic Curve for rock bolts

It is assuming that the system of bolts is equally spaced in the circumferential direction, the maximum support pressure (p_s^{max}) provided by the support system and the elastic stiffness (K_s), can be evaluated by using equations (Carranza-Torres, 2000):

$$p_s^{max} = \frac{T_{bf}}{s_c s_1} \quad (19)$$

$$\frac{1}{K_s} = s_c s_1\left[\frac{4L}{\pi d_b^2 E_s} + Q\right] \quad (20)$$

Where: d_b - diameter of bolt (m); L - free length of the bolt (m); T_{bf} - ultimate load obtained from a pull-out test (MN); Q - deformation load constant for the bolt and the head (m/MN); E_s - Young's modulus for bolt (MPa); s_c - circumferential bolt spacing, ($s_c = 2\pi R/n_b$), where n_b is the total number of equally spaced bolts installed in cross-section; s_1 - longitudinal bolt spacing (m).

2.4. Combination effect of support systems

If more than one of the support systems are installed as composite lining, their combined effect can be determined by adding the elastic stiffnesses for each of the individual supports. This has the effect of increasing the total elastic stiffness of the whole system. Consider for example, the case in which two supports characterized by maximum pressure p_{s1}^{max} and p_{s2}^{max} and elastic stiffnesses K_1 and K_2, respectively are installed in a section of tunnel. The stiffnesses K_s for the two systems acting together can be calculated as follows (Carranza-Torres and Faihurst, 2000):

$$K_s = K_1 + K_2 \quad (21)$$

This value is assumed to remain valid until one of the two supports achieves its maximum possible elastic deformation u_r^{max} calculated by formulas (Carranza-Torres, 2000):

$$u_{r1}^{max} = \frac{p_{s1}^{max}}{K_{s1}} \quad (22)$$

$$u_{r2}^{max} = \frac{p_{s2}^{max}}{K_{s2}} \quad (23)$$

$$u_r^{max} = u_{r1}^{max} + u_{r2}^{max} \quad (24)$$

The combined support system is assumed to fail at that point. The support with the lowest value of u_r^{max} determines the maximum support pressure available for the two supports acting together because if one assumes that the collapse of the support system coincides with the collapse of the weakest element, so the maximum support pressure that the system can sustain before collapse is calculated as following (Carranza-Torres and Faihurst, 2000):

$$p_s^{max} = u_{r\,min}^{max} K_s \quad (25)$$

3. Application of Ground Characteristic Curve and Rocsupport 3.0 to analyze effective reinforcement of rock bolts and steel ribs for geological conditions at Nam Mau coal mine

Rocsupport 3.0 was manufactured by Rocscience group in Canada and was built on the GCC and CCM. This software can be applied to analyze and select rock supports for tunnels from Safety Factor (SF). However, to use software with other tunnel shapes must be converted to the circular tunnel shape, for example, the conversion of rectangular tunnels and tunnels with arch and vertical walls can be shown in Figure 3.

Drift excavated at level + 125, geological conditions consist of claystone with the fine layer, the uniaxial compressive strengths by Prof. Protodiakonov M.M are 110 ÷ 400 kG/cm^2, the average 331 kG/cm^2 (Nguyen, 2006).

The thickness of claystone is 23 m. Siltstone with thin structures and average uniaxial compressive strengths equal 618 kG/cm^2. The hardness of sandstone and gritstone is 10.67. The plan view of drift is described in Figure 4.

The width of drift b = 3.92 m, the height h = 3.563 m, the cross-section area of drift S = 10 m^2, the drift excavated by conventional method (drilling and blasting), the thickness of coal seam m = 2.7 m, the inclined angle of the seam $\alpha = 60^0$ (Figure 5). In the basic roof of drift located the siltstone with the thickness 5.5 m and its uniaxial compressive strength R_c = 40 MPa. Under the floor of drift consisted of claystone and siltstone R_c = 60 MPa, the thickness of them m = 5 m. The compressive strength of coal ranges from 20÷30 MPa. The operation time of drift is 15 years, the depth of drift H = -135 m below the surface, and the drift is located in the tectonic area.

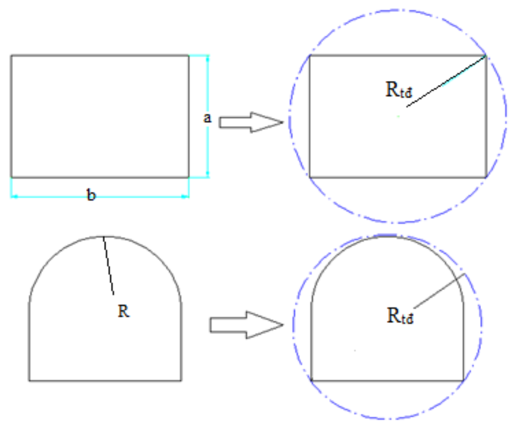


Figure 3. The conversion of rectangular and arch tunnels to analyze in Rocsupport 3.0.

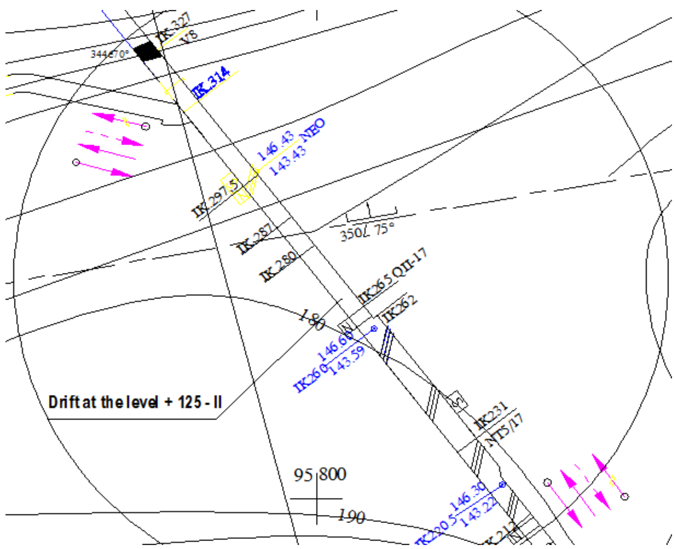


Figure 4. Plan view of drift at level +125 (Nguyen, 2006).

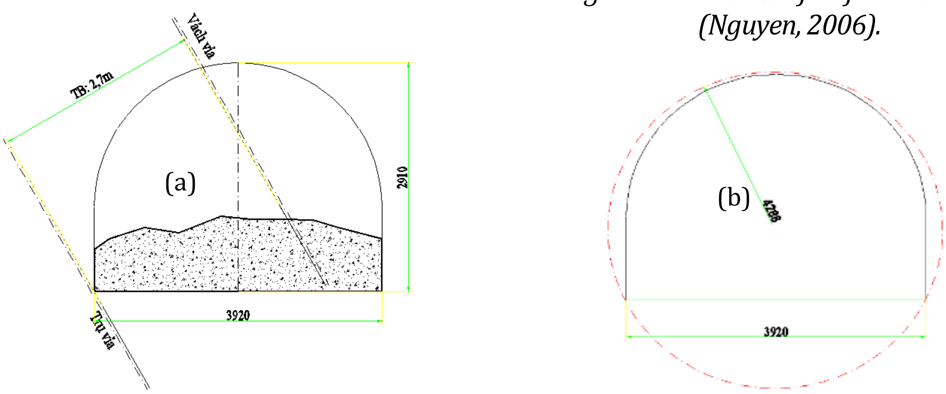


Figure 5. Equivalent cross-section to select rock support in drift: (a) Cross-section of drift; (b) Equivalent cross-section.

Cross-section and equivalent section of drift can be described in (Figure 5), the radius of the equivalent section received R_{td} = 2.143 m. Because the drift is located in the rock mass and coal seam, so the analysis only used average compressive strength R_{tb} = 25 MPa.

Design options 1

Using rock bolts and shotcrete: to design this option, the first step is to apply the thickness of shotcrete 50 mm. Mobilized pressure of shotcrete received 0.14 MPa. In this case, shotcrete and rock bolts are installed at the tunnel face according to the regulations of Coal and Mineral Group. After installation of the shotcrete (Figure 6) can be obtained the minimized plastic zone (Figure 6), the results of the analysis and safety factors for roadways design can be described in Table 1 and Figure 7.

The results in Table 1 and (Figures 6, 7) show that, received the safety factor SF = 1.09 < 2.0 and the final tunnel convergence 10.2%. Hence, the displacement of rock mass on the boundary of drift is 216.62 mm still too large, the tunnel will be needed the implement reinforcement. Assuming the addition of rock bolts with fully grouted; the pattern spacing of rock bolts a = 1.5x1.5 m, the diameter of rebar 19 mm; the length of rock bolts defined as exceeding the plastic zone, the results can be shown in Figures 8, 9 and the out parameters can be plotted as:

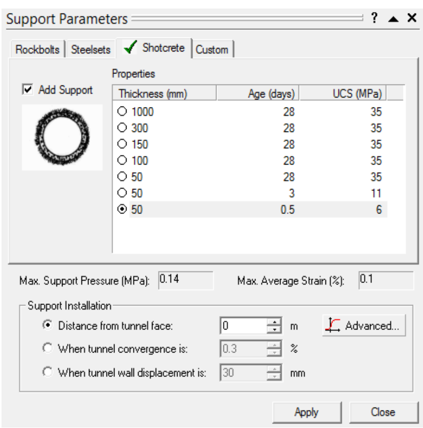
Support Parameters:

Total combined:

Maximum support pressure: 0.222 Mpa.
Maximum average strain: 0.15%.
Installed at distance from tunnel face: 0 m.
Initial Tunnel Convergence: 10.11%.
Initial Wall Displacement: 216.62 mm.

Rock bolts:

Type: 19 mm Rock bolt.
Maximum support pressure: 0.082 Mpa.
Maximum average strain: 0.2%.
Rock bolt square pattern spacing: 1.5 x 1.5 m^2.
Shotcrete:



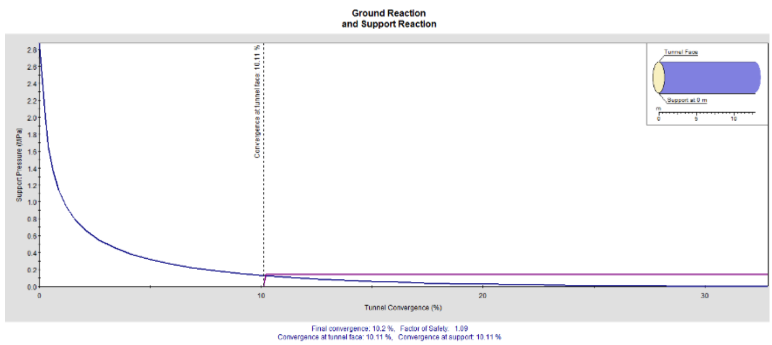


Figure 7. Safety factor in case of using the thickness of shotcrete 50 mm. (Received SF = 1.09).

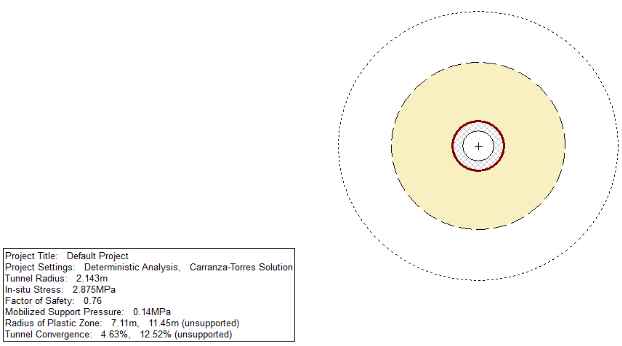


Figure 6. Procedures for the assigning shotcrete and radius of the plastic zone around the drift.

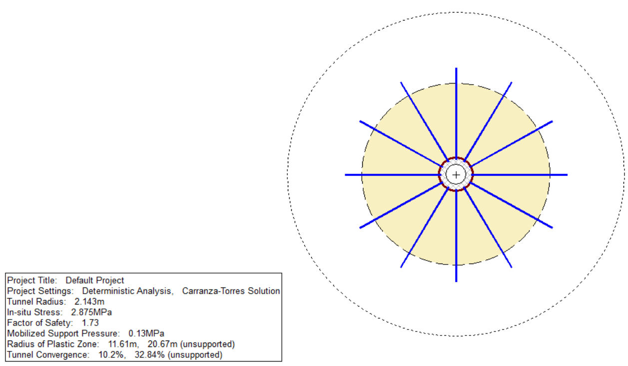


Figure 8. The radius of plastic zone with shotcrete and rock bolts.

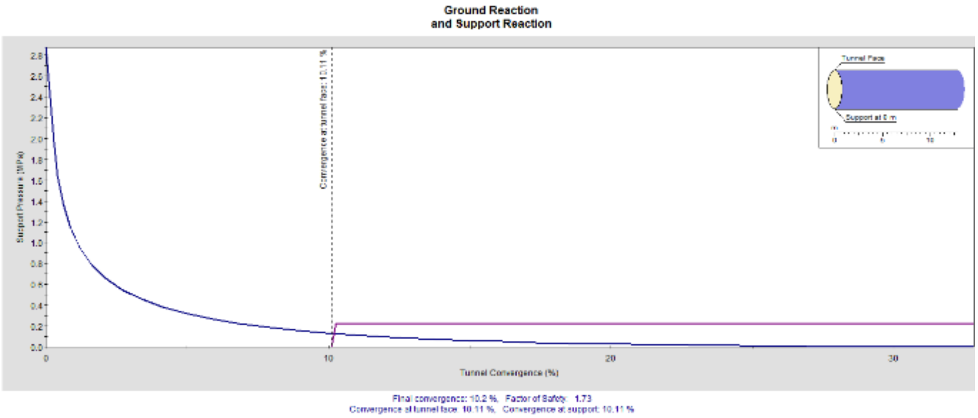


Figure 9. Final tunnel convergence and safety factor in case of shotcrete and rock bolts.

Table 1. Analysis results in case of using the shotcrete 50 mm.

Analysis Results: Factor of Safety: 1.09 Mobilized Support Pressure: 0.13 MPa With support installed: Radius of Plastic Zone r_p: 11.61 m Wall Displacement up: 218.58 mm Tunnel Convergence: 10.2% With no support installed: Radius of Plastic Zone r_p: 20.67 m Wall Displacement up: 703.81 mm Tunnel Convergence: 32.84% Deformation at the tunnel face: Wall displacement: 216.62 mm Tunnel Convergence: 10.11% Critical Pressure pcr: 1.97 MPa	**Tunnel and Rock Parameters:** Tunnel Radius r_o: 2.143 m In-Situ Stress p_o: 2.875 MPa Young's Modulus of Rock Mass E: 446 MPa Poisson Ratio v: 0.35 Dilation Angle ψ: 0^o Compressive Strength of Intact Rock σ_{ci}: 25 MPa Peak Strength Parameters Defined As: GSI, m_i, D Geological Strength Index: 22 Rock Mass Constant m_i: 10 Disturbance Factor: 0.8 Not using residual strength parameters
Support Parameters: Total combine: Maximum support pressure: 0.14 MPa Maximum average strain: 0.1% Installed at distance from tunnel face: 0 m Initial Tunnel Convergence: 10.11% Initial Wall Displacement: 216.62 mm Shotcrete: **Properties**: Thickness = 50 mm, age = 0.5 days, UCS = 6 MPa Maximum support pressure: 0.14 MPa Maximum average strain: 0.1%	

Properties: Thickness = 50 mm, age = 0.5 days, UCS = 6 Mpa.

Maximum support pressure: 0.14 Mpa.

Maximum average strain: 0.1%.

The results indicate that the safety factor will be increased from 1.09÷1.73. However, this value is still low, the mobilized support pressure is smaller than the criterion support pressure P_{cr} = 1.97 MPa. Final tunnel convergence is also large, the drift will be continuously required more support. There are two solutions in this case: 1-increasing the thickness of shotcrete; 2-increasing density or the length of rock bolts. In fact, mining activities in Quang Ninh of Viet Nam the increasing the thickness of shotcrete will be more complicated by manual spraying, costly construction time, the solution for rock bolts also will be similar too. Therefore, must be applied other solutions in the drift, after site investigation and documents of mine the steel ribs should be used.

Design options 2

In this option, the steel ribs will be applied to create the mobilized support pressure bigger than the criterion pressure, and safety factor respectively. Using TH section ribs with the section depth 108 mm, weight 21 kg/m, out of plane spacing 700 mm. After installing the steel sets the support pressure can be received P_i = 1.98 MPa bigger than the criterion pressure at the time transmits to the plastic state in the rock mass. The structure is durable enough (Figure 10), the obtained main results can be listed in Table 2.

Table 2. Analysis results in case of options 2.

Support Parameters: Total combined: Maximum support pressure: 1.98 MPa Maximum average strain: 0.55% Installed at distance from tunnel face: 0 m Initial Tunnel Convergence: 10.11% Initial Wall Displacement: 216.62 mm	Steel ribs: Type: TH section rib Properties: Flange width = 124 mm, section depth = 108mm, weight = 21 kg/m Maximum support pressure: 1.98 MPa Maximum average strain: 0.55% Steelset out-of-plane spacing: 0.7 m

4. Conclusion

By the above mention and analysis can be seen that GCC and CCM methods have brought about the effectiveness of using rock supports to use of load-carrying of rock mass and released the initial stress in the rock mass (by the time for installation of support). The use of rock bolts and shotcrete in many cases is effective for the initial reinforcement, over time the displacement of rock mass around drift will keep increasing which can cause the failure of rock supports. This requires additional permanent supports to maintain the stability of drift.

Previous solutions and analyzes still have not considered the next development of GCC or the restoration of the initial stress state in the rock mass around drift (recovered deformation of GCC). The degree of long-term convergence of drifts depends greatly on the displacement of GCC at the time of installing the supports (system of rock mass-supports). This is also a calculation tendency that needs to be studied in more detail in the actual excavation and protection of drifts. However, the disadvantages of Rocsupport 3.0 (in Figures 7÷10) are not shown the BD segment curve (Figure 1) when there is an anti-erect structure. In further research this problem should be investigated and more evaluated.

The detailed input conditions of the problems are the same as the geological conditions of the drift at level +125 Nam Mau coal mine. The TH section ribs with properties such as flange width 124 mm, section depth 108 mm, weight 21 kg/m, maximum support pressure 1.98 MPa, and spacing 700 mm should be applied.

Author contributions

Minh Tuan Tran - proposes ideas and contributes to the manuscript. Hiep Huy Nguyen

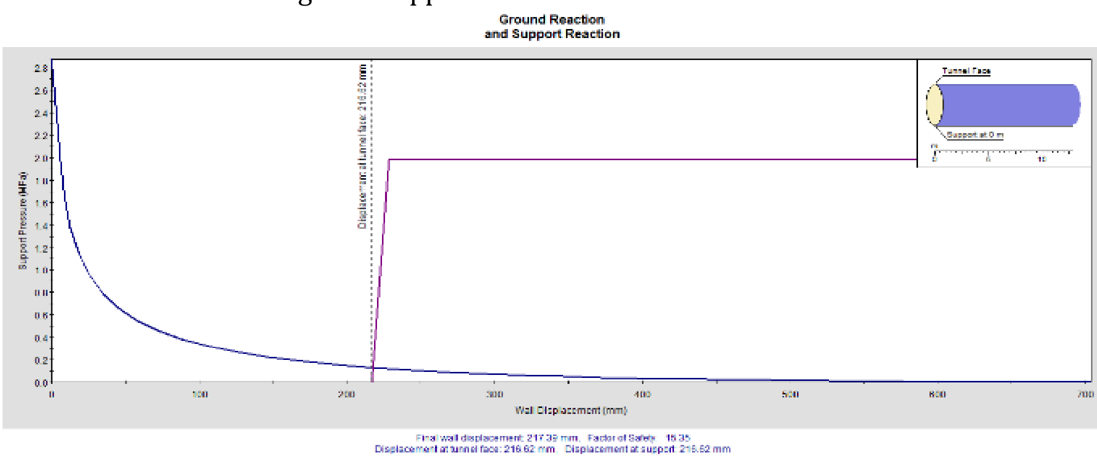


Figure 10. Tunnel supported by the steel ribs.

and Thanh Trung Dang - construct the manuscript and contribute to the material analyses.

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