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Stabilization of Deep Roadways in Weak Rocks Using the System of Two-level Rock Bolts

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Abstract. Large rock mass deformation around deep roadways in the weak rocks was a significant problem in mining activities in Vietnam and other countries. The excavation of roadways leads to high releasing stress, which exceeds the peak strength of spalling surrounding rock and causes it to enter the post-failure stage. Tensile failures then initiate and develop around the roadways, which causes the fragmentation, dilation, and separation of surrounding rock. The capacity of the primary support system is low, which results in a severe contraction in the whole section of roadways, which requires finding solutions to prevent the deformation of rock mass around roadways and technical solutions from stabilizing for deep roadways. To stability analysis of roadways can be applied analytical, experimental, semi-experimental, and numerical methods. This paper introduces the prevention mechanism of large deformation of rock mass around roadways using 2-level rock bolts. The research results show that using the system of two-level rock bolts can reduce the values of tensile stress on the boundary of roadways range from 10 to 15% compared with only one. The importance of the total displacement of rock mass on the boundary of roadways will be reduced from 3.47 to 13.85% using six long cable bolts.

Keywords: Deep roadways, Large deformation mechanism, Control techniques, Numerical simulation, Weak rocks, Rock bolts

1. Introduction

The rapid development of the economy and society in the world and Vietnam requires consuming a significant amount of energy. Therefore, shallow minerals are gradually depleted, and the exploitation requirements of deep mineral resources are imperative. Currently, coal mining countries have carried out the deep mining trend - the depths of exploitation are 1000 m from the surface, which could be seen in the Russian Federation, South Africa, Canada, America, India, Germany, and China [1-12]. The types of rock mass often have variations with the other depths and extreme alterations, so the problem of design and selection of supports is considered different, complicated, and complex. The theories of analysis and calculation of supports for roadways and drifts in case of exploitation at the superficial level are unsuitable for deep roadways and have many inadequacies [13-17]. The deep mining is also accompanied by difficult ventilation conditions in the roadways and drifts; the ventilators also have significant capacity because of fresh air increasing. Drainage has also become complicated and varies complexity, the flow of underground water will be increased.

In Vietnam, the variation of geological conditions has been described in the related geological documents [14-17], especially at underground mines such as Hon Gai, Ha Lam, and Nui Beo coal mines which are located near the sea. Not only is the sea level high, but also many mines are exploited under open pit mining. The drainage and design of supports are specifically complex and dangerous. The excavation of deep roadways could also encounter soft and swelling rock conditions. When underground water appears in the rock mass, the earth pressure will be increased; the rock mass zone consists of tectonic forces that change the initial and the second state of stress around roadways. Because of growing earth pressure, the cross-section of roadways will be reduced during their operation [14-17]. The theoretical analysis application with rock bolts, steel ribs, and rock bolt and shotcrete [14, 16] has become effective in the actual operation of supports.

The trend to design rock supports based on utilizing the bearing capacity of rock mass around roadways and releasing initial stress (Rock mass - supports) [15-17] is more attention to maintaining the stability of roadways and reducing the cost of their excavation. The design ideals utilizing the load-carrying capacity of rock mass around roadways in Vietnam are less focused, requiring further research to ensure sustainable development of national energy security.

With the development of technologies and software, numerical modelings are widely used and brought more efficiency in the design process the stability of roadways [4, 15, 16]. The currently specialized software can be divided into different groups, such as Discontinuous Deformation Analysis (DDA), Finite Element Method (FEM), Difference Element Method (DEM), Boundary Element Method (BEM), etc [19, 20]. The advantage of these method groups can be simulated problems likely close to the actual conditions, including many influence parameters of geological and hydrogeological conditions of the working areas at the same time. In addition, they can also be simulated for the construction, excavation, and installation of rock supports in the roadways.

2. Background of the theory short rock bolts combination with long rock bolts and other supports in a high-stress rock mass

In a deep coal mine research, the author observed that geological discontinuities in the rock mass become less in density and less opened with an increase in depth. For instance, at a depth of 1000 m, all discontinuities (not many) exposed on excavation faces were closed entirely. Therefore, it can be said that the rock mass quality is improved at great depth due to the reduction of geological discontinuities. However, the in-situ rock stresses increase with depth. At depth, the major instability issue is no longer the falling of loosened rock blocks but rock failure. High pressures could lead to two consequences in underground openings: large deformation in soft and weak rock and rockburst in hard and robust rock (Fig. 1). In some metal mines in Russia, strain burst usually occurs below 600 m and becomes intensive below 1000 m. Rock failure is unavoidable in high-pressure conditions. The task of rock support at depth is not to equilibrate the deadweight of loosened blocks but to prevent the failed rock from disintegration. In high-stress rock masses, the support system must be not only strong but also deformable to deal with either stress-induced rock squeezing in weak rock or rockburst problems.

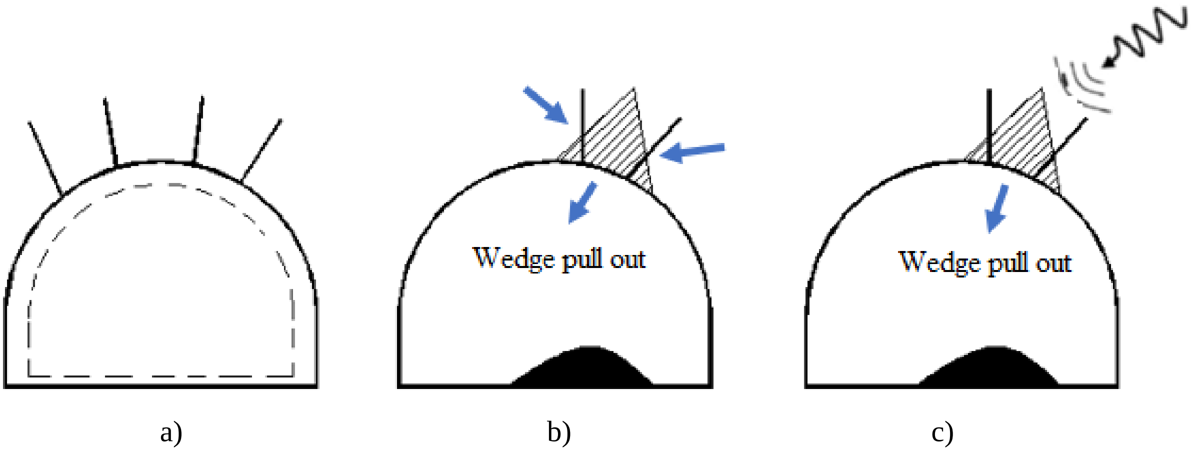

Fig. 1. Loading conditions of rock bolts around roadways: a) squeezing rock; b) strain burst; c) seismic loading or blasting.

A rock supports system may be composed of one or more than one of the following support systems, depending on the loading condition and the expansion of rock failure zone such as (Fig. 2):

Layer 1 - Bolting (short rock bolts): Short rock bolts are installed locally or systematically (Spot bolts or pattern rock bolts on the boundary of roadways).

Layer 2 - Surface retaining: Retaining elements like meshes, straps, lacing, thin liners, shotcrete, and cast concrete lining is installed on the rock surface.

Layer 3 - Cable (length rock bolts): Single - or multi-strand cables are installed into the sharp rock behind the failure zone.

Layer 4 - External support: Structurer elements, including steel ribs, concrete arches, invert, cast concrete lining, and thick shotcrete liners, reinforced concrete lining are set up in tunnels - layer 4A.

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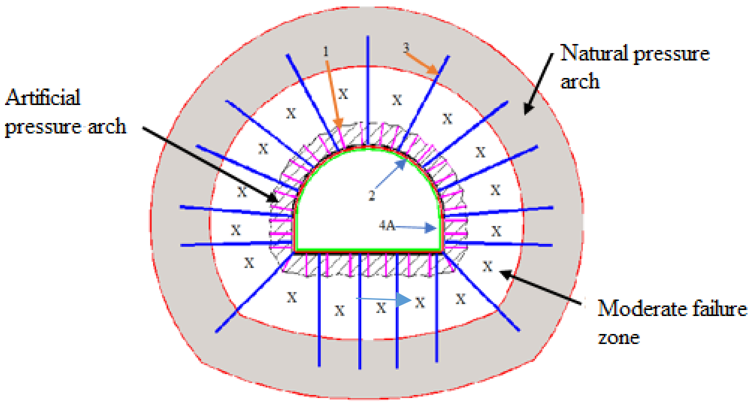


Fig. 2. The characteristic of a reinforced zone by short rock bolts combined with long rock bolts (cable bolts) around roadways: 1 - the short bolts under level; 2 - shotcrete layers; 3 - the long rock bolts; 4A - final (permanent) support layers.

In weak rocks, the failure zone can extend to a depth beyond the length of rock bolts (Fig. 2). In this case, both rock bolts (layer 1) and retaining surface elements (layer 2) are needed. Rock bolts must be tightly installed so that they, together with the surface support elements, help to establish an artificial pressure arch in the failure zone. The artificial pressure arch forms a protective shield over the opening. Either cable bolts (layer 3) or moderately strong external support elements (layer 4A), or both, are added to restrict the movement of the protection shield. The 1-2-3 layer support is often used in deep mines and underground constructions of large span.

Moreover, in the squeezing and swelling rock, the short rock bolts (1) and shotcrete (2) will cause the temporary artificial reinforced arch. This solution leads to reduce the pressure on the permanent supports of roadways (Fig. 2). However, in actual excavation activities, because of the span of roadways, excavated technologies, and geological conditions, the deformation of rock mass around roadways will continuously increase, and the residual deformation will appear. In the points far from the boundary of roadways, the state of stress are initial stress and equal constant. In this case, the conditions are permitted, using the long rock bolts suspended the inner reinforcement layer and external stability and undisturbed rock mass (1+3). Thanks to the advantages of support systems 1 and 3, the pressure impacted on the permanent support system 4A will be declined. Consequently, the thickness of this system will also be reduced, and the cost of roadway excavation will be decreased.

3. The effects of reinforcement in the case of two-level rock bolts

3.1 Support Characteristic Curve for rock bolts

To clearly show the effect of rock bolts combined with other supports, derived from Ground Characteristic Curve (GCC) by Carranza-Torres. Carranza-Torres (2004) proposed the GCC with the sandstone by using the elastoplastic solutions for circular tunnels with extremely initial stress of infinity [1].

It is assuming that the system of short bolts is equally spaced in a circumferential direction, the maximum support pressure (p_{smax}) provided by the support system, and the elastic stiffness (Ks) can be evaluated by using the following equations [1, 5].

$$p_s^{\max} = \frac{T_{bf}}{s_c s_1} \tag{1}$$

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

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 nb is the total number of equally spaced bolts installed in cross-section
s_1 - longitudinal bolt spacing (m).

3.2 Combination effect of support systems

If more than one of the bolt support systems are installed as two-level systems, their combined effect can be calculated by adding the elastic stiffnesses for each of the individual rock bolts, which increases the total elastic stiffness of the whole system. Consider, for example, the case in which two supports characterized by maximum pressure p_{s1max} and p_{s2max} and elastic stiffnesses K_1 and K_2, respectively, are installed in a section of the tunnel. The stiffnesses K_s for the two systems acting together can be calculated as following [1, 5]:

$$K_s = K_1 + K_2 \tag{3}$$

This value is assumed to remain valid until one of the two supports achieves its maximum possible elastic deformation u_{rmax} calculated by formulas [1, 5]:

$$u_{r1}^{\max} = \frac{p_{s1}^{\max}}{K_{s1}} \tag{4}$$

$$u_{r2}^{\max} = \frac{p_{s2}^{\max}}{K_{s2}} \tag{5}$$

$$u_{rmax} = u_{r1max} + u_{r2max} \tag{6}$$

The combined support system is assumed to fail at that point. The support with the lowest value of u_{rmax} determines the maximum support pressure available for the two-level rock bolts acting together because if one assumes that the collapse of the support system, so the maximum support pressure that the system can sustain before destruction is calculated as following [1, 5]:

$$p_s^{\max} = u_{r\min}^{\max} K_s \tag{7}$$

Safety Factor (SF) will be applied in case of using the method of GCC and Convergence Confinement Method (CCM) to design support in tunnels (Fig. 3) to indicate the role of two-level rock bolt systems in the design process of supports in roadways. The ratio can calculate SF mobilized support pressure P_s and equivalent pressure P_{eq} (the time system of rock mass-support works together - intersection point GCC and SCC). For example, to design rock support by GCC and CCM in Rocsupport 3.0 (Fig. 4).

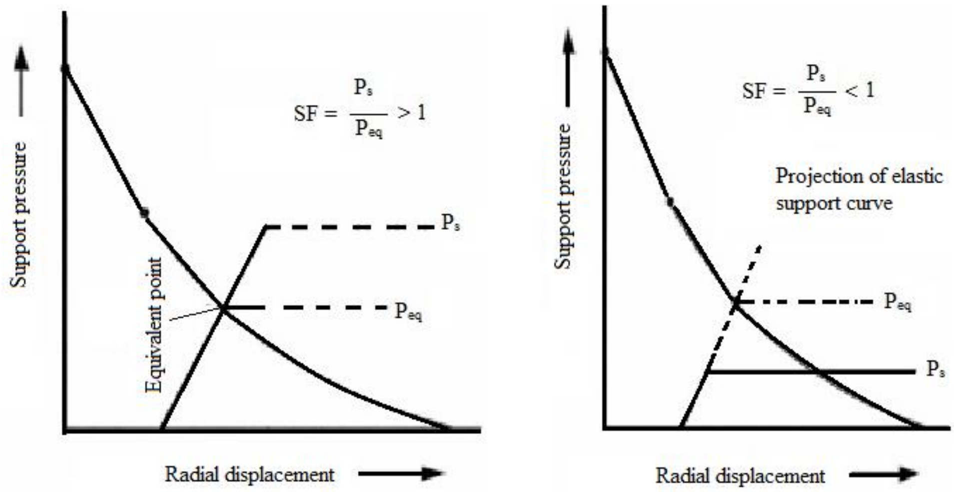


Fig. 3. Defined the design of support according to Safety Factors (SF).

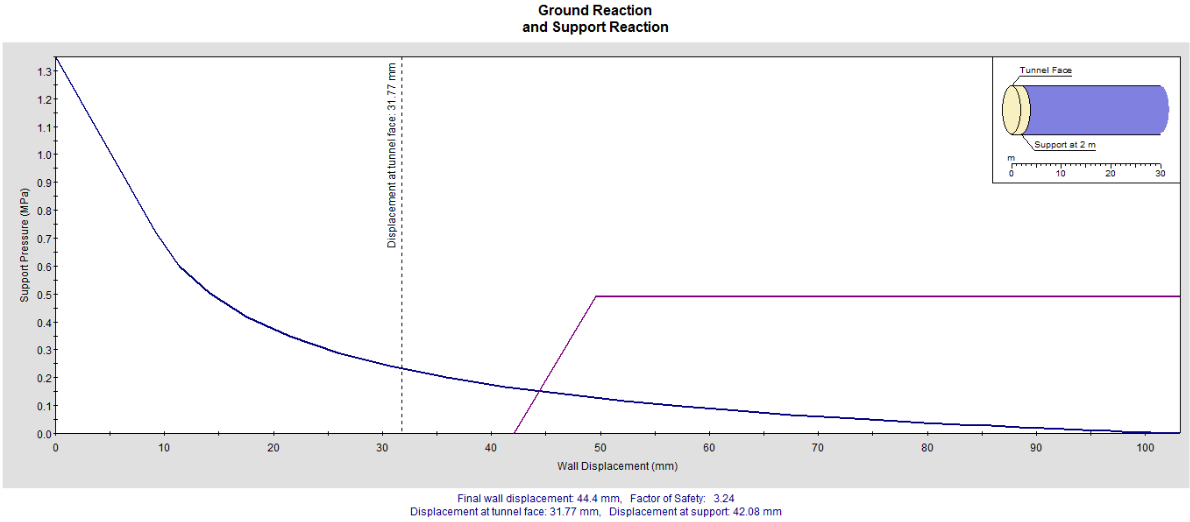


Fig. 4. Example of model analysis by SF coefficient in Rocsupport 3.0.

Currently, a different ideal to design two-level rock bolts in the deep roadways is being used and has become the design standard of the Russian Federation. According to the rules and guidelines of the Russian Federation [13], when the displacement of rock mass on the boundary of roadways exceeds 300 mm, roadways must be applied rock bolts with two levels (shot - long rock bolt system).

The long rock bolts (deeper rock bolts) will be installed near the short rock bolts during excavation roadways and drifts after longwall with the distance 0.1H (H - the depth of roadways or drifts from the surface).

When calculation the parameters of upper-level rock bolts with the theory collapsed arch, the pressure over 1 meter in length P_{cb}, kN/m impact on the rock bolt system can be determined by the following formula [13]:

$$P_{cb} = \frac{2}{3} B_p h_{ph} \gamma \qquad (8)$$

where: B_p - width of roadways, h_{ph} - height of collapsed rock mass around roadways can be calculated by formula [13]:

$$h_c = k_{cb} B_p \qquad (9)$$

where: k_{cb} - coefficient depending on the properties of type and structures of the rock mass.

The length of rock bolts in upper levels (cable bolts) l_{ka} can be calculated by formula [13]:

$$l_{ka} = h_{cb} + l_z + l_b \qquad (10)$$

Where: l_z - length of upper rock bolts located exceeding the boundary of natural arch usually can be chosen l_z = 0.8 - 1.0 m or by support passport, l_b selected 0.15-0.20 m. The length of rock bolts is rounded to 0.5 m.

4. Numerical modeling for effects of reinforcement of 2-levels rock bolts in the geological conditions at the deep roadways

In this study, the alteration of stress state around roadways using 2-levels rock bolts will be explained in the geological conditions likely observed and investigation site of roadways in Mong Duong coal company [18]. Roadways were excavated in the geological areas consisting of siltstone and sandstone mixed with thin coal seams. The uniaxial compressive strength σ_{ci} = 20-30 MPa. The thickness of sandstone ranges 23.0-25.0 m on the roof of roadways, underfloor located siltstone and claystone with σ_{ci} = 40 MPa, the thickness of layer m = 5.0 m, below these layers is sandstone layer with σ_{ci} = 100 MPa. The service times of roadways are 15 years, the depth of roadways H = 100 m from the surface, and roadways are located in the tectonic zone. The underground water exists in the area where roadways, sandstone, and siltstone will be soft and have behaviors of soft and swelling rocks. Tab. 1 describes the properties of rock mass layers and the surface of stratification layers. The properties of joints and stratification layer can be calculated by criterion Barton and Bandis, 1990 [21].

The numerical modeling was applied to investigate this problem in Phase 2 for two cases: Case 1 - in the homogeneous rock mass, roadways supported by pattern bolts with nine bolts, spacing of bolts 1.5×1.5 m for short level, and three cable bolts for the second level, spacing of cable bolts 1.5×1.5 m. Cable bolts are installed between the short bolts. Case 2 - in the stratification rock mass with an inclined angle of layers - 45^0, roadways are applied by nine short and six long cable bolts. The spacing of short bolts and cable bolts are used the same as in case 1. Fig. 5 shows the modeling results, and Figs. 6 - 8 shows the tensile stress distribution and the failure zone around roadways.

Tab. 1. The parameters of sandstone and siltstone.

N0	Parameters	Symbol	Values		Units
			Sandstone	Siltstone	
1	Unit weight of rocks	γ	0.26	0.27	MN/m^3
2	Tensile of rock mass	σ_t	0.5	0.7	MPa
3	Cohesion of rock mass	c	1	2	MPa
4	Friction angle of rock mass	φ	25	35	Degree
5	Elastic modulus of rock	E	1800	2000	MPa
6	Poisson ratio	μ	0.30	0.28	-
7	Residual friction angle	φ_{re}	22	32	Degree
8	Residual cohesion	c_{re}	0.5	1.0	MPa
9	The width of roadways	5	-	-	m
10	Type of material	-	Elasto-Plastic	Elasto-Plastic	-
11	Cohesion on the surface of stratification sandstone/siltstone	c’	0		MPa
12	Friction angle of the surface of stratification sandstone/siltstone	φ’	35		Degree
13	Normal stiffness on the surface of stratification sandstone/siltstone	σ_T	100000		MPa/m
14	Shear stiffness on the surface of stratification sandstone/siltstone	τ	10000		MPa/m

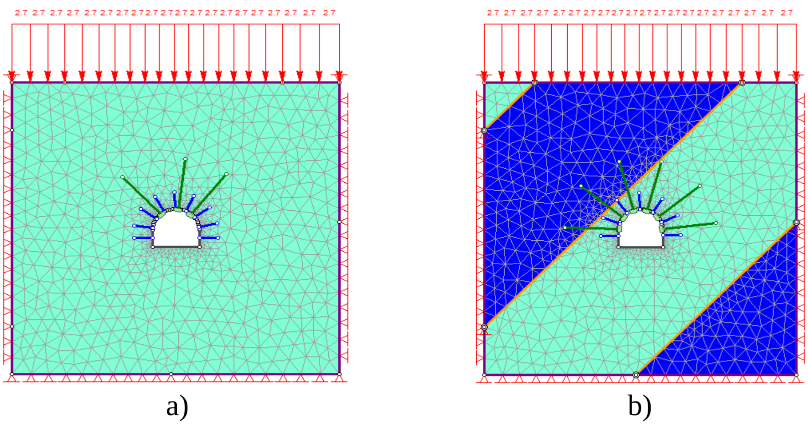
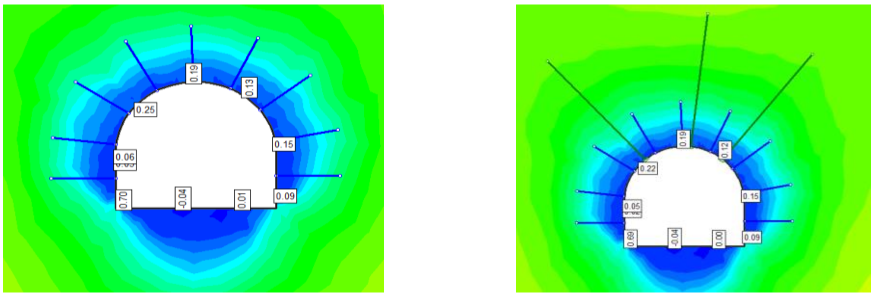
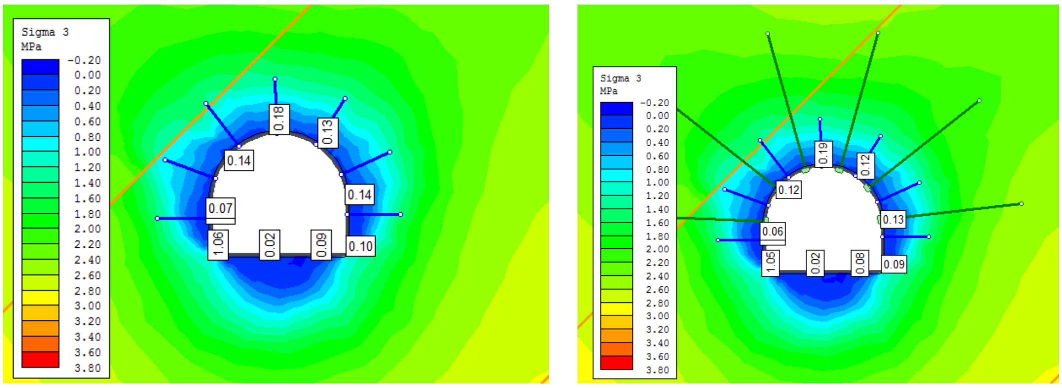


Fig. 5. Using rock bolts with two levels: nine short bolts and three long cable bolts (a), nine short bolts, and six long cable bolts in stratification rock mass (b).



a) pattern bolts - 09 bolts b) pattern bolts and 03 long cable bolts

Fig. 6. The tensile stress distribution around roadways in the short rock bolts pattern combination with three long cable bolts.

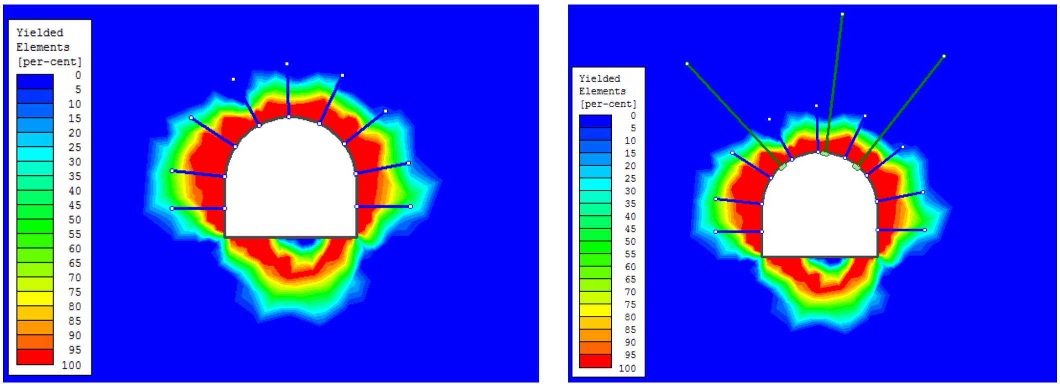


a) pattern bolts - 09 bolts b) pattern bolts and 06 long cable bolts

Fig. 7. The tensile stress distribution in case of the short rock bolts pattern combination with six long cable bolts in a stratification rock mass.

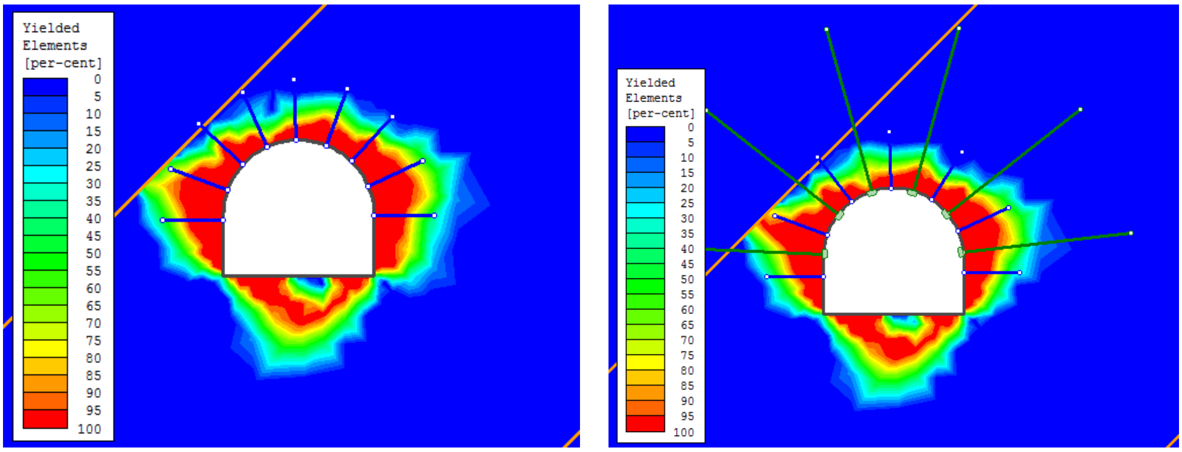
The results in Figs. 6-7 show that the tensile stress on the shoulder of roadways is changed using the pattern bolts and long cable bolts. In the detailed conditions applied for three long cable bolts, the tensile stresses are 0.25 MPa; 0.22 MPa; 0.13 MPa; 0.10 MPa, respectively. In long cable bolts in the second level - six bolts are 0.14 MPa; 0.12 MPa; 0.13 MPa; 0.12 MPa. When adding a long cable bolt system, the tensile stresses on the boundary of roadways should be reduced and rock mass around roadways reinforced to become more stable.

Figs. 8-9 describe the failure zone around roadways for two cases in the homogenous and stratification rock mass using rock bolt pattern by nine short bolts, 3 or 6 cable bolts.



a) pattern bolts - 9 bolts b) pattern bolts and 3 long cable bolts

Fig. 8. Failure zone around roadways.



a) pattern bolts - 9 bolts b) pattern bolts and 6 long cable bolts

Fig. 9. Failure zone around roadways in the stratification rock mass.

The results indicate that the lengths of the short bolt pattern are small. The efficiency of the bolt system is not inadequate. The long cable bolts prevented the rock mass in the failure arch to the stability rock mass around roadways in the homogenous and stratification rock mass. By statistic can be established the graphics of tensile stress and total displacement on the roadway boundary for two cases in (Figs. 10-11).

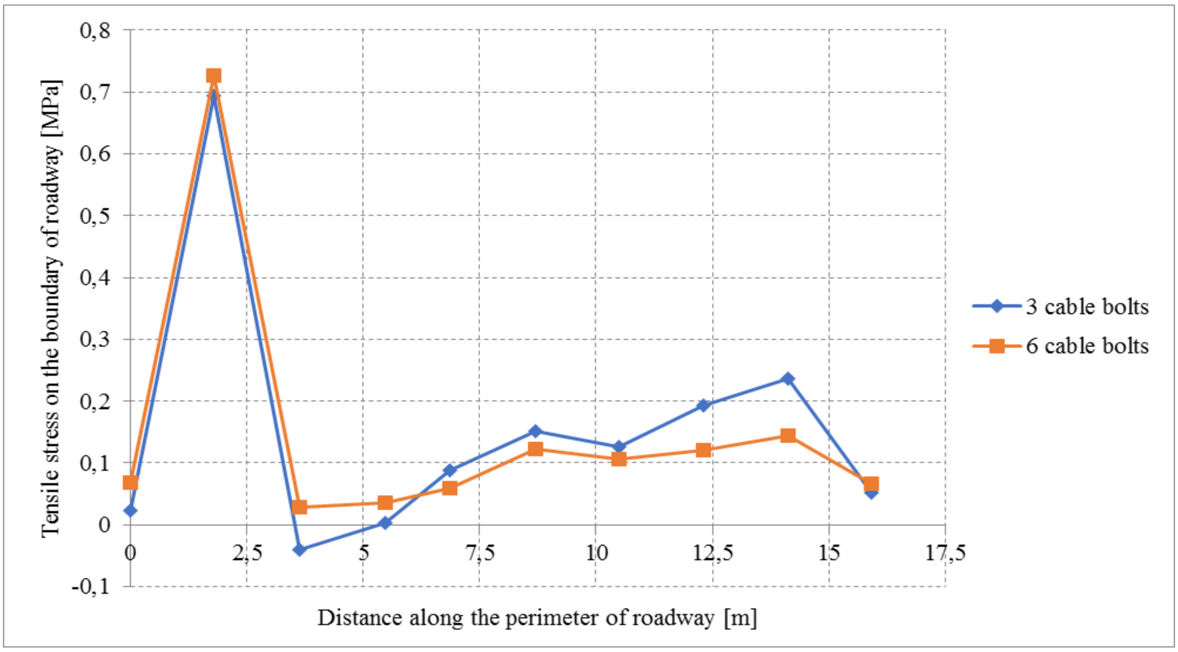


Fig. 10. The tensile stress distribution of rock mass on the boundary of the roadway.

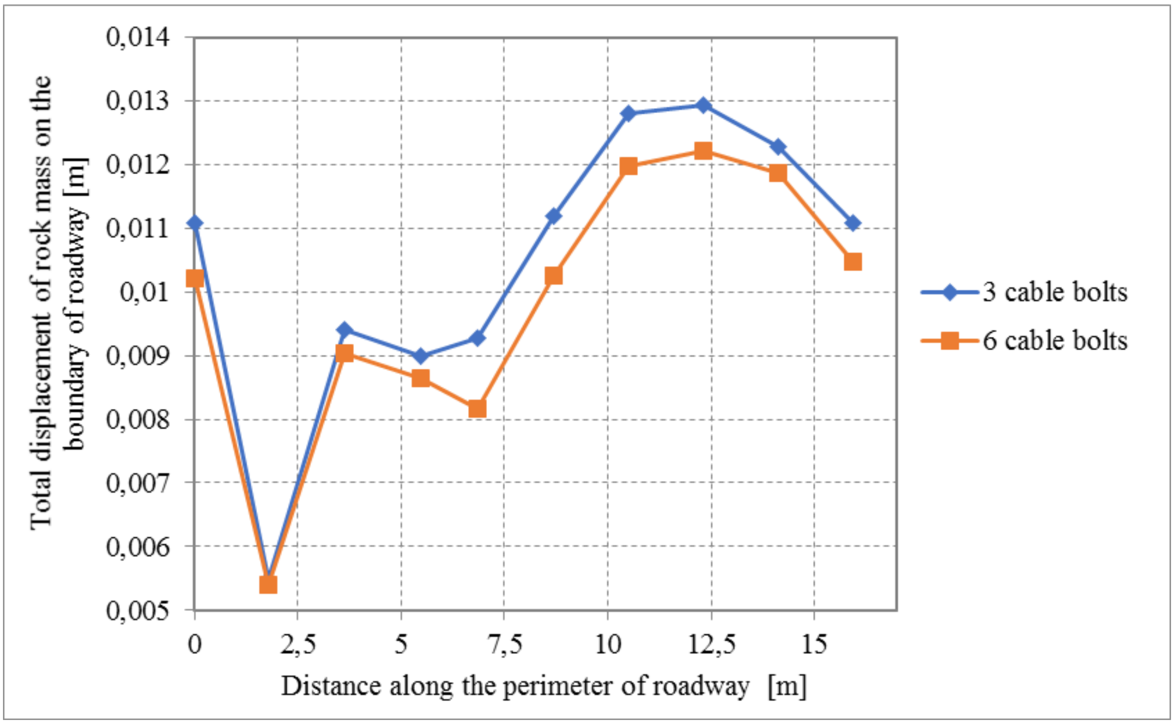


Fig. 11. The total displacement on the boundary of the roadway.

The results on Figs. 10-11 indicate that on the roadway boundary located six cable bolts, the tensile stress and total displacement values are smaller than in the case of three cable bolts. The values of the rock mass displacement on the boundary of roadways will be reduced from 3.47% to 13.85%. This comment explained that the rock mass around the roadway would be more reinforced for similar geological conditions.

5. Conclusions

The above theoretical analysis and the numerical model results show that the rock bolts influence the stability of roadways. Rock bolts can be applied and combined with other supports such as shotcrete, steel ribs, concrete linings, precast concrete, short bolts, and long bolts, as in this research.

The numerical method results also show that in the case of application of short pattern bolts, combined with the long rock bolts, the tensile stress values on the boundary of roadways will be reduced range from 10% to 15%. In the case of applied six long cable bolts, the total rock mass displacement on the boundary of roadways will be reduced from 3.47% to 13.85% compared with three long cable bolts in similar geological conditions, the earth pressure also decreased.

In the stratification rock mass, the distribution of pressure is not symmetrical, and the pattern rock bolts should not be applied because of reinforcement effects. The short rock bolts combination with long rock bolts are not efficient.

Numerical simulation, GCC, and CCM should be applied in the design process to predict the values and distribution of rock pressure early and preliminary selection of temporary supports in analysis. It is necessary to have flexibility, change design ideals of supports, and update each roadway's actual geological conditions.

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