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Cut slope reinforcement technique in open-pit mines

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Abstract: The design and practice in supporting the cut slope of an open-pit mine were introduced, in which the high pressure grouting method was used in reinforcing the weak formation in the slopes. Based on a detailed geological survey of the slope, a theoretical analysis was carried out, and the design parameters were proposed, where the Tresca or Mohr-Coulomb yield criteria was employed. A patent technology, named "Technology of high pressure and multiple grouting in different levels within a single hole", was employed in the construction. Anchor bars were also installed as grouting proceeds. This method combines anchoring and grouting comprehensively and was found successful in practice.

Key words: mining engineering, open-pit slope; weak formation; supporting; high pressure grouting

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Slope collapse is common but would be a disaster during the course of mining and transportation of open-pit mines. It often induces a serious accident that causes the pause of production and the fatal casualty. Therefore, an effective reinforcement to the unstable slope, particularly that the slope is facing with the unstable state, is an important and difficult technical problem that we often faced with and must be solved in the construction of open-pit mines, highway, railway, irrigation engineering, hydraulic-power engineering, and so on. In this paper, a new reinforcement technique is described for the excavation of a cut-slope of the transportation line in an open-pit mine. It is proven a great success in practical engineering [1, 2].

1 Geology characteristics of the slope and its influence

The slope body was considerably unstable in the geological examination. It is formed by quartzite formation, in which a weak interlayer is distributed. The geologic features can be summarized as followings.

Firstly, the body of the slope is made of silicarenite, where joints and crevices reach 20 to 30 per meter. Although the strength of the rock is high, the stability of the slope is poor regarding to the rock strength (see **figure 1**, **tables 1** and **2**).

Table 1 describes the mechanical properties of the silicarenite formation and the weak formation. Both the cohesion (c) and the internal friction angle (φ) in the silicarenite formation are much higher than those at the interface. Generally, both the cohesion and the internal friction angle of the silicarenite formation are higher than those of the weak formation. However, the internal friction angle of the silicarenite at the interface is significantly higher than that of the weak formation at the same position. This means the silicarenite is so fractured that the inclusion of the weak formation has been fulfilled the joints and crevices, resulted in the reduction of internal friction factor. Water in the slope body flew through the joints and crevices, which brought the inclusion in the weak layer and filled in the joints and crevices of the silicarenite formation.

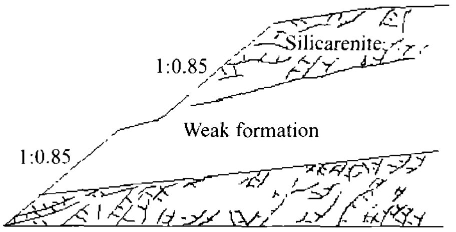

Figure 1 Rock stratum of the road cut of a section of E-BS (LIGS, 1998).

In table 2, it can be found that the rock at the shallow is less weathered than that in the deep.

Secondly, the main angle of rock formation is closed to the inclination of the right slope of the road cut, increases the instability of the slope.

Thirdly, the potential risk is the weak formation (as shown in figure 1), which is made of a lamprophyre

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Corresponding author: Yongtao Gao, **E-mail:** gaoyongt@vip.sina.com vein of 7 m in width. The lamprophyre formation was found on the slope root, which is located in the silicarenite formation. The weak formation inclines to the road, and it brings the stability problem of the right slope.

Table 1 Mechanical properties of the silicarenite formation and the weak formation

Rock type	Unit weight		Rock stratum		Interface	
	Nature / (kN·m^{-3})	Saturated / (kN·m^{-3})	c/ kPa	φ/ (°)	c / kPa	φ/ (°)
Weak formation	25.0	25.4	35	27	5	26
Up and buried silicarenite formations	27.0	27.3	60	31	20	20

Table 2 Physical characteristics of the silicarenite rock mass

RQD / %		Density of joints and crevices (joints per meter)		Stability evaluation of rock mass			
Deep	Shallow	Deep	Shallow	Deep (NGI)	Shallow (NGI)	Deep (CSIR)	Shallow (CSIR)
45	40	20	20 to 30	1.2	0.81	45	29

Notes: 1) Data of deep situation was acquired from the border of the collapsed section; 2) RQD—rock quality degree; 3) NGI—Norwegian Geotechnical Institute, CSIR—Council for scientific and industrial research.

From the geology characteristics of the open-pit mine slope as mentioned above, the weak formation would directly cause the slope collapse. The reasons are as follows.

(1) Plastic deformation. The water content in the weak formation is high, and the water conductivity of both the weak formation and the silicarenite layer are also comparatively high due to densely developed joints and crevices (also see table 2). During the excavating, water flows out of the slope and brings the silt filled the formation. The bearing capacity of the layer would then reduce. The pressure in the upper layer caused the plastic deformation of the weak formation. The integrity of the above silicarenite formation is not so high that the whole slope would hereby collapse. It is the main reason that a section of the slope has collapsed.

(2) Supply of the rainfall. Since the high water conductivity of the slope, the slope would soon get supply from the rainfall. Hereby, the water in the slope continuously brings the fillings out of the slope and the plastic deformation is then accumulated.

(3) Slide component force of gravity. The weak formation inclines to the same direction as the slope does. The above silicarenite formation would slide along the weak formation.

(4) Hazardous position of the weak formation. The weak formation presents at the risk position of the slope, which is located 2 to 3 m above the slope base and exposes at a range of 140 m.

2 Technical options

In order to avoid the collapse of the slope, it is of most importance to provide reinforcement or support to the weak formation. The proposed options could be as follows.

(1) Reducing the slope angle. If the slope is reduced to 1:1.2, and a shotcrete wall of mortar of 500 mm thick is constructed, the slope would then keep stable. Whereas, this option has disadvantages of enlarging the right boundary of surface land and increasing the excavation work.

(2) Pre-stress anchoring. In this option, belt beams made of reinforced concrete need to be constructed on the surface of the slope first, because the surface of the slope is heavily fractured. One end of anchor bar is then installed on the belt beam, and also cement is injected in the slope. At last, the pre-stress is applied to the bar to improve the stability of weak formation [3].

(3) High-pressure grouting. Instead of applying prestress to the anchor bars, high pressure grouting can improve the physical characteristics of the rock mass in the slope. It is a much simple method and has advantages as the following:

- The cement can spread in the weak formation effectively and become the backbone of the weak formation when it hardens. The supporting capacity of the hardened grout can reach more than 8 MPa.

- Under the high pressure, a cement medium is injected into the fillers of the formation, through which the weak formation is modified. The spreading of grout cement also combines the ruptured silicarenite formation with the joints and conceives. It gives rise to the stability of the formation by 50%.

- In construction, steel bars are installed when the grout hole is taken the shape. Then the hole is cemented. This combines the grouting and anchoring comprehensively. Here, steel bars are shorter than those in option (2).

3 Mechanism of high-pressure grouting

3.1 Mechanism of strength increase

Cement grouting is to improve the characteristics of the existing soil and rock and to form a new medium in the grouting area. The chemical mechanism of grout includes the following three aspects [4, 5]:

(1) Chemical cementation. The soil or rock body structure is strengthened by the chemical action of grout, which brings cementing power through either grout or chemical grout.

(2) Inert filling action. The grout, which is fulfilled in the void of soil and rock, hardens and improves the load bearing capacity and the rigidity module of the slope. The deformation of the slope is hereby constrained.

(3) Ion exchange action. Some elements of cement grout have ion-exchange reaction with the elements in the rock and clay, which the new generated materials have more ideal mechanical properties.

3.2 Split-grouting mechanism

The mechanism of high pressure split grouting is eventually a question of the expanding of a round hole [6]. As shown in **figure 2**, the plastic zone is distributed around the hole and the elastic zone is around the plastic zone. For simplicity, some basic hypotheses are given as follows.

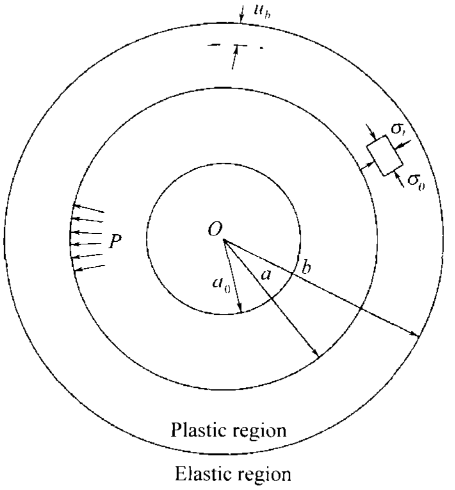

Figure 2 Expanding diagram of a round hole.

The material around the hole is an ideal homogeneous isotropic elasto-plastic mass, which is accordance with the Tresca or Mohr-Coulomb yield criteria.

In the plastic zone, where '*r*' is specified between '*a*' and '*b*', the distribution of expanding compressive force is quite different from that in the elastic zone. The expanding compressive force distribution can be derived through Tresca Yielding Criteria:

$$\sigma_r - \sigma_\theta = 2K \tag{1}$$

where K is the yielding strength of the material, σ_r the radial stress, and σ_θ the circumferential stress.

Accordingly, the critical expanding stress P_c can be obtained by the following equation [6]:

$$P_c = \frac{2K}{\beta_r + \beta_\theta}\beta_r = m_1\beta_r \tag{2}$$

where $\beta_\theta = \dfrac{1-\alpha\nu^+}{1-\nu^+\nu^-}E^- > 0$, $\beta_r = \dfrac{\alpha-\nu^+}{1-\nu^+\nu^-}E^+ > 0$,

$$\alpha = \frac{1}{2}\left[\sqrt{(\beta\nu^+ - \nu^-) + 4\beta} - (\beta\nu^+ - \nu^-)\right] > 0,\quad \beta = \frac{E^-}{E^+};$$

E^+ and E^- are the compressive and tensile modulus respectively; ν^+ and ν^- the compressive and tensile Poisson ratio respectively; P_c is the critical expanding stress.

If the grouting compressive force p is less than P_c, the border of the grouting hole would not yield, so that the material is in elastic state. However, if p is greater than P_c, then the plastic zone begins to expand gradually. Moreover, if p is enlarged to a certain number, P_u, the radium of the plastic zone would then reach b. The P_u and b can be derived as follows [6]:

$$P_u = 2K\ln\frac{b}{a} + m_1\beta_r \tag{3}$$

$$b = a\sqrt{\frac{1}{2m_1}} \tag{4}$$

From the derivation given above, it is seen that P_c, P_u and b can be determined by the physical characteristics of the material. Theoretically, the critical grouting compressive force P_c is defined by the tension modules of the material, and the radium of the plastic zone b is determined by the characteristic of the surrounding rock [6, 7]. Under the high pressure, the weak stratum is compacted. When the grouting compressive force exceeds P_c, the grouting cement is injected in the weak stratum. This improves the mechanical characteristics of the weak stratum, which surrounds the grouting hole (as shown in **figure 3**).

The grouting compressive force p can be calculated through equation (3) and table 1. In this case, the grouting compressive force was calculated greater than 3 MPa. Another important grouting parameter b was also calculated less than 3 m. Hereby, the distance between adjacent grouting holes can not exceed 3 m.

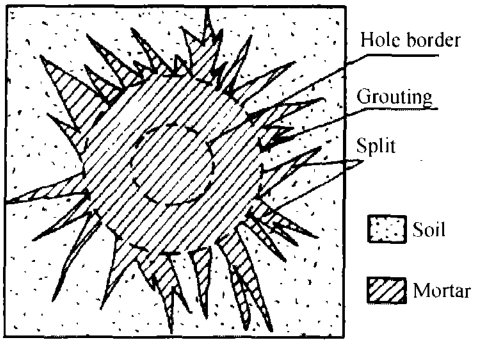

Figure 3 Grout splitting diagram in soil.

4 Construction

Following the analysis of geological characteristics of the slope given in section 1, the collapse of the slope comes from three aspects: (1) the plastic deformation of the weak formation, (2) water in the stratum, and (3) the slide force of the gravity on the inclined layer. The construction methodology is to cope with three aspects: Firstly, cement was grouted in the weak formation to enhance its geological characteristics (as shown in **figure 4**); Secondly, anchored rods were installed to improve the monolithic of the slope; Thirdly, water outlets was made on the slope to allow the water in the slope flowing out.

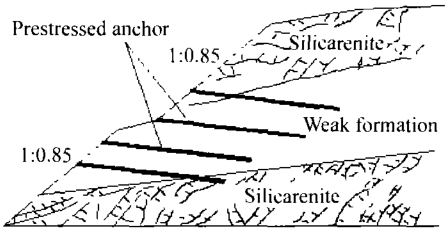

Figure 4 Diagram of slope support design.

The procedure of 'high pressure grouting in differential level in a single hole' was carried out successfully through the core sample of the rock stratum. The results are given in **table 3**. A comparison of physical and dynamic characteristics is before and after the cement grouting in the weak formation. It shows that the unit weight does not change so significantly before and after grouting; whereas, the shear yield capacities of both the weak formation and the interfaces are improved considerable, especially their cohesion improved greatly.

Table 3 Mechanical characteristics improvement of the weak formation

Weak formation	Unit weight / (kN·m^{-3})		Shearing capability of the formation		Shearing capability at the interface	
	Nature	Saturated	c / kPa	φ/(°)	c / kPa	φ/(°)
Original	25.0	25.4	35	27	5	26
After grouting	25.9	26.0	42	28	19	28

On the other hand, water was found to flow out of the embedded outlets in the slope surface. Moreover, cracks on the hip of the slope measured did not develop, which eventually demonstrated the success of the supporting options.

5 Conclusions

(1) An ideal option, the high pressure grouting, is obtained by comparing different options.

(2) Based on the theoretical model, the grouting parameters were determined.

(3) An important technique, named 'high pressure grouting in different level in a single hole', was introduced to solve the problems faced in practice, and was found successfully.

(4) It should be pointed out that some mechanisms still remain uncertain. For instance, after the grouting cement is injected into the slope, a kind of 'retaining wall' formed the superficial stratum of the road cut, which keeps the slope more stable. This study does not take the effect of the retaining wall into account. The question if the thickness of the retaining wall can be reduced, or, if less cement can be injected, will be discussed in a separated paper.

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