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Original scientific paper

BLAST-INDUCED DAMAGE AND ITS IMPACT ON STRUCTURAL STABILITY OF UNDERGROUND EXCAVATIONS

UTICAJ MINIRANJA NA STRUKTURNU STABILNOST PODZEMNIH PROSTORIJA

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Abstract: Analysis of rock wedge stability plays important role in tunneling and hard rock mining. Today there are many procedures for prediction of wedge formation and their stability. These procedures consider preexisting joints in rock mass, and there is no procedure that considers blast-induced cracks and their impact on structural stability of excavations. Using main principles of new rock blasting theory it is possible to assess length and density of radial cracks around blastholes. Herein, one simple excavation situation in hard rock is presented, where only two joint sets were present. This made it impossible for rock wedges to form. After blast-induced crack with limited persistence was added to analysis as result unstable rock wedge was formed. In addition to presented problem it is suggested how mechanical properties of blast-induced cracks could be estimated using Barton-Bandis failure criterion. As final result it was clear that without blast-induced cracks no wedge stability analysis is complete.

Keywords: Tunneling in hard rock, rock blasting, key block theory, rock wedges

Apstrakt: Analiza stabilnosti stenskih klinova igra važnu ulogu u rudarstvu i izradi podzemnih prostorija. Ova metodologija je danas široko primenjivana, ali svi postojeći modeli u obzir uzimaju samo postojeće pukotine u stenskom masivu. Ni jedna od procedura ne uzima u obzir pukotine nastale miniranjem. Na osnovu principa nove teorije miniranja moguće je prognozirati dužinu i gustinu radijalnih pukotina koje nastaju miniranjem. Ovaj rad predstavlja pojednostavljenu sistuaciju otkopavanja u stenskom masivu u kome su prisutna samo dva pukotinska sistema. U ovim uslovima formiranje stenskih klinova je nemoguće. Kada su u analizu uzete i pukotine koje nastaju miniranjem dolazi do formiranja nestabilnog klina koji narušava stabilnost same podzemne prostorije. Kao dodatak prezentovanom problemu predstavljena je procedura za procenu mehaničkih osobina pukotina nastalih miniranjem koristeći se Barton-Bandisovim kriterijumom loma. Kao razultat jasno je istaknuto da analiza formiranja i stabilnosti stenskih klinova prilikom izrade podzemnih prostorija nije potpuna ukoliko se u obzir ne uzmu i pukotine nastale miniranjem.

Ključne reči: Izrada podzemnih prostorija, miniranje, teorija ključnog bloka, stenski klinovi

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1. INTRODUCTION

Since it was introduced by Goodman and Shi (1985) key block theory found wide application in analysis of underground and surface excavations. Theory describes formation of rock wedges by joint intersection and gives prediction of their stability. Also, this made new approach for support design. Up to date this research made foundation for new researches in this field. Sofianos (1986), Crawford (1983) analyzed the influence of the stress field on the stability of the rock wedges. Discrete fracture network approach was used to analyze rock wedge formation in Éléonore mine in Canada (Grenon, 2016). Elmouttie (2010) develops the algorithm that is capable of handling curved, finite persistence joints for detection of the polyhedral rock blocks. Those procedures analyze rock wedge formation from preexisting joints in rock mass. Since excavations in hard rock are mostly done using explosives, surrounding rock mass is subjected to loading from explosive charges. Explosive load induces new cracks in rock mass around excavation. Depending on quality of blasting process, induced cracks may reach length of almost 3m. These blast-induced cracks may intersect with preexisting joint in rock mass and form unstable rock wedges, or may “cut” already formed wedges and make them unstable. Malmgrena (2006) analyzed the impact of blast induced vibrations on the stability of the shotcrete supported rock wedges. However, there is no procedure that describes impact of blast-induced cracks on formation and stability of rock wedges in underground excavations. Herein, focus is on explaining how blast-induced cracks may impact stability of underground excavations, and the fact that without blast-induced crack consideration no rock wedges analysis is complete.

2. ROCK BLASTING THEORY

According to the rock blasting theory, Torbica and Lapcevic (2014a), it is possible to calculate radii of zones with different density of radial cracks around the blasthole. This theory explains fracturing mechanism of rock under explosive load. Here main part of that theory is presented since it is basis of this paper.

Detonation of an explosive charge in rock results in dynamic loading of the walls of the borehole and generation of a stress wave that transmits energy through the surrounding medium. Pressure wave extends from borehole walls circularly around the borehole (Figure 1). At the distance r_{cn} from the borehole compressive stress of the rock in the radial direction is:

$$\sigma_{rc} = P_h \cdot \frac{r_h}{r_{cn}} \quad (1)$$

Where:

σ_{rc}- radial compressive stress

P_h- borehole pressure

r_h- borehole radius

r_{cn}- crack zone radius

On the other hand:

$$\sigma_{rc} = M \cdot e_r \tag{2}$$

Where:

$$M = E \cdot \frac{(1-\nu)}{(1+\nu)\cdot(1-2\nu)} \tag{3}$$

$$k = \frac{(1-\nu)}{(1+\nu)\cdot(1-2\nu)} \tag{4}$$

$$\sigma_{rc} = E \cdot k \cdot e_r \tag{5}$$

M - pressure wave modulus
e_r - radial strain
E - Young`s modulus of rock
ν - Poisson’s ratio

Or:

$$e_r = \frac{\sigma_{rc}}{E \cdot k} \tag{6}$$

Therefore:

$$e_r = \frac{P_h \cdot r_h}{E \cdot k \cdot r_{cn}} \tag{7}$$

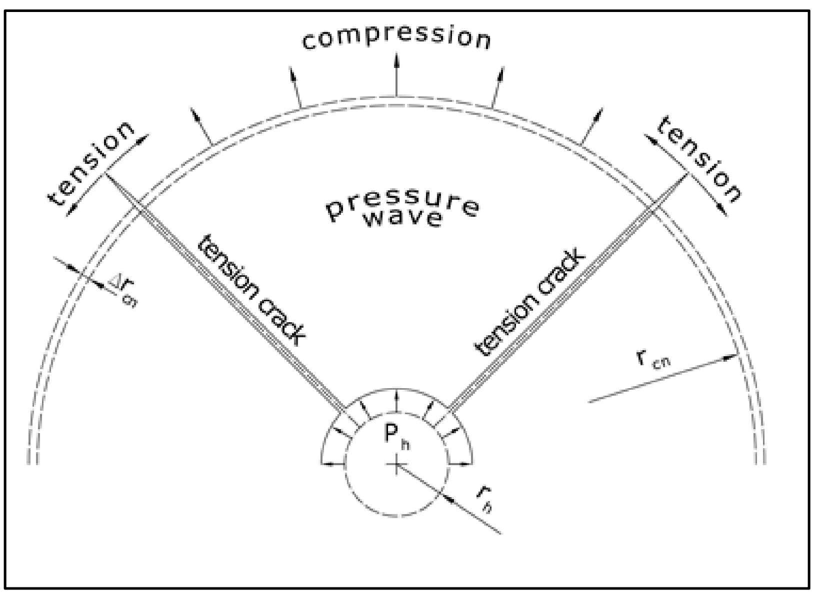

Figure 1 Schematic illustration of rock blasting model

At the distance r_{cn}, before the pressure wave gets to it, the perimeter of the closed circular ring zone of rock mass is:

$$O_r = 2\pi \cdot r_{cn} \tag{8}$$

When the pressure wave reaches the closed circular ring zone of rock mass, it is moved to a new position with a radius$(r_{cn} + \Delta r_{cn})$, and with the perimeter:

$$O_{(r_{cn}+\Delta r_{cn})} = 2\pi \cdot (r_{cn} + \Delta r_{cn}) \tag{9}$$

Therefore:

$$O_{(r_{cn}+\Delta r_{cn})} = 2\pi \cdot (r_{cn} + e_r \cdot r_{cn}) \tag{10}$$

Once the closed circular ring zone of rock mass is subjected to tension with a lateral strain:

$$e_l = \frac{O_{(r_{cn}+\Delta r_{cn})} - O_{r_{cn}}}{O_{r_{cn}}} = e_r \tag{11}$$

For the formation of the radial tension cracks it is required tensile strain:

$$e_t = \frac{\sigma_t}{E} \tag{12}$$

Where:

e_t - tensile strain
σ_t - tensile strength
E - Young`s modulus of rock

In addition, the number (n) of radial tensile cracks formed at a distance r_{cn} will be:

$$n = \frac{e_l}{e_t} \tag{13}$$

Therefore, it is:

$$n = \frac{P_h \cdot r_h}{k \cdot \sigma_t \cdot r_{cn}} \tag{14}$$

Therefore:

$$r_{cn} = \frac{P_h \cdot r_h}{k \cdot \sigma_t \cdot n} \tag{15}$$

Practical application of this theory was demonstrated by Torbica and Lapcevic (2014b, 2015) for estimation of blasted rock fragmentation and for the assessment of the blast damages zones around underground excavations.

3. IMPACT OF BLAST-INDUCED TENSION CRACKS ON STRUCTURAL STABILITY OF UNDERGROUND EXCAVATIONS

Existing procedures for assessment of structural stability of underground excavations consider only preexisting joint sets in rock mass. However, blasting in hard rock induces new cracks in surrounding rock mass. Being able to estimate length and density of blast-induced cracks around blastholes it is possible estimate their impact on structural stability of excavations. To illustrate how blasting impacts structural stability, following example is used.

Excavation is done (by blasting) in limestone (compressive strength σ_c=70MPa, tensile strength σ_t=7MPa, Poisson's ratio ν=0.3) rock mass where two joint sets are present, as shown in Figure 2. Blasting is done using boreholes with radius r_h =0.051m, and expected borehole pressure is P_h=1.6 GPa. All boreholes are charged with same amount of explosive, even contour ones. In this case, the highest damage in surrounding rock mass is expected. For this situation, it is possible to calculate radial cracks length using equation 15, as shown in Table 1. Excavation orientation is in North-South direction. In Figure 3 blast-induced cracks length and density around blasthole is shown.

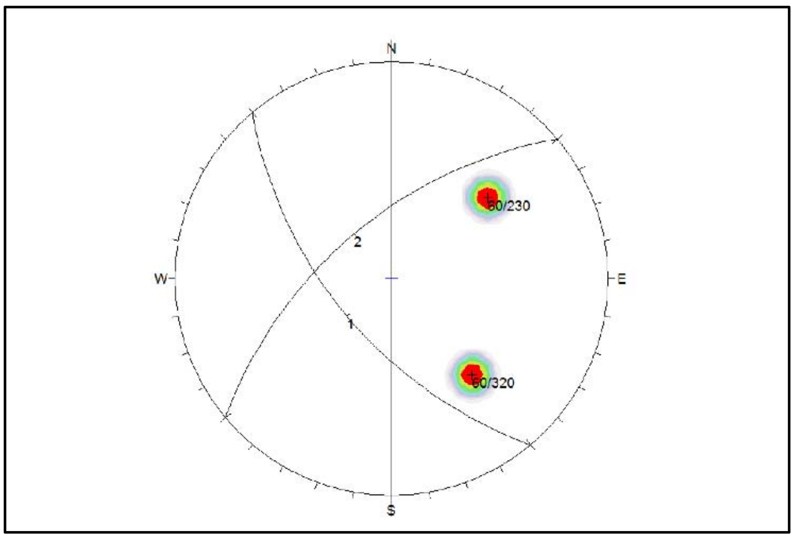

Figure 2 Preexisting joint sets in rock mass

Table 1 Zone radius with crack density

Zone name	r_2	r_4	r_8	r_{16}	r_{32}
n	2	4	8	16	32
r_{cn} (m)	4.32	2.16	1.08	0.54	0.27

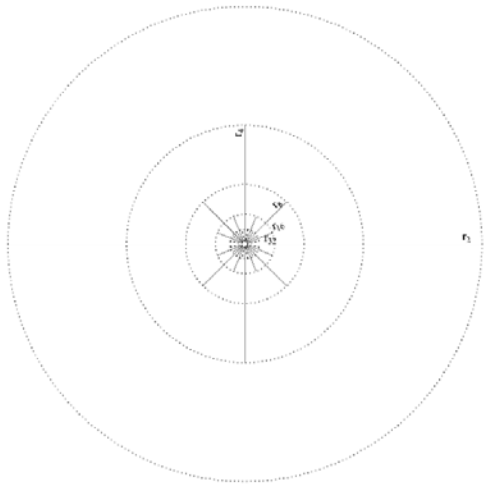

Figure 3 Blast-induced cracks length and density around blasthole

Main point of this paper is to explain that blast-induced cracks may intersect with preexisting joints in rock mass and form rock wedges with possibility of kinematic failure. Also, if there are three or more joint sets in rock mass, blast-induced cracks may *"cut"* already formed rock wedges and make new wedges that may fail. In order to make this example simple and more illustrative situation described in Figure 2 is analyzed.

At this point it is obvious that there is no possibility for rock wedge formation, as minimum of three joint sets are needed for this. Now, if third joint set is added, which is a blast-induced, situation changes. To keep it simple as possible we will analyze only one blast-induced crack that is assumed to be horizontal and has length same as zone r_4 in Table 1. For wedge formation analysis we are using software Unwedge (Rocsciene Inc.). Before we analyze wedge formation we need to define input data. In Table 2 joint sets properties are shown. To quantify strength properties of blast-induced cracks we are using Barton-Bandis failure criterion Barton and Bandis (1990). Barton-Bandis failure criterion has three key parameters JRC, JCS and phi_r. As explained in section 2 blast-induced cracks are formed due tensile failure, therefore it is to be expected that these cracks are very rough. Therefore, JRC of blast-induced cracks should have highest possible JRC value which is 20. JCS and phi_r describe compressive strength and friction angle of joints and have same values as main rock. It is important to mention that tensile strength of blast-induced cracks is zero. Figure 4 shows new situation where blast-induced cracks are included in analysis.

Table 2 Analysis input data

Joint set	Description	Failure criterion	Maximum persistence	Dip/Dip Direction (˚)	Phi (˚)	C (MPa)	Sigt (MPa)	JCS (MPa)	JRC	phi$_r$ (˚)
JS 1	Preexisting	Mohr-Coulomb	Unlimited	60/230	35	0	0	-	-	-
JS 2	Preexisting	Mohr-Coulomb	Unlimited	60/320	35	0	0	-	-	-
JS 3	Blast ind.	Barton-Bandis	2.16 m	0/090	-	-	-	70	20	35

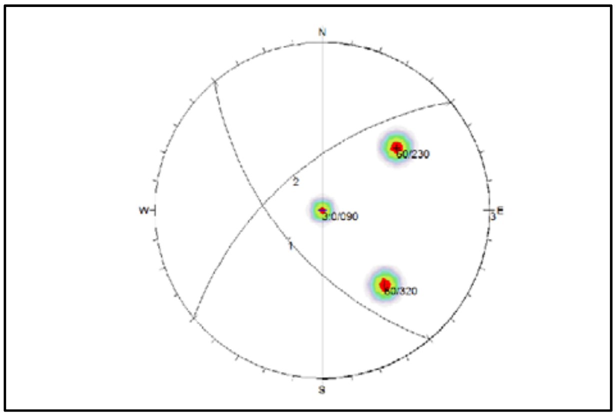

Figure 4 Preexisting and blast-induced joints orientation

In Figure 5 it is illustrated how unstable rock wedge formed from intersection of preexisting joints in rock mass with blast-induced tension crack. Figure 6 shows rock wedge in detail with sliding direction. In this case wedge is formed in excavation side wall. Wedge is sliding on JS1 and JS2, since blast-induced crack doesn't have tensile strength, and has factor of safety FS=0.723, weighs 0.0135 MN. As it could be seen analysis showed that there is possibility of formation of unstable wedges in excavation surrounding.

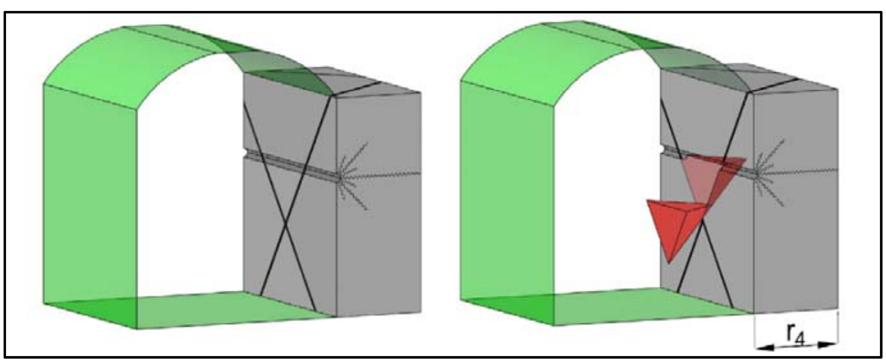

Figure 5 Unstable rock wedge formed in blasting process

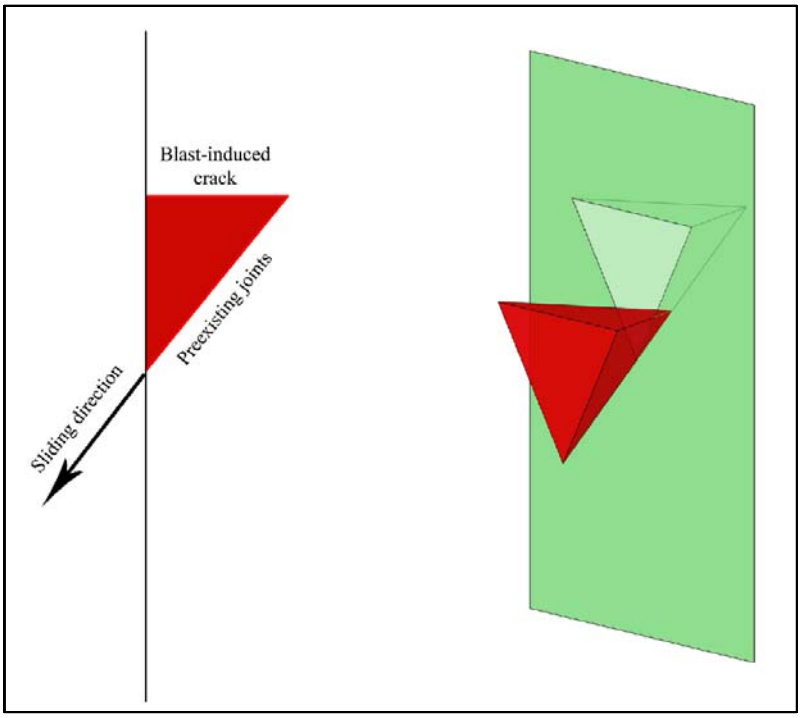

Figure 6 Rock wedge formed from preexisting and blast-induced joints

Existing wedge analysis procedures do not consider blast-induced cracks. Following this logic, in case of existence of only two joint sets, one can easily be misled into false conclusion which is that no rock wedges could be formed in that case. Here, it is showed and emphasize that blast-induced cracks may impact structural stability of underground excavations and should be considered in analysis. Without this rock wedge analysis is incomplete.

4. CONCLUSION

As stated, there is no procedure that analyses impact of blast-induced cracks on structural stability of underground excavations. Herein, main part of new blasting theory is presented, where it is explained how blast-induced cracks are formed, and how to estimate their length and density around blasthole. This principle is used to illustrate impact of blast-induced cracks on structural stability of underground excavations. Situation where excavation is done in rock mass where only two joint sets are present is analyzed. With only two joint sets it is impossible that rock wedges are formed. When third joint set, that is blast-induced, was added to analysis unstable rock wedge was formed. It should be mentioned that in this paper only one possibility of wedge formation is analyzed to keep it as simple as possible. Since stability analysis needs strength properties of joints, Barton-Bandis failure criterion is used to quantify blast-induced cracks. It turned out that wedge was formed in excavation side wall and was sliding on preexisting joints in rock mass with tension crack on top of it. Since blast-induced crack has no tensile strength it made it possible for wedge to slide on other two joints. In some cases where rock mass has three or more joint sets improper blasting may cause that existing rock wedges are *"cut"* and may fall.

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