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ABSTRACT

With the increase of mining depth, rockburst is one of the most serious disasters which threaten the safety of mine operators and the surface stability. Several approaches have been developed since the sixties to assess rockburst potential in underground hardrock mines. Some of the approaches are based on energy balance around mining excavations such as the Energy Release Rate (ERR) that was developed in South Africa and more recently the strain Energy Storage Rate (ESR). This paper presents the results of a detailed numerical modeling case study for the assessment of rockburst potential in a room-and-pillar copper mine in Poland. The method of numerical simulation is a quasi-static finite difference method (FDM - FLAC3D). The Energy Storage Rate (ESR) is numerically calculated to predict burst occurrence.

KEYWORDS

Deep mine, Numerical Modeling, Rockburst, Energy balance

INTRODUCTION

The assessment of rockburst occurrence is essential for the design and the safety of a deep mining exploitation. This type of dynamic event corresponds to a sudden release of energy from a highly stressed rock. Most frequently, rockburst causes rocks to crush and collapse together. Several factors are known to have an impact on the rockburst hazard (Butra, 2010): depth of mining, lithology of rockmass, thickness of deposit, presence of discontinuity planes, geo-mechanical characteristics of rock-mass. Some of the mining factors also have an influence on the occurrence of rockburst: mining method, roof control method, pattern of deposit cut, concentration of mining operations, spatial limits of mining operations.

For mining areas, numerical modeling is often used to identify zones of high stress concentration. Areas where calculated stresses are predicted to exceed the strength criterion of the rock can then be monitored to prevent instabilities. Another approach is the consideration of energy instead of stresses. Various methods involving energy balance have been developed; their main advantage is their consideration of rock's stress and strain state in a unique value of energy. These methods rely on the definition of a critical energy threshold corresponding to the amount of energy that can be stored in the rock before being brutally released as energy waves. For example, the evaluation of the Energy Storage Rate (ESR) provides an indication on the state of the rock surrounding an excavation.

After a review of the methods of detection of mining induced seismicity, this paper presents a numerical modeling study using FLAC-3D software, which is used to calculate the ESR. The efficiency of the modeling technique is demonstrated for a cylindrical excavation in an infinite elastic rockmass under hydrostatic stresses. The calculation of energy is then applied to a case study of a Polish underground mine, showing the need to define accurate levels of critical energy. Finally, a method for the calculation of critical amount of energy stored in the particular case of a triaxial test is presented.

ENERGY BALANCE IN MINING

Review of rockburst detection/prevention methods

The prediction of the occurrence of rockburst is based on detection and prevention methods used by mining companies. Primarily, micro-seismic monitoring systems (consisting of uniaxial or triaxial accelerometers) have become an integral part of most hard rock deep mines in an effort to characterize mining induced seismicity (Trifu, 2009, Archibald, 1990). The location, timing and magnitude of the induced seismic events can be determined, but the cause of these events is not directly identifiable. In fact, this seismicity can be created by high stresses, fault slip, fracture propagation, or strain burst. The main objective of monitoring is to adapt ground control support or to calibrate numerical modeling.

Optimization of the mining sequence in order to store high stresses into the free faces and good ground support practices have also been applied to reduce the proneness to rockburst.

The occurrence of strain bursts, a type of rockburst caused by the burst of a pillar, a face or a floor in a mine, has also been investigated based on analytical and numerical modeling. Various methods have been developed to locate the areas that are prone to rockburst occurrence and rockburst indicators were introduced depending on stress concentration (Tadjus, 1997), energy concentration (Wang, 2001), ratios of stress/strength (Mitri et al., 1988).

Among them are the Energy Storage Rate (ESR) (Mitri et al., 1999) and Energy Release Rate (ERR) (Cook et al., 1966), which were introduced to relate rockburst occurrence and the amount of energy stored in rockmass. The use of ERR as a measure of underground conditions rather than an indicator of seismicity was discussed. The present study uses ESR to characterise the amount of energy that can be stored in a rockmass.

Description of the different energy components

As first described by Cook (1967), reviewed by Salamon (1984), and then refined by Brady and Brown (1985) and Hedley (1992), every transition from one state of equilibrium to another during a mining operation is associated with energy transfers. The energy components associated with a transition between these arbitrary states of mining are described as follows: W_{ext} is the work done by external and body forces, $U_m$is the elastic strain energy initially stored in rock mined during the transition between the two states, U_c is the increase in stored energy, W_r is the released energy, W_s is the work applied on the support of the excavation, and W_{pla} is the related to plastic deformation. The energy balance is therefore defined by:

$$(W_{ext} + U_m) - \left(U_c + W_s + W_{pla}\right) = W_r > 0 \qquad (1)$$

An incremental approach is used to follow the changes due to mining (see figure 1). The mining sequence is decomposed into different stages of excavation and the value of ESR is calculated at each stage. Hereafter, the subscript *k* represents the number of the current stage of excavation, *k-1,* the number of the previous one, and $\sigma_{..,k}$ $\sigma_{..,k-1}$, $\varepsilon_{..,k}$ $\varepsilon_{..,k-1}$, the corresponding components of the stress and strain tensors in a Cartesian coordinate system:

$$\overline{\overline{\sigma_k}} = \begin{pmatrix} \sigma_{xx,k} & \sigma_{xy,k} & \sigma_{xz,k} \\ \sigma_{xy,k} & \sigma_{yy,k} & \sigma_{yz,k} \\ \sigma_{xz,k} & \sigma_{yz,k} & \sigma_{zz,k} \end{pmatrix} \qquad \overline{\overline{\varepsilon_k}} = \begin{pmatrix} \varepsilon_{xx,k} & \varepsilon_{xy,k} & \varepsilon_{xz,k} \\ \varepsilon_{xy,k} & \varepsilon_{yy,k} & \varepsilon_{yz,k} \\ \varepsilon_{xz,k} & \varepsilon_{yz,k} & \varepsilon_{zz,k} \end{pmatrix}$$

As noticed by Mitri et al., (1999), an increase in stored energy in a volume V, can be separated into e_1, which is the energy due to induced stress and e_2 , which is the energy due to in-situ stress (initial stress before excavation).

$$U_{c,k} = e_{1,k} + e_{2,k} \qquad (2)$$

Where:

$$e_{1,k} = \frac{1}{2} * \int \overline{\overline{\Delta\varepsilon_k}} : \overline{\overline{\sigma_{ind,k}}} * dV \ , \qquad e_{2,k} = \int \overline{\overline{\Delta\varepsilon_k}} : \overline{\overline{\sigma_{k-1}}} * dV \qquad (3)$$

$\overline{\overline{\Delta\varepsilon_k}}$ is the transposed incremental strain tensor associated with the stage k
$\overline{\overline{\sigma_{ind,k}}}$ is the induced stress tensor $\overline{\overline{\sigma_{ind,k}}} = \overline{\overline{\sigma_k}} - \overline{\overline{\sigma_{k-1}}}$

A FISH command was created in FLAC-3D for the purpose of this study, using a formula adapted to the Cartesian coordinates, applied in each zone of the model (v_zone is the volume of the zone considered):

$$e_{1,k,FLAC} = \frac{1}{2} * v_{zone} * \left(\sigma_{ind,k,xx} * \Delta\varepsilon_{xx,k} + \sigma_{ind,k,yy} * \Delta\varepsilon_{yy,k} + \sigma_{ind,k,zz} * \Delta\varepsilon_{zz,k} + 2 * \left(\sigma_{ind,k,xy} * \Delta\varepsilon_{xy,k} + \sigma_{ind,k,xz} * \Delta\varepsilon_{xz,k} + \sigma_{ind,k,yz} * \Delta\varepsilon_{yz,k}\right)\right)$$

$$e_{2,k,FLAC} = v_{zone} * \left(\sigma_{xx,k-1} * \Delta\varepsilon_{xx,k} + \sigma_{yy,k-1} * \Delta\varepsilon_{yy,k} + \sigma_{zz,k-1} * \Delta\varepsilon_{zz,k} + 2 * \left(\sigma_{xy,k-1} * \Delta\varepsilon_{xy,k} + \sigma_{xz,k-1} * \Delta\varepsilon_{xz,k} + \sigma_{yz,k-1} * \Delta\varepsilon_{yz,k}\right)\right)$$

The Energy Storage Rate (ESR) is then given by

$$ESR_k = \frac{d}{dV}\left(e_{1,k} + e_{2,k}\right) \quad \text{and} \quad ESR = \sum_{k} ESR_k \qquad (4)$$

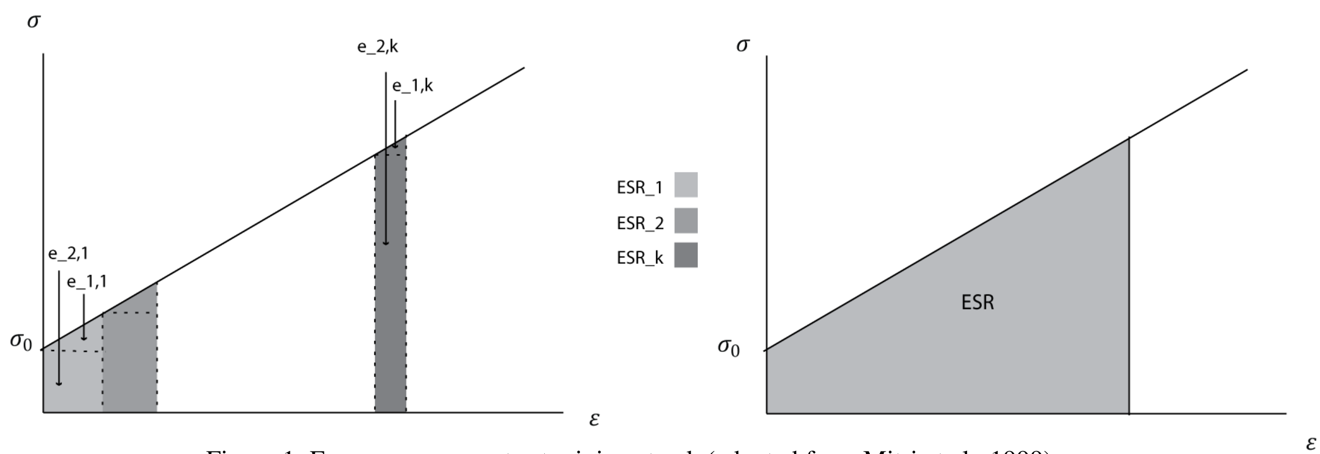

Figure 1: Energy components at mining step k (adapted from Mitri et al., 1999)

Cylindrical excavation in elastic rockmass

We first compare the results of a numerical modeling using the commercial codes UDEC and FLAC-3D with the analytical solution calculated by Salamon, (1984) for a cylindrical opening created instantaneously in a linearly elastic material. The results of this modeling ensure that the value given by the FISH-command (developed in FLAC-3D) is accurate.

Stage 1 corresponds to the excavation of a 1m-radius cylinder and stage 2 corresponds to a 2m-radius excavation (figure 2). The analytical solution can be easily found from this geometry. Work done at the outer boundary is calculated at a distance of 10 m from the center.

Bulk modulus (MPa)	$38.9*10^3$
Shear modulus (MPa)	$29.7*10^3$
Initial stress (MPa)	100

Table 1: Properties of the material

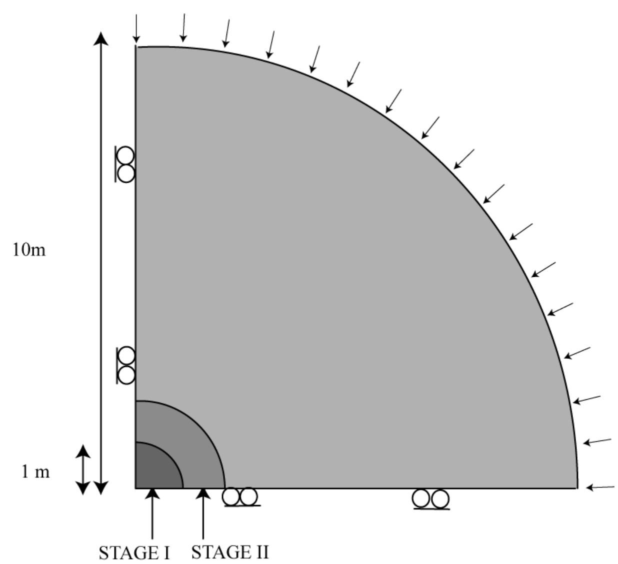

Figure 2: Dimensions of cylindrical excavation model

	STAGE I			STAGE II		
	Analytical value	UDEC	FLAC-3D	Analytical value	UDEC	FLAC-3D
e_1 (MJ)	0.0266	No value	0.0264	0.0581	No value	0.0591
e_2 (MJ)	0	No value	0.002	0.0386	No value	0.0385
U_c (MJ)	0.0266	0.0266	0.0274	0.0969	0.0934	0.0976
W_{ext} (MJ)	0.0535	0.0527	0.055	0.157	0.152	0.163

Table 2 : Energy balance for a cylindrical excavation in an elastic material

The absence of values for e_1 and e_2 in the column corresponding to UDEC is explained by the fact that this software does not distinguish between stored energy resulting from induced stress versus in-situ stress. The results are very close to those given by the theory. The predicted relations for stage 1 should be:

$$\begin{gathered} Uc = 0.5 * W_{ext} \\ Uc = e1 + e2 \end{gathered} \tag{5}$$

These relations are observed with an error of less than 4% and imply that half of the boundary work is stored into the rock mass. As described by Hedley (1992), this proportion is not the same for the enlargement of the cavity. The other part of energy should be dissipated by damping of the spherical waves emitted during the instantaneous excavation.

The same type of calculation was also performed for a spherical excavation in an infinite, elastic and homogenous material, and was compared with the results of the analytical solution and the boundary element program Examine-3D (Rocscience). Again, the results fit the theoretical solution, which allows us to affirm that the FISH command can efficiently predict the amount of energy stored following an excavation sequence while modeling an elastic rockmass in three dimensions.

CASE STUDY

Presentation of the Rudna Copper Mine

The Rudna mine is one of three mines in the Polish Legniga Glogowski Copper Belt, along with the Polkowice mine and the Lubin mine. The mined ore corresponds to a thin and flat rock layer, at an actual average depth of 1250 m below ground surface, exploited since the 1970's with different variant of room-and-pillar method. The production of copper ore in this mine amounts to about 12.5 Mt per year, with a grade below 2%.

Because of the mine depth, the geology and the presence of fault, this mine is subject to many rockbursts. As described by Butra, (1998), even if the geological conditions above this mine are fair (thick and strong dolomite layer overlaying the ore), the size of mined out area (about 75 km^2), the number of dynamic events and the high stress concentration have made the mining environment increasingly complex. Every year, about 3000 induced tremors are registered in the LGOM district, with the energy of tremors reaching up to 10^{10} Joules (Orzepowski, 2008).

Rockbolting and hydraulic backfilling is commonly used to support the roof and to improve the stability during the first stage of excavation. Moreover the method of the yielding remnant pillars is used. This approach provides immediate roof strata protection in the working zone, as well as advantageous stress distribution due to instant support of main roof strata on yield pillars.

Control of this method constitutes a real achievement for the Polish copper mining industry. The main idea behind room-and-pillar mining with a roof-deflected system consists in the creation of pillars whose size permits yielding simultaneously with lowering and deflection on the roof strata. Crushed yield pillars of wedge-column shape behave similarly to a deformable artificial support which does not accumulate elastic strain energy. For the modeling, the pillars were designed to be rectangular instead of wedge.

Geometry, properties and assumptions of the model

According to Katulski et al. (1997), horizontal principal stresses are considered to be 40% larger than the vertical stress, which is estimated to be about 30 MPa. Model geometry (figure 3 and 4) is taken from the map of the Rudna mine provided by KGHM (the company that operates the mine). Attention was focused on a block currently under excavation. The mining method is a one-phase room-and-pillar of type J-3S, the remnant pillars have a width of 8 m.

Geologic strata	Thickness (m)	γ (MN/m3)	ν	E (MPa)	Rc (MPa)	Rt (MPa)
Dolomites	30	2.7e-2	0.24	8550	136	8.8
Orebody	3	2.7e-2	0.18	2039	67.59	3
Sandstones	30	2.7e-2	0.13	15000	18.4	0.8

Table 3: Properties of the material (adapted from Pytel, 2003)

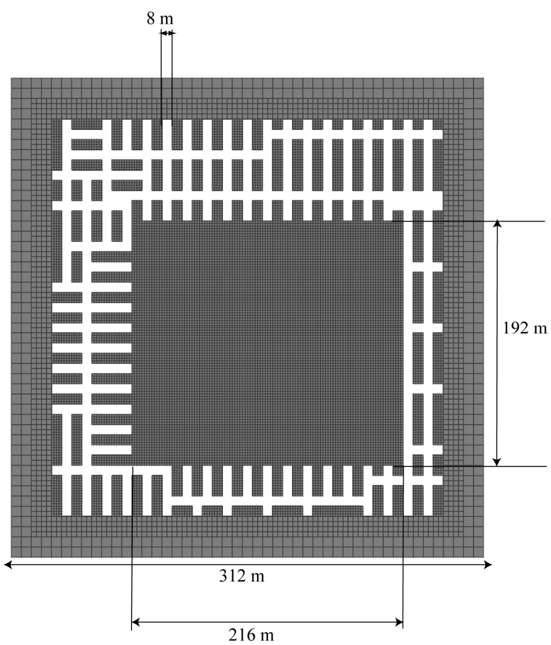

Figure 3: Horizontal view and dimensions of the model

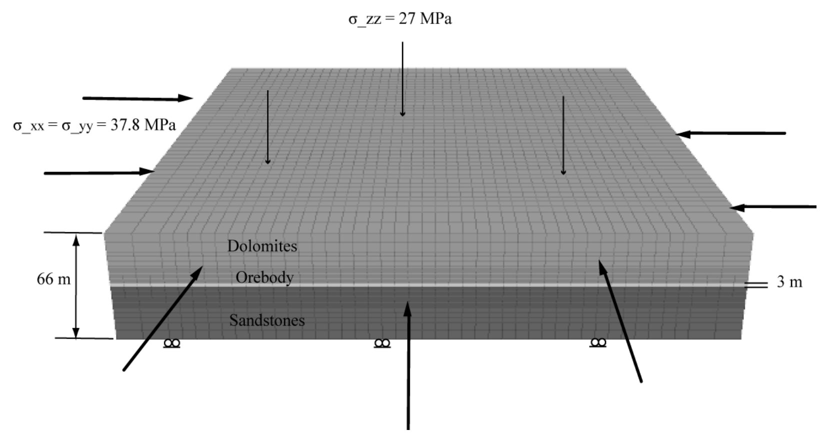

Figure 4: Initial stress distribution

Description of the mining sequence

The mining sequence followed in the mine is decomposed in 3 stages represented in figure 5. The dimensions of the remnants pillar and their shape shown in the figure 5 corresponds to another part of the mine which is out of the scope of the study. The cut A-A shows the first stage of development, the cut B-B the creation of the remnant pillars and the cut C-C a stage of caving of the blocks.

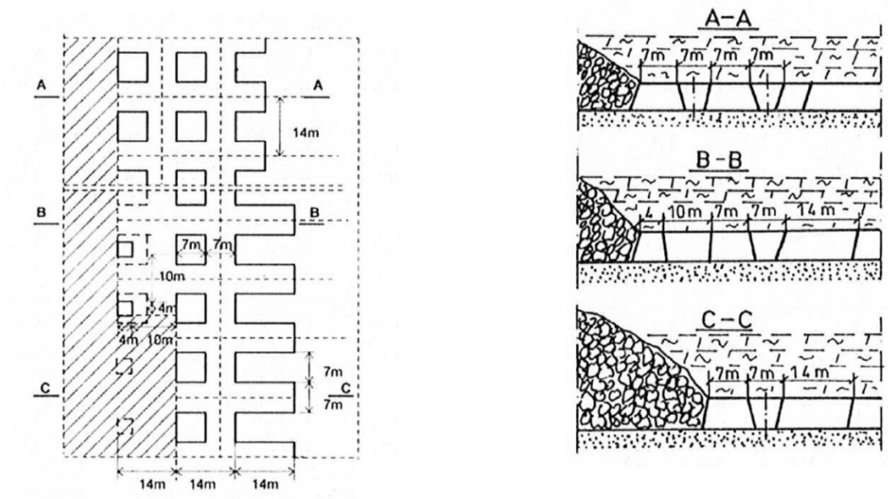

Figure 5: Examples of stages in the mining sequence

The numerical model aims to reproduce a room-and-pillar mining sequence. The remnant pillars of the zone modeled have the dimensions 8 m x16 m. A distinction was made between 2 types of excavation A and B. Steps A correspond to the development work, required to prepare the flat bedded deposit for mining and also to obtain a precise geologic description of the orebody. These stopes are roadways for ore transport and communication are established inside production stopes. Steps B are the ore recovery steps, corresponding to the creation of the remnant pillars. The backfilling stage by roof caving method is not in the scope of this study.

Results of the modeling

Comparison of the vertical stress distribution with solution given by SUIT 3D

A modeling of the mine was conducted with a boundary element software, SUIT-3D. Similarly to the FLAC-3D result, the distribution of vertical stress shows a concentration of high stresses (> 90 MPa) in the center of mining area, where remnant pillars are created (figure 6 and 7). The construction of the geometry with SUIT-3D is easier and the time of calculation is shorter. However, the abilities of FLAC-3D to change the behavior of the material into elastic-plastic with strain hardening/ softening, or to insert faults, dykes and other geological parameters, make FLAC-3D the preferred code for further analysis. Moreover, the calculation of energy components is harder to implement with SUIT-3D.

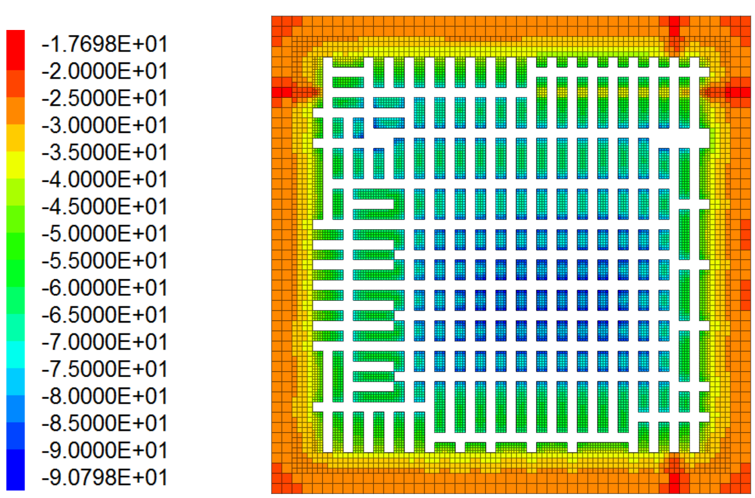

Figure 6: Vertical stress (MPa) at the end of mining sequence with FLAC-3D.

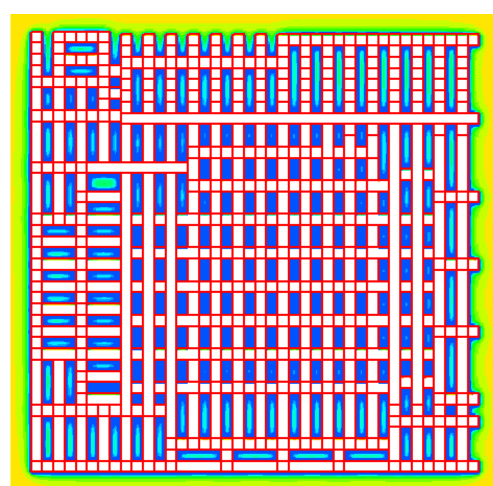

Figure 7: Vertical stress at the end of the mining sequence with SUIT-3D (the scale is not the same)

Evolution of the ESR during mining sequence

The central block was excavated in 10 stages and ESR was estimated at each one. Distribution of the values of ESR in a plan view is illustrated in figure 8 for four stages.

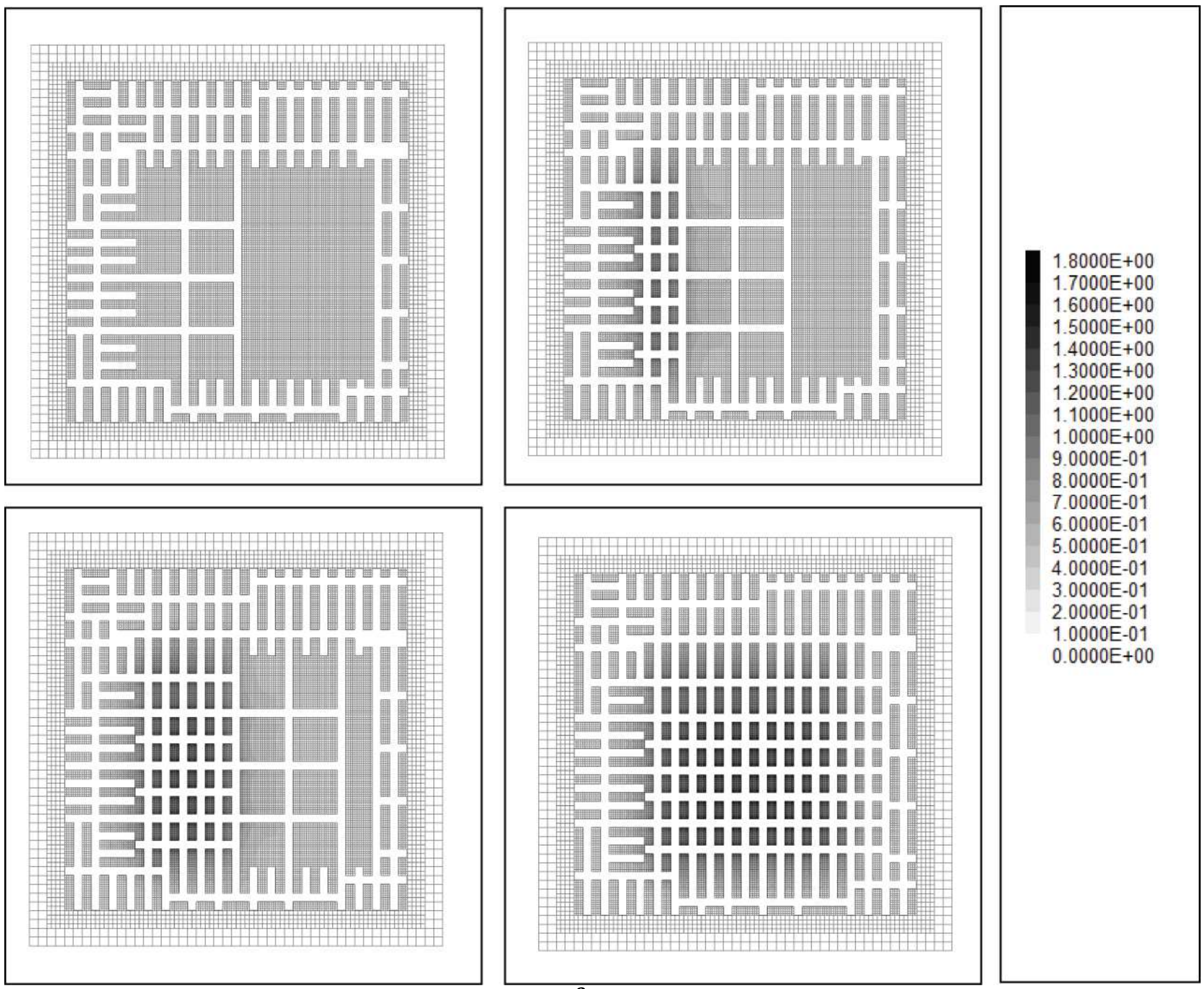

Figure 8: Energy storage rate: ESR (MJ/m^3) during a mining sequence in the Rudna Mine

During the first mining steps, the energy stored in the pillars around the excavation increases, especially in the pillars at the border of the initial block. These pillars have already been disturbed during their creation and therefore this perturbation may increase the probability of strainburst occurrence. The creation of the remnant pillars leads to an increase in stored energy. The evolution of the mining sequence shows a "flow" of stored energy following the mining front.

Between 1990 and 2010, the high energy tremors caused 323 events with consequences in the mines of the Legnica-Glogow Mining Basin (Butra, 2011). The number of events could be partially explained by a quantity of energy stored in the pillar close to a critical energy. We describe a way of calculating a critical value of the ESR to be applied in further work that would assess the probability of failure of the pillars. To continue this work, a model with accurate data and a more realistic mining sequence could also be realized.

CALCULATION OF A CRITICAL ENERGY

As reported by Mitri et al. (1999), Mitri (2007), and by Xie (2009), a value of critical energy has to be determined, representing the maximum amount of elastic energy that can be stored in a rock before it fails. Previous works chose this value based on the uniaxial compressive strength, which is a conservative assumption that does not take into account the effect of a confining pressure. The state of the stresses in the pillars was considered to be uniaxial because the failure is taking place at the pillar skin, where the normal stress must be zero. If we consider the yielding of the center of a pillar, this normal stress is not zero and acts as a confining stress. During a triaxial test, the value of critical energy highly relies on the value of the confining stress. The critical value of energy stored can be obtained by considering that the plastic yielding will lead to an unstable state close to the failure of the pillar.

A triaxial test was modeled with FLAC-3D to determine the critical amount of energy that can be stored depending on the confining pressure. The energy balance during a triaxial test is conducted at a constant axial strain rate (constant downward speed of the upper plate V represented in figure 9). A yield criterion of Mohr-Coulomb type is considered. The material is characterized by its cohesion c, its friction angle φ and its dilation angle ψ. The dimensions of the sample are given in figure 9. Let Ω be the volume of the sample and dΩ its surface.When the sample is compressed, a part of the work done at the external boundary is stored while the other part is dissipated by plasticity. The energy balance is given by:

$$U_c = W_{ext} - W_{pla} \quad (6)$$

Where $W_{ext} = \iint_0^{d\Omega} (\bar{\bar{\sigma}}.\bar{n})\bar{V}\,dS$ is the boundary loading work

$W_{pla} = \iiint \bar{\bar{\sigma}}:\overline{\overline{\varepsilon^p}}\,dV$ is the energy dissipated by plastic work

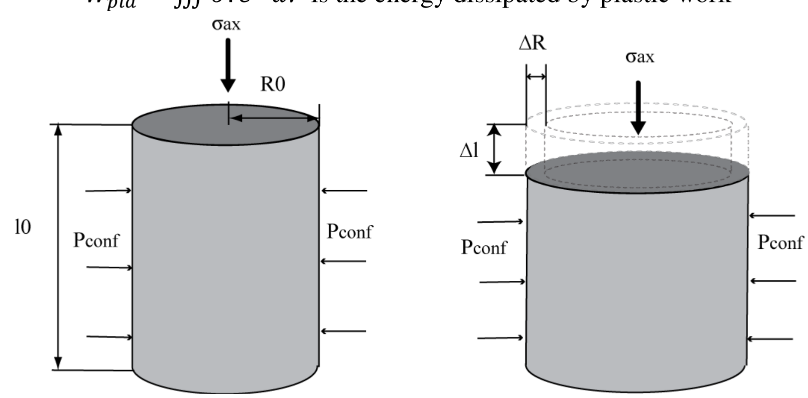

Figure 9: Modeling of a triaxial compressive test on a cylindrical sample

The evolution of the stress and strain between the initial state and any state of equilibrium can be summarized by the following matrix introducing the initial and final stress tensor, and the strain tensor:

$$\overline{\overline{\sigma_{ini}}} = \begin{pmatrix} \sigma_{conf} & 0 & 0 \\ 0 & \sigma_{conf} & 0 \\ 0 & 0 & \sigma_{conf} \end{pmatrix} \longrightarrow \overline{\overline{\sigma_{fin}}} = \begin{pmatrix} \sigma_{ax} & 0 & 0 \\ 0 & \sigma_{conf} & 0 \\ 0 & 0 & \sigma_{conf} \end{pmatrix}$$

$$\bar{\bar{\varepsilon}} = \begin{pmatrix} \varepsilon_{ax} & 0 & 0 \\ 0 & \varepsilon_{rad} & 0 \\ 0 & 0 & \varepsilon_{rad} \end{pmatrix}$$

Where $\varepsilon_{ax} = -\frac{\Delta l}{l0} = \frac{Vt}{l0}$ and $\varepsilon_{rad} = -\frac{\Delta R}{R0}$

During the elastic phase, the work done by the loading is entirely converted into strain energy stored in the rock sample. During the plastic phase, all of the energy brought by the loading is dissipated as plastic work. Let t_1 be the timestep of transition between the elastic behavior and the plastic behavior.

The analytical solution for the total amount of energy stored in the elastic state at a timestep "$t < t_1$" is:

$$U_{c,el} = \pi R_0{}^2 l_0(\sigma_{ax}{}^2 + (2v - 1)\sigma_{conf}{}^2 - 4v\sigma_{ax} * \sigma_{conf})$$

The solution for the total amount of energy dissipated by plastic work in the plastic state at a timestep $t > t_1$ is:

$$W_{pla} = \pi R_0{}^2 Vt((K_p - \beta)\sigma_{conf} - 2 * c * \sqrt{K_p})$$

Where: $K_p = \frac{1+\sin(\varphi)}{1-sin(\varphi)}$ and $\beta = \frac{1+\sin(\psi)}{1-sin(\psi)}$.

The solution given by the FISH command in FLAC-3D can be verified by studying the theoretical solution in the case of a triaxial test (figure 10). Subsequently, the critical energy density value in the sample can be evaluated for different confining stress (figure 11). The critical energy density is defined by:

$$e_c = \frac{U_{c,max}}{Volume} \quad (7)$$

When a zone has its stored energy that reaches this critical energy, it is possible to consider that the pillar is close to failure.

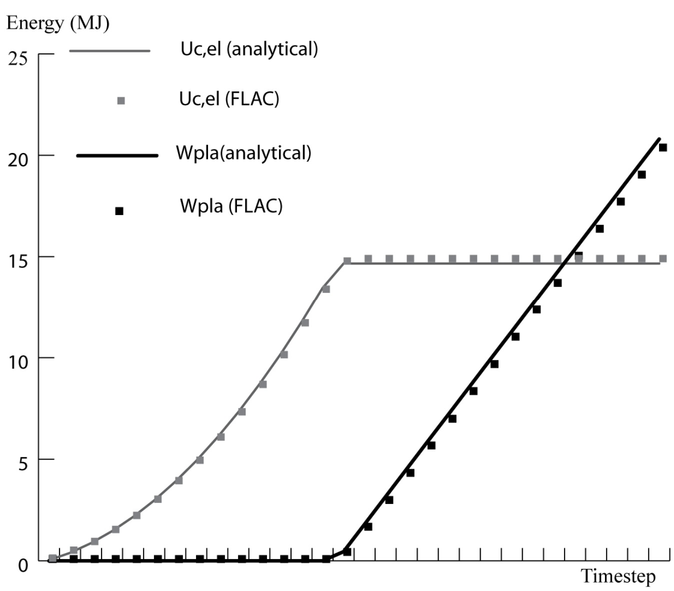

Figure 10: Analytical and calculated evolution of stored elastic energy and Plastic work during triaxial test

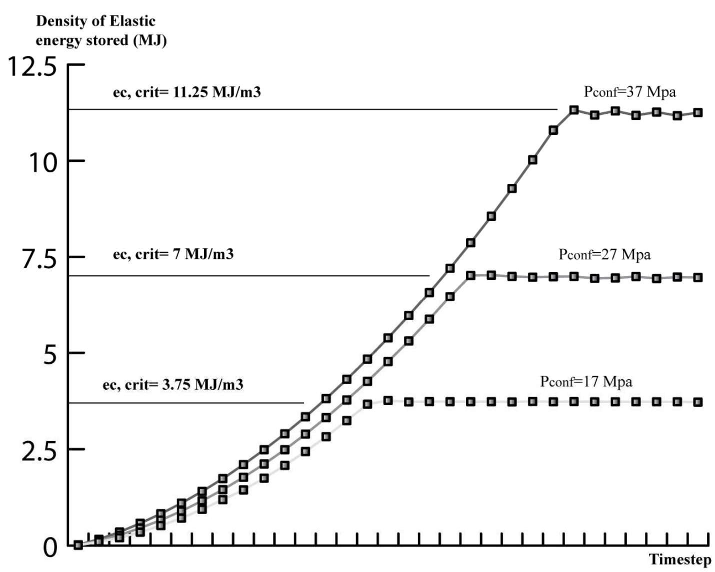

Figure 11: Example of calculus of critical energy density for 3 confining stresses ($\boldsymbol{\sigma_{conf}}$=17 MPa, $\boldsymbol{\sigma_{conf}}$=27 MPa, $\boldsymbol{\sigma_{conf}}$=37 MPa)

CONCLUSION

This paper focuses on the prediction of mining induced strain bursts using an energy approach. The distinction between the different energy components involved in a mining excavation is discussed. The calculation of these components is implemented into the commercial numerical modeling code FLAC-3D and tested through a comparison with the analytical solution for a cylindrical excavation in an infinite, homogenous and elastic rockmass. It was then applied to an underground copper mine in Poland.

The evolution of the stored elastic energy was considered at each stage of mining. A triaxial test on an elastic-plastic sample was modeled in order to calculate the value of a critical energy density including the influence of the confining stress. The next step of study will be to compare the critical energy to the energy stored in the pillars of the Rudna mine in order to determine which pillars are the most likely to be unstable and to release a high quantity of stored energy as rockbursts.

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