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INFLUENCE OF MINING OPERATING CONDITIONS ON FAULT BEHAVIOR

WPŁYW GÓRNICZYCH WARUNKÓW EKSPLOATACJI NA ZACHOWANIE SIĘ USKOKU

This article concerns numerical modeling of the impact of mining operations on fault behavior, carried out on the basis of a calculation program based on the finite element method. The calculations and their graphic results related to the reactions of vertical discontinuity on the mining operations that run along its boundary under changing operating parameters, such as geometry of the field and direction of mining with respect to the fault, as well as the method of liquidation of the caving zone. The behavior of the fault was analyzed based on distributions in the plane of shear stress and slip, together with their range and energy dissipated due to friction. The results of numerical calculations made it possible to draw conclusions on the impact of faults and the impact of operating conditions of mining in their vicinity on the level of seismic hazard.

Keywords: geomechanics, underground mining, faults, mining tremors

W artykule w oparciu o program obliczeniowy bazujący na metodzie elementów skończonych przeprowadzono numeryczne modelowanie wpływu eksploatacji na zachowanie się uskoku. Obliczenia i ich graficznie rezultaty dotyczyły reakcji pionowej nieciągłości na prowadzoną wzdłuż jej granicy eksploatację górniczą przy zmieniających się parametrach eksploatacji, takich jak: geometria pola i kierunek wybierania względem uskoku oraz sposób likwidacji zrobów. Zachowanie się uskoku analizowano w oparciu o rozkłady w płaszczyźnie uskoku naprężeń stycznych i poślizgu wraz z ich zasięgiem oraz energię zdyssypowaną wskutek tarcia. Rezultaty obliczeń numerycznych pozwoliły na sformułowanie wniosków dotyczących oddziaływania uskoków oraz wpływu górniczych warunków eksploatacji w ich sąsiedztwie na wielkość zagrożenia sejsmicznego.

Słowa kluczowe: geomechanika, eksploatacja podziemna, uskoki, wstrząsy górnicze

1. Introduction

A characteristic feature of Polish coal and copper ore mining is a high level of seismicity of the rock mass induced by mining operations resulting in high risk of rock bursts. One of the

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causes of high-energy shocks is the fact that mining operations are conducted in fault zones. This applies especially to copper mines, where operations in the vicinity of major fault zones are accompanied by a high level of seismicity, often resulting in the occurrence of rock bursts.

The impact of faults on the level of seismic hazard in regions where mining operations were conducted has been the subject of numerous studies. In Polish literature, the issue of faults has been addressed using analytical and numerical methods. The theory of elasticity allowed to determine the level of deformation and stress around the fault (Golecki & Jóżkiewicz, 1962; Jóżkiewicz 1964; Podgórski & Kleta, 1980). The conditions of fault fissure propagation were specified using theory of cracks (Gil & Litwiniszyn, 1972), also taking into consideration the impact of the fault on the possibility of rock bursts (Gil, 1976; Zorychta et al., 1999). The impact of faults has been described in terms of compaction of the rock mass (Goszcz, 1985) and as a shear mechanism of shock formation (Goszcz, 1986; Zuberek, 1993; Zorychta & Burtan, 2012). The shapes of displacements and stresses in the vicinity of faults were also analyzed in terms of the risk of gas and rock outbursts (Chlebowski, 2009). The strain and stress of the rock mass in the regions of tectonic disruptions were determined using numerical models (Kleta & Duży, 1995; Kwaśniewski, 1999), also analyzing the impact of faults on the level of rock burst hazard (Tajduś et al., 1994; Cieslik & Tajduś, 2011).

Although previous studies on the impact of faults managed to clarify many issues, they did not show the link between the behavior of faults and parameters of mining operations carried out in their vicinity. This represented an inducement to carry out a numerical evaluation of the impact of mining operating conditions on the possibility of fault activation and the level of seismic hazard.

2. Assumptions and construction of numerical computational models

To begin the numerical modeling of the operating parameters and their impact on the behavior of the fault, it was assumed that the location and geometry of the workings affects the formation of mining situations, in which exploitation fronts are conducted along the planes of faults with large discharges, moving closer or away from them. In such cases, favorable conditions for activating the fault are created, thus initiating the dynamic phenomena in the rock mass.

Assessment of the possibility of fault activation induced by mining operations conducted in its vicinity was carried out on the basis of spatial numerical models using the finite element method (Burtan, 2012). Conditions adopted in the model correspond to the operating parameters of the room-pillar system and the geological determinants of copper ore deposits in LGOM (Burtan, 2012).

The fault was assumed as a vertical discontinuity plane dividing the model into two parts (Fig. 2a), and the conditions of contacting surfaces were described by the classical Coulomb model of friction (Abaqus v6.8 User's Manual 2008). A working (Fig. 2b) featuring changing geometry, excavation direction with respect to the fault, and different way of liquidation of the caving zone, was modeled in a part located directly next to the fault.

On the contact surface, normal stresses s were determined from the equilibrium of forces on the edges of the model (Fig. 2a) and the shear stresses were calculated as the resultant vector of the two components in the plane of contact:

$$\tau = \sqrt{\tau_1^2 + \tau_2^2} \tag{1}$$

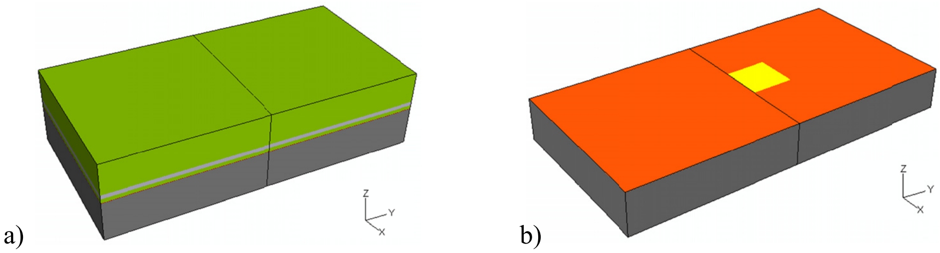


Fig. 1. Geometry of the model with fault (a) and sample working's geometry (b)

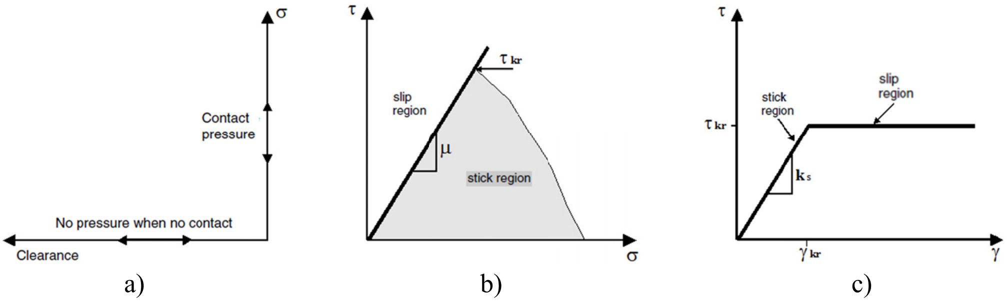


Fig. 2. Contact model with Coulomb's physical conditions (Abaqus v6.8 User Manual)

Similarly, the resultant vector of displacements (slip) was calculated on the basis of the components in the plane of contact

$$\gamma = \sqrt{\gamma_1^2 + \gamma_2^2} \tag{2}$$

Up to the moment of the slip, shear stresses t are proportional to a certain parameter of elasticity k_s, defined as the elasticity:

$$k_s = \frac{\tau_{kr}}{\gamma_{kr}} \tag{3}$$

Classical Coulomb slip condition (Fig. 2b) assumes that slip does not occur until:

$$\tau \le \tau_{kr} \tag{4}$$

where:

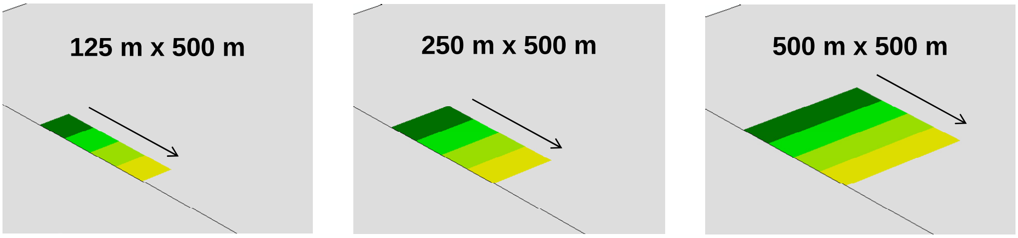
$$\tau_{kr} = \mu \cdot \sigma \tag{5}$$

μ — coefficient of friction (static),
σ — stress normal to the contact surface.

Fulfillment of the condition of equal shear stresses on the contact plane determines the condition of equilibrium or slip. In a situation where the value of shear stress is less than the critical value: $t \le t_{kr}$, slip does not occur (Fig. 2c), while if $t > t_{kr}$, there will be a slip, lasting until equilibrium conditions are reached again.

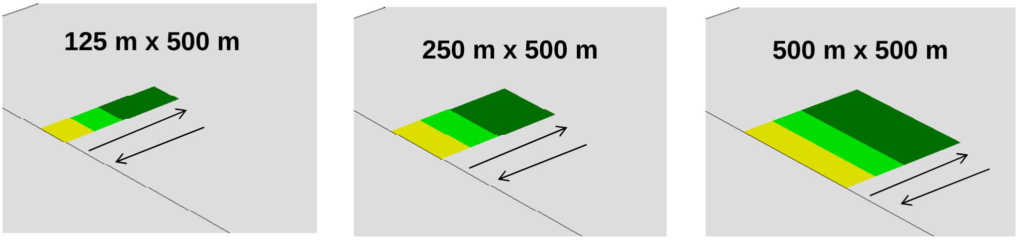
Analysis of the impact of the method of liquidation of the caving zone on fault behavior assumed operation with the use of a deflected roof and a hydraulic floor. On the other hand, in consideration of the impact of the geometry of exploitation, a different size of the working surface and its shape was assumed, and the selection was modeled for operations carried out along (Fig. 3) and perpendicularly (Fig. 4) to the fault.

Calculations and analysis of the presented results related to the fault's response to the additional "burden" caused by mining. The results of calculations illustrated changes in the shear stresses, slip and dissipated energy by friction, occurring in the fault plane.



a) b) c)

Fig. 3. Geometry of exploitation: a) 125 m × 500 m, b) 250 m × 500 m, c) 500 m × 500 m and location of the front (rundown) with the operation conducted along the fault



a) b) c)

Fig. 4. Geometry of exploitation: a) 125 m × 500 m, b) 250 m × 500 m, c) 500 m × 500 m and location of the front (rundown) with the operation conducted perpendicularly to the fault

3. Behavior of a fault subjected to the influence of exploitation

Analyzing the behavior of the fault under the influence of mining operations carried out in its vicinity, it was assumed that the exploitation was carried out with deflection of the roof along a fault front of a width of 250 m, and the various stages of the calculation concerned the runways: 125 m, 250 m, 375 I 500 m (Fig. 3b).

The results of calculations with regard to the roof and floor of the working in subsequent stages of exploitation are illustrated by the maps of new vertical shear stresses in the plane of the fault (Fig. 5a) and the corresponding slip of its walls relative to each other (Fig. 5b).

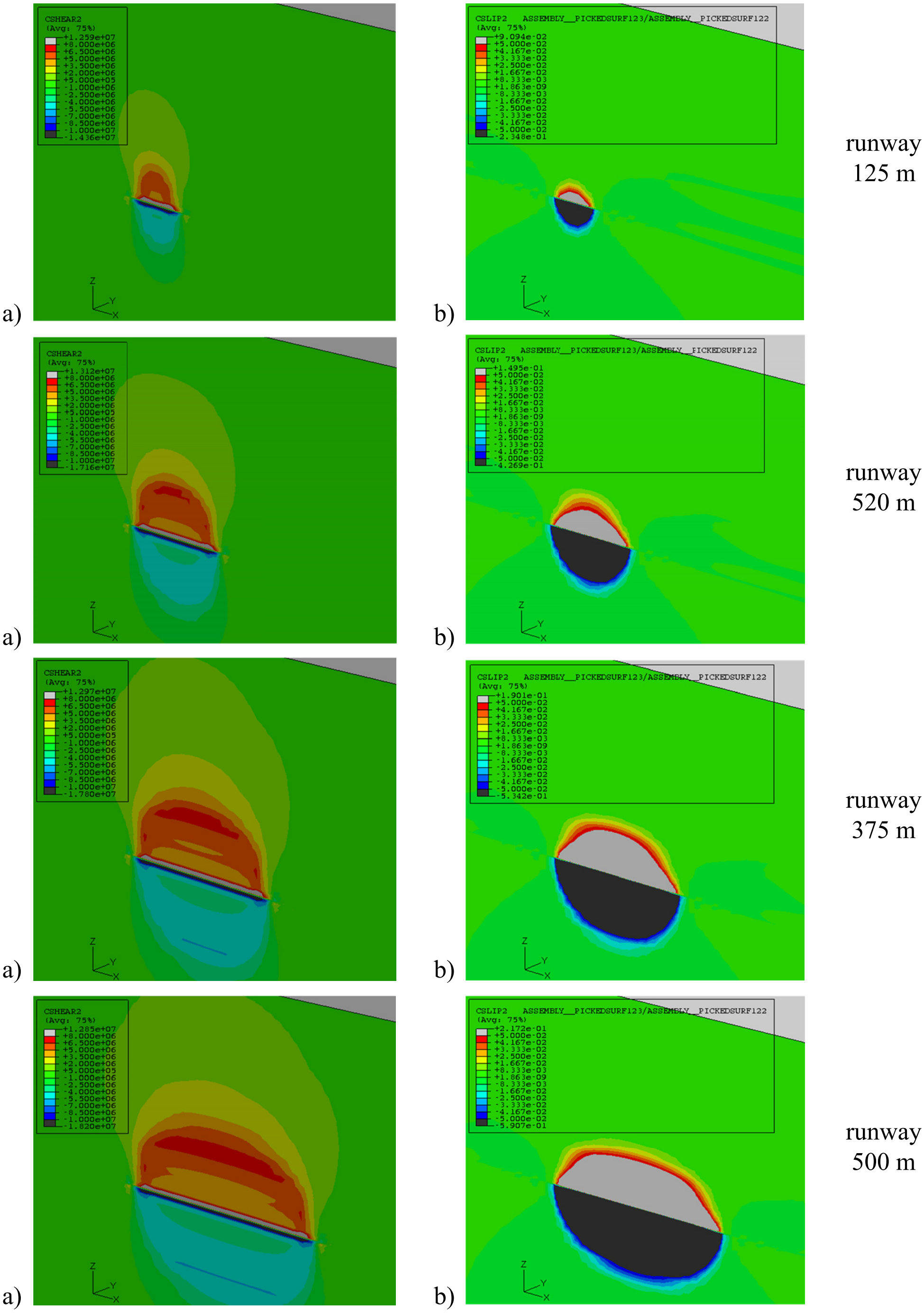
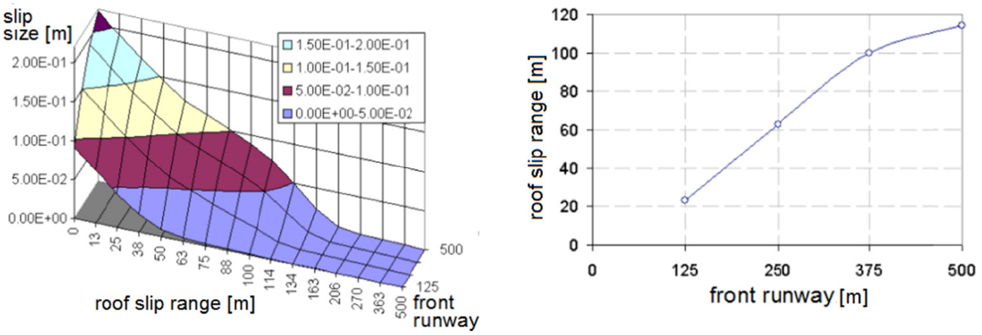


Fig. 5. Maps of vertical shear stresses (a) and the corresponding slip of the fault walls relative to each other (b) in subsequent stages of exploitation

The maps indicate that:

- shear stresses in the fault plane are the highest directly above and below the caving zone,
- the range of shear stress changes in the roof and floor are relative to the development of mining operations; the smallest are for the runway with a length of 125 m and the highest for the one with 500 m,
- from the very beginning, operation conducted along the fault line is accompanied by a slide (adopted as relative displacement of the fault walls greater than 0.05 m), the range of which increases up to 375 m runway and then stabilizes,
- vertical shear stress and slip values of the fault plane in the roof of the working are comparable with the values of these quantities in the floor; the ratios in the roof and the floor are similar in quality.

Graphs of slip magnitude and range in the runway function (position of the exploitation front) are shown in Figure 6.



a) b)

Fig. 6. Graph of size (a) and range (b) of the slip depending on the exploitation front runway

These dependencies confirm that the amount of slip increases with the runway and is higher for longer exploitation fronts. Range of the slip increases in the initial phase of operation, but stabilizes in the advanced stage of operation.

Important information on fault behavior result from the analysis of energy dissipated due to shear stress on the fault plane. The graph showing energy changes as a function of the exploitation front range (Fig. 7) indicates that in the initial phase of operation, up to 250 m of runway, the effects related to shear stresses acting on the fault plane are less varied than during further exploitation, where the increase of energy changes is proportional to the exploitation front runway.

The energy values represent the effects caused by the slip over the entire surface of the fault, wherein the analyzed slip on the fault plane is not an indication of a dynamic nature of the fault walls' movement relative to each other. Mining and laboratory observations indicate that slip of rock formations in the presence of discontinuities often occurs by leaps and bounds, accompanied by a shock. In such case, the power of the shock will be proportional to the energy dissipated due to shear stress on the fault plane.

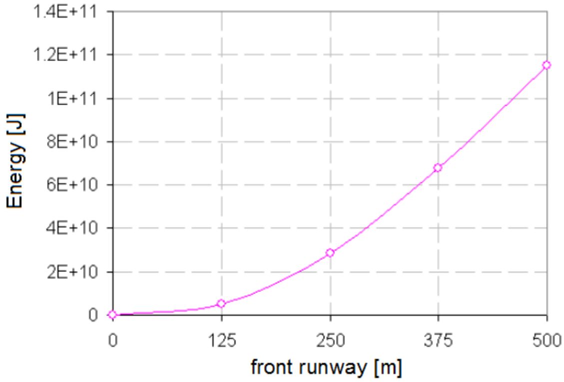


Fig. 7. Graph of energy dissipated due to shear effect in the fault plane

4. Impact of mining operating conditions on fault behavior

4.1. Impact of the working geometry

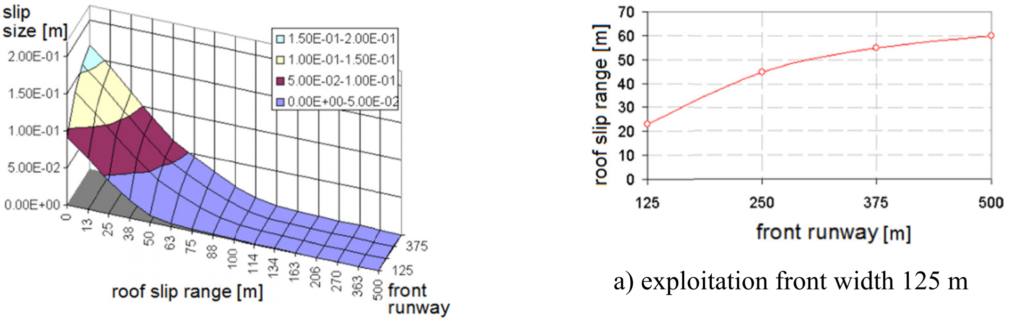
Assessment of the impact of geometry of the working was carried out for models varying in exploitation front width. Exploitation runway in all models was 500 m, and the mining operations were carried out along the fault (Fig. 3a-c). In the calculations, the impact of the width and runway of the front on fault behavior was analyzed, assessing displacement (slip) and energy dissipated due to shear stress on the fault plane.

Graphs of slip magnitude and range in a fault plane of the roof differing in exploitation front width and runway are shown in Figure 8, and the slip range for the subsequent calculation steps are illustrated in Figure 9.

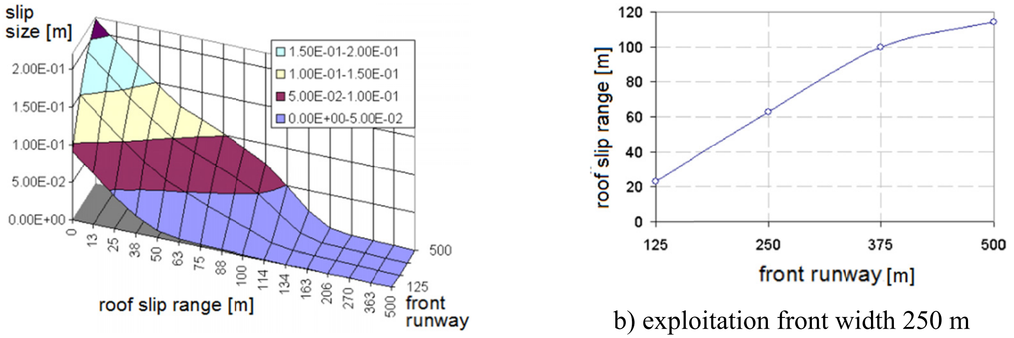
Flat and spatial graphs of energy dissipated due to the effects of friction in the fault plane, depending on the runway for the analyzed width of the exploitation front, are shown in Figure 10.

Based on the results of calculations, it can be concluded that:

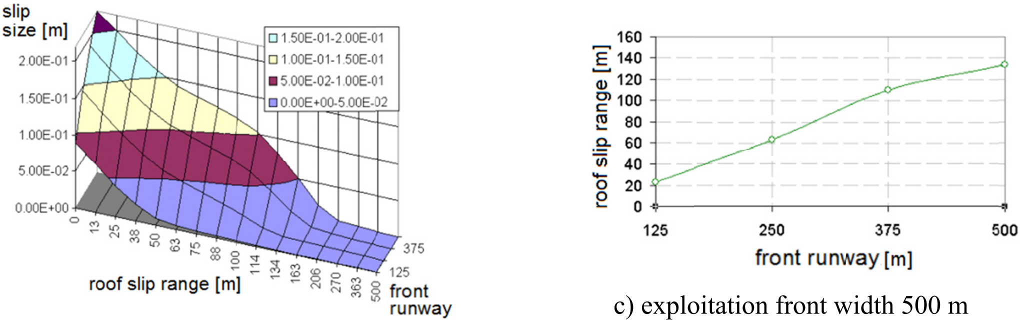
- from the very beginning, operation conducted along the fault line is accompanied by slip in the fault plane. Depending on the width of the exploitation front, the magnitude of slip in the fault plane is similar for models with front widths of 500 m and 250 m, and smaller for front width of 125 m;
- the nature and range of the slip changes relatively to the front width. In the case of front width of 125 m, the range of slip remains largely unaltered after obtaining the level of 250 m. For the front with a width of 250 m, the slip range changes slightly after reaching 375 m. In the case of the front with a width of 500 m, the runway at which the slip in the roof would undergo minor changes, has not yet been reached.
- along with the width and runway of the exploitation, the level of energy dissipated due to shear stress also rises.



a) exploitation front width 125 m



b) exploitation front width 250 m



c) exploitation front width 500 m

Fig. 8. Slip magnitude and range depending on exploitation front runway

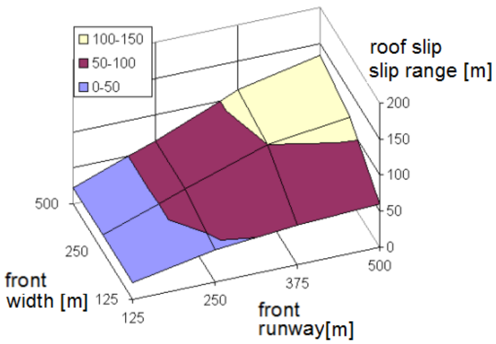
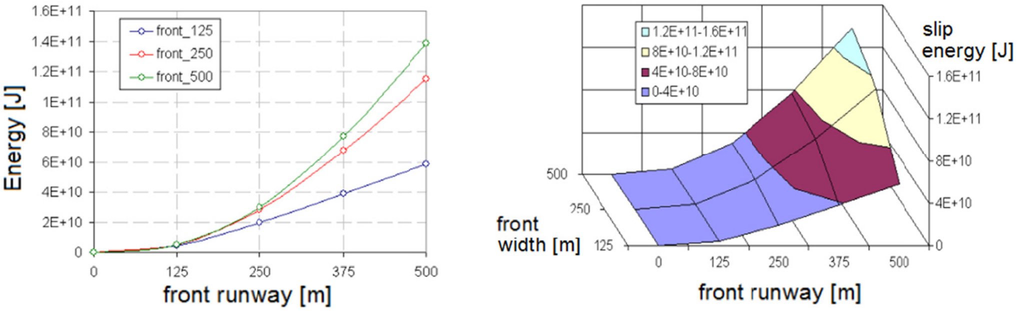


Fig. 9. Slip range in the function of width
and runway of the exploitation front



a) b)

Fig. 10. Flat (a) and spatial (b) graph of dissipated energy due to shear stress in the fault plane

4.2. Impact of the direction of exploitation

The impact of the direction of exploitation on fault behavior was analyzed for mining operations moving towards and away from the fault. Exploitation front widths of 125 m, 250 m and 500 m were assumed as well as roof deflection. The subsequent calculations were carried out for the following runway lengths: 250 m, 375 m and 500 m moving towards, and 125 m, 250 m and 500 m moving away from the fault (Figure 4a-c).

The maps of vertical shear stress (Fig. 11a) and slip (Fig. 11b) in a fault plane for the model with a front width of 250 m show, that in the course of exploitation, the fault exhibits the highest level of activity in the first stage of operation until obtaining a runway of 250 m. Upon further extension of the runway, changes in the distribution of shear stress and slip range are small. A significant drop in the value of shear stress in exploitation runway with a length of 125 m to 250 m can also be observed.

A different course of changes in shear stress (Fig. 12a) and the corresponding slip (Fig. 12b) takes place during operations carried out in the direction of the fault. From the distribution of these values for exploitation runways of 375 m and 500 m (in the case of which the edge of the exploitation runway coincides with the fault plane), one can observe that the entire process of slip practically occurs in the last stage of the front's approach to the fault, since at the distance of 125 m from the fault (runway of 375 m), both shear stress and slip in the fault plane are still very small.

The nature of the process of slip in the fault plane for all the analyzed scenarios of exploitation is illustrated by the graphs of dissipated energy as the result of friction (Fig. 13). These diagrams also show the different behaviors of the fault:

- in case of operations conducted along the fault plane, the energy increases gradually throughout the runway front,
- in case of operations conducted in the direction moving away from the fault, the biggest changes of energy occur in the first stage of operation and either get smaller with further extension of the runway (for the front with a width of 500 m) or do not change at all (for fronts with a width of 125 and 250 m),
- in case of operations conducted in the direction moving towards the fault, there are no energy changes on the significant part of the runway, except in the final stage of the operation, when the front is located in the immediate vicinity of the fault, a very large increase in energy may be observed.

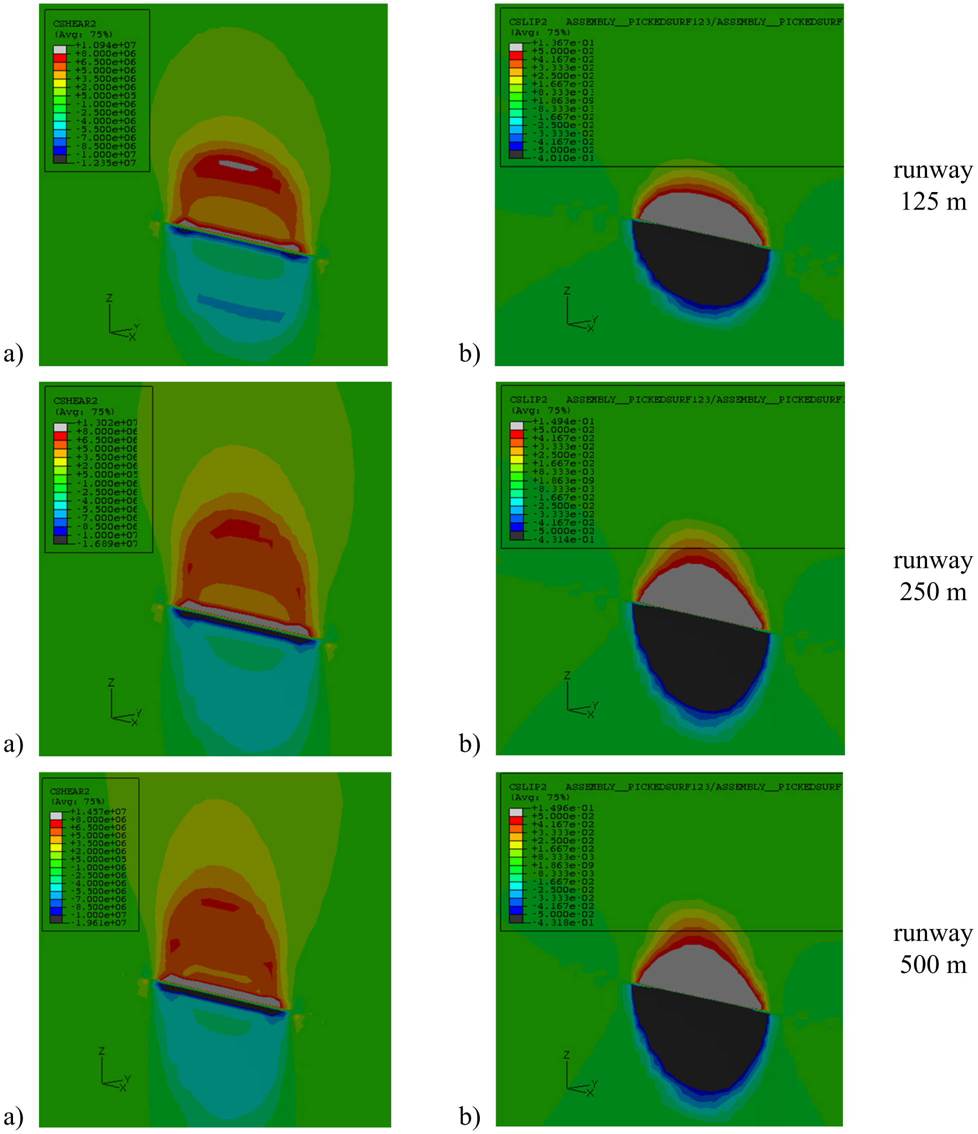


Fig. 11. Maps of vertical shear stress in a fault plane (a) and the corresponding slip of the walls relative to each other (b) in subsequent stages of operation with a front of 250 m in width, moving towards the fault

4.3. Impact of the method of caving zone liquidation

Numerical analysis of the impact of the method of caving zone liquidation, on the working, on the behavior of the fault was carried out for models with exploitation fronts of 250 m. In the first model, the caving zone was liquidated with the use of backfill, and in the second one by deflection of the roof.

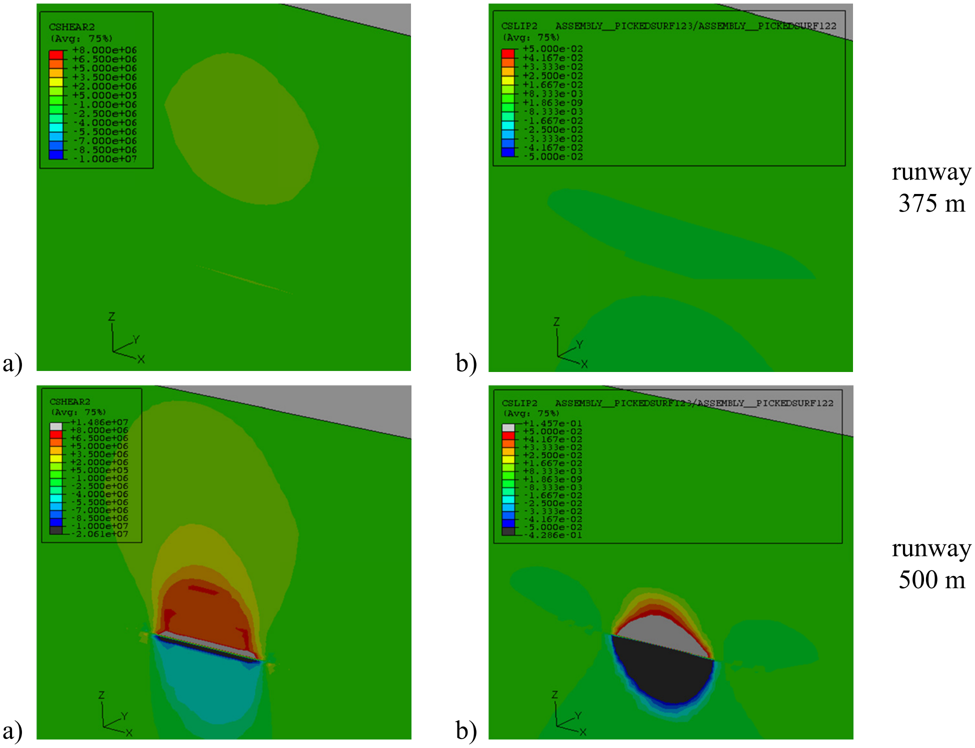
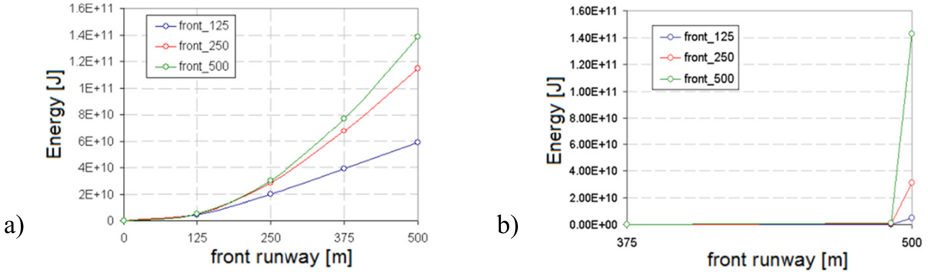


Fig. 12. Maps of vertical shear stress in a fault plane (a) and the corresponding slip of the fault walls relative to each other (b) in subsequent stages of operation with a front of 250 m in width, moving towards the fault



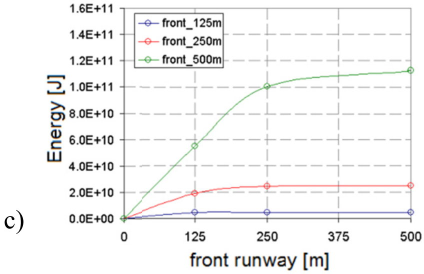


Fig. 13. Graphs of energy dissipated due to friction for exploitation:
a) along the fault,
b) towards the fault,
c) away from the fault

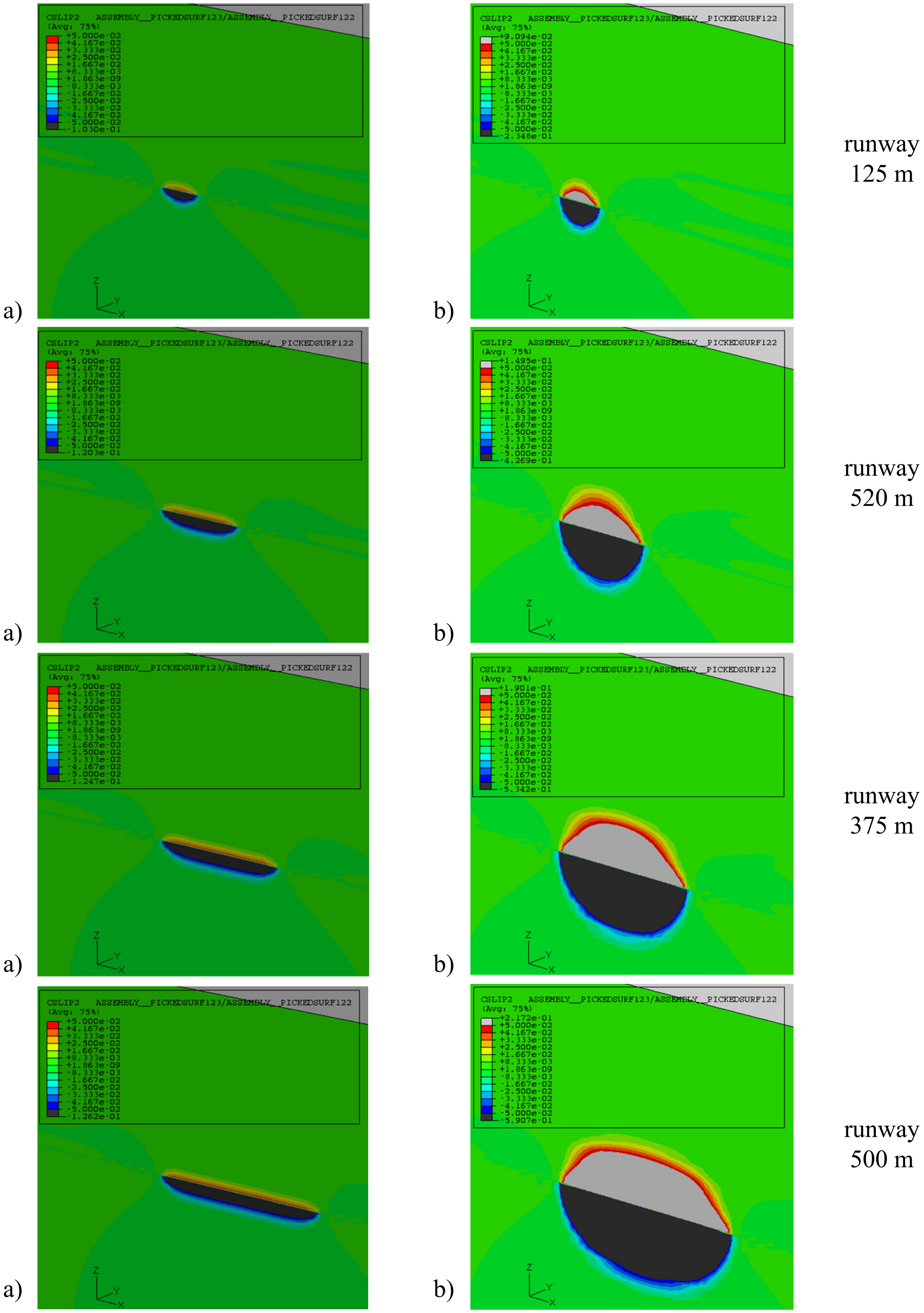


Fig. 14. Maps of vertical displacement (slip) of the fault walls relative to each other in the subsequent stages of operation with backfill (a) and roof deflection (b)

Maps of displacement (slip) in the fault plane (Fig. 14) show that the values for the operation using deflection of the roof are much higher than for backfill, or that the use of backfill virtually eliminates the slip in the roof (displacements are smaller than 0.05 m) and significantly reduces it in the floor.

Comparison of graphs of energy dissipated due to friction (Fig. 15) shows that reducing slip in the fault plane by using backfill is often accompanied by a very significant inhibition of energy dissipated due to friction in the fault plane.

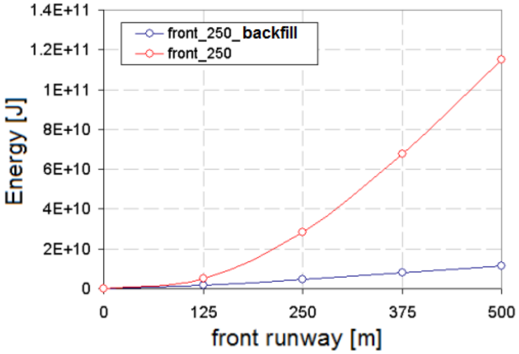


Fig. 15. Graphs of energy dissipated due to friction in the fault plane for models with the use of backfill and roof deflection

5. Summary

Based on the results of numerical calculations related to the impact of mining operating conditions on fault behavior, the following conclusions can be drawn:

- Conducting operations in the area of tectonic disturbances resulting in violations of the equilibrium conditions on the surface of the fault creates the possibility of fault activation.
- The roof and floor strata exhibit qualitatively similar relations of changes in shear stress and slip.
- Shear stresses in the fault plane have the highest values above and below the caving zones of conducted operations. The range of any underlying changes in shear stress increases along with the development of the mining operation.
- The size and scope of the slip in the fault plane increases with the development of the mining operation and stabilizes after reaching a certain length of the runway.
- The measure of assessment of the fault behavior is the amount of energy dissipated due to the effects of friction in its plane, which increases with the development of exploitation. Displacement of rocks triggered by slip may occur stepwise, which is why some of that energy can be used to describe the dynamic nature of this phenomenon.
- Excavation direction with respect to the fault affects its behavior. When operating along the fault, a gradual increase in energy dissipated due to the effects of friction may be observed. Intense energy dissipation accompanies the initial stage of operations conducted moving away from the fault as well as the final stage of the operations moving towards it.

- The process of caving zone liquidation can have a decisive impact on fault behavior. Operations with the use of backfill significantly reduce the risk of slip. Reducing slip in the fault plane is accompanied by a significant reduction of the amount of energy dissipated due to the effects of friction.

In summary, it is clear that although any operation in the vicinity of faults creates conditions for their activation, a suitable way of mining in the fault area can limit the level of seismic hazard.

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