AGH Journal of Mining and Geoengineering • vol. 36 • No. 3 • 2012

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CONDITIONS OF FAULT ACTIVATION IN THE AREA OF EXPLOITATION[**]

1. Introduction

The high level of mining tremors and rockburst hazard in Polish hard coal and copper mining is frequently the result of exploitation in the areas of tectonic disturbances. Basing on the experience from mines localized in Upper Silesian Coal Basin and Legnica-Głogów Copper Mining District, it is suggested that exploitation in the vicinity of the faults with considerable throws causes their activation, as evidenced by the presence of high-energy shocks, what often results with destressing and rockbursts.

Analysis of the impact of fault disturbances on the possibility of tremor formation suggest that defining of the conditions for the activation of the fault is the essential issue. While it is possible to assess the impact of the fault on the state of stress [3, 4], or the state of rockburst hazard [6, 8], this issue is much more complicated when it comes to the activation of the fault and the following seismic energy emission.

Models that define the conditions for the activation of the fault assume that this process is a consequence of the loss of stability of the mechanical system modeling the rock mass. Currently, the most physically realistic models are based on an analysis of movement of rock masses adjacent to the fault [1, 2, 5, 7, 9]. The fault plane friction forces that occur provide a balance between the upthrown and downthrown. Conducting mining operations close to the fault might — through affecting the balance at the fault surface — activate the fault. When operating in the vicinity of the fault, the fault plane changes its state of stress, and — as a result — a critical level is reached. As a consequence, the rock masses move from the state of

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[**] This study is supported through the statutory research registered in AGH University of Science and Technology in Krakow at No. 11.11.100.281.

equilibrium to the state of unstable equilibrium. When the value of shear stress generated at the fault is greater than the critical value, it causes a slip, which lasts until the new equilibrium state is reached. Slip movement at the fault plane is associated with the activation of the fault. This movement, depending on the geomechanical parameters at the fault, may be stable or unstable and therefore might result in the occurrence of tremor.

Such behavior of the fault and the resulting mathematical apparatus allows to determine the conditions that define the possibility of the activation of the fault disturbance close to the exploitation area.

2. Geomechanical model of the activation of the fault

Analyzed model of the activation of the fault assumes that this process is the result of the movement of rock masses at the surface of the fault (Fig. 1).

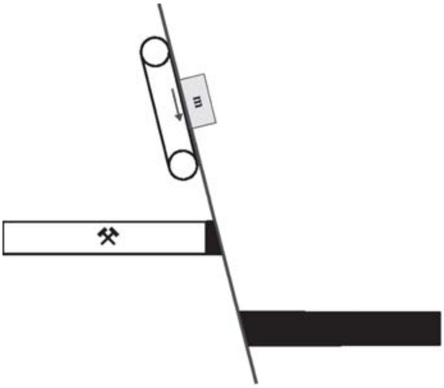

Fig. 1. Model describing the activation of the fault [9]

It is the result of the impact of the exploitation in the vicinity of the fault. Resulting change of state of stress at the fault surface may lead to the situation when the critical state is reached what triggers a dynamic transition from the initial state of equilibrium to the final state. The effect of mining operations in the vicinity of the fault provokes following changes at the surface of the fault [5]:

- Vertical displacements (both of the roof and floor rocks) caused by successive exploitation, which cause an increase (in case of mining towards a fault) or decrease (in case of the opposite direction) of vertical stress,
- Horizontal displacements in the direction of the approaching exploitation front (in case of mining towards a fault) or into abandoned workings (in case of the opposite direction), which always leads to a decrease in horizontal stress at the fault resulting as a change of contact conditions at the surface of the fault.

Model describing the possibility of the movement at the fault plane, caused by the occurrence of vertical and horizontal displacements, is illustrated by a mass on a moving conveyor belt, which movement in relation to initial position is — among other things — dependent on the friction forces (Fig. 2) [7].

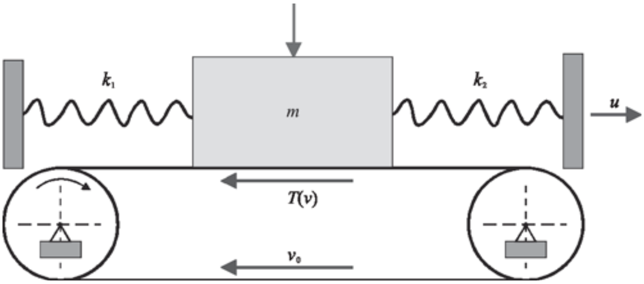

Fig. 2. Geomechanical model describing the movement at the fault plane [7]

The equation of motion describing the analyzed model is:

$$m\frac{d^2u}{dt^2} = -k_1 \cdot u - k_2 \cdot u + T(v) \tag{1}$$

the friction force is expressed by the equation:

$$T(v) = T_o \cdot sign(v) - \theta \cdot v + \vartheta \cdot v^3, \quad v = v_o - \frac{du}{dt} \tag{2}$$

where:

m — mass,
u — displacement in relation to the fault plane,
k_i — stiffness of the i-th elastic element,
v — relative velocity,
v_0 — initial velocity,
θ, ϑ — parameters characterizing the change in friction.

As a result of movement, there is an increase of stress until the critical value of shear stress (corresponding to the static friction) is reached. This moment is characterized by the state of unstable equilibrium, and thus resulting instability. Mass transfer can be stable or unstable. If it is completely controlled by the energy from outside of the system, there is a stable displacement, which results in regular, usually slow increase in fault displacement (Fig. 3a).

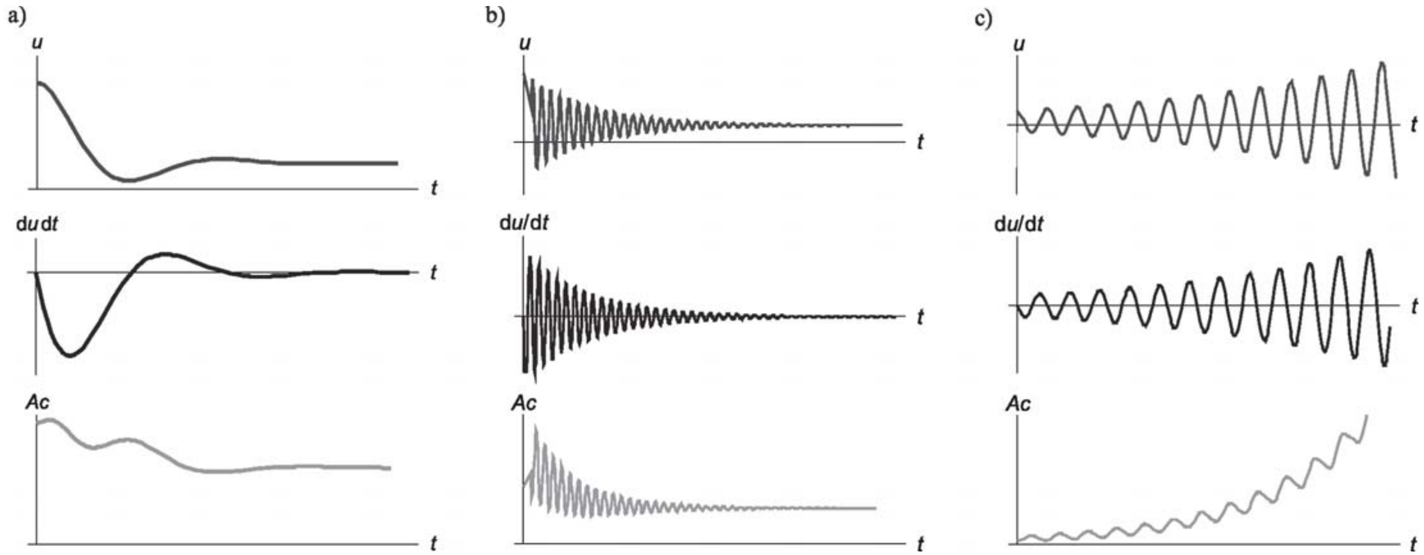

Fig. 3. Changes in displacement, velocity and total energy at the fault as the result of the [7]:
a) constant movement; b) stepwise movement; c) long-term movement

However, in certain circumstances the deformation process may change its character, while short-term, damped periodic movement combined with a change of displacements (Fig. 3b) or long-term movement with gradually increasing amplitude of oscillations may occur (Fig. 3c).

Analyzing the changes of displacements $u(t)$, velocity $\frac{\mathrm{d}u(t)}{\mathrm{d}t}$ and total energy $A_c(t)$ shown in Figure 3, it can be concluded, that:

- Non-linear character of the differential equation describing the nature of the studied model is the reason of three types of movements:
  - a stable movement of the mass (Fig. 3a),
  - a stepwise movement to a new equilibrium position; practically speaking, this phenomenon occurs in a very short time (Fig. 3b),
  - unstable oscillating motion, which is characterized by gradually increasing amplitude of vibrations (Fig. 3c); an increase of total energy $A_c(t)$ comes from the supply of the energy coming from the movement of conveyor belt (velocity of v_0).
- Movement type depends on the parameters describing the model, namely:
  - mass,
  - parameters defining the friction force,
  - stiffness of the elastic components.
- Physical reason for the creation of these types of moves is the difference between the amount of static friction and dynamic friction, while the value of dynamic friction is usually lower.

Presented analysis has shown, that the oscillating motions induced by the changes of the friction forces are possible to occur, while the phenomenon of the self-excited oscillations is the starting point for describing of the process of the activation of the fault.

3. Conditions of the activation of the fault

In order to determine the conditions for activation of the fault, the following assumptions have been made [5, 7]:

- Within the roof rocks above the deposit (up to the end of the fault fissure), "n" layers with a thickness of hi and mass of mi $\{i = 1, 2, ..., n\}$ have been isolated (Fig. 4). Therefore, the actual continuous model is replaced with a discrete model.
  Balance at the fault plane is maintained by the forces of friction, whose value for each layer is T_i.

The value of the friction force is determined with the following formula:

$$T_i(t) = \sigma^*_{x_i} \cdot \mu\left(\frac{\mathrm{d}u_i}{\mathrm{d}t}\right) \cdot sign\left(\frac{\mathrm{d}u_i}{\mathrm{d}t}\right) \tag{3}$$

while the variation of coefficient of friction μ in function of speed $\frac{\mathrm{d}u_i}{\mathrm{d}t}$ is determined with the following expression (Fig. 8):

$$\mu_i\left(\frac{du_i}{dt}\right) = \mu_{st_i}\left[\frac{\mu_{d_i}}{\mu_{st_i}} + \left(1 - \frac{\mu_{d_i}}{\mu_{st_i}}\right)\right] \cdot e^{-\xi_i\left|\frac{du_i}{dt}\right|} \tag{4}$$

where:

μ_{st_i} — coefficient of static friction for the *i*-th element,
μ_{d_i} — coefficient of the dynamic friction for the *i*-th element,
ξ_i — parameter for the *i*-th element.

- Deformability of each layer is described by the Kelvin model with the following parameters: E_j, η_j, $\{j = 1, 2, ..., n, n + 1\}$, so that it is possible to consider not only the impact of the forces of elasticity, but also the friction forces,

  while:

  E_j — modulus of elasticity,
  η_j — viscosity.

- In equilibrium state (its original state), analyzed system of elements is subjected to:
  - vertical stress: p_z^p,
  - horizontal stress: p_x^p,

  taking into consideration the impact of exploitation, it is subjected to:

  - vertical stress:

    $$\sigma_z^* = p_z^p + \sigma_z^d,$$

  - horizontal stress:

    $$\sigma_x^* = p_x^p + \sigma_x^d.$$

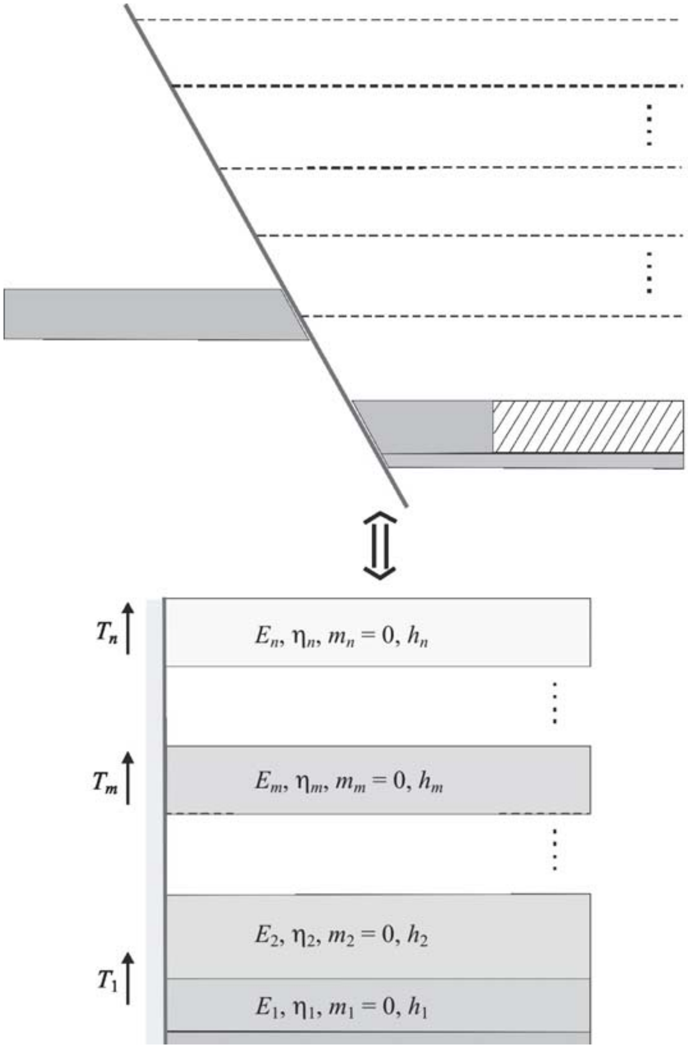

Fig. 4. Geomechanical model of the activation of the fault [7]

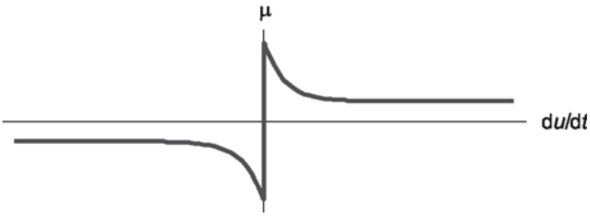

Fig. 5. Variation of the coefficient of friction [7]

These assumptions lead to the geomechanical system, which scheme is presented in Figure 6.

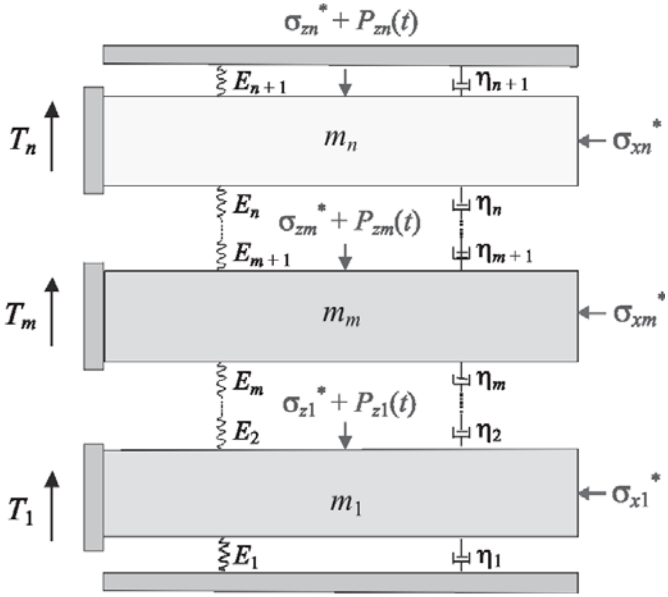

Fig. 6. Geomechanical model of the activation of the fault [7]

It is suggested that the activation of the fault is a consequence of the mass movement at the fault plane, and the corresponding equations describing the motion of individual masses modeling floor layers have the following form:

a) model with one mass ($n = 1$):

$$m_1 \frac{\mathrm{d}^2 u_1}{\mathrm{d}t^2} = -\left(k_1 + k_2\right) u_1 - \eta_1 \frac{\mathrm{d}u_1}{\mathrm{d}t} - \eta_2 \frac{\mathrm{d}u_1}{\mathrm{d}t} + \sigma_{z_1}^{*} + T_1(t) + P_{z_1}(t) \tag{5}$$

a) model with two masses ($n = 2$):

$$m_1 \frac{\mathrm{d}^2 u_1}{\mathrm{d}t^2} = -\left(k_1 + k_2\right) u_1 + k_2 u_2 - \eta_1 \frac{\mathrm{d}u_1}{\mathrm{d}t} + \eta_2 \left(\frac{\mathrm{d}u_2}{\mathrm{d}t} - \frac{\mathrm{d}u_1}{\mathrm{d}t} \right) + \sigma_{z_1}^{*} + T_1(t) + P_{z_1}(t) \tag{6}$$

$$m_2 \frac{\mathrm{d}^2 u_2}{\mathrm{d}t^2} = -\left(k_2 + k_3\right) u_2 + k_2 u_1 - \eta_2 \left(\frac{\mathrm{d}u_2}{\mathrm{d}t} - \frac{\mathrm{d}u_1}{\mathrm{d}t} \right) - \eta_3 \frac{\mathrm{d}x_2}{\mathrm{d}t} + \sigma_{z_2}^{*} + T_2(t) + P_{z_2}(t) \tag{7}$$

b) multi-mass model ($n \geq 3$):

$$m_1 \frac{\mathrm{d}^2 u_1}{\mathrm{d}t^2} = -\left(k_1 + k_2\right) u_1 + k_2 u_2 - \eta_1 \frac{\mathrm{d}u_1}{\mathrm{d}t} + \eta_2 \left(\frac{\mathrm{d}u_2}{\mathrm{d}t} - \frac{\mathrm{d}u_1}{\mathrm{d}t} \right) + \sigma^*_{z_1} + T_1(t) + P_{z_1}(t) \tag{8}$$

$$\begin{aligned} m_2 \frac{\mathrm{d}^2 u_2}{\mathrm{d}t^2} = k_2 u_1 - \left(k_2 + k_3\right) u_2 + k_3 u_3 - \eta_2 \left(\frac{\mathrm{d}u_2}{\mathrm{d}t} - \frac{\mathrm{d}u_1}{\mathrm{d}t} \right) + \\ + \eta_3 \left(\frac{\mathrm{d}u_3}{\mathrm{d}t} - \frac{\mathrm{d}u_2}{\mathrm{d}t} \right) + \sigma^*_{z_2} + T_2(t) + P_{z_2}(t) \end{aligned} \tag{9}$$

$$\begin{aligned} m_m \frac{\mathrm{d}^2 u_m}{\mathrm{d}t^2} = k_m u_{m-1} - \left(k_m + k_{m+1}\right) u_m + k_{m+1} u_{m+1} - \eta_m \left(\frac{\mathrm{d}u_m}{\mathrm{d}t} - \frac{\mathrm{d}u_{m-1}}{\mathrm{d}t} \right) + \\ + \eta_{m+1} \left(\frac{\mathrm{d}u_{m+1}}{\mathrm{d}t} - \frac{\mathrm{d}u_m}{\mathrm{d}t} \right) + \sigma^*_{z_m} + T_m(t) + P_{z_m}(t) \end{aligned} \tag{10}$$

$$\begin{aligned} m_n \frac{\mathrm{d}^2 u_n}{\mathrm{d}t^2} = -\left(k_n + k_{n+1}\right) u_n + k_n u_{n-1} - \eta_n \left(\frac{\mathrm{d}u_n}{\mathrm{d}t} - \frac{\mathrm{d}u_{n-1}}{\mathrm{d}t} \right) - \eta_{n+1} \frac{\mathrm{d}u_n}{\mathrm{d}t} + \\ + \sigma^*_{z_n} + T_n(t) + P_{z_n}(t) \end{aligned} \tag{11}$$

where:

$$k_i = \frac{E_i}{h_i}$$

u_i — displacement of the *i*-th element,
m_i — mass of the *i*-th element,
$P_{z_i}(t)$ — additional vertical load (e.g., characterizing the impact caused by blasting works).

By analyzing the equations describing the motion of the masses modeling the behavior of the roof layers in the vicinity of the fault, it can be shown, that these equations describe the self-excited oscillations, and thus can characterize both slow movement of the masses at the fault plane, as well as rapid movement to the new state of equilibrium, identified with the activation of the fault. Due to the fact, that the functions describing the friction at the fault surface are non-linear differential equations, all findings ought to be based on the numerical results.

Generally speaking, the problem of the activation of the fault (start of the movement along the surface of the fault) can be analyzed in both the local and global context. The first approach assumes that the movement began in the *i*-th element, and it does not cause movement of the other elements. Meanwhile, in a global context, aforementioned movement encompasses the whole analyzed system, though the movement may involve a finite number of elements. Assuming that activation of only one of the masses will not generate enough energy, it is adequate to determine the conditions for activation of the fault in the global context, which may cause high-energy tremors.

For the global system, transition from a state of equilibrium into a movement could be described taking into account the following parameters for the moment of $t = 0$ ($t \leq 0 \Rightarrow$ equilibrium, $t > 0 \Rightarrow$ movement):

$$u_i = u_i(0), \quad \frac{\mathrm{d}^j u_i(0)}{\mathrm{d}t^j} = 0, \quad T_i(0) = \sigma^*_{x_i}(0) \cdot \mu_{st_i}, \quad \sigma^*_{z_i} = \sigma^*_{z_i}(0), \quad \frac{\mathrm{d}\sigma^*_{z_i}}{\mathrm{d}t} = \frac{\mathrm{d}\sigma^*_{z_i}(0)}{\mathrm{d}t} \tag{12}$$

where $u_i(0)$ — initial value of the vertical displacements for the *i*-th element.

Using the equations of motion for the individual masses of the global system, equations or systems of algebraic equations that define the conditions for the activation of the fault could be obtained.

4. Summary

Geomechanical model describing the process of the activation of the fault disturbances assumes that the activation of the fault and resulting occurrence of tremors is a consequence of the displacement of the roof rock masses at the fault plane, caused by a disorder of the state of stress triggered by mining works carried out close to the fault.

On the basis of the results of the analysis it can be stated:

- Occurrence of certain types of rock mass movements at the fault plane is a function of geomechanical parameter values characterizing the deformability of rock formations, the values of the parameters characterizing the conditions at the fault plane and specifically the parameters defining the friction at the fault plane and the changes of the stress values caused by the mining works carried out in the vicinity of the fault (taking into account their type and duration).
- Movement at the fault plane (fault activation process) may take many forms, including no movement, so-called stick-slip, oscillating movements and — in special cases — oscillating movements with gradually increasing amplitude. It is also possible, that chaotic process of individual impulses may occur, which can cause both the occurrence of the main tremor and accompanying aftershocks.
- More accurate and more complex models (considering a large number of masses) do not allow to formulate (in a closed analytical expression) a criterion of the fault activation because of the large number of parameters determining the type of the movement and

possible loss of stability (described by non-linear differential equations). In such case, the assessment of the impact of mining on the possibility of the activation of the fault should be carried out through numerical calculations.

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