Investigation of Stochastic Fluctuation Spreading through a Longwall Gob

Victor Nazimko[1], Artem Merzlikin[2] and Ludmila Zakharova[1]
[1]*Institute of Geotechnical Mechanics, National Academy of Sciences of Ukraine, Simferopol Str. 2A, Dnipro, Ukraine*
[2]*Department of Mining, Donetsk National Technical University, Shybankova Square 2, Pokrovsk, Ukraine*
victor.nazimko@gmai.com, artem.merzlikin@donntu.edu.ua

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Abstract: We considered a problem of random fluctuation spreading in complex multilayer rock strata during longwall extraction of a coal seam at a great depth. This issue is urgent because it is not easy to forecast harmful and dangerous events in underground environment having extremely uncertain geologic structure and variation of the rock properties. This paper aimed to investigate the process of the rock property random fluctuation to understand if it is possible to forecast the state of the longwall and ground pressure distribution in the gob in particular. We used a numerical computer simulation of the stress-strain redistribution during the longwall advance. The computer models were verified by the results of the ground pressure experimental monitoring in situ. We investigated the distributions of the fluctuation disturbance and revealed the underlying patterns that follow a simple and complex system. We concluded that it is possible to forecast the harmful situation during longwalling but it is need to select a direct and simple chain of cause-effects. We developed efficient proactive technologies to control the longwall operations.

1 INTRODUCTION

Certain processes are rear in real life. On the contrary, uncertainty evolves in any area of human activity, namely politics, economics, nature, technique, and many others. This paper discusses the mining technology process, particularly, coal mining because of the current energy global crisis [1].

Those countries having coal deposits can mitigate the crisis, intensifying the development of their own reserves. However, the depth of mining steadily increases which worsens development conditions because of the high level of ground pressure, coalbed methane content and temperature. These factors elevate the risks of dangerous dynamic processes, coal and rock bursts [2]. These problems has increased even more due to the high level of geologic uncertainty that expands the range of possible technological outcomes, in particular, risks of underground roadways failure [3], and stability of the longwall operation [4].

The modern long-walling technology of underground coal extraction is very complex employing powerful equipment, which operates intensively in hard and uncertain conditions. The practice has shown that big damage, which causes financial lost, is triggered by a small random fluctuation of geologic environment, the voltage of energy, or simple neglect of the regulations and technical standards [5].

Despite the great amount of research that has been made on the longwall reliability problem [6],[7], the chain from the triggering fluctuation down to failure or breakage of the entire longwall panel has not been investigated properly. This paper aims to trace how this random fluctuation spreads and multiplies on an example of the rock strata surrounding a moving longwall face.

2 METHODOLOGY

We used numerical simulation of the stress state of surrounding rock mass in dynamics employing the longwall movement simulation. First, we simulated certain situation, monitoring the stress state of surrounding strata along the whole panel. Then a small fluctuation was introduced into a spot on the immediate roof of the coal seam and this simulation has been repeated. After this, we found the difference between the previous and secondary simulation to investigate it.

We employed two numerical models, namely simple and complex one. The simple model simulated only one rock layer that covered the extracted coal seam. Real geological strata was presented in the complex model and the task was repeated for the 3D state of the rock mass, where adjacent rock layers interacted. Such an approach helped to trace the spread of the fluctuation in a single rock layer and the entire 3D rock mass.

2.1 Simple Model

A thin plate presented the strata of the immediate and main seam roof [8]. This plate rested on the elastic base from the coal seam and its floor (Figure 1).

The bending and sag of this plate were found solving the differential equation by the final difference method on a regular grid (1):

$$\frac{\partial^4 \omega}{\partial x^4} + 2\frac{\partial^4 \omega}{\partial x^2 \partial y^2} + \frac{\partial^4 \omega}{\partial y^4} = \frac{q}{D} - \frac{K\omega}{D}, \quad (1)$$

where ω is the sag, x and y are coordinates of 2D space, q is overburden pressure of the strata, K is the base rigidity, and D is the cylindrical rigidity of the plate-roof. The roof was caved when

$$\sigma_e = \sqrt{\left(\sigma_{x(y)} + 3\tau_{xy}^2\right)} > [\sigma], \quad (2)$$

where σ_e is equivalent stress, σ_x is the normal stress, τ_{xy} is shear stress, and $[\sigma]$ is a tensile limit of the roof rock.

The roof strata caves not for the entire thickness immediately behind the longwall face [9],[10]. First, the immediate roof caves, then the main roof caves by portions while the face withdraws. The caving process starts when condition (2) is satisfied. However, the height of the caving depends on the difference between σ_e and $[\sigma]$. The more the height the bigger the rigidity of the gob (3):

$$K_g = \frac{c_1 K \sigma_e}{[\sigma]} \le c_2 K, \quad (3)$$

where K is the base rigidity in the gob area, c_1 and c_2 are empirical coefficients.

Such a simple algorithm was available to simulate feasibly the periodic caving of the roof after proper tuning of the empirical coefficients.

We used “Pokrovs’k” coal mine geological conditions (Ukraine) as a prototype to simulate the strata behavior. The depth of mining was 1000 m. A flat 2.0 m coal seam has been extracted by the 256 m longwall with complete caving of the roof. Rate of advance was 300 m per month.

2.2 Complex Model

FLAC3D commercial code was employed to simulate the caving dynamics of strata in the 3D state. This code has essential advantage that allows simulating the real path of the model loading for the condition when the ground moves irreversibly [11].

FLAC3D solves equation of Newton second law (4):

$$\left(\frac{d\sigma_{ij}}{dx_j} + pd_i = \rho\frac{dv_i}{dt}\right), \quad (4)$$

where ρ is density, v is velocity of the ground movement.

Therefore, this code accounts for dynamics of the ground movement explicitly which allows tracing the path of the fluctuation and understanding how it spreads in the gob.

Damping of the unbalanced forces in the model was simulated according to (5), (6):

$$F_i^l + F_i^l = M^l\left(\frac{dv_i}{dt}\right), \quad (5)$$

$$N_i^l = -\alpha\left|N_i^l\right| sign\left(v_i^l\right), \quad (6)$$

where F is an active force, N is a damping force, M is mass. Technically, the damping process has been realized iteratively. To reach the static equilibrium, the share of unbalanced forces should be less than a predetermined limit, for example 10^{-5}. However, the rock mass that surrounds a moving longwall face is not in equilibrium. Thus, we control the rate of the longwall face advance by the number of iterations [12]. The fewer number the more rate of the advance.

The overall view of the model is depicted in Figure 1. We removed the upper left part of the model to show it inside.

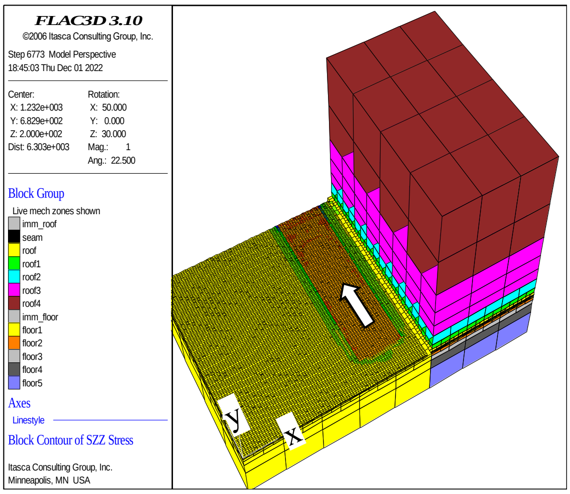


Figure 1: View of the model.

Dimensions of the model were 2048 m by 1280 m by 1500 m along the longwall (X-axis) and along the panel (Y-axis) correspondingly. The coal seam was covered by 1100 m overburden strata. Four hundred meter strata bedded the seam. Such dimensions allowed placement the longwall panel inside the model and provided relevant boundary conditions. The arrow indicates direction of the longwall advance.

Table 1 presents the initial properties of the rock mass.

Table 1. Properties of the rock in the model.

Name of the rock	Bulk modulus, MPa	Shear modulus, MPa	Cohesion, MPa	Angle of friction, degree	Tension limit, MPa	Dilation, degree
rock	24.0	14.4	9.0	35	7.0	0.1
roof2	24.0	14.4	9.0	35	7.0	0.1
roof1	24.0	14.4	7.0	28	5.0	0.5
roof	24.0	14.4	7.0	28	5.0	1.0
main_roof	20.0	12.0	4.0	35	3.0	2.0
imm_roof	19.0	11.0	4.0	35	3.0	2.0
seam	20.0	12.0	4.0	32	2.5	2.0
imm_floor	20.0	12.0	7.0	28	5.0	1.0
floor1	24.0	14.4	9.0	35	7.0	0.1

Fluctuation of the rock properties was inserted in one zone of immediate roof at the range of $840 \leq Y \leq$ 850 m and $976 \leq X \leq 1024$ m. This range is indicated in Table 1 as ‘imm roof’ line.

Here is fragment of a subroutine in FISH code that has been used to simulate the longwall movement:

```
def advance_dp
    x_vent = 1168 ;positioning the face
    x_conv = 864
    ystart = 170.0
    yfinish = ystart + d_y        ;-----   ;advance
        along Y-axis
    loop while yfinish <= ymax
       command
            mo null range group seam     x x_vent
            x_conv    y ystart yfinish
            ini szz -0.1e0  sxx -0.1e0 syy -0.1e0
            range group seam    x x_vent x_conv    y
            ystart yfinish
            interface 1 face range  x x_vent x_conv
            y ystart yfinish z -0.2 0.2
            interface 1 prop kn 100e9 ks 100e9 fric
            30 coh 15e9 ten 10e9
       end_command
          command
               run01;----cycling
               id_contact
            end_command
        ystart = yfinish
        yfinish = ystart + d_y
     end_loop;--while
     num_panel = 0
end ;--advance_dp
```

The startup room of the longwall was set 170 m from the boundary to prevent its impact. The face was moving by 10 m-runs (d_y = 10 m). The extracted portion of the coal seam was replaced by an empty room (model null). An interface was put down to the immediate floor to prevent intrusion of the roof into the floor. It should be noticed that we input the dilation angles of the rocks to simulate their actual dilation due to caving. This approach helped to simulate the real contact of the roof and floor in place of equivalent rigidity of the gob [13],[14] which increased reliability of the simulation results [15].

The contact moment was determined after every step of the advance. The state of the model was saved before the longwall went into the fluctuation zone to analyze all components of the strata stress-strain state.

3 RESULTS OF SIMULATION

Figure 2 demonstrates the difference between the initial stress state in the gob plane and that disturbed by a fluctuation. Fragment (a) shows the effect of the small fluctuation, the magnitude of which is 1% from the average level of the ground pressure, whereas fragment (b) demonstrates the influence of the big fluctuation. Its magnitude exceeds 23%. These distributions were made with the simple model [8]. This simulation proved that process of any fluctuation spreading is stochastic. This process develops even if the magnitude of the fluctuation is less than 1%. The fluctuation multiplies itself along both the longwall line and the line of the advance direction.

There is a spatial threshold and an incubation period when a local fluctuation starts to develop. For example, the effect of the fluctuation became evident when the face withdrew to 205 m from the spot where the fluctuation occurred and to 550 m for the fluctuation magnitude of 24% and 1% respectively. Therefore, the less the fluctuation magnitude the longer the incubation period and the farther the longwall face withdraws before the effect of the fluctuation becomes obvious. When the total disturbance accumulates to a sufficient amount, the effect from the initial fluctuation bursts up and spreads as the chain reaction [16]. Thus, the big fluctuation caused a quick or prompt effect whereas the influence of the small fluctuations delayed.

Histograms of the accumulated perturbations are symmetrical both in simple and complex models (Figure 3).

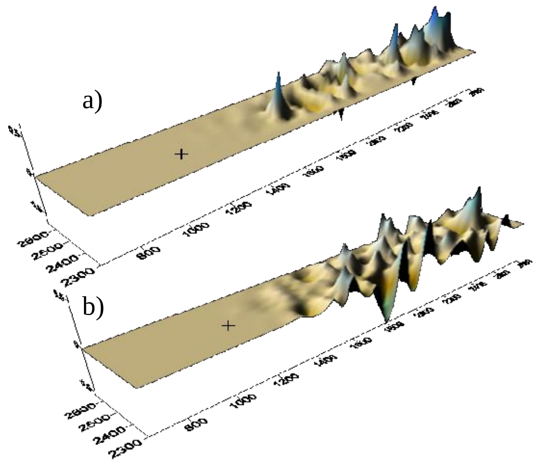


Figure 2: Evolution of the disturbance: a) small fluctuation, b) big fluctuation.

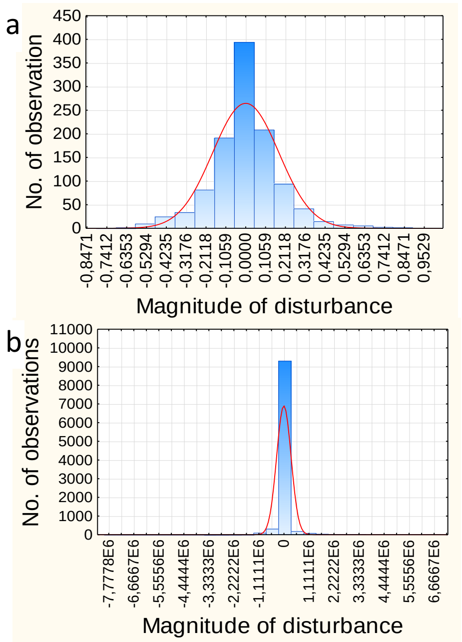


Figure 3: Distribution of the disturbance: a) simple model; b) complex model: STD is 10% and 3% correspondingly.

The histograms correspond to the normal distribution but have abnormal excess which means prevailing the minor agitations.

The analysis of the complex model results has shown that they fairly correspond to well-known pattern of stress state around the longwall gob [17],[18]. Figure 4 illustrates distribution of the damaged zone around the gob far behind the longwall. Shear strain plays the principal role in the process of rock transition over the strength limit [19]. The tensile stress caused damage in the immediate and main roof of the coal seam.

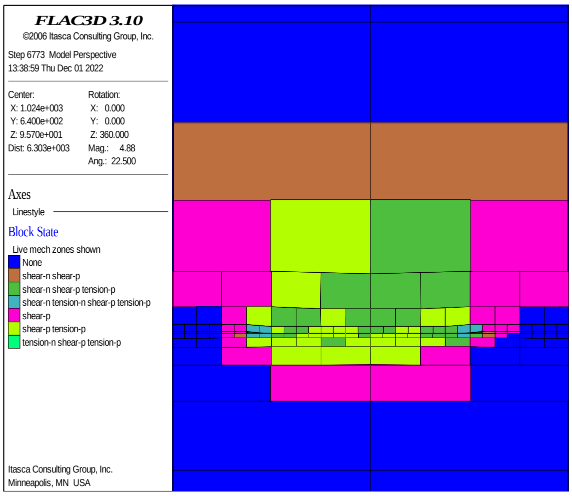
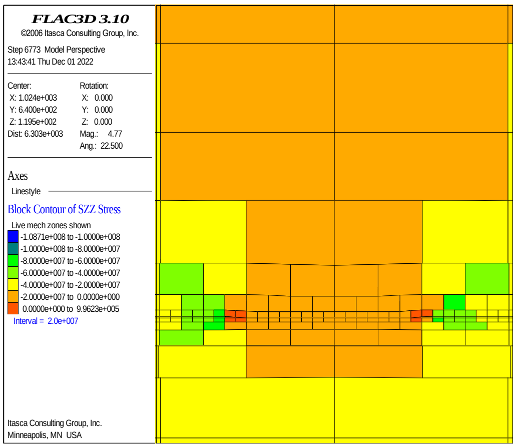


Figure 4: Damage zone distribution around the gob.

Extraction of the coal seam caused evident stress relief around the gob (Figure 5). The minimum stress vertical component occurs at the ribs of the gob where stress is even tensile. The compression stress level is 12-14 MPa in the middle of the gob or 43% from the geostatic background.



Fugure 5: Ground pressure distribution around the gob.

The maximum stress concentration occurs at the abutment zone [20],[21] where the stress' component exceeds 60 MPa.

Figure 6 demonstrates periodic variation of ground pressure in the gob along the longwall advance. The step of stress variation varied in the range of 10-20 m which perfectly matched the experimental data (Figure 7) [22],[23].

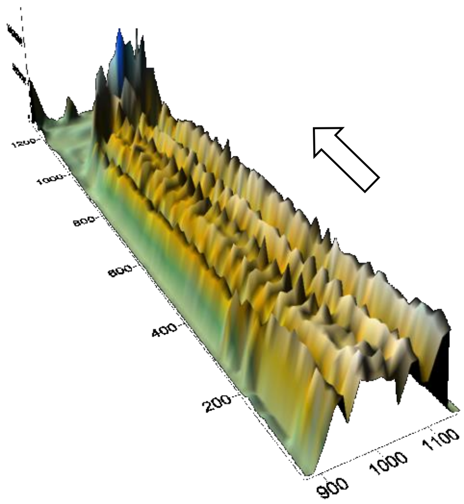


Figure 6: Ground pressure distribution along the gob: the arrow indicates the direction of the longwall advance.

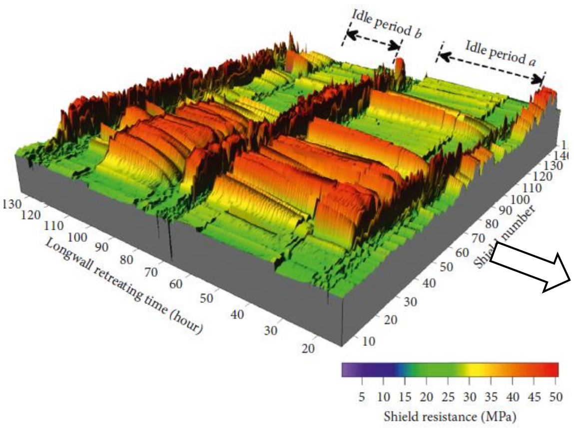


Figure 7: Experimental variation of the ground pressure according to [21].

Figure 8 presents the disturbance of the fluctuation in the complex model. These distributions are similar to those provided by the simple model. The common feature of the both distributions is that magnitude of the perturbations does not depend on the amplitude of the triggering fluctuation. This is a consequence of the fundamental law of nature that governs the complex systems [24].

In addition, even a small fluctuation might find the shortest way to disturb any point of a big complex system through the intermediate numerous chains, events, and reasons [25],[26]. That is why the complex model did not reveal the delay and incubation period.

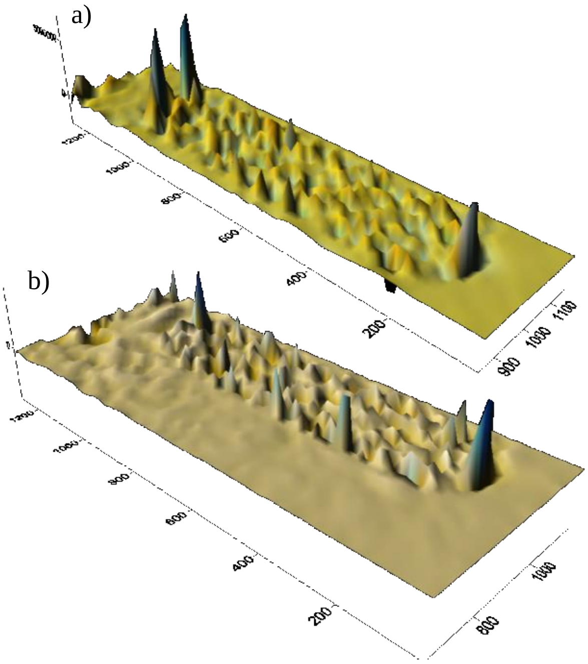


Figure 8: Distributions of the perturbations in the complex model: a) and b) are big and small fluctuation respectively.

4 DISCUSSION

Does it mean that it is impossible to forecast dangerous or harmful situation during longwalling? It is definitely not. The longwall technology involves a set of technological processes, which interact and have direct and indirect links. We found such chains, decomposed them, and revealed typical patterns that could be used to forecast the critical state of the longwall and to prevent it by employing proactive control [27].

We proposed to monitor the current variation of the longwall output using a sliding window having the optimal width varying in the range from 12 to 16 days. The everyday output was reduced according to a coefficient that is in the exponential dependence on the time tardiness from the current day. We used an entropy potential, which is proportional to the sum of derivatives from the output standard deviation. The failure of the longwall operation occurs if the positive value of the entropy potential keeps going a certain period that is proportional to the predetermined risk level. This approach helped to take the proactive measures against the risk.

5 CONCLUSIONS

Stochastic numerical simulation has been used to investigate the spreading and multiplying the random fluctuation in the rock strata during longwall mining a coal seam. It was found that the histogram of the perturbations caused in the rock mass by rock property fluctuation is symmetrical and is similar to the normal distribution having abnormal excess.

The magnitude of the disturbance does not depend on the amplitude of the triggering fluctuation. The simple cause-effect chains can functioned with delay, when there is the incubation period while the fluctuation will spread over the entire volume of the rock mass. The less the fluctuation magnitude the longer the incubation period. However, in the complex system of the multilayer rock strata any fluctuation might find the shortest paths to any point of the strata without evident delay. The fundamental laws of chaos' evolution in nature govern the process of fluctuation spreading. It is possible to forecast and prevent harmful or dangerous situation by employing proactive control of the longwall. We selected simple direct cause-effect chains [28] to realize such a control.

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