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V. S. Portnov[1],
orcid.org/0000-0002-4940-3156,
S. B. Imanbayeva[1],
orcid.org/0000-0003-0049-2642,
R. K. Atygayev[2],
orcid.org/0000-0002-0735-099X,
E. N. Filimonov[2],
orcid.org/0000-0001-8081-9005,
A. D. Maussymbayeva[1],
orcid.org/0000-0002-7214-8026

1 – Karaganda Technical University, Karaganda, the Republic of Kazakhstan, e-mail: svetakaz77@mail.ru
2 – USShMD CD JSC "Arcelor Mittal Temirtau", Karaganda, the Republic of Kazakhstan

ASSESSMENT OF SUDDEN SOIL FAULTS HAZARD WHEN DEVELOPING A COAL SEAM

Purpose. Development of a methodology for assessing the occurrence of sudden fractures in the soil on the example of the development of seam d_6 of the Karaganda coal basin.

Methodology. Theoretical and experimental studies on the gas content of a coal seam, analysis of technologies for its development.

Findings. Studies have shown that sudden fractures of the overworked massif with and without a breakthrough of methane are of the same nature. A necessary condition for the formation of sudden fractures of the seam soil (SFSS) in a mine is the presence of a pack of coal or rock with reduced strength and high gas content in the soil; in this case, the breakthrough of methane into the development occurs only if the cracks formed in the soil of the workings reach the sources of gas release – gas-bearing layers (interlayers) of coal.

Originality. A predictive indicator of the hazard of the occurrence of SFSS in the working face is proposed, a dimensionless criterion which is the product of dimensionless coefficients reflecting the influence of the development depth, gas content of the seam, the width of the bottomhole zone, the thickness of the protective layer, the thickness of the crumpled coal pack of the lower layer, longwall withdrawal from the assembly chamber, the length of the working face. A nomogram is developed for assessing the risk of SFSS in the development of reservoir d_6.

Practical value. According to the results of the research, it was proposed to predict the SFSS at the design stage, for the early implementation of regional measures for their prevention. To assess the WSP, a nomogram is to be used for the prevention of SFSS, which includes advanced development of protective seams, measures to reduce the ability to delaminate coal in the lower layer, change in technology for coal mining with intensive degassing of the developed seam and use of interval hydraulic fracturing.

Keywords: *gas content, swelling of soil rocks, mine, mining, degassing, Karaganda coal basin*

Introduction. Geodynamic phenomena (GDP) in the course of underground coal mining are manifested in the form of squeezing and pouring out of coal at the face, sudden fractures of soil rocks with the coal fines and gas emission, gas bleeding and actual outbursts [Bolshinsky, 2003]. When mining, a close relationship of such factors as the stress-strain state of the rock massif, the gas content of coal and technological intervention is common to all the types of GDP [1, 2].

Methane gas in a coal seam is in the sorbed state, possibly in the state of chemisorption (solid coal-methane solution), in the adsorbed state and in the free state (Alekseev, 2007). With increasing the depth of coal bedding, the processes of dynamo-morphism intensify that reduce significantly the concentration of the last two states of gas, with increasing the proportion of sorbed gas, as evidenced by the results of observations of the gas content of coal seams at different depths [3, 4]. It should be noted that saturation of coals with gas reduces their surface energy of destruction by 2.5–4 times (Alekseev, 1994).

According to the present day concepts, sudden faults of the overworked massif with and without the methane breakthrough are of the same nature [2, 4]. The methane breakthrough into the working occurs only if the cracks that are formed in the rocks of the working soil reach the sources of gas emission: gas-bearing layers (interlayers) of coal [4].

Thus, upon reaching the initiating crack of the gas-bearing coal seam, there is formed a zone from which a large number of tortuous cracks grow at high speed and form a vast zone of finely fractured coal (similar to cracking of tempered glass). In this case, the crack length and surface increases sharply due to its tortuosity (Griffiths, 1924). This process leads to the sorbed gas transition into free gas, which is transferred under pressure to the maximum crushed coal zone. This leads to additional generation of methane during the destruction of coal in the GDP zone, which is confirmed by changing the ratio of the quality of carbon in the aromatic and alpha groups of coal (Gamow, 2004).

The GDP energy is the sum of the elastic energy of enclosing rocks, coal and gas: $E = Wn + Wy + Wg$. In the normal, i. e. safe conditions during mining, the flow of energy to the bottom hole zone is completely spent on deformation of the edge parts, temperature rise, and so on. Potentially dangerous conditions are formed with an imbalance between the flow of energy and its consumption [3].

Griffiths A. formulated a criterion for the destruction of a body with a crack, according to which the growth of a crack should be an energetically favorable process with energy conversion. A crack in a solid body will develop during its deformation if the rate of releasing the potential energy of deformation is greater than the increasing surface energy of the body, which is formed as a result of the new surface formation. The crack length element is determined by the product of a linear element of the crack surface by some function depending on the stress state in the vicinity of this element. For brittle fracture that occurs in a coal seam, this function is proportional to the normal highest stress or the highest linear deformation for a non-cracked body under the same load system [5]. The crack trajectory is a geodesic line in the non-Euclidean space, whose metric depends on the stress-strain state of the medium, in this case, the coal seam (Reva, 2006).

The behavior of unsteady, growing cracks is determined by the difference between the absorption energy spent for the progress of destruction and the supply energy released during the crack growth. This difference can be considered as the free energy or as the value proportional to the increment of internal entropy [6].

The intensity of releasing the supply energy, "energy supply", is associated with a unit increase in the area of the crack. It is spent on its formation, and only after the formation of a crack element, its excess can dissipate or transform into kinetic energy [2, 7].

An imbalance in the energy ratio can be in three cases: when there is an increased flow of energy; an increased energy outflow and a limited energy outflow. In the first two cases of imbalance there is manifested extrusion, collapse, precipitation, and slipping of the formation. In the third case, there is a delay in deformations in the bottom hole part of the working followed by an intensive outflow of energy in the form of a rock burst, a sudden outburst of coal and gas, and a sudden fracture of the seam soil (Mustafin, 2002).

Object of the study. Sudden fractures of soil rocks (SFSR) in the face of the d_6 coal seam at Kazakhstanskaya mine of the Karaganda coal basin first occurred in the face in the western wing, during the development of the $312D_6$-1z longwall face and continued during the development of the $322D_6$-1z longwall face. In the eastern wing, where no advance degassing treatment (ADT) was performed using hydraulic fracturing wells, no SFSR phenomena were recorded at the same treatment depths. The hypothesis of the occurrence of SFSR as a consequence of the harmful effect of the early degassing preparation of the hydraulic fracturing was not justified, since at neighboring Lenin mine, during the development of mining areas $401D_6$-1v and $402D_6$-1v in the zones of hydraulic fracturing wells 16, 17, 18, 19, 20, 21, 25 at the levels of –120 and –160 m, similar gas-dynamic phenomena were not observed.

From the practice of combating this phenomenon at Lenin mine in seam workings, it was found that the reason for these GDP is a feature of the d_6 seam, which has a layer of prepared coal with the thickness of 0.4–0.7 m in the lower part with low strength, a high gas recovery rate, practically zero gas permeability. This layer is separated from the upper layer by a clayey waterproof mudstone with the thickness of up to 0.2 m. Degassing and unloading the lower layer prevents SFSR phenomena, which are characterized by the following mechanism: soil rocks being freed from the overlying rocks pressure, due to elastic recovery expand along the normal and replace a certain volume of mined-out space; they are simultaneously compressed along the bedding [5].

As a result of these processes, soil rocks are destroyed first in the form of their stratification, with the formation of transverse cracks in the soil, then in the form of a fracture of layers with the formation of three-hinged arches, and then with destruction in the form of shear with extrusion and folding of destroyed layers.

At high geostatic pressure, methane in the coal seam is in the sorbed state, possibly forming a solid coal-gas solution (SCGS) (Gamow, 2004). Methane emission is possible only if the thermodynamic state of the system is disturbed and the said solution decays (Karasan, 2008).

The process of the solid coal-methane solution decomposition proceeds with releasing energy, which is realized, among other things, for the destruction of the solid component of the seam with the formation of an additional inner surface. The higher the gas content of the coal seam is, the more intense the gas-dynamic destruction is, up to its self-destruction [3]. But decomposition occurs in the cramped conditions of a porous medium. Consequently, emission of even a small amount of methane is accompanied by the formation of corresponding pressure. Since the condition for decomposition is decreasing the stresses in the coal skeleton, its destressing from rock pressure is immediately compensated by the gas pressure in the pores, and the decomposition process can develop only as gas emits from them through cracks associated with the atmosphere of the mine working. Methane contributes to achieving the extremely stressed state of the protective layer at lower external loads, softens the environment and develops additional internal stresses. Thus, without rock pressure, the protective layer destruction will not begin, but without gas it will not acquire the self-sustaining nature and be realized in the form of a GDP [6, 8]. If the weak layer is represented by a coal band with a low gas content or a rock with low strength properties, SFSR is realized without significant methane emission or even without it. The possibility of SDSR manifestation depends on the depth of mining operations, the methane content of the weak layer, the protective layer strength and thickness and the width of the mine working [1].

Measures of preventing sudden soil rock faults. Measures to prevent SFSR when developing the d_6 seam at Kazakhstanskaya mine are as follows:

- reducing the rock pressure (the stress state) in the vicinity of the mine workings;
- reducing the ability of coal bands delaminating in the lower layer;
- changing the technology of seam extraction;
- enhanced degassing of the developed layer and the lower layer.

Drilling boreholes from the bottom hole of the breakage face to the lower layer under the coal pillar does not seem to be an effective preventive measure, since the destressing zone around the borehole is insignificant and cannot affect the geomechanical processes occurring in the longwall soil. The effect is possible if the distance between the holes is ≈ 0.1 m [9].

Reducing the rock pressure is achieved by advanced mining of protective layers. The mechanism of the protective action of such operations consists in reducing the rock and gas pressure, increasing gas permeability as a result of destressing and degassing the under- and overworked massif.

A protective layer is such a layer, the development of which ensures prevention of sudden methane breakthroughs from the soil of workings driven the protected zone along the higher or lower rock massif. At Kazakhstanskaya mine, there is no protective layer for the d_6 layer.

The destruction of the soil, as well as the roof rocks begins with stratification of bands, layers. Stratification is one of the most characteristic features of joint deformation and failure of a stratum of layered rocks [10]. The places of rock separation are determined by the ratios of their strength and deformation properties, the magnitude of normal and shear stresses, the magnitude of the bond forces of the layers along the contact surfaces. In those bands of layers in which the bond forces along the contact surfaces are sufficiently large, stratification does not occur. Such bands work as a single plate (Mustafin, 2002).

One of the most effective ways to reduce the ability of soil to stratification reducing the differences in the rigidity and mechanical properties of the soil layers of the working is the roof bolting or saturation of the coal seam with water in the filtration mode [11]. Such processing allows in addition moving the maximum support pressure into the depth of the massif further by 1.5–2.5 m. In this case, the lateral thrust forces $\mu/(1-\mu)-1\gamma H$ become insufficient to shear and squeeze out the soil layers into the working. This is one of the factors explaining the absence of the SFSR phenomenon at Lenin mine, where the development of hydraulic fracturing wells No. 16–22 was carried out in two stages. At the first stage, the working fluid was pumped out and methane was extracted, while the gas content of the coal was reduced by 1.3–2.4 m^3/t. At the second stage, additional hydraulic treatment of the formation was carried out in the filtration mode (≈ 1,500 m^3/well), which made it possible to reduce the residual gas content of coal by 20–30 % due to the replacement of methane with water, its displacement and blocking in the smallest pores and cracks. The total efficiency of the two stages of these wells development is estimated by the equivalent reduction in the gas content of the formation by 5–6 m^3/t.

Changing the seam extraction technology is possible when the d_6 seam is mined in one layer for the entire thickness. However, in this case, having avoided the SFSR phenomenon, conditions can be formed for the implementation of GDP in the form of a sudden coal and gas outburst.

It is possible to reduce the mined thickness of the upper layer (mв) to 1.8–2.0 m and to increase the thickness of the protective layer (*lz*) and the threshold of forces for its destruction. Most of the cases (66 %) were noted in the range of ratios of the working width (*b*) to the thickness of the protective layer (*lz*) from 2 to 5, in 34 % they occurred at $b/lz > 5$ and no cases were recorded at $b/lz < 2$. The overwhelming majority of these rock bursts occurred at the low rocks dip (Biryukov, 1996).

The most effective is reducing the width of the bottom hole b (b is the distance from the bottom hole to the first row of props). The width of the bottom hole part of the working is the most significant parameter that determines the conditions for the SFSR occurrence. The main feature of rock outbursts in breakage faces is that they occur at 6–8 meters width of the working space and are manifested in the form of raising coal from the soil in the face zone of the longwall without causing destruction of coal in the breakage face [1, 3]. Realizing elastic energy of coal in the soil of the mine working causes its disintegration, in the first approximation by half of the working space of the face. In other words, the width of the face bottom hole part must satisfy the ratio

$$lz > 0.5b.$$

In this case, cracks formed in the soil of the breakage face will not grow to the underlying crumpled outburst-hazardous band.

It is also possible to reduce simultaneously the width of the bottom hole of the breakage face and the removed thickness of the upper layer.

Deep degassing of the developed coal seam aimed at reducing the gas pressure and gas content of the seam, that is, at eliminating one of the factors causing GDP, is an effective means of preventing SFSR in breakage faces [5].

The criterion of the sufficiency of degassing the d_6 seam to prevent SFSR is the residual gas content, which is safe for this factor. The degassing efficiency can be determined by the degree of gas content reduction, that is, the ratio of the amount of methane extracted from one ton of coal to the gas content of the seam

$$K_D = (X - X_o) \cdot X^{-1}.$$

The efficiency of degassing, upon reaching which it is possible to prevent SFSR by this method, is determined by the formula

$$K_{D1} = 1 - X_s \cdot X^{-1},$$

where X_o, X_s are respectively the seam gas content after degassing and the safe magnitude for the SFSR factor.

The degassing method will be efficient if the condition is satisfied

$$K_D \geq K_{D1}.$$

The value of the coal seam gas content, which is safe for SFSR can be found using statistical data of the gas content at the depth of the first manifestation of this type of GDP (Fig. 1).

Based on the above studies at Kazakhstanskaya mine, the value of the gas content X_s that is safe in terms of SFSR was obtained for the d_6 seam and is equal to 17 m^3/t. Taking this value into account, the required value of the degassing coefficient K_{D1}, in order to bring the seam into the non-hazardous state in terms of the gas factor, should be 0.40–0.50.

The data presented indicate the need to increase the efficiency of degassing the d_6 seam at the prepared production

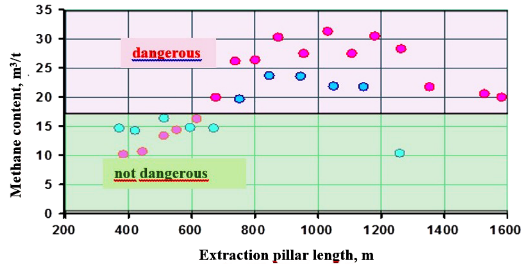

Fig. 1. The level of the SFSR safe methane content of the d_6 seam at "Kazakhstanskaya mine"

area 332D$_6$-1z by means of additional artificial stimulation in order to increase the intensity of methane emission into the seam wells.

At present among a lot of methods, the most widespread both from the point of view of scientific substantiation and practical implementation, is hydraulic action (hydraulic fracturing, hydraulic separating, hydraulic pulse blasting, and others). As mentioned above, in the early 2000s, advance degassing treatment (hydraulic separating) was carried out in the western wing of the mine, as a result of which 1.5 to 6.5 m^3/t of methane was extracted from the processed reserves. However, in the last 4–5 years, the work for the development of hydraulic fracturing wells, which allows maintaining the flow of methane into the wells, was practically not carried out, due to the absence of the proper amount of material, human and financial resources. Hydraulic fracturing wells have operated and are operating in the self-flowing mode, which leads to siltation of the wells and the wellbore zone. In this situation, it is not possible to initiate hydraulic fracturing wells, especially since a certain amount of work has been done to drill underground seam wells for preliminary degassing. The way out can be a method of interval hydraulic fracturing from underground wells, which allows several times increasing the methane production of the seam wells, thereby providing the required degassing efficiency (Biryukov Yu. M. 1990, Mustafin M. 2002).

Soil heaving hazard indicator. Dimensionless criterion Z is proposed as a predictive indicator of the SFSR risk in the breakage face and is the product of dimensionless coefficients reflecting the impact of the development depth H, the gas content of the seam X, the width of the bottomhole zone b, the thickness of the protective layer lz, the thickness of the crumpled coal band of the lower layer m, the longwall departure from the assembly chamber Δl, the length of the working face L_1.

$$Z = (a_1 \cdot a_2 \cdot a_3 \cdot a_4 \cdot a_5)^2,$$

where $a_1 = H_i \cdot H_s^{-1}$ is the coefficient taking into account the depth of the stoping working H_i (rock pressure), H_s is outburst-safe depth, $H_s = 350$ m; $a_2 = X_i \cdot X_s^{-1}$ is the coefficient taking into account the coal seam methane content X_i: X_s is SFSR-safe methane content of the coal seam $X_s = 17$ m^3/t; $a_3 = m_i \cdot m_s^{-1}$ is the coefficient taking into account the crumpled coal band thickness, m_i; m_s is the safe thickness of the crumpled coal band with which there are no GDPs, $m_s = 0.2$ m; $a_4 = K_i \cdot K_s^{-1} = 0.5 \cdot K_i$ is the coefficient taking into account the protection layer thickness l_{zi} and the longwall bottom hole zone width b, $K_i = b \cdot l_{zi-1}$, $K_s = 2.0$; $a_5 = 1 + \Delta l \cdot L_1^{-1}$ is the coefficient (no more than 2) taking into account the operating mode of the main roof rocks.

With $\Delta l \approx L_1 = 2$, the roof rocks operate in the mode of the fixed pressure [17].

Fig. 2 shows that at $Z < 40$ there is not expected the GDP realization in the form of SFSR in the breakage face.

Results and discussion. For practical purposes, it is much easier to assess the risk of SFSR based on the nanogram shown in Fig. 3. It follows that when the methane content of the seam is lower than 17 m^3/t, the working depth

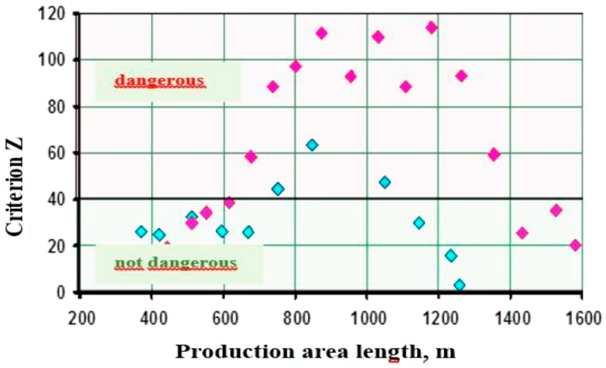

Fig. 2. Changing the rock soil sudden outburst hazard indicator Z depending on the extraction pillar length of the production areas 312D_6-1z *and* 322D_6-1z

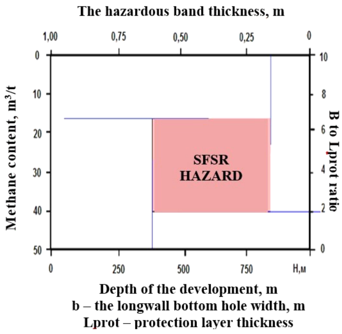

Fig. 3. Nanogram of estimating the SFSR hazard when developing the d_6 *seam at Kazakhstanskaya mine*

is smaller than 350 m, the thickness of the weak layer is smaller than 0.2 m and the ratio of the width of the bottom hole longwall zone to the thickness of the protective layer is less than 2, there will not be GDP in the form of SFSR in the breakage face.

It is necessary to perform the SFSR forecast at the design stage for the early implementation of regional measures of their prevention. The effectiveness of the preventive measures can be assessed by the residual gas content of the seam, by sampling coal at the depth more than 20 m from wells drilled from the workings outlining the extraction pillar.

If the forecast establishes that there is a possibility of methane breakthrough in the case of SFSR, it is necessary to provide measures to maintain the safe concentration of methane in the atmosphere by means of ventilation.

The current SFSR forecast by the rate of gas emission from boreholes drilled to the bottom layer is a palliative, it is laborious and ineffective.

Conclusion. It has been established that sudden faults of the overworked massif with and without the methane breakthrough have the same nature. The necessary condition for the formation of SFSR in the mine working is the presence in the working soil under a strong (protective) layer, of a band of coal or rock with reduced strength.

The methane breakthrough into the mine working occurs only if the cracks formed in the mine working reach the sources of gas emission: gas-bearing coal seams (interlayers).

The reason for the SFSR manifestation of the d_6 seam is a layer of prepared coal with the thickness of 0.2–0.7 m lying in its bottom, while the probability of SFSR is determined by the depth of mining operations, the gas content of the layer of reduced strength, the thickness of the protective layer, the width of the bottom hole part of the breakage face. These factors are used as the basis of the nanogram for assessing the SFSR risk.

For the SFSR prevention the following measures should be performed: advanced development of protective seams, measures to reduce the ability of the lower layer coal to delaminate, changing the technology of coal mining and intense degassing of the developed seam using interval hydraulic fracturing, as well as the use of dimensionless criterion Z and a nanogram to predict the risk of SFSR occurrence.

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Оцінка небезпеки виникнення раптових розломів підошви при розробці вугільного пласта

В. С. Портнов[1], *С. Б. Іманбаєва*[1], *Р. К. Атигаєв*[2], *Є. М. Філімонов*[2], *А. Д. Маусимбаєва*[1]

1 – Карагандинський технічний університет, м. Караганда, Республіка Казахстан, e-mail: svetakaz77@mail.ru

2 – УСШМД УД АТ «Арселор Міттал Теміртау», м. Караганда, Республіка Казахстан

Мета. Розробка методики оцінки виникнення раптових розломів підошви на прикладі розробки пласта d_6 Карагандинського вугільного басейну.

Методика. Теоретичні та експериментальні дослідження газоносності вугільного пласта, аналіз технології його розробки.

Результати. Дослідження показали, що раптові розломи надроблюваного масиву з проривом і без прориву метану мають одну й ту ж природу. Необхідною умовою формування раптових розломів підошви пласта (РРПП) у гірничій виробці є наявність у підошві пачки породи зі зниженою міцністю й високою газоносністю, при цьому прорив метану до виробки відбувається тільки в тому випадку, якщо тріщини, що утворюються у підошві виробки, досягають джерел газовиділення – газоносних пластів (прошарку) вугілля.

Наукова новизна. Запропонований прогнозний показник небезпеки виникнення РРПП в очисному вибої – безрозмірний критерій, що представляє собою добуток безрозмірних коефіцієнтів, які відображають вплив глибини розробки, газоносності пласта, ширини привибійної зони, товщини захисного шару, потужності перем'ятої вугільної пачки нижнього шару, відходу лави від монтажної камери, довжини очисного вибою. Розроблена номограма для оцінки небезпеки виникнення РРПП при розробці пласта d_6.

Практична значимість. За результатами досліджень запропоновано виконувати прогноз РРПП на стадії проектування, для завчасного здійснення регіональних заходів щодо їх попередження. Для оцінки РРПП використовувати номограму, плануючи запобігання РРПП, що включає: випереджальне відпрацювання захисних пластів; заходи для зменшення здатності до розшарування вугілля нижнього шару; зміна технології виїмки вугілля з інтенсивною дегазацією пласта, що розробляється та застосування поінтервального гідророзриву.

Ключові слова: *газоносність, пучення порід підошви, шахта, гірнича виробка, дегазація, Карагандинський вугільний басейн*

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