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GENERATING OF DISSIPATIVE STRUCTURES DURING GROUND IRREVERSIBLE MOVEMENT

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Purpose. To detect dissipative structures which emerge due to irreversible movement and deformation of the rock mass, to trace their evolution and determine their parameters. **Methodology** of this research encompassed combination of thermodynamics of irreversible processes, computer simulation, physical modeling, and actual measurements the nonreversible deformation of the rock mass that surrounds an underground roadway. **Results.** Special monitoring of the irreversible movement of the ground revealed that the dissipative structures disperse the ground pressure energy and bifurcate periodically, evolving their pattern. Average interval between sequential bifurcations is reversely proportional to the vertical component of the ground pressure and extended as the strength of the surrounding rock increased. Evolution of the dissipative structures minimized entropy production due to close or short interaction of rock fragments and long cooperation of their clusters. **Originality.** For the first time, it has been found close and far interaction in the process of irreversible movement of the ground and damaged rock mass. New principle of ground stabilization has been developed based on restriction both transversal and rotational degrees of freedom of the rock mass, which has been involved to irreversible movement. **Practical value.** The principle of the degree of freedom restriction facilitates the development of new methods and improvement existent technologies for ground control. References 12, tables 1, figures 7.

Key words: ground movement, irreversible deformation, short interaction, clusters, far cooperation.

ВИНИКНЕННЯ ДИСИПАТИВНИХ СТРУКТУР У ПРОЦЕСІ НЕОБОРОТНИХ ЗРУШЕНЬ ГРУНТУ І МАСИВУ ГІРСЬКИХ ПОРІД

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Досліджено дисипативні структури. що утворюються в ґрунтах і масивах гірських порід у процесі їх незворотних зрушень і деформування. За допомогою методів термодинаміки незворотних процесі, моделювання і шахтних інструментальних спостережень було досліджено еволюцію вказаних структур та визначено їх параметри. Показано, що дисипативні структури розсіюють енергію гірського тиску і періодично здійснюють біфуркації, змінюючи мозаїку або паттерн дисипативних структур. Основними джерелами виникнення дисипативних структур є ближні взаємодії породних фрагментів, а також дальні взаємодії кластерів, які формуються з зазначених породних фрагментів. У якості практичної реалізації отриманих наукових результатів обґрунтовано новий принцип підвищення стійкості ґрунтів і масивів гірських порід шляхом обмеження всіх трьох поступальних і обертальних ступенів свободи.

Ключові слова: масив гірських порід. незворотні деформації. ближні взаємодії. кластери. дальня взаємодія.

PROBLEM STATEMENT. Dissipative structures reflect self-organization of the substance [1] and emerge in the open thermodynamic systems. Second law of thermodynamics governs behavior of the dissipative structures due to development of irreversible processes [2]. Nonreversible ground movement follows mining, tunneling, landslides, chimney subsidence, hydro-fracturing, and other perturbation of the rock mass [3]. The rock mass is a typical open thermodynamic system that transfers energy and substances and disperse them that should induce some dissipative structures.

However, it is a common opinion that damage and disintegration of the rock mass, which follows by the irreversible movement, may create a disorder only and increases entropy of the ground [4]. Meanwhile Vattre demonstrated [5] that cooperation between sets of dislocations may generate dissipative structures what reflects capability of the solid to self-organization during irreversible (plastic) deforming.

Furthermore, Miles and Thorpe found [6] that non-reversible movement of pebbles at a beach may create dissipative structures, what is the consequence of self-organization of the open thermodynamic system. Therefore, there should be essential chance to generate a dissipative structure for the ground, which is in the process of non-balanced irreversible movement.

According to Ritz and Streibig [7], the dissipative structures may emerge if some cooperation occurs between the components of an open thermodynamic system. Thus, the aim of this paper was to investigate interaction and cooperation among the rock fragments to reveal dissipative structures in the rock mass that moved irreversibly.

MATERIAL AND RESULTS. Shemiakin, Khomenko and others [8] registered self-organization of rock mass around an underground roadway due to irreversible ground deformation. They found concentric rings of solid unbroken and fragmented rocks, but the principal question - which components of the rock mass have cooperated - remains unanswered. There is not a tangible explanation concerning the participants of the cooperation. In order to clarify this problem, let make use the second law of thermodynamics for excess entropy production dS/dt [2]

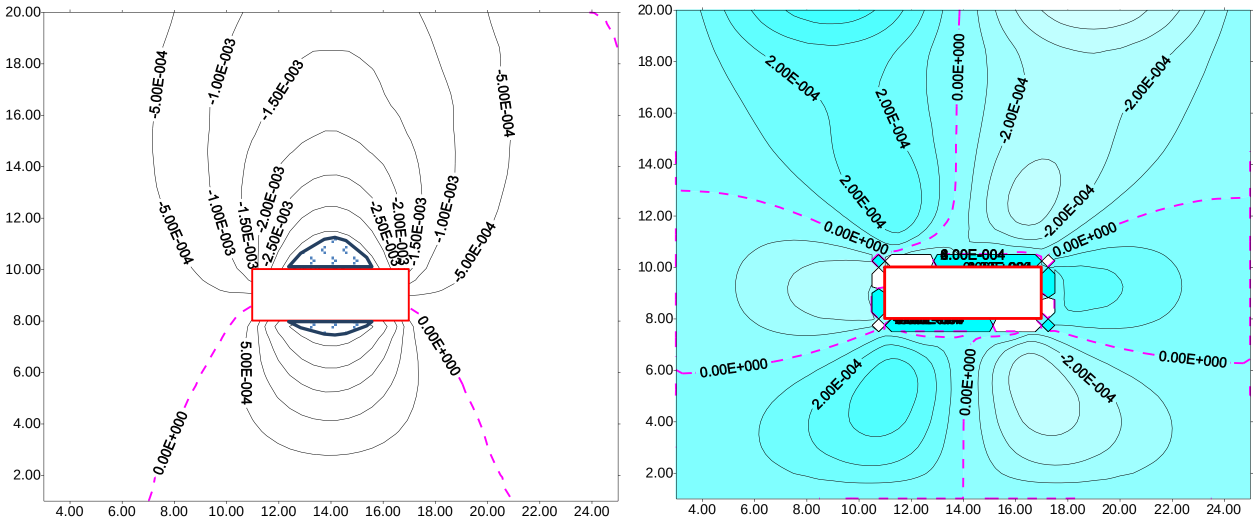
$$dS/dt=\sum \delta I_k \, \delta(dX_k/dt)\leq 0, \qquad (1)$$

where t is time, I_k and X_k are thermodynamic forces and flows respectively. This dependence reflects the condition when a new dissipative structure may emerge under influence of fluctuation δ. Evolution of this dissipative structure reproduces the self-organization of the irreversibly moving ground. For this case, the principal thermodynamic force is the ground pressure, and the irreversible movement stands for the thermodynamic flow. This movement is a tangible item that can be directly and explicitly registered and measured.

Extant procedures of ground movement monitoring make use integral assessment of the ground movement during long periods, partly because this process is expensive so far. The irreversible ground movement depends on the way of loading, when some essential features may mask due to process of the integration. The author of this paper found such an interval of sequential measurements that provides the reliable registration of a dissipative structure. This interval should afford accumulation of such magnitude of ground movement, which is no less than two standard errors of the measurements and not exceed ten errors. When this interval is less, the dissipative structure hides in the noise, whereas magnitude, which is beyond of the ten-fold error, abets missing of the structure.

Figure 1 demonstrates elastic displacement of the ground around the roadway. The roof subsided into the roadway cavity whereas the floor heaved (Figure 1,a). Sides of the roadway converged, and roof and floor rocks horizontally displaced to the centerline of the roadway (Figure 1, b). Both vertical and horizontal distributions of the displacements where symmetrical relatively vertical centerline of the roadway section. This is a natural consequence of the vertical load symmetry relatively the centerline.

Plastic state of surrounding rock mass has been simulated using Drucker-Prager constitutive model:



a) b)

Figure 1 – Elastic distribution of displacements around the rectangular opening:
(a) – vertical subsidence of the roof and the floor heave; (b) – horizontal displacement

Thus, the optimal interval between sequential measurements allowed revealing incremental irreversible movements of the ground that demonstrated individual patterns of the dissipative structure. I investigated this structure with a computer model, by physical modeling, and in situ, using actual measurements of irreversible ground movement around underground opening.

To compare elastic and irreversible ground movement in vicinity of the roadway, computer simulation has been employed first.

I used finite element method to simulate elastic ground movement around underground roadway that had rectangular section 2 m by 5 m. The elastic behavior of the ground stood for the benchmark to compare elastic and irreversible behavior. The roadway was simulated at the depth of 600 m. Five 1,9 m rock bolts reinforced the roof, which has been represented by 1,5 m shale having moderate stability and uniaxial compression strength (UCS) of 40 MPa. The shale layer followed with competent rocks having UCS of 60 MPa. Floor of the roadway has been represented by sandy shale having UCS of 50 MPa. Elasticity module of the rock mass was 10 GPa and Poison ratio 0,25.

$$\sqrt{\frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_3 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2\right]} = A + B(\sigma_1 + \sigma_2 + \sigma_3). \quad (2)$$

Where $\sigma_1,\ \sigma_2,\ \sigma_3$ are principal stresses.

$$A = \frac{2}{\sqrt{3}}\left(\frac{\sigma_c\,\sigma_t}{\sigma_c + \sigma_t}\right); \qquad B = \frac{2}{\sqrt{3}}\left(\frac{\sigma_c - \sigma_t}{\sigma_c + \sigma_t}\right)$$

$\sigma_c,\ \sigma_t,$ are compression and tension limits respectively.

Increase of the ground pressure by 1,5 times caused damage of the roof and the floor, although symmetry of the zones, which passed through the strength limit, saved despite their damage. This zones indicated by direct (in the roof) and revert (in the floor) domes in the fragment (a) of Figure 1. Noticeably, these damaged zones have kept symmetry relatively centerline of the roadway. Furthermore, the damaged zones grew synchronously, namely every consequent boundary of the collapsed zone encompassed previous one. In the other words, boundaries of the serial damages zones spread coaxially in space and time.

Therefore, there is not any sign of explicit cooperation. It is natural, because there is not intrinsic algorithm or feature in the finite element method, which could simulate such cooperation. That is why I used a special physical modeling to unveil such cooperation.

Zakharov et al., 2003 [9] modeled the roadway behavior for the same initial conditions using physical model from synthetic material, which was composed of sand, plaster, and mica mixtures. Geometric scale of the model was 1:40 that allowed registration of displacements in the model with accuracy of ±0,1 mm or 4 mm in situ. It means that the interval of displacement registration should be more than 0,2 mm and not exceed 1 mm.

Figure 2 demonstrates a typical frame of displacement field during transition of the surrounding rock mass to over-peak state. The field consists of several explicitly shown patterns.

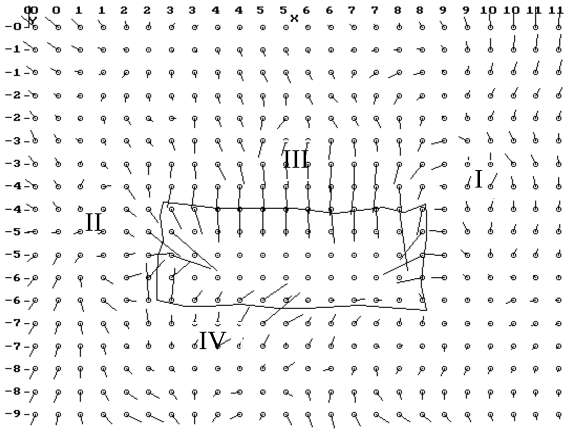


Figure 2 – Field of the irreversible displacement

For example, rotor I promotes the roof sagging involving rocks from the right side of the roadway into process of roof subsidence, mainstream of which coincides with the torrent III. Source II stimulates process of dilatation of the left side of the roadway. Torrent IV provides asymmetric heaving of the floor from the left to the right.

All the patterns create so called clusters that emerged because of close or short interaction of adjacent rock fragments, which developed after collapse and disintegration of surrounding rock mass. For example torrent III is the results of transversal movement of all adjacent rock fragments in certain direction, whereas rotor I occurred because several adjacent blocks coordinated their movement in a circular pattern. Therefore, it is possible to classify the dissipative structure, separating it into a cluster mosaic.

Such mosaic evolves as the dissipative structure bifurcates, changing their patterns. Figure 3 shows overlay of such structures that emerged during successive bifurcations. Boundaries of separate clusters may not be the same in space during process of irreversible movement. Some 'parent' clusters disintegrate and their fragments may create new 'offspring' that compose of fragments of different ancestors. Meantime, overall trend of the clusters movement is stable: clusters in the roof subside (their boundaries marked with solid lines), whereas floor clusters move in upright direction due to rock heaving (marked with the intermitted lines).

between stages 1-2-3-4-5

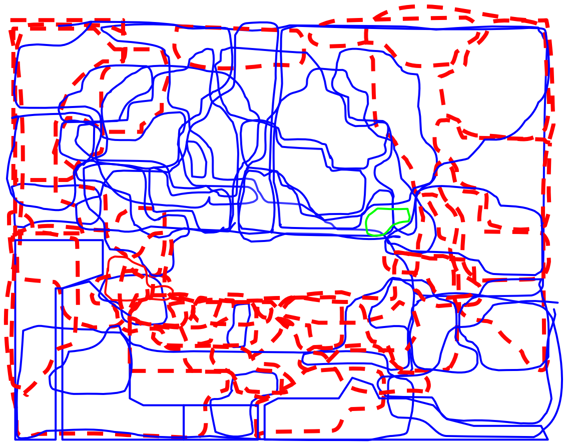


Figure 3 – Overlay of four cluster dissipative structures

According to the results of computer simulation, average interval between sequential bifurcations is reversely proportional to the vertical component of the ground pressure. This interval extends as the strength of the surrounding rock increases. Thus, the rate of structure bifurcation depends on two contradictive factors: stress level and strength of the surrounding rock mass. This perfectly concords with the well-known criterion of roadway stability that is the ratio of the vertical component of ground pressure to UCS of the rock mass.

Complex ground behavior during irreversible movement includes both close interaction of adjacent rock fragments and distant cooperation of their clusters. Figure 4 illustrates number of newly emerged clusters in the left and in the right side of the model during all stages of modeling. Significant dependence has been found between numbers of the clusters. It does mean that the clusters on the both sides of the model coordinated their activity by turn or one after another: when the clusters on the left side of the model boosted multiplication, the clusters on the right side subsided their activity and vice versa.

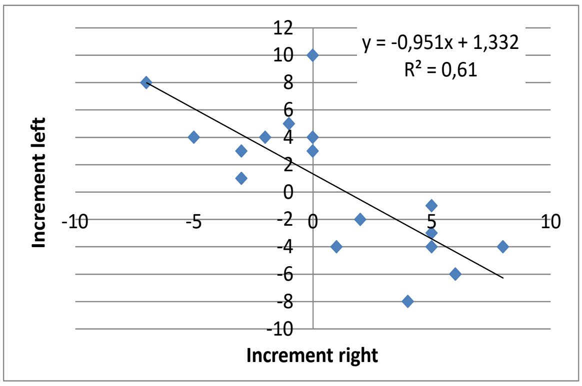


Figure 4 – Illustration of anti-phase clusters cooperation

It is natural, because all clusters should compete for degrees of freedom, which is critical for rearranging of the clusters. The only way to develop the process of irreversible ground movement was to use the limited number of degrees of freedom by turn, one after another. That is why the number of active clusters changed in anti-phase mode in the left and in the right sides of the model, what violates the symmetry of irreversible ground movement.

Validity of distant cluster cooperation has been confided by experiment in situ (Griniov et al., 2017 [10]) when effect of discrete expansion of the damaged zone has been found (Figure 5). The rock mass disintegrates around underground opening and expands in space and in time by discrete steps. Numbers indicate sequential positions of the boundaries of the damaged zone.

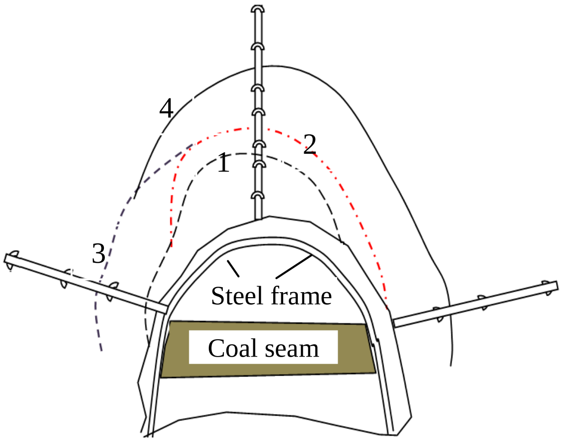


Figure 5 – Development of the damaged zone around underground roadway (after Griniov et al., 2017)

Development of the disintegrated zone around underground roadway was asymmetrical relatively centerline. Furthermore, concentric expansion of the zone disrupted and asymmetric portions of the zone evolved by turn, one after another. This behavior demonstrates another side of complex irreversible process that is governed by self-organization of the dissipative structures. However, thermodynamic nature is the same: process of the irreversible ground movement chooses a way that minimizes entropy production and reduces competing of clusters for the degrees of freedom.

Another important question concerns the period of following the patterns of the dissipative structures. The structures replace one another as the ground irreversible movement progresses. The author of this paper employed the results of actual measurements to determine the average period of the dissipative structures. I used the data from monitoring of convergence and support loading in the underground roadways and entries in several coalmines.

Thirteen underground roadways from four coalmines have been selected for analysis. Physical modeling demonstrated that any variation in the dissipative structure induces acceleration of the roof and floor convergence in a roadway or generates additional load to the frame support or rock bolts. It is natural, because a new dissipative structure emerges in response to rearrangement of the clusters and increases the degrees of freedom that follow with upsurge of the volume of the surrounding rock mass.

Thus, abrupt growth of the convergence or support loading may be used as an indicator of the dissipative structure shift. Such the process has been examined by monitoring of the convergence diagrams. Majority of the data was from the head and tail entries, which were maintained inby and outby of a longwall face, when the entry was in abutment zone or in area of active subsidence of the undermined strata. This interval ranged from -50 m inby the longwall up to +100 m behind it and was very convenient for the gathering sufficient amount of oscillation of the dissipative structures. In addition, I used several main roadways to collect the data.

Geologic conditions of the experiment covered wide range of the stratigraphic sequences and strength of the rock. For example, West Donbas’ka coalmine extracted 1 m coal seam having unconfined compressive strength (UCS) of 20 MPa, whereas UCS of surrounding rock was less. South Donbas’ka coalmine maintained the experimental entries in the competent rocks having UCS from 40 up to 55 MPa.

Steel yielding frames having maximal bearing capacity 300 kPa supported the experimental roadway. Five additional rock bolts enforced the roof (Figure 6).

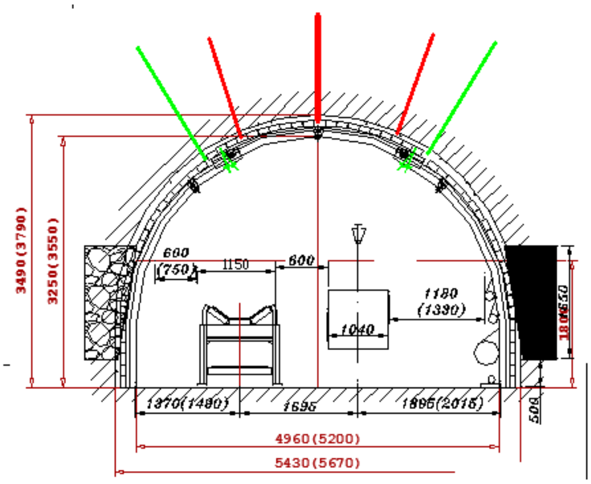


Figure 6 – Example of entry supporting with steel yielding frame and rock bolts

Length of the bolts varied from 1,5 m to 2,9 m depending on the stratigraphy and strength of the rock. Distance between adjacent frames was from 0.5 m to 1.0 m and specific weight of the frame profile varied from 27 to 33 kg/m. Bearing capacity of the rock bolts was 200 kN.

Rate of the longwall advance extended from 50 m per month to 200 m/month. Complete caving has controlled roof of the coalfaces. In the cases of especially gaseous coal seams, the direct flow ventilation has been used, and tail entries were maintained outby the longwall faces to provide pushing off the coal bed methane that could explode. Cement cribs were used to maintain the tail entries behind the longwalls. Specifically this interval was the most productive for gathering relevant data concerning parameters of the dissipative structures because there are severe damage of the surrounding strata and intensive irreversible movement of the ground behind an advancing longwall face.

Table 1 contains initial data that characterize experimental sites. Depth of the mining ranged from 450 m to 1300 m or by 2,89 times, abutment pressure concentration varied in diapason from 1 up to 3, factor of roadway stability (FRS) oscillated from 0,325 to 1,08, what provided representative conditions of the experiment. I calculated FRS as the ratio of the vertical component of the ground pressure to the UCS of the surrounding rocks.

Table 1 – Initial characteristics of the experimental sites

Coal mine	Depth of mining, m	Abutment pressure concentration	Vertical component of the ground pressure, MPa	Unconfined compressive strenght, MPa	Factor of stability	Interval, day
South Donbas'ka	610	1	15,25	45	0,339	19
	590	1	14,75	40	0,369	21
	630	1	15,75	45	0,350	29
	610	3	15,25	45	0,339	35
	600	*2*	*15*	*46*	*0,326*	*60*
	624	*1.3*	*15,6*	*48*	*0,325*	*80*
Pokrovs'ka	850	1	21,25	45	0,472	15
	850	1	21,25	50	0,425	14
	850	1	21,25	30	0,708	10
	825	3	20,625	30	0,687	1
Zasiad'ko	1250	1	31,25	35	0,893	5
	1300	2	32,5	30	1,083	2
	1250	1	31,25	50	0,625	11
	1160	1	29	38	0,763	6
West Donbas'ka	450	1	11,25	15	0,750	4
	450	2	11,25	15	0,750	10
	450	1	11,25	15	0,750	6

I reduced duration of the interval between successive dissipative structures to integer number of days. The minimal duration was 1 day whereas the maximal 80 days. Two sets of data, which highlighted with italic font, correspond to the intervals that may be at least those indicated in the Table. It means that these intervals may be larger and just are restricted from the lower limit.

Diagram in Figure 7 demonstrates power dependence of the interval duration upon stability the factor. This dependence has negative exponent, what emphasizes asymptotic decrease of the interval as geomechanical conditions become worse.

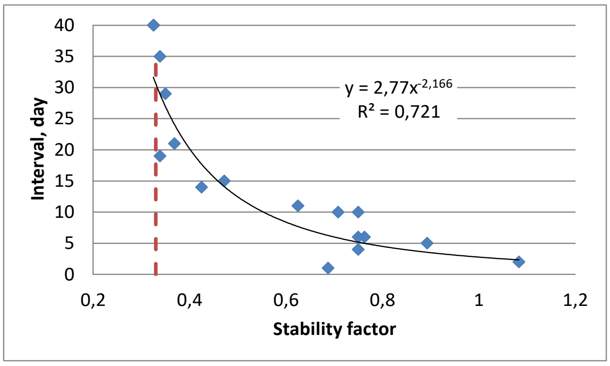


Figure 7 – Decreasing of interval duration between successive dissipative structures due to increase of the stability factor

This is consistent with the geomechanical principles: the more the depth of a roadway location and the less the strength of the surrounding strata the more intensive their damage, what increases frequency of shifting of the subsequent dissipative structures.

It should be stressed this dependence has the interval of admissible values of the argument, which is restricted by minimal limit of FRS=0,33. If FRS is less than this critical level, surrounding strata are not predisposed to damage. Thus, the irreversible displacements and deformations do not occur and the interval tends to infinity.

Alteration of the dissipative structures in space and in time emphasizes their discontinuous nature. Noticeably, abrupt and discrete shifting of the dissipative structures occurs through relatively smooth irreversible displacements. Strictly, these displacements may be intermittent in time in different points of the rock mass surrounding an underground opening. However, these discontinuities may smooth out. Therefore the fact that discrete dissipative structures alter each other in time, it testifies process of self-organizing of the rock mass due to irreversible movement.

I described self-organization of irreversibly moving ground as short-range or close interaction of ground fragments and distant or long cooperation of their clusters. Such approach concords with modern investigations in other area of physics (see Cuestas et al. (2017) for example [11]). Dissipative structures help to disperse the energy of ground pressure optimally minimizing entropy production according to (1). This provides maximum irreversible ground movement for minimum spending of potential energy of ground pressure. Literally, any rock mass tries to move the easiest way.

Traditional technologies practice restriction of principal degree of freedom in vicinity construction or underground opening [12]. For example, generally, miners direct rock bolts and props along and against gravity to prevent roof fall or floor heave. However, there are other degrees of freedom, which may be used as a reserve for accumulation of the empty space. These degrees are traversal to gravity.

Furthermore, nobody has mentioned before rotational degrees of freedom that the ground may use to accumulate emptiness and room for development the irreversible movement. Therefore, it is expedient to restrict not only translational degrees of freedom but as well rotational ones. Such a task is actually a challenge for designers. However, it is worth to invest efforts to develop new devices and technologies, which will efficiently restrict both translational and rotational degrees of freedom in 3-dimensional space.

CONCLUSIONS. Dissipative structures are a product of short interaction of adjacent rock fragments and distant cooperation of their clusters. The short interaction facilitates coordination of the rock fragments, what promotes creation of specific patterns in the field of irreversible ground movement. The distant or far cooperation of the clusters reflects in several ways. First, distant cooperation breaks the symmetry of ground movement around underground roadway. Second, activity of cluster reorganization changes in anti-phase mode: when one group of clusters accelerates their motion and rearrangement, the other set recede activity. This reflects coordination and competition for limited number of degrees of freedom.

Restriction both traverse and rotational degree of freedom of rock fragments and their clusters is prospective way to improve the technologies of support and maintenance of underground openings in a complex geologic environment.

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ВОЗНИКНОВЕНИЕ ДИССИПАТИВНЫХ СТРУКТУР В ПРОЦЕССЕ НЕОБРАТИМЫХ СДВИГОВ ГРУНТА И МАССИВА ГОРНЫХ ПОРОД

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Исследованы диссипативные структуры, образующиеся в грунтах и массивах горных пород в процессе их необратимых сдвижений и деформирования. С помощью методов термодинамики необратимых процессов, моделирования и шахтных инструментальных наблюдений были исследованы эволюция указанных структур и определены их параметры. Показано, что диссипативные структуры рассеивают энергию горного давления и периодически испытывают бифуркации, изменяющие мозаику или паттерн диссипативных структур. Основными источниками возникновения диссипативных структур являются ближние взаимодействия породных фрагментов, а также дальние взаимодействия кластеров, которые формируются с указанных породных фрагментов. В качестве практической реализации полученных научных результатов обоснован новый принцип повышения устойчивости грунтов и массивов горных пород путем ограничения всех трех поступательных и вращательных степеней свободы.

Ключевые слова: массив горных пород, необратимые деформации, ближние взаимодействия, кластеры, дальние взаимодействия.

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