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Dissipative Structures Following Damaging and Irreversible Deforming of the Ground and Rock Mass

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The purpose of the paper is investigation of the dissipative structures that occur in solids on the instance of rock mass during its damaging and irreversible deforming. Ground movement monitoring of surrounding underground roadway rock mass and landslides has been employed as the method of investigation. The author of this paper registered the dissipative structures that dispersed the ground pressure energy, periodically changing their patterns during irreversible deformation. It was found for the first time that short interaction of the rock fragments and far cooperation of the clusters minimize the entropy production, and are the form in which the dissipative structures appear. Space and time parameters of these structures evolution have been investigated. In order to achieve the practical relevance of the experimental findings a new principle of constructions stability enhancement were developed. Both the translational and rotational degree of freedom should be restricted for moving ground in three dimensional state.

Key words: solids, strength, irreversible deformation, dissipative structure, self-organization, far interaction, cluster.

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Introduction

Dissipative structures (DS) derivate in the open thermodynamic systems during development of irreversible processes (Kondepudi et al., 2015). Recently, self-organization of such structures are intensively investigated in different areas such as fundamental theory of the substance (Ma et al., 2015), phase transition (Mar'yan et al., 2016), genetics (Nitzan et al., 2014), optics (Wu et al., 2011). All processes that occur in micro-world have attracted the primary concern. However, the DS structures are visible in the macro-scale as well, for example, during cooperation of distant neurons in the brain (Vuksanović et al., 2014), in liquids that act together, such as in well-known reaction of Belousov-Zhabotinski (Marchettini et al., 2010). Investigation of the DS from the position of the fundamental thermodynamics of irreversible processes have provided fruitful results, which reflected as successful practical decisions introduced in applied areas, namely in the industry, medicine, economy.

However there are some areas, which remain scarcely studied as possible objects where the DS may emerge and evolve. Such an area is the solid mechanics that has been studied and investigated with traditional methods of the continuum, first of all theory of elasticity and plasticity is to be mentioned. However employing a new approach that, for example, considered interaction of dislocations in a metal as process of evolving the DS rendered essentially new knowledge as has demonstrated Vattré (2017). In this case, again, the dislocations emerge at the crystalline lattice of the solid, namely in micro-level. Presumably, DS may emerge at microscopic scale during the collapse of a solid body. However thermodynamic analysis of the solid destruction is set up on the maximum entropy principle so far, because it is believed that after transition over strength limit, there a chaos may be emerged only in a solid body, as considered Zhang et al. (2016), who investigated destruction of a brittle rock.

Failure of the material is considered as a catastrophe in such areas as machine building or architecture for example. However transition of the ground to over-peak (plastic) state or its fracturing does not mean programmed failure of a natural object or artificial construction. For instance, a slow landslide, sliding of a fletcher may evolve for moths and even years thereat do not finish by catastrophic outcome mandatory. Furthermore, hydro-fracturing of oil-bearing strata is useful effect boosting up production of a well. Damage of certain area of a rock mass around of an underground roadway may produce positive effect that follows with local distressing from mechanical stresses and balancing of the roadway stability, what is urgent problem at a great depth of mining.

Irreversible movement of solid material nay be considered as natural processes, which accomplish certain creative function, for instance shaping a seashore (Miles et al., 2015). Thus it is important to investigate destruction and nonreversible deforming of the rock mass from the thermodynamic point of view, considering possible evolving of the DS and taking into account urgency of the problem of safe mining that is important for energetic and raw material independence of our country.

I. Thermodynamics of irreversible deformation of the rock mass

According to Glensdorf et al., (1971) DS may emerge in an open thermodynamic structure if

$$d\acute{S}/dt = \sum \delta I_k \, \delta(dX_k/dt) \leq 0 \qquad (1)$$

where $\acute{S}$ is entropy production, t is time, I_k and X_k are thermodynamic forces and flows respectively.

Entropy production is the second term of the expansion in the numbers that reflects behavior of the entropy due to perturbation δ of thermodynamic forces and corresponding flows.

For the rock mass as the open thermodynamic system, role of thermodynamic forces performs gravity, tectonic forces, gas pressure gradient (for example coal bed methane or carbon dioxide), gradient of underground liquids pressure (oil, water), and temperature gradient. Irreversible ground movement, plastic and non-elastic deformations, torrents of gases and liquids, as well as heat flows stand for the thermodynamic flows.

Investigation of the DS is accomplished using examination of the dynamic behavior of a system of differential equations. Initial, boundary conditions, and the equations take into account concrete structure of the dynamic system and circumstances under which it operates. However results of the investigation strongly depend upon the parameters confidence and uncertainty of the geologic environment that may not be determined accurately. That is why the investigation of DS and their parameters has been undertook, using monitoring of the irreversible movements of the ground, which directly reflect the thermodynamic flows. Extant methods have been analyzed, having that such DS have not been detected in rock mass so far, although theory of thermodynamics of irreversible processes predicts possibility of such phenomenon in the open thermodynamic systems.

It turned out that monitoring of the ground movement was accomplished through sufficiently long intervals because of high cost of the accurate measurements of the ground displacements. However the irreversible ground movement essentially depends on the way of loading. Accurate measurements of the ground movements have been accomplished by the author of this paper in the head entry of 4 south panel at Pokrovs'ka coal mine. The entry has been driven at the depth of 830 m, had arch cross section with area of 17.7 m^2, and was supported with steel yielding frames standing at 0.67 m from each other. The roof of the entry has been reinforced by 2.4 m fully encapsulated rock bolts, 5 bolts in a row. Height of the coal seam was 1.8 m and the longwall retreated with rate of 180 m per month. Shale represented the roof having unconfined uniaxial strength of 48 MPa.

Table 1

Incremental movement of the plumb relatively the bottom rock bolt

Time, day	Distance from the longwall face, m	X, mm	Y, mm
0	-84	0	0
9	-35	16	8
11	-20	18	17
12	-10	8	11
14	0		
16	9	-8	4
18	24	-19	-3
20	38	-35	-6
23	62	-38	3
29	106	-29	11

A plumb was suspended to a rock bolt, which was in the apex of the entry cross section. Another bolt has been installed in the floor right against the plumb. Horizontal distance from the plumb to the bottom bolt was monitoring for a month period as the longwall retreated (Table 1).

Standard errors of the relative horizontal movement of the plumb was ±1 mm. Significant deviation of the plumb from the head of the bottom bolt has been registered as the longwall approached to 35 m when the experimental section of the entry was disturbed by the abutment pressure. Figure 1 demonstrates the trajectory of the plumb horizontal movement. Horizontal axis of the diagram coincides with the longitudinal axis of the entry.

Final deviation of the plumb indicated by intermitted arrow and was 31 mm, but direction of the deviation varied essentially during experiment. It is impossible to judge concerning the complex behavior of the roof and floor movements if to consider the final displacement of the plumb only. Rock mass that surrounds the entry transited over peak strength in the abutment zone and in the interval behind the longwall where intensive subsidence of undermined strata occurred. Thus the relative movement of the experimental rock bolts was irreversible and their real behavior was much more complex in comparison to those characterized by intermitted arrow. Therefore irreversible movement of the rock mass may change their direction, sign and magnitude that causes loss of important information due to integration of the results.

Minor oscillations of the movement directions and their deviation from 'theoretical' smooth trajectories are usually ignored as casual errors, which should be neglected. In addition, omitting of the information may be caused by reciprocal annihilation of the incremental movements having opposite signs. In other words, increment of the displacement in certain direction may be compensated by opposite movement in the next moment as well as compression might be neutralized by tension.

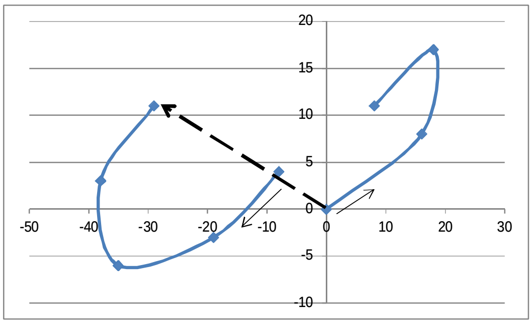

Fig. 1. Trajectory of relative movement of the plumb.

Therefore the author of this paper found such diapason of allowable incremental movements that provided reliable detection of the DS. It was determined that experimental histogram of confident unveiling of the DS is consistent with lognormal law, whereas the optimal interval of the incremental displacements monitoring has been limited from 2 to 10 standard errors of measurements. Such interval provides 75% confidence of detection of a DS, and maximum confidence of 95% corresponds to diapason from 3 to 5 standards. Registration of the displacement that is less than 2 standards increases uncertainty, whereas exceeding of 10 standards rises the risk of omission of certain structure.

II. Investigation of short interaction of the rock fragments

Haken (1981) has proven that DS emerge as a result of synergetic processes, which should unavoidably follow by interaction of the components which comprise the thermodynamic system. Wide experience of DS investigation has shown that so called short or near and long or distant interactions of the components of the open thermodynamic systems play important role.

This has been emphasized by Cuestas et al., (2017) and Ma et al., (2015), who discovered important role of short and long interactions of the molecules due to their attraction, Nitzan et al., (2014), who revealed distinctive effect of gens cooperation, what are positioned at the distant locus, Vuksanović et al., (2014), proving reciprocal activity of scattered areas of the brain, Wu et al., (2011), who pointed out importance of consideration of the long atom's interaction.

Therefore the author of this paper decided to investigate short interaction of the rock fragments at the skin of an underground opening. A tail entry has been driven in c_{10} 1.9 m coal seam in South-Donbas'ka coal mine at the depth of 560 m. The roadway has been supported by steel frames and 2 m rock bolts, five units in a row and 1 m between rows. The longwall extracted this seam retreating with the rate of 3.1 m per day. Average unconfined compressive strength (UCS) of surrounding rocks was 30 MPa. Area of the roadway cross section was 13.7 m^2. Intensive irreversible movement of the ground occurred in the abutment zone.

It was expected that a long horizontal roadway is in a state of plane strain, when all displacements and

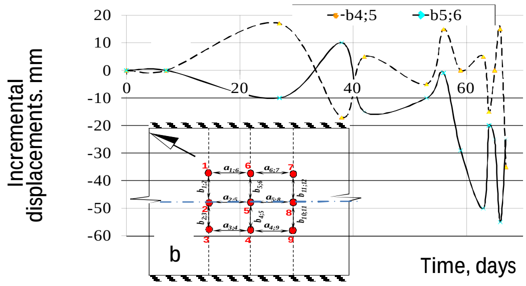

Fig. 2. Distance variation between adjacent rock bolts.

deformations occur exclusively in the vertical plane that is normal to the longitudinal axis of the roadway, although there is not any displacement and deformation that are perpendicular to this vertical plane. The results of the investigation have refuted this assumption. Irreversible movement of the ground has been monitored on the nine adjacent rock bolts (Fig. 2, b). Standard error of the measurement was ±1.9 mm.

It was found that the displacement of the ground along the roadway axis exceeds the standard error by factor from 7 to 30. As a result, initial flat vertical cross sections of the roadway distorted. Moreover, an anti-phase mode of rocks movement was registered on the all pairs of the rock bolts. When a pair of the bolts diverged, the other adjacent pair converged and vice versa. Therefore incremental deformation of surrounding rock mass shifted their sign along the roadway axis. This may be seen in 28th, 37 th, 43 ^{d}, 63 ^{d}, and 66 th day of the monitoring. For example the pairs of the rock bolts demonstrated difference 'expansion – contraction' of the normal deformation along the axis of the roadway at diapason from +56 mm (expansion) to -76 mm (contraction), what is 30 times more than standard error and has proven that the alternative normal deformation occurs along the axis of the roadway. This excludes opportunity to simulate the plain strain state of the surrounding horizontal roadway ground, which deforms over the peak-strength.

Noticeably, adjacent rock blocks and fragments irreversibly moved into roadway cavity by turn, or one after another: when one fragment accelerates, another recedes movement in order to pass the neighboring block. Confidence of this conclusion has been confirmed with the leveling of the bolts heads: the difference of the adjacent bolts sagging reached from 100 to 240 mm on the background level of the average subsidence of 385 mm.

This experiment demonstrated that adjacent blocks and rock fragments move irreversibly by turn in space and in time. This distinguishing behavior facilitated deformation of the cross section of the roadway. If adjacent rock fragments did not move successively, in serial manner or one after another, it would be impossible to deform the roadway because there is strong deficiency of degrees of freedom underground. Specifically, serial irreversible movement of adjacent rock fragments in anti-phase mode is the core of short interaction mecnanizm.

Average duration of the interval Δt between successive changing of acceleration of the irreversible

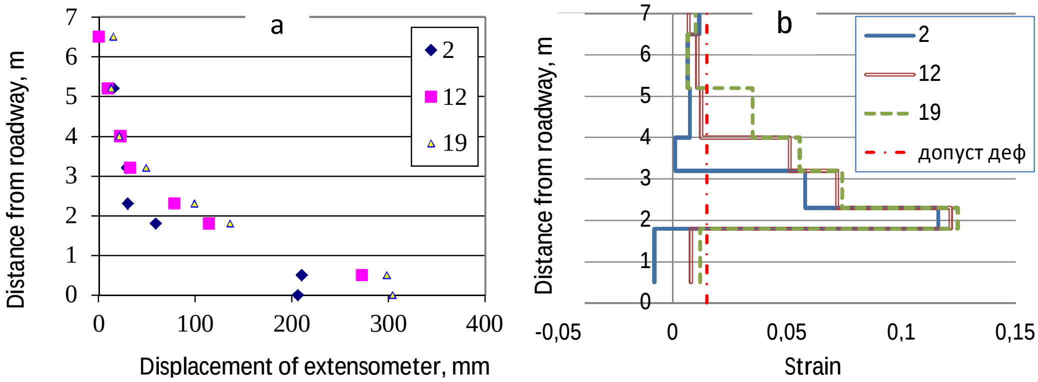

Fig. 3. Subsidence of the roof (a) and extension of intervals (b).

movement to slowing down and vice versa depends on the index ***x*** characterizing the stability of a roadway. This index has been calculated as the ratio of the vertical component of the ground pressure and UCS:

$$\Delta t = 4{,}61x^{-1.473}, \qquad (2)$$

Confidence of this dependence is 87% and the interval of the values of the index should be no less than 0.33. This limit determines the threshold which indicates condition when the surrounding ground transits to the irreversible state.

III. Unveiling of the distant cooperation of the ground clusters

It is well-known that the distant cooperation of the components is the main factor of DS emerging (Cruz et al., 2017; Cuestas et al., 2014). In situ experiment was conducted in Pokrovs'ka coal mine to examine this conclusion on the rock mass instance that experiences the irreversible movement. Main entry has been selected at the depth of 845 m for the experimental observation. The roadway has been driven by CSP43 miner in the coal seam d_4. The entry had cross section of 20.3 m^2 and was supported by steel yielding frames standing at the diapason of 0.8 m. Two 5 m cable bolts and five 2.9 m rock bolts reinforced the immediate roof of the roadway. The gaps between the roadway skin and the frames have been filled with the flexible bags inflated with cement and sand mixtures.

Experimental section of the roadway was equipped with extensometers, which have been installed into three holes, namely one 7 m hole in the roof and two 4 m holes in the sides of the roadway (Griniov et al., 2017). The extensometers were installed between frames №1430 and №1429 one day after roadway driving. Positions of the extensometers were as those: in the roof – at 0.5 m 1.8 m, 2.3 m, 3.2 m, 4.0 m, 5.2 m and 6.5 m; in the left side – at 1.9 m, 2.9 m and 3.8 m; in the right side – 1.0 m, 2.5 m and 3.9 m.

Nineteen days later displacement of the roof reached 300 mm and abated to the depth of the hole (Fig. 3.a). Maximum separation of the strata were in the roof at the interval from 1.8 m to 3.2 m accumulating tensile strain from 0.116 up to 0.125 on the lower part of the interval and from 0.058 to 0.074 on the upper section of the interval (fragment b). The farther from the roadway cavity was the less dilatation of the strata.

Special testing of the roof rock indicated that critical tensile strain for this rock was 0.015. This limit has been used to delineate boundaries of the zones where the ground collapsed. Dynamics of this zone development indicated in Fig. 4. Zone of the damaged rocks expanded discontinuously, by discrete portions. First, it expanded to 2 m in the roof and to the depth of 0.4 m in the left side of the experimental roadway on the second day after extensometer installation. Position of this boundary marked with number 2.

Twelve days later, zone of the collapsed rocks extended to 3.6 m into the roof, and then it stretched out to 3 m in the left side of the roadway the next day. Consequent spreading of the damaged zone occurred to 4.8 m in the roof and to 2 m in the right side of the roadway at 19th day after beginning of the experiment.

Thus widespread belief that a damaged zone expands around a roadway synchronously and concentrically (Khomenko et al., 2016), were corrected. Separate clusters of the rock mass coordinate their movement during expansion of the collapsed area in vicinity of a roadway. Synchronous expansion of the collapsed zone is not relevant from the point of view of energy expenditure. Dissipation of the energy is not consistent with the second law (formula 1) of thermodynamics if the collapsed zone will expand synchronously. That is why boundaries of the damaged zone developed

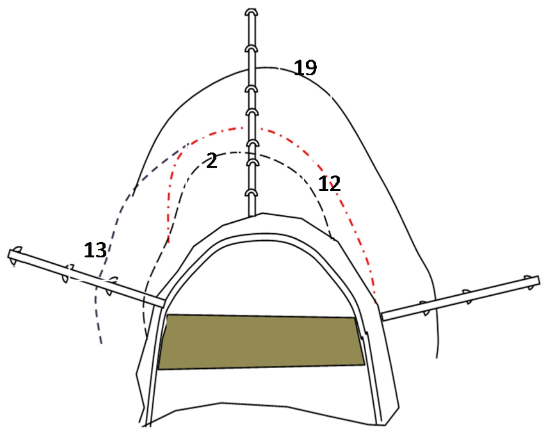

Fig. 4. Development of disintegrated zone around underground roadway.

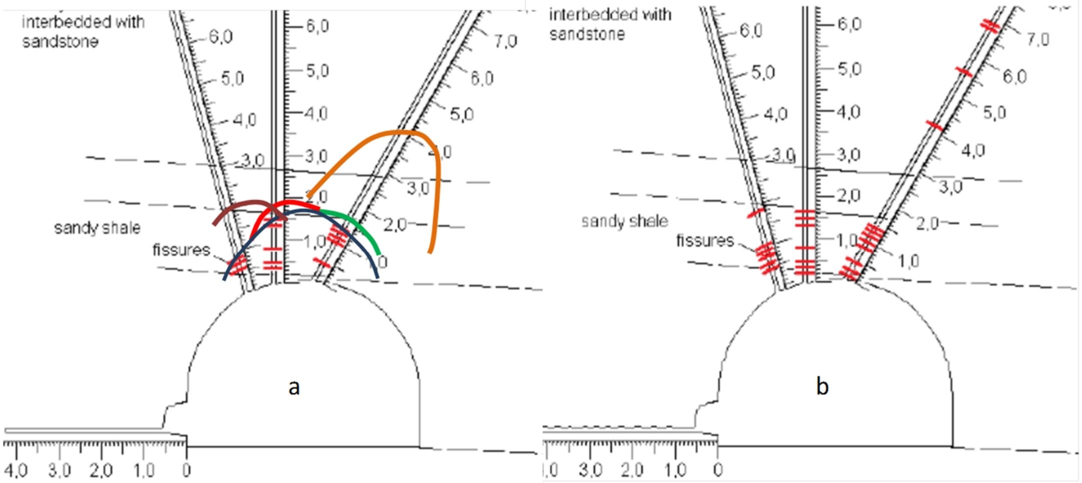

Fig. 5. Sequential kinematics of fracture development according to Lubosik et al., 2015: (a), (b) – at the distance 220 m and 12 m in front of the longwall respectively.

discontinuously, by turn or one after another, what facilitated minimizing of entropy production according to (1). This important and distinguishing peculiarity has been unveiled because of planning the schedule of the monitoring according the optimal interval for incremental displacements measurement.

Reliability of this specific behavior of the irreversible moving ground has been proven by the results of independent investigations (Lubosik et al., 2015). Polish scientists studied reaction of three entries on the approaching longwalls at the great depth of mining. There, 130 m longwall extracted 3.4 m coal seam at the depth of 960 m. UCS of the roof strata, coal seam and floor layers were 46.6 MPa, 10 MPa, and 28.1 MPa correspondingly. Head entry was supported with LP10/V32 steel yielding frames standing at 0.75 m from each other. Dimensions of the entry cross section were: 5.5 m width and 3.8 m height. Steel friction props were used in the center line of the roadway immediately in front of the longwall face to assists the frames withstand intensive ground pressure.

A set of measurements has been carried out during longwall approaching to the monitoring station. In particular, fracture evolution was monitored using an endoscoping camera, periodically inserted into special holes (Figure 5). Polish authors did not present the intermediate results of the observation, but it is possible to recover some positions of the fractured zones, comparing the data, gathered in the moments when the longwall face was at 220 m and 12 m from the station. The boundaries of these zones were applied on the fragment (a) in Fig. 5 by the author of this paper and are indicated by color convex curves. Evidently, the fractured area has been expanded discontinuously, by discrete portions, which emerged each after other.

The fact that DS emerge due to distant interaction or cooperation of the ground clusters, may be validated by computer simulation. FLAC3D was employed to simulate the irreversible ground movement around an underground opening. This model reflected the same initial conditions, geologic stratigraphy, and technologic situation, which described the experimental site in Pokrovs'ka coal mine. Coulomb-Mohr constitutive model has been used to check if the ground transited to over-peak state and further irreversible movement of disintegrated ground was simulated by the second law of Newton in 3-dimensional state. Therefore the irreversible processes of the ground collapse and successive nonreversible movement has been simulated properly as the Newton law explicitly takes the time into consideration.

Figure 6 depicts a field of incremental irreversible displacement of the ground surrounding the roadway. Analysis has shown that the development of the damaged zone follows with periodic bifurcations of the DS, patterns of which comprise of groups or clusters of the rock fragments. According to the current state, pattern of DS consists of three major clusters. Cluster 1 appears as a rotor that emerges in bottom of the road side and tends to the lateral part of the ground pushing the damaged rock into roadway cavity through the bottom section of the ground that forms the roadway side. In the same time,

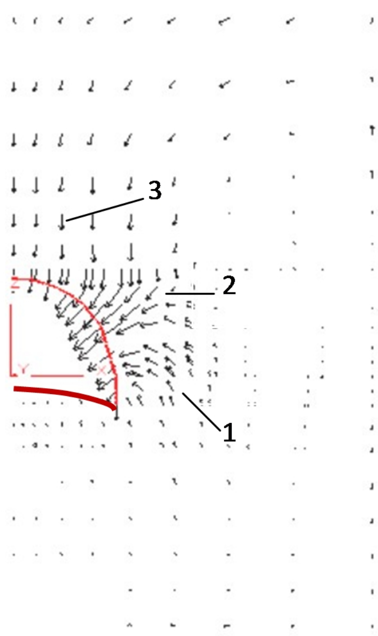

Fig. 6. Cluster patterns of dissipative structures.

cluster 2 looks like a torrent, integrates damaged fragments from the roof and the side wall, and drives them into roadway opening through the upper section of the wall. Cluster 3 originates in the roof feeding cluster 2 by energy.

It is important that pattern of DS periodically and abruptly was changing many times (several dozens) during development of the damaged zone around the roadway, that reflects bifurcations of DS, occurring in the open thermodynamic system. Distant cooperation of the ground clusters appeared as activity of DS, which are changed in space and time. There was not any case, when intensive irreversible movement occurred to all three major directions, namely from the roff, side walls and floor. These general streams replaced and succeeded each other every time. Fig. 6 demonstrates the case, when the most intensive dissipation of the ground pressure energy takes place in the lateral wall of the roadway. Rocks in the roof assisted as a secondary factor, while the floor strata took pause and have abated the process of dissipation.

Next moment, the pattern of DS changed radically and activity of dissipation relocated to the roof or floor and so forth. Specifically, this behavior explicitly indicates on the distant cooperation of the clusters and facilitates minimization of entropy production, coordinating in space and in time. These experiments have shown that short interaction of the rock fragments occurs in a scale of tens of centimeters, whereas the cooperation of the clusters takes place on the distance of several meters that is more by factor of 10. Therefore the short and the long interaction are characterized by different agents of the cooperation (relatively small rock fragments versus big clusters) and distinguished with different scale of distances.

New mechanism of DS evolution in the rock mass, which is in the state of irreversible movement helped to put forward a new principle of ground control in mining, tunneling, or construction. So far, all methods and technologies using for reinforcement of the underground constructions and roadways or slopes and hillsides are founded on the resistance against the ground irreversible movement in the major direction, basically, in opposite direction to gravity or gravity gradient. The irreversible movement in this direction is explicit having maximal magnitude. For example, slopes are usually reinforced to restrict ground displacement along the gravity gradient. Props and rock bolts are slanted towards the gravity in underground openings.

However DS bifurcations enable accumulation of all the available degrees of freedom, which encompass both translational degrees (for the torrents) and rotational degrees (for the rotors) in 3-dimensional space. Therefore it is expedient to restrict not only one translational degree of freedoms that is oriented along the gravity but six degrees, namely three translational and three rotational. It is not correctly to consider the other five degrees of freedom as secondary or subordinate and to neglect them. Dissipative structures do not differentiate these degrees of freedom involving and using them as equipollent reserve.

Conclusion

Ground, alluvia, and rock mass are open thermodynamic systems that may create DS under action of thermodynamic forces and flows, namely gravity or tectonic forces and irreversible movements. These DS emerge in the ground, which transited over limit of strength and are a product of the short interaction of the ground fragments and distant cooperation of their clusters. DS may be detected by monitoring of the incremental displacements in diapason from 2 to 10 standard errors of measurement.

Short interaction of the ground fragments appears as sequential irreversible movement of adjacent ground fragments in anti-phase mode: when one fragment accelerates, the other slows down and vice versa. Average duration of the interval between successive changing of acceleration of the irreversible movement to slowing down and vice versa is proportional the ratio of the vertical component of the ground pressure and unconfined compressive strength.

Distant cooperation of the ground clusters reproduces by serial discontinuous evolving of the disintegrated zone in the ground and with oscillation of the cluster mosaic or bifurcation of DS patterns inside this zone.

This allowed developing of new principle for controlling stability of the ground restricting all its translational and rotational degrees of freedom in 3-dimensional space.

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Дисипативні структури, що супроводжують руйнування й необоротне деформування ґрунту і масиву гірських порід

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Метою роботи є дослідження дисипативних структур, які виникають у твердому тілі на прикладі масиву гірських порід під час його руйнування й необоротного деформування. При виконанні досліджень використані інструментальні методи моніторингу зрушень ґрунту й масиву гірських порід у процесі розвитку зсувів схилів та зрушень масиву гірських порід навколо підземних виробок. Виявлені дисипативні структури, що розсіюють енергію гірського тиску, й паттерни яких періодично змінюються у процесі незворотного деформування. Вперше встановлено, що мінімізація виробництва ентропії цими структурами досягається завдяки близькій взаємодії породних та ґрунтових фрагментів, а також дальній кооперації їх кластерів. Знайдені також параметри еволюції вказаних структур у часі і просторі. Практична цінність результатів досліджень полягає в обґрунтуванні нових принципів підвищення стійкості природних об’єктів та споруд на основі обмеження як поступальних, так й обертальних ступенів свободи у тривимірному просторі.

Ключові слова: тверде тіло, міцність, необоротні деформації, дисипативні структури, самоорганізація, дальня взаємодія, кластери.