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CLUSTER BEHAVIOR OF THE GROUND IRREVERSIBLE MOVEMENT DURING DEVELOPMENT OF A LANDSLIDE

The aim *of this work was identifying of dissipative structures as a product of the ground surface irreversible movement during a landslide development.*

A complex methodology *has been used. Ground has been considered as an open thermodynamic system. It dissipates ground pressure energy and potential energy of the irreversibly sliding body along the gravity gradient. The author of this paper used geodetic monitoring, statistical analysis, and computing geometry for investigation of movement kinematics.*

Results*. It was found that in the ground, which transferred over peak strength of the rock, dissipative structures emerge due to short interaction of the rock fragments and distant cooperation of rock clusters. This self-organization can be detected by monitoring of incremental movements having the magnitude from 2 to 10 standard errors of displacement measurement. Positions of centers of the clusters are determined by K-means clustering, and boundaries of these clusters may be outlined by Voronoi diagram in Euclid space. This facilitated unveiling of dissipative structures and developing of a new approach to provide stability of the ground. The main principle uses restriction of the three translational and three rotational degrees of freedom for the ground, which transferred over peak strength.*

Novelty. *It was determined for the first time that the dissipative structures of the ground, which disperse ground pressure energy, are altered discontinuously due to their bifurcation. These structures have the patterns such as differently oriented irreversible moves of short-living ground clusters and domains, what provides accumulation of degrees of freedom for the development of the irreversible movements and deformation. It was for the first time when K-means clustering and Voronoi diagrams in Euclid space have been employed to detect the ground clusters, and short interaction of the ground fragments and long cooperation of the clusters were identified.*

Practical implementation *of this novelty was used for the development of a new approach when the landslides are stabilized with the restriction all the degrees of freedom both translational and rotational.*

Key words: *ground, irreversible movement, clusters, short interaction, distant cooperation.*

Introduction.

Landslides cause big loses and expose the people to the danger. Urgency of this problem steadily grows, what demands increasing of concern for the researchers and specialists. [1]. In addition, Klimeš et al. [2] demonstrated that the landslides follow with serious social problems. Therefore, the problem of investigation of the causes and the landslides development mechanisms has attracted constant attention.

Choi et al. [3] made analysis of a wide array of technologies, methods, and tools for preventing of the landslides. In spite of this, efficacy of these methods remains insufficient. Zerathe et al. [4] indicated that it is important to investigate kinematics of the landslides, what provides understanding of the ground deformational behavior during development the landslides and failure of a quarry ledge. Slow slides are especially relevant for investigation of the kinematics behavior of the ground [4]. Quick slides last for several minutes and even seconds and finish by catastrophic devastation of the surface and constructions, whereas the slow slides may develop during months and even years, what allows investigating of the slides in details and provides possibility to obtain essentially new knowledge.

It is the common point view that rainfalls are the main trigger of the slides because they reduce internal friction in the ground and decrease its strength. Chen et al. [5] investigated dependence of the rainfalls and the landslides. They demonstrated that the large-scale landslides, which involve soil, alluvia, and rocks, occur when the rains intensity is large and ranges in diapason from 11.5 to 31.0 mm/hr lasting more than day or from 26.5 to 62.5 hours. On the other hand, small-scale landslides may occur at the wide range of climatic conditions, when precipitation varies from 8.5 to 31.0 mm/hr and the rains last from 4.0 to 62.5 hours. This shown that the large-scale slides requires not only intensive wetting of the ground but elevation of the groundwater level too. Frequency of the large-scale slides depends of their area reversibly according to power law with the exponent of -1.1 ± 0.07.

Statistical indicators of the landslides are important, but there is a need to know the peculiarities of the slide bodies behavior and their evolution during development of the slides. This task is solved in this paper.

Methodology of investigation.

So far, collapse of the ground body due to triggering and development of the slide is considering as the transition from the order to the chaos, what follows with the mandatory increase of entropy up to the maximum level. As an example, let consider the paper of Lombardo et al, [6]. However it should be kept in mind that, as the physical body, ground or quarry ledge involving in active sliding are an *open* thermodynamic systems, because they convert potential energy of the gravity into kinetic energy of the movement, surface energy of the fractures, and heat. According to Kondepudi and Prigogine [7] such the systems disperse the energy and are potential to create so called dissipative structures.

It means the rock mass, ground, or alluvia involving in development of the slide may independently organize or self-organize their movement thereat minimizing the entropy production. To say it in other words, the entropy may increase but not to maximum. This hypothesis will be examined in this paper.

According to Haken [8], such a state is called as synergetic one, and dissipative structures emerge only if there is interaction among the components of the open thermodynamic system. In the case of the landslides, such the system is represented with the ground that participates actively in development of the slide.

The author of this paper assumed that the components, which would interact, are separate fragments of the ground. The interaction is the most relevant to investigate on the sliding surface using geodetic instruments. Such works were accomplished many times, but the investigators did not reveal the self-organization.

As an example, it may be demonstrated by Gaffet et al. [9], who monitored coordinates of special marks fixed on the ground surface within the boundaries of a slow landslide at an Alp region. Distribution of the ground displacements that were monitored during several years did not provide any new knowledge. Well known fact have been just acknowledged, namely vectors of the slide movement are oriented along the gravity gradient and velocity of the sliding accelerated during rainfall season.

The author of his paper has suggested that the absence of the self-organization effect may be elucidated by the fact that the French specialists emphasized on the integral movement measurement and ignored small incremental displacements. Noticeably, derivative of the integral movement does not provide the relevant information concerning possible signs of the dissipative structures. The reason is that determination of the derivative relies on the assumption concerning continuity of the displacements. However when discrete movement occurs, the derivatives cannot uncover some important details, which may put the dissipative structure in the light.

Therefore the main attention in this paper has been paid to the incremental displacements. Such an approach makes possible to account *irreversible* nature of ground fragments displacement. It is common knowledge that process of irreversible deforming of the rock depends on the way of loading after transition the rock through the peak strength. That is why the integration of the separate interval displacements may cause omission of the important information. The reason is the incremental deformation may alter not only magnitude but orientation as well. Therefore the incremental deformations may neutralize each other.

Based on this assumption, the author of this paper hypothesized that the dissipative structures may emerge in the ground under action of fluctuations, what conforms to the theory of thermodynamics of irreversible processes founded by Kondepudi and Prigogine [7]. According to them, these fluctuations might follow by bifurcations, irreversible nature of which is discrete. Therefore, the dissipative structures may be unveiled by monitoring the incremental displacements of the geodetic marks in certain moments of time.

Special investigations were accomplished to determine the optimal interval of the incremental displacements, what facilitates defining those dissipative structures that are close to their real number.

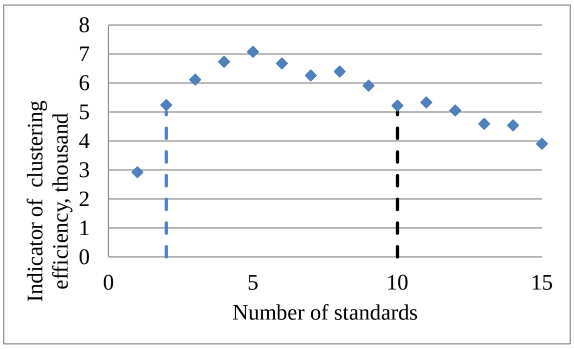

Figure 1. Optimal diapason for the incremental displacement

Lower boundary of this interval corresponds to two standard errors of measurement and upper boundary is ten standards (Figure 1). Such the interval provide with confidence of 93% that detected structure is the real dissipative structure but not a casual mosaic, which is a result of errors of measurements. The same confidence level defines impossibility to skip or overlook a dissipative structure.

Investigation of dissipative structures during slow slide development.

Evolution of the structures was being investigated during development of a slow landslide. This slide has been inspected at sea of Azov shore having abrasion-ravine-sliding category. Abrasion kind of the shore with short ravines and sliding terraces is typical at the East Ukraine. The slides occur on the upper Pliocene clays and activate after lasting period of precipitations, which moisturize the ground (Figure 2). Such the slides are the best candidates for investigation, because they are slow and provide possibility to detect important details of the irreversible ground movement.

Geodetic marks were installed at the distance from 2.5 m up to 4 m, what provided reliable fixation of the dissipative structures during triggering and development of the landslide. Instrumental monitoring of the ground surface movement was carried out during spring – summer - autumn period. This allowed investigation of subsidence dynamics both during active spring period, when the soil moisture was high and in summer, when the moisture was perspired because a hot season.

Frequency of the instrumental sessions has been determined according actual current intensity of the ground movement in the ground plane and in vertical dimension, keeping interval between sequential sessions in the range from 2 to 10 standards of the measurements. On the one hand, this allowed unveiling of the major dissipative structures and on the other hand not duplicate measurement sessions saving time and labor.

Figure 2. Landslide at the seashore of Azov

Distributions of integral movement of the ground on the representative area of the landslide are depicted in Figure 3. In addition to slide movement monitoring, another experiment has been run at the distance of 2 km from the seashore. The second experimental area had horizontal surface and has been selected as a benchmark that was used to control possible movement of the marks as a result of wetting of the ground and drying. Variation of the benchmark coordinates was in the limits of measurement error.

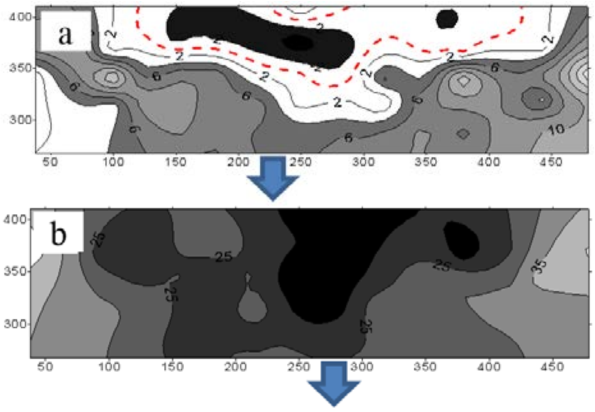

Figure 3. Distribution of the integral traversal displacement (a) and along the gravity gradient (б)

To the beginning of the autumn, magnitude of sliding along gravity gradient was from 150 mm up to 400 mm (fragment (b) of the Figure 3), whereas traversal movement varied from -62 mm to 139 mm (fragment (a).

Vertical subsidence of the geodetic marks was from 14 mm to 71 mm. These distributions indicate that all components of the landslide integral movement were distributed unevenly and irregularly, because the lines of the fixed displacement are not parallel and traversal displacements had different signs (plus and minus), are asymmetrical relatively gradient of the gravity, and exceeded error of measurement by 20-60 times more.

Figure 4 demonstrates typical patterns of the ground displacement field that has been built from incremental vectors of the ground displacements during two weeks in the spring period. Maximum vector magnitude was 19 mm that is more by 10 folds than error of the measurements.

As a first approximation, incremental vectors were separated in four categories: those, which oriented to the right and upward, right and downward, left and upward, and left and downward. These groups of the vectors were marked with different colors and named as clusters, because ground fragments within a cluster move consistently. The clusters indicate that ground creates the dissipative structures, which are the results of cluster cooperation.

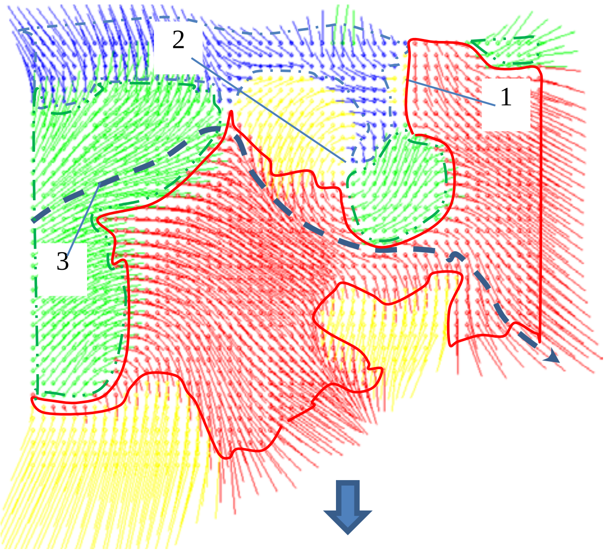

Figure 4. Typical patterns of dissipative structures: 1- divergence; 2 – rotors; 3 – torrents; -·-·- cluster, moving up and left; — downward and right; -··- up and right; no marked boundary - left and downward

It is possible to define a set of the patterns, namely divergence 1 that produces fissures between the clusters, rotors 2, and torrents 3. It is evident that such structures are the consequence of the cluster cooperation. Noticeably, such dissipative structures are temporary and periodically alter as the landslide progresses. These dissipative structures have been investigated in more details in physical models from synthetic materials, which have been selected for the conditions of the experiment.

There were such patterns as rotors, divergence, convergence, which were verified in the physical model. The fissures close as the clusters converge. It is important that the ground mass moves unevenly after transition over peak strength, but creates short-living clusters, interaction of which generates typical patterns of dissipative structures.

Bulking factor of the ground increases proportionally to fractures aperture and average amplitude of sliding. Increase of the emptiness in the ground facilitates accumulation of the degree of freedom, which enable irreversible sliding of the ground.

Period between altering of the dissipative structures varied from a week up to month. Figure 5 demonstrates that shifting of the dissipative structures occurs abruptly and discontinuously, what reflects bifurcations that follow irreversible processes in the open thermodynamic systems. Such bifurcations trigger under influence of stochastic fluctuations of ground pressure, humidity, temperature, and free surface energy of the fractures. It may be seen that the patterns alter radically, and the boundaries of descendant clusters do not coincide with the boundaries of the predecessors as a rule.

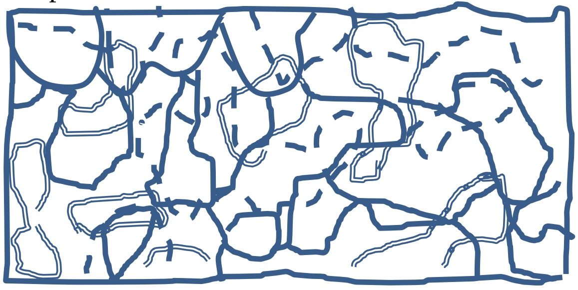

Figure 5. Evolution of cluster mosaic during three consecutive bifurcations of dissipative structure

Immediately after transition of the ground to the over-peak state, approximately one half of the clusters boundaries run through intact areas of the sliding ground. However, share of the boundaries, which coincided with existent fractures and discontinuities grew steadily as the landslide progresses.

Author of this paper developed a method for reliable delineation of the cluster boundaries using combination of K-means clustering and Voronoi diagrams. Average distance from the ground clusters have been determined as weighted Euclid distances:

$$D(i,k) = \sqrt[2]{\frac{1}{M}\sum_{j=1}^{M}(X_{i,j} - X_j^{(k)})^2}$$

where *D(i,k)* is distance from ground fragment to center of cluster *k*, *M* is the number of the fragments, *Xi,j* are coordinates of the fragments, *Xj(k)* is average distance from cluster *k* center to current origin of coordinates. These distances are recalculated iteratively in such a way that dispersion of the distances within a cluster was sought to a minimum, whereas variation of the distances between centers of the clusters pursued to maximum.

Computer simulation has demonstrated that such regularity takes place as the number of the clusters grows, and respective dispersions stabilize, what is a sign for finishing of cluster determination.

After this, boundaries of the clusters have been delineated using Voronoi diagrams. Figure 6 demonstrates overlay of the displacement field and Voronoi mosaic.

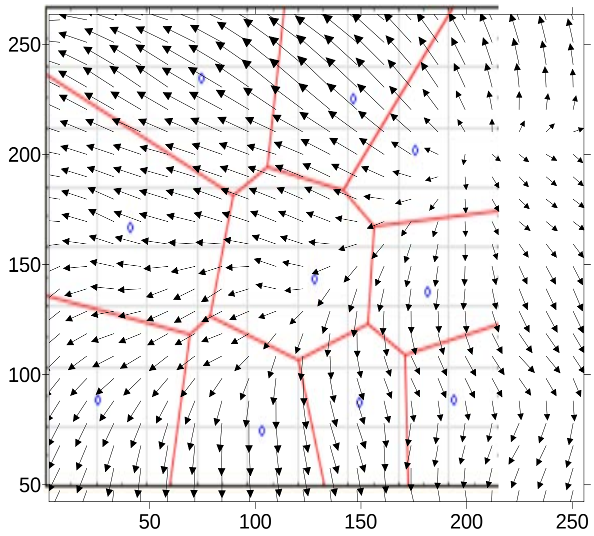

Figure 6. Overlay of the incremental displacements field and Voronoi diagram

Rate of the dissipative structures self-organization has been studied using variagram statistic of the nearest neighbors proposed by Karlis and Ntzoufras [10] and Malkov et al. [11]. It was found that conformity of the vectors orientation and their lengths is maximal at the beginning of the irreversible movement of the ground. For example, Skellam indicator was 560 at the beginning, whereas it dropped down to 176 or by 3.18 times as the sliding body accumulated emptiness and degrees of freedom (Figure 7).

The same behavior of the incremental vector coherence was registered on the other indicators. It means that maximal self-organization occurred at the beginning of the irreversible movement of the ground, when there were not sufficient degrees of freedom to enable dilatation of the sliding body and development of the landslide. However, separate ground fragments increase the opportunity to move and necessity for the self-organization decreases as the degrees of freedom accumulate.

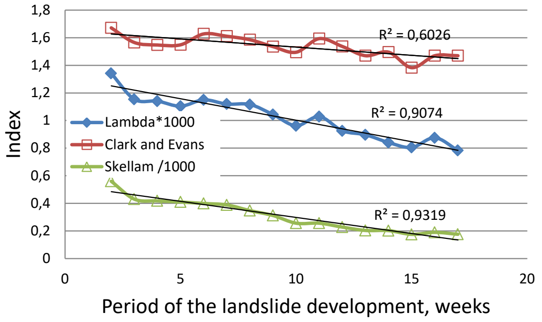

Figure 7. Decaying of the conformity indexes during development of the landslide

Discussion of the results.

Novelty of the dissipative structures unveiling in the sliding ground is essential. The author of this paper demonstrated that sliding ground is not a passive conservative system that slides under gravity force along the gradient of the gravity and, as a result, increases the entropy because of degradation from the fracturing and disorientation of the ground fragments. On the contrary, the ground mass disposed to the self-organization during the stage of irreversible movement and deformation. Ground fragments interact actively among themselves. This facilitate emerging of the dissipative structures, which evolve in forms of bifurcations that are triggered by stochastic fluctuations of thermodynamic parameters such as ground pressure, temperature, humidity.

Interaction between ground fragments is direct and occurs within the distance of fragments dimensions and may be assessed from several centimeters up to quite a few meters depending on the ground strength and fracture intensity.

Such interaction the author of this paper named as *short* one, as the adjacent ground fragments interact through the direct contact.

As a result of the self-organization, the short interaction of adjacent fragments transforms to *far* or *distant* interaction or cooperation of the clusters. This distant cooperation reflects in the emerging of the clusters and domains that move coherently, what provides accumulation of the degrees of freedom, which are used for development of the landslide.

These findings essentially develop modern understanding of mechanism and kinematics of irreversible movement of the ground that slides along the gravity gradient. So far, specialists consider landslide body as a passive conservative system. For example, Conte et al. [12] made an assumption, considering the sliding mass as a rigid body that slides without any deformation but major deformations occur along the contact of this body and sliding surface of the bottom ground.

On the contrary, sliding body experiences irreversible deformations accommodating them to minimize entropy production. It means the ground fragments and their clusters accumulate degrees of freedom involving coordination of their movement, interaction and cooperation, what enables development of the landslide. It would have lost the opportunity to progress the movement if there were not necessary degrees of freedom. Collapse of the ground is not sufficient condition for development of sliding without reserve of the degree of freedom.

Therefore, it is expedient to improve extant technologies for stabilizing of the landslides by restricting all the three degrees of freedom both translational and rotational. So far, these technologies restrain one major degree of freedom that coincides with the gravity gradient.

A popular technology allows preventing landslide development using piles. However, the piles resist to siding ground passively with reactive forces. The author of this paper has developed a method that employ three orthogonal systems of pretensioned cables, which suppress the dissipative structures and prevent development of a landslide.

Conclusion.

Dissipative structures in the ground, which transited into over-peak stress state, emerge because of short interaction of adjacent ground fragments and distant cooperation of their clusters. These dissipative structures may be detected through monitoring of incremental ground displacements in the range from two standard errors of measurement to ten standards. Centers of the clusters can be positioned using K-means clustering and their boundaries may be delineated by Voronoi diagram in Euclid space. This allows unveiling of the dissipative ground structures. New approach has been developed to provide stability of the ground restricting all the three degrees of freedom both translational and rotational.

Patterns of the dissipative structures in the ground are developed with the fields of incremental displacement. Length and orientation of the field vectors are different with Skellam indicator of 600-800 immediately after damaging of the ground, however spatial variation of the vectors decays proportionally to elapsing time as the landslide progresses because of accumulation of degrees of freedom. This allows developing new methods of reinforcing of the ground.

A new technology uses three systems of orthogonal pretensioned cables, which suppress evolving of the dissipative structures, thus reduces probability of the irreversible ground movement.

The author of this paper plans to investigate evolution of the dissipative structures in time and in space for different ways of the loading and boundary conditions.

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КЛАСТЕРНИЙ ХАРАКТЕР НЕОБОРОТНИХ ЗРУШЕНЬ ПІД ЧАС РОЗВИТКУ ЗСУВУ ҐРУНТОВОГО СХИЛУ

Метою роботи *є дослідити кінематику необоротних зрушень ґрунтової поверхні й масиву гірських порід під час розвитку зсуву схилу земної поверхні.*

Методи досліджень. *У роботі грунт, наноси й масив гірських порід розглядається як відкрита термодинамічна система, яка під час необоротних зрушень розсіює енергію гірського тиску, або/і потенційну енергію зсувної маси, яка сковзає уздовж градієнту сили тяжіння. Для дослідження кінематики зрушень застосовані геодезичні методи інструментальних спостережень, статистичного аналізу, а також обчислювальної геометрії.*

Результати досліджень. *Встановлено, що дисипативні структури у масиві гірських порід, що перейшов у позамежний стан, виникають у результаті близької взаємодії породних фрагментів й дальньої взаємодії кластерів і виявляються моніторингом його елементарних зрушень, величина яких знаходиться у межах 2-10 середньоквадратичних похибок вимірювання зрушень, причому центри кластерів визначаються методом К-середніх, а їх межі полігонами Вороного у Евклідовому просторі, що дозволяє виявити вказані дисипативні структури й обґрунтувати новий принцип забезпечення стійкості масивів гірських порід шляхом активного обмеження кількості (аж до трьох) поступальних й обертальних ступенів свободи масиву, що деформується у позамежному стані.*

Наукова новизна. *Вперше встановлено, що дисипативні структури, які розсіюють енергію гірського тиску змінюються внаслідок їх біфуркацій стрибкоподібно і мають паттерни у вигляді різнонаправлених незворотних зрушень короткоживучих кластерів й доменів масиву, які формуються з породних фрагментів, що забезпечує ступені свободи для розвитку й накопичень незворотних зрушень і деформацій; вперше доведено, що центри кластерів надійно визначаються методом К-середніх й полігонами Вороного у Евклідовому просторі; вперше встановлена близька взаємодія суміжних породних фрагментів та дальня взаємодія кластерів зруйнованого масиву.*

Практична цінність *роботи полягає в обґрунтуванні нового принципу забезпечення стійкості масивів гірських порід шляхом активного обмеження кількості (аж до трьох) поступальних і обертальних ступенів свободи масиву, що деформується у позамежному стані. На основі вказаного принципу розроблено нові способи управління стійкістю масиву гірських порід.*

Ключові слова*: масив гірських порід, необоротні зрушення, кластери, близька й дальня взаємодії.*

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КЛАСТЕРНЫЙ ХАРАКТЕР НЕОБРАТИМЫХ СДВИЖЕНИЙ ВО ВРЕМЯ РАЗВИТИЯ ОПОЛЗНЕЙ ГРУНТОВЫХ СКЛОНОВ

Целью *работы является исследовать кинематику необратимых сдвижений поверхности почвы и массива горных пород при развитии сдвижения склона земной поверхности.*

Методы исследований. *В работе грунт, наносы и массив горных пород рассматривается как открытая термодинамическая система, которая при необратимых сдвижениях, рассеивает энергию горного давления или / и потенциальную энергию оползневой массы, скользит вдоль градиента силы тяжести. Для исследования кинематики сдвижений применены геодезические методы инструментальных наблюдений, статистического анализа, а также вычислительной геометрии.*

Результаты исследований. *Установлено, что диссипативные структуры в массиве горных пород, перешедших в запредельное состояние, возникают в результате близкого взаимодействия породных фрагментов и дальнего взаимодействия кластеров и обнаруживаются мониторингом его элементарных сдвижений, величина которых находится в пределах 2-10 среднеквадратических погрешностей измерения сдвижений, причем центры кластеров определяются методом К-средних, а их границы полигонами Вороного в евклидовом пространстве, позволяет выявить указанные диссипативные структуры и обосновать новый принцип обеспечения устойчивости массивов горных пород путем активного ограничения количества (до трех) поступательных и вращательных степеней свободы массива, деформируется в запредельном состоянии.*

Научная новизна. *Впервые установлено, что диссипативные структуры, рассеивают энергию горного давления изменяются в результате их бифуркаций скачкообразно и имеют паттерны в виде разнонаправленных необратимых сдвижений короткоживущих кластеров и доменов массива, которые формируются из породных фрагментов, обеспечивает степени свободы для развития и накоплений необратимых сдвижений и деформаций; впервые доказано, что центры кластеров надежно определяются методом К-средних и полигонами Вороного в евклидовом пространстве; впервые установлена близкое взаимодействие смежных породных фрагментов и дальнее взаимодействие кластеров разрушенного массива.*

Практическая ценность *работы заключается в обосновании нового принципа обеспечения устойчивости массивов горных пород путем активного ограничения количества (до трех) поступательных и вращательных степеней свободы массива, деформируется в запредельном состоянии. На основе указанного принципа разработаны новые способы управления устойчивостью массива горных пород.*

Ключевые слова: *массив горных пород, необратимые сдвижения, кластеры, близкое и дальнее взаимодействие.*

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