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ORIGINAL PAPER

CLUSTER BEHAVIOR OF THE GROUND DURING ITS IRREVERSIBLE MOVEMENT

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ABSTRACT

Irreversible behavior of the ground or a rock mass encompasses both the transition of the ground over a peak strength and further development of the nonreversible movement and deformation. The irreversible ground movement is traditionally considered as the transition to chaos. However the moving ground passes through itself the energy of ground pressure, thermal energy, and exchanges by substances with surrounding rock mass. According to thermodynamics of irreversible processes, such a non-equilibrium ground behavior may create dissipative structures that are the embodiment of self-organization. The paper describes the results of the structures investigation, which have been unveiled with incremental fields of the irreversible ground movement during a landslide development and underground roadway maintenance. These structures were evolving from close interaction of the separate blocks or fragments of the ground and distant cooperation of the short-lived clusters that were periodically rearranging in time and space as the irreversible ground movement started and progressed. Extant techniques restrain basically one prevalent component of the irreversible ground movement. The other two collateral transversal components were usually ignored. However, blocking of these transverse components can prevent the development of a dangerous irreversible movement of the ground and a rock mass.

1. INTRODUCTION

Investigation of irreversible behavior of the ground and rock masses is an important part of geomechanics (Kumsar et al., 2016), civil engineering (Bloodworth, 2002) and structural geology (Wilson et al., 2016). In contrast to elastic behavior, the nonreversible movement and deformation may cause disintegration of a rock mass (Malinowska and Hejmanowski, 2016), damage of a support and even failure of an underground or a civil structure, and trigger landslides. For instance, a roof fall in an underground opening is preceded with the irreversible movement of the roof rock layers. Nonreversible deformation of a dam foundation after its consolidation deteriorates stability of the dam eventually. A dangerous landslide evolves after the accumulation of irreversible ground deformations.

On the other hand, the irreversible rock mass movement is the natural process that follows roof weighting in an advancing longwall face. Garvey and Ozbay (2013) illustrate that delay of the roof caving causes a danger of a catastrophic roof bump. Therefore a rock irreversible movement may be desirable in this case. Also, the irreversible flow of the Earth crust was the main process which has formed the modern rock mass structure during certain geological periods (e.g. Wallis et al., 2015), so geologists use this structure to investigate geological processes. Furthermore, the irreversible deformation of a rock mass accumulates long before its collapse as demonstrated by Grenon et al., (2017) despite the generally accepted theory separates process to elastic (Devies and Selvadurai, 1996) and post-peak stages (Jaeger and Cook, 1969). Therefore the irreversible ground movement is inherent in many geomechanic and geologic processes and plays the important role in safety maintenance and formation of the complex structures and their evolution. That is why the irreversible behavior of the ground and rock masses is of constant interest for researches.

Any irreversible process reflects a specific behavior of a thermodynamic system (Kondepudi and Prigogin, 2015). The irreversibility involves the accumulation of the entropy. If a thermodynamic system is open – namely exchanges by energy and substance with its surrounding – it becomes dissipative and tends to form a structure or to transfer to the self-organized state. According to Kondepudi et al. (2015), certain structure might emerge as the dissipative system when the excess of entropy production is negative. The ground and a rock mass are the typical thermodynamic systems. Their structure might appear in different patterns: the seismic waves during an earthquake, specifically oriented fracture systems (Jaeger et al., 1969), the folds as a result of the Earth crust flow (Bigoni and Gourgiotis, 2016), and thin details of the strain facies, which Tikoff and Fossen (1999) demonstrated. Seismologists developed a set of experimental and numerical methods to visualize the seismic waves that

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decay due to irreversible processes in the crust. The structures of a deformed rock mass have been traditionally investigated by geologists as a final "frozen" result of the crust flow during geologic epochs. However, a wide range of irreversible processes in the ground and the rock mass remains unexplored from the perspective of self-organization state investigation.

So far, evolution of the rock mass around an underground excavation has been considered as the rock and ground deterioration that follows with reduction of the rock strength and increase of the entropy. For instance Kumsar et al. (2016) associated growth of the entropy with the rock collapse, and Lombardo et al. (2016) related increase of entropy to the triggering of a landslide. However, this deterioration leads to the chaos, whereas development of a structure contributes to an order. The seismic waves and the ancient geological structures are apparent and easily attracted attention of researches. However, self-organized structures that might emerge during progressive landslide development, ground subsidence over extracted longwall panels, floor heave in an underground roadway, a pile driving, may be more delicate and subtle. These structures may mask and do not express explicitly. An important question is how do disintegrated fragments of the ground move relatively each other? How do they coordinate their movement?

The traditional approach to consideration of the irreversible deformation relies on the selection of a relevant constitutive model. It is believed that an appropriate constitutive model automatically provides reliability of the irreversible process expression as a whole. However, researchers apply the results of rock samples testing to construct a constitutive model, whereas irreversible processes encompass much more volume of a rock mass that disintegrates into myriads of such samples or fragments, which cooperate during irreversible movement. In addition, any constitutive model implies a certain deterioration of the rock. How this degradation may convert to self-organization of the structures? As Peng (2015) indicated, the problem of selection or development new constitutive models remains of vital importance despite the good agreement between the model forecast and the experiment. An important reason may be the difference between the behavior of the rock sample or a fracture according to chosen constitutive model and behavior of the rock mass as a whole body. Consideration of a possible self-organizing process during the irreversible deforming of the rock mass may cover this gap. Furthermore, the theory of irreversible thermodynamics implies a possible self-organization of a ground body or rock mass volumes that pass through them the flow of ground pressure energy, underground water or gas, and are in a non-equilibrium state of progressive moving and deforming.

Therefore this paper presents a theoretical assessment of a possible event in a form of self-organization of a ground body or a rock mass volume during their irreversible moving and deforming. Researchers have not emphasized on the ground self-organization. The most probable reason is this state has been overlooked in spite of the numerous set of sophisticated methods and technologies for monitoring of irreversible processes of the ground and rock mass movement. Hence the choice of a relevant method may assist detecting of a new feature of self-organizing behavior in addition to apparent folding, fracture system generating, or strain facies emerging. Investigation of the ground irreversible movement and deformation can help to find additional patterns of self-organization and to develop specific measures that reduce negative effects or amplify positive features of self-organized states during irreversible moving and deforming of the ground and the rock mass.

The aim of this paper was to demonstrate that irreversible ground movement may self-organize producing complex dissipative structures. In this paper, we accomplished such tasks:

(i) We made theoretical consideration of a possible self-organization of the ground and a rock mass during their irreversible moving and deforming.
(ii) Chose a relevant method for monitoring of the ground irreversible movement and deformation for detection of the structures and self-organized states.
(iii) Investigated process of irreversible moving and deforming and find new patterns of self-organization.
(iv) Developed specific measures that reduce negative effects or/and amplify positive features of self-organized states during non-reversible moving and deforming of the ground and rock mass.

2. THEORETICAL CONSIDERATION OF A POSSIBLE SELF-ORGANIZATION OF THE GROUND AND A ROCK MASS DURING THEIR IRREVERSIBLE MOVING AND DEFORMING

Let us consider a ground volume, the thermodynamic state of which is far out from equilibrium. The main peculiarity of such system is the possibility to form an ordered in time and space structures using external energy from the surrounding. These structures can persist only due to the external energy flow that allowed calling these systems as 'dissipative'. According to Glensdorf and Prigogine (1971), such self-organization of ordered structures is possible only if there is a *cooperation* of system's components. Haken (1981) pointed out that these components feel mutual influence.

Giving (Glensdorf et al., 1971), the thermosdynamic system will evolve in self-organized state if

$$d\acute{S}/dt=\int I(dX/dt)dv\leq 0 \qquad (1)$$

where $\acute{S}$ is the entropy production, t is time, I and X are thermodynamic flow and force in that order, v is an elementary volume of the system through which the integration accomplished.

Let us consider a ground body or a rock mass volume that surrounds an underground roadway. The irreversible behavior of a continuum ground starts

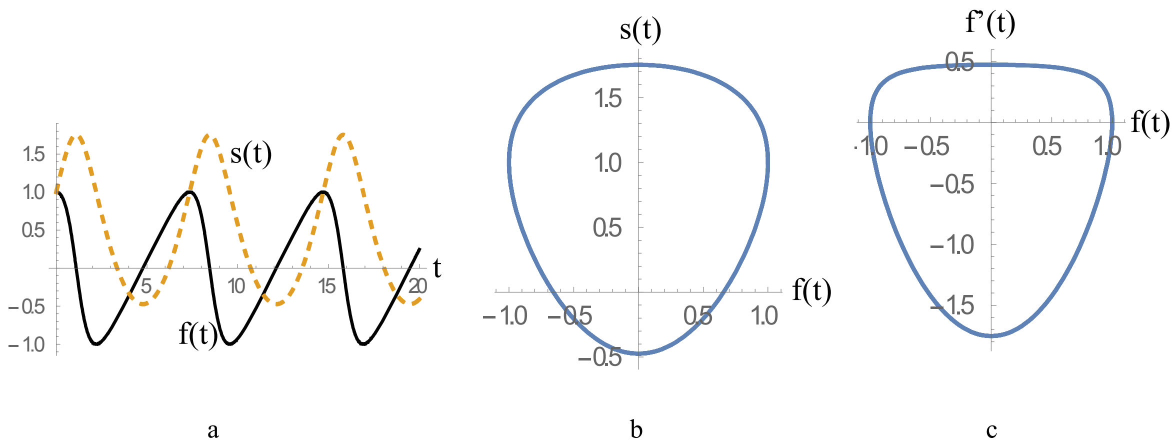

Fig. 1 Results of system solving: variation of active fractures and stress in time (a); phase portrait of the system in s-f (b) and f'-f coordinates (c).

from its disintegration. Any discrete body of a rock mass accumulates the irreversible deformation due to aperture variation of the existent fractures or sliding adjacent blocks along the boundaries of the fractures and the gaps. The expansion and the sliding produce irreversible movement of the rock blocks and, as a consequence, irreversible deformation of the whole body of the rock mass. When separate blocks of a ground converge and the fractures or the gaps close, the domains or clusters composed of the consolidated blocks moves and deforms as a monolithic body.

It should be stressed that the plastic irreversible deformation occurs due to sliding along the shear bands (Bigoni, 2012) which are natural boundaries between separate clusters or elementary volumes of the plastic ground. These shear bands are the natural boundaries between adjacent clusters. Let us call the fractures and the shear bands as 'active boundaries' (AB for short) if they participate in the accumulation of the ground irreversible deformation. Elastic deformation of the blocks and clusters are reversible and do not contribute to the irreversible process. Therefore discrete blocks (in a discrete brittle rock mass) or discrete clusters (in a plastic ground) are the natural components that comprise the ground volume as a thermodynamic system. It does mean that cooperation of these blocks and clusters is the way to create a well-organized in time and space structure due to the irreversible moving and deforming of the ground.

The process of AB evolution can be described in terms of ground pressure s and AB density f because s is the thermodynamic force in the case and f is the thermodynamic flow. Requirement $f>0$ is the mandatory condition for active irreversible deforming of the whole ground body and irreversible moving and deforming of the separate components (blocks and clusters). We will use ABs only in the case, whereas those fractures and shear bands that are not in process of active deforming are excluded from consideration. The transition of AB in an active state and vice versa means that they may vary during irreversible deformation of the ground. Variables f and s are functions of time (t) and will be analyzed in certain local volume of a ground in the vicinity of the underground opening.

Fracture area has the quadratic dimension. It means the rate of AB density increment may be proportional to the square of the AB. On the other hand, AB density reduces as the ground pressure rises because Coulomb friction prevents sliding and is proportional to the pressure. Such simple assumptions yield first differential equation:

$$f'(t) = -s(t) + f(t)^2 \quad (2)$$

We also may assume that the rate of ground pressure is proportional to AB density because the higher the pressure the more probable destruction of the ground or the rock mass in vicinity of the underground excavation:

$$s'(t) = f(t) \quad (3)$$

The system (2-3) has been solved for the simplest initial conditions:

$$f(0) = 1, \; s(0) = 1 \quad (4)$$

indicating, that active fractures were present when analysis of the irreversible process of the ground moving and deforming had started.

Figure 1 demonstrates the solution and the phase portraits of the system (2-3). Fragment (a) indicates to the periodic variation of the fracture density and ground pressure. Fragments (b) and (c) depict cycles that clearly demonstrate that the dissipative system has generated the time-dependent structure. However, the most reliable proof of the time and space structures rests in an experiment because significantly more variables cooperate in reality and their interdependences are much more complex.

3. SELECTION OF A RELEVANT METHOD FOR MONITORING OF THE GROUND IRREVERSIBLE MOVING AND DEFORMING FOR DETECTION OF STRUCTURES AND SELF-ORGANIZED STATES

The methods that structural geologists use to recover historically formed structures in the crust are not applicable for the unveiling self-organization and new patterns of a structure because only the final states of the structures are available *in-situ*. However, any irreversible process is path-dependent, thus the structures might vary both in time and space during their developing. Therefore the concrete path of the irreversible process or its history should be monitored in order to reveal the structure dynamics and important details of the self-organization. This means the monitoring should be carried out continuously in time and in space. The most popular method that satisfies this conditions and requirements is micro-seismic monitoring (Lei et al., 2016; Yu et al., 2017). The micro-seismic monitoring provides continual registration of the dynamic events that have been triggered by the collapse of the ground or growth of a fracture (Cui et al., 2016). The majority of observations have demonstrated that intensive micro-seismic events follow the sources of ground agitation by artificial or natural processes, for instance, underground roadway driving, a longwall face advance, pillars forming, injecting of fluids during hydro-fracturing, landslides development. In spite of the fact the clouds of micro-seismic activity are apparently tied to these processes, development of the clouds occurs chaotically in a random manner. At least, experimenters have not noticed the signs of self-organization or certain obvious structures so far. To say otherwise, micro-seismic monitoring has not helped to reveal the cooperation among the blocks or clusters during active irreversible deforming, sliding, or moving of the ground.

Registration of the blocks movement and clusters displacement is another popular method that is used for monitoring of the irreversible ground movement. Amitrano et al. (2007) illustrated the results of such monitoring during a mudslide progress investigation in a mountainous region. They demonstrated integral displacement field and average velocity distribution of ground movement. Vectors of ground displacement report obvious facts, namely the mud moves according to gravity gradient along ravine axis; moreover, the forefront outpaces the tail part of the slide that indicates to dilation of the mud body. This information does not add a new essential knowledge and does not provide evidence concerning a possible structure formation. On the contrary, the distribution of the ground velocity demonstrates an unusual behavior of the sliding ground. The average velocity of the central cluster of the mudslide is more than the velocity of surrounding peripheral ground mass, although the central cluster is not the front-runner part of the slide.

It is evident that process of sliding is not as simple as the displacement field reported. This experimental fact can be considered as a hint that indicates to a complex hierarchy or a structure of the landslide. However, this possible structure has been hidden because integrating approach, namely the mud movement was indicated as a total displacement during 8-year period, and the sliding velocity was averaged. Therefore an incremental approach should be used to recover the history of monitored irreversible ground movement. The advantages of the incremental attitude have been reported for different cases (Bloodworth, 2002; Lia et al., 2016; Huang, 2016). As was mentioned above, irreversible behavior is path dependent, therefore the incremental methodology is the best way to reveal this behavior in details because individual increments of non-reversible movement may have opposite signs and thus annihilate each other.

The trial and error method has shown that visualization of the displacement field in a form of incremental vectors is an appropriate technique to unveil the structure in the moving ground. However, unlike the distribution presented by Amitrano et al. (2007), time increment should be as small as possible, what assures that the finest details of the irreversible movements will not be lost. Practically, such method is available for recovering of a structure on the ground surface, for example on the roof of an underground roadway or on the landslide surface. Length l of a vector is:

$$l=\sqrt{(\Delta x^2 + \Delta y^2)} \quad (5)$$

where $\Delta x=x_{t-1} - x_{t}$, $\Delta y=y_{t-1} - y_{t}$, x and y are the coordinates of a fixed point on a plane. This plane should approximate the surface of the ground on which displacements are monitored. Subscript t indicates the current state of the ground, whereas index $t-1$ denotes its previous state.

Traditionally, points on the ground surface are fixed with monuments or benchmarks, and the coordinates of these benchmarks are measured geodetically. In addition, modern applications in remote sensing such as synthetic aperture radars (Assilzadeh et al., 2010; Delbridge et al., 2016) may be used. The time interval between successive measurements should be chosen in such a way that l would be essentially more than error of measurement, for instance, more than three standards of the error. However, some important details of structures evolution will be missed if the interval of duration growths.

Examples of the incremental analysis will be demonstrated in the next paragraphs for the cases of a landslide progress and displacement of surrounding rock mass in an underground roadway.

4. INVESTIGATION OF STRUCTURES DEVELOPMENT DURING LANDSLIDE PROGRESS

Figure 2 demonstrates a steep shore near shallow inland Sea of Azov which is connected to the Black Sea (Nazimko and Nazimko, 2002b). A clay ground composed the coastline which is in the state of slow permanent sliding similar to the mudslide reported by Amitrano et al. (2007). Slowly developed landslides are typical phenomena as Zerath et al. (2016) stated. Sea waves deteriorate, dissolve the shore and absorb diluted clay removing the retaining action that supports the steep ground. Eventually, this steep shore loses stability and slides down to the sea. The probability of the landslides increases after a long period of precipitation. Massive landslides occur often

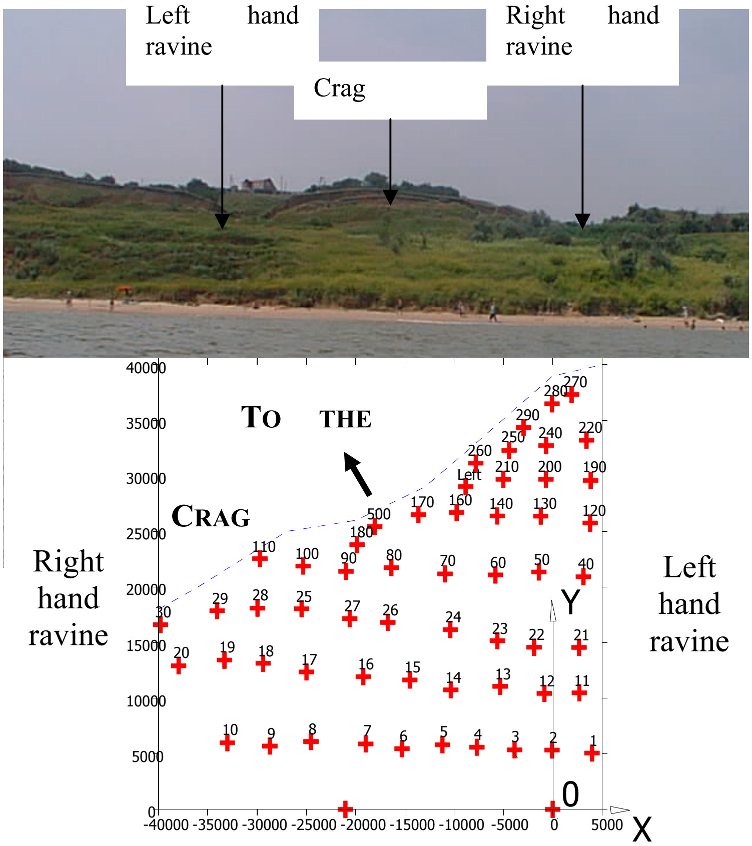

Fig. 2 View of the progressing landslide (a) and layout of the monuments (b).

in spring periods. The climate at the area is dry and intensive precipitations happen once during 5-10 years. Therefore activation of the landslides follows these periods of ground wetting. Monitoring of a slowly developed landslide is the best way to capture the ground structures in details.

The total height of the shore above the sea level typically ranges between 20 m and 30 m. The average slope of the shore is 20^0 but sometimes reaches 30^0 and more. Fine homogeneous brown clay having density from 1850 to 2040 kg/m^3 represents ground at the site. This clay becomes a perfectly plastic material when saturated with water. Uniaxial compressive strength (UCS) of a dry sample that contains 4 % of water was approximately 18 MPa and collapse of the sample occurred at a strain level of 0.018. After this collapse, the resistance of the sample reduced quickly. After absorption 33 % of water, the clay barely resisted to compression at the level of 1 MPa and maximum resistance occurred at a strain level of 0.05. Approximately the same level of the resistance kept up to the strain of 0.2 what demonstrates perfect plastic properties of the clay ground. Limit of tension varied in the range from 0.35 to 0.55 of UCS.

We monitored geodetically irreversible sliding of a crag that was surrounded with two deep ravines. The standard error of displacement measurement was 2.1 mm. We installed sixty-five monuments on the surface of the landslide area approximately 40 m by 30 m (Fig. 2b). The average distance between adjacent monuments varied between 3 m and 5 m. Two sessions of geodetic measurements were accomplished during 44 days period.

Incremental displacements of the monuments were determined as a difference between successive and subsequent measurements. These data were interpolated and used to design the incremental vector distribution (Fig. 3). The step of gridding was comparable to the average distance between adjacent monuments that prevented possible distortion of experimental results.

Field of displacements was apparently divided into clusters. It is possible to separate the ground surface with several methods. To delineate these clusters, we used different colors for upright, up left, down right and down left vectors. Such fist approximation is relevant because it is impossible to exactly detect the defects that existed in the ground before the experiment. The whole area near the sea is in permanent slow movement and there was a great number of fractures, shear bands, and the other defects before the experiment started. Therefore a comparison of the measured deformations and of the peak (allowable) deformation is not relevant in the case because any level of the deformation can be overcritical (irreversible).

Maximum movement of the ground was 49 mm. An experimental area separated to 15 apparent clusters having dimensions from 2 to 10 m. Cluster 1 slipped to the right-hand ravine and cluster 2 moved to the opposite direction that resulted in the divergence between these clusters. In Figure 3, the empty arrow

a b

Fig. 4 View of the model front (a) and top (b).

indicates a fracture fragment that emerged between these clusters. While cluster 2 moved to the west, cluster 8 displaced to the opposite direction. Clusters 3 and 4 separated from the other ground and are going to fall down. Clusters 6, 7, and 15 drifted into a left-hand ravine. Pairs of clusters 12, 15 and 9, 10 created two clockwise vortexes.

Therefore despite the general trend of the slide movement to the sea, forty-four-day incremental displacements demonstrated different directions of clusters' movement and their unusual behavior. The landslide separated into clusters and developed through their asynchronous movement. The direction of separate cluster incremental displacement does not concord with the general direction of the landslide development (to the sea). Some clusters converged whereas other diverged. Groups of selected clusters created vortex structures. Apparently, adjacent clusters cooperated that promoted self-organization of the ground movement.

Physical modeling helped to study the landslide in more details. The landslide was investigated in the physical model in geometric scale 1:200. Dimensions of the model were 8 cm left height, 7 cm right height, 34 cm width and 20 cm length (Fig. 4). Therefore the model represented the behavior of the seashore along the distance of 68 m. Slight gradient from the left to the right, viewing from the seaside, reflected real inclination of the land in situ.

Dynamic scale factor may be calculated according to the formula:

$$F_n/F_m = (200/1)\bullet(\gamma_n/\gamma_m) \quad (6)$$

where F_n and F_m have force or stress dimension and are physical parameters of natural ground and model synthetic material; γ_n and γ_m are corresponding densities.

Synthetic material was composed of fine sand (grain size <0.8 mm), cement, gray clay and water in proportion 94:3:1:2. This mixture has been poured by layers into a box having sidewalls and back wall and consolidated by the pressure of 15 kN. Density of this mixture after compression was 1550 kg/m^3. To satisfy the dynamic scale factor, UCS of the synthetic material should be in the range from 0.072 to 0.004 MPa. To simulate deterioration of the ground strength due to its saturation with water and to accelerate the process of modeling, vibration technique has been employed. The power of a vibrator was 50 W, frequency and magnitude of vibration were 50 Hz and 0.5 mm. The vibrator has been fixed to the bottom of the model.

Subsidence of the model surface has been measured by a ruler with standard error of ±1.5 mm. Displacements in the horizontal plane (X and Y – displacements) were registered by a digital camera and processed by special software. One pixel in a picture corresponded to 0.56 mm in the model. Errors of measurement of X and Y–displacements registration was ± 2.35 pixels or ± 1.32 mm with the confidence of 95%. Pictures of the model were made every time when apparent modification of the model state has been registered during consecutive stages of the landslide development. This helped to assemble maximum information concerning the complex behavior of the ground during generation and development of the landslide. We have made 32 pictures during the experiment and chosen 17 pictures to create the incremental fields of ground deformation.

Stages 1 through 8 reflected an incubation period during damage accumulation and preparation to ground separation development. Figure 5a demonstrates the typical patterns of ground incremental movement during 7th stage. The movement generated clusters divergence, their counter motion, mutual sliding and the creation of vortexes like those registered in situ. The ground mass organizes itself into clusters that interact and rearrange during the ground sliding.

Even after sufficient destruction and separation, ground and rock blocks should adjust their mutual movement, rotating, changing the velocity of their movement and even its direction. The vortex pattern of incremental movement is the most probable between the adjacent clusters moving with different velocity or in opposite directions. That is why we registered both in situ and in physical model complex cluster organization, vortexes and unusual behavior of ground clusters including short-term incremental movement in the direction that is opposite to sliding of the whole body of the ground.

Such complex behavior occurs at initial stages of the landslide development when there is not sufficient space for the movement. The pattern of ground self-

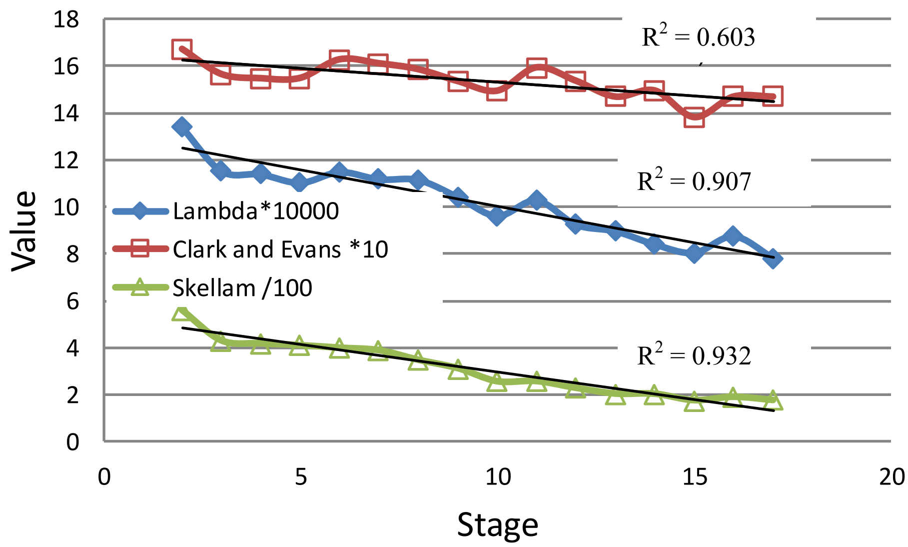

Fig. 6 Decay of spatial randomness of incremental vectors.

organization evolves from a complex versatile and clearly expressed set of bocks, clusters, and vortexes during landslide development to a simple picture of straightforward flow in the slide direction, when disintegrated ground accumulates sufficient degree of freedom and dilation. In fact, variogram analysis of the nearest neighbor statistics (Noel, 1991) has demonstrated that complete spatial randomness of the incremental vector length and direction were decaying as the landslide has developed (Fig. 6). The higher Clark-Evans index (Clark and Evans, 1934) or Hopkins-Skellam factor (Hopkins and Skellam, 1954) the more probability that there is an aggregation of the vectors. All diagrams in Figure 6 quantitatively corroborated that self-organization process subsides actually because these indexes decreased steadily.

The cluster organization is manifested not only in the mutual arrangement of the movement but also in involving of hierarchy (Fig. 7). For instance, to continue the process of sliding, the clusters at stage 7 should rearrange and give origin to new clusters at stage 8. Meantime, some clusters existing at stage 7 should collide at stage 8. The majority of the antecedent clusters mentioned above should collide to create large clusters-offspring at the 9th stage of sliding. Hence we may notice the hierarchy of solid blocks – clusters. Blocks create short-lived clusters that disintegrate to produce new clusters. Thus a cluster may split into clusters and blocks eventually. Rearrangement of the clusters might be followed by cutting of the ground or rock blocks because the boundary of a cluster-ancestor may not coincide with the boundary of the cluster-offspring. Sliding may develop only if the separated blocks will adjust their mutual movement, rotating, changing velocity and direction of sliding, and organizing into clusters of the blocks. These clusters obey the hierarchy that demands them to reunite during sliding.

Figure 7 can illustrate this conclusion where mosaics of the clusters at stages 7, 8, and 9 have been overlapped. The nature chooses such a way of slide development that energy spent for this process would be minimal or, in other words, the same amount of energy produces minimum entropy. It does mean that process of ground sliding combines the rock block destruction, the clusters rearrangement and their recombination in time and in space to dissipate the difference of the potential energy due to loss of the height level.

There is another peculiarity of this pattern of ground self-organization: adjacent blocks and clusters promote their cooperation giving the way one after the other, moving in turn, alternatively. Next paragraphs explain this behavior.

5. SHORT INTERACTION OF ADJACENT FRAGMENTS OF THE GROUND

Alternative irreversible movement of the adjacent ground blocks has been investigated in an underground head entry at the depth of 540 m. The head entry provided fresh air for a longwall face that retreated with the rate of 3.1 m per day and extracted 1.8 m coal seam which had UCS of 20 MPa. Section of the entry was of arched shape and had the area of 13.7 m^2. The entry has been supported by fully encapsulated rock bolts, 5 bolts in a row and 1 m between the rows.

The angle of inclination of the strata was 6^0. The immediate roof of the coal seam consisted of 10 to 12 m of sandy shale having UCS of 30 MPa. This was overlain with a competent thick layer of sandstone. The immediate floor of the coal seam was represented with 1 to 1.5 m sandy shale having UCS of 27 MPa and followed by 2 m sandstone with UCS of 50 MPa. Three-meter shale layer followed this sandstone.

Non-reversible roof movement has been monitored on a set of 9 rock bolts. Plan view of the set depicted in the fragment (c) of Figure 8. Dimensions a_i were parallel to the entry center line, moreover $a_{2\text{-}5}$ and $a_{5\text{-}8}$ coincided with it, whereas intervals b_i were normal to the axis. The distance between adjacent bolts was about $a_i = b_i = 1$ m. Distance a_i and b_i

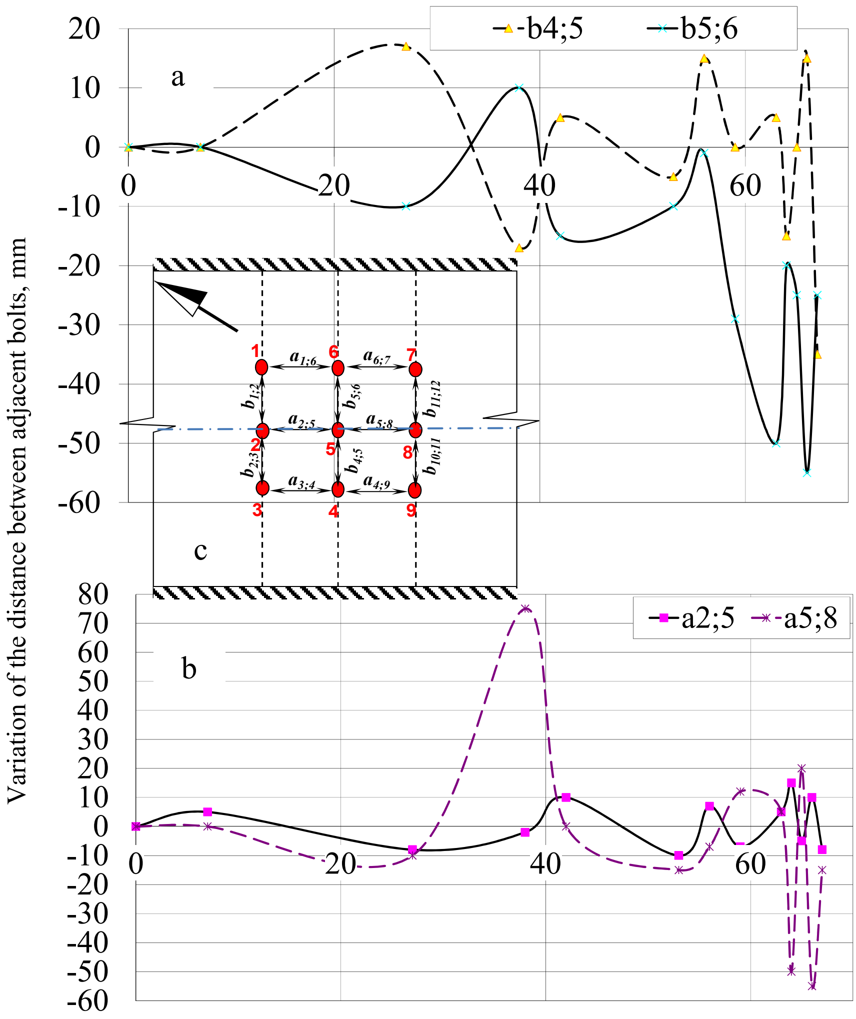

Fig. 8 Variation of the distance between adjacent rock bolts along the head entry (a) and in its cross section (a); fragment (c) indicates to layout of the monitored bolts.

and subsidence of the experimental bolts were monitored periodically during retreating of the longwall face. The standard error of the measurements was ± 1.9 mm. The monitoring started when the longwall face was at the distance of 93 m from the nearest experimental bolt and finished when the face approached the experimental site. Fragment (a) and (b) in Figure 8 demonstrate the variation of a_i and b_i respectively.

An anti-phase pattern of incremental bolt movement prevails and is the most important peculiarity of the irreversible behavior of the rock mass in this experiment. When one pair of the bolts diverged, adjacent pair converged to yield room for the first pair. This behavior is apparent at the moments of 28, 37, 43, 63, and 66 days in fragment (a) of Figure 8 as well as on 37, 59, 64, and 66 days in Figure 8b. This behavior is typical and representative because the other pairs of the dimensions between the adjacent bolts demonstrated the same pattern of cooperation: the rock blocks gave the possibility to expand one after the other.

Such alternative and asynchronous deformation of the rock mass in horizontal plane eliminates the possibility of plane strain state in vertical section of a long underground horizontal roadway. For example, 56 mm expansion and 75 mm contraction of the roadway axis on the basis of 1 m do not allow considering its vertical section in plane strain state which is usually implied to employ a 2-dimensional computer model: variation of axial strain from -0.056 to +0.075 is much more than error of measurement.

Subsidence of the experimental bolts reflected the same anti-phase behavior (Fig. 9). Leveling of the bolts started earlier than monitoring of the distances between them; therefore the time scale does not coincide in Figures 8 and 9. However, right ends of the time scale matched actually. Bolts 4, 5, 7, 8, and 9 accelerated their subsidence at the moment I, whereas bolt 6 ceased to move actually.

At the moment II, vice versa, the five leading bolts delayed their downward movement, and bolt 6 speeded up the sagging over 50 mm. In addition, the final incremental subsidence of the bolts was essentially different. Furthermore, the greater incremental subsiding was experienced by bolts 5 and 9 which terminated their movement at the previous stage.

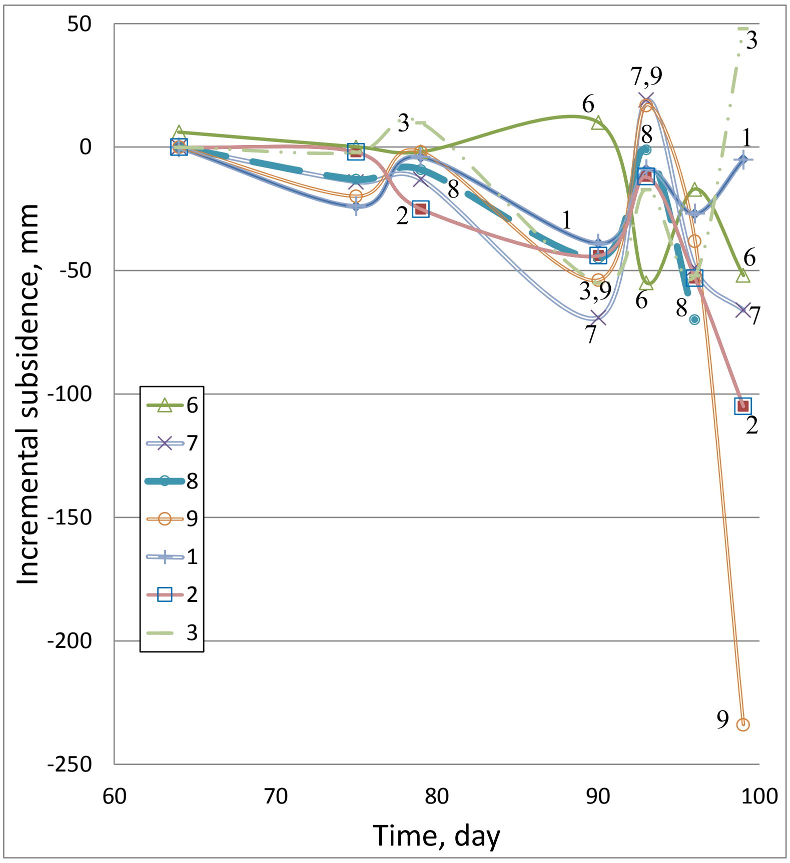

Fig. 9 Variation of the incremental subsidence of the monitored rock bolts.

This experiment demonstrated that the adjacent rock blocks alternated their horizontal movement and subsiding in turn giving the way one after other. Should the adjacent blocks do not cooperate they would not move or their movement would be blocked essentially. This behavior causes an important effect that will be discussed in the next paragraph.

6. SEQUENTIAL DEVELOPMENT OF THE DAMAGE ZONE AROUND AN UNDERGROUND OPENING

The alternative irreversible movement of the adjacent blocks describes a close interaction of the thermodynamic components of the ground. However, these interactions can generate a distant effect in the ground body as a whole as a result of the self-organization. This effect has been registered in a case of underground roadway maintenance (Nazimko et al., 1997). The main entry was driven in the 2.0 m shale layer at the depth of 820 m. The floor of the roadway consisted of 10.5 m argillite, and roof has been presented with competent 11 m sandstone overlain with a coal seam which has been extracted with a longwall face (Fig. 10). Plan view of mine map is shown in Y0X plane (fragment (a)) and vertical section of the strata is in Z0Y plane in fragment (b). Mechanical properties of the surrounding rocks presented in Table 1.

We monitored the evolution of the damage zone around the roadway using multi-point borehole extensometers. Fragment (c) of Figure 10 depicts the depth of the extensometer installation. The deepest extensometer in the roadway roof has been positioned at 13.9 m, in the sidewalls at 7.45 m and 10.2 m, in the floor at 7.9 m. Initial zone of damaged rock mass around the roadway was registered with the special optical device. The extensometers were installed before extraction of an adjacent panel.

Extraction of the coal in the 3rd east panel increased ground pressure and induced activation of rock mass movement around the experimental roadway. Figure 11 demonstrates strain of the ground after the longwall face of the 3rd east panel passed by the monitored site to the distance of 25 m and 182 m. The strain of the ground is indicated in mm/m and critical level of the tensile strain was 5 mm/m according to the rock samples testing. The tensile strain has a negative sign. Noticeably, the ground movement activation has been registered in the sides and the floor of the roadway during the initial stage of deformation, while the competent sandstone remained stable. Eventually, damage of the ground expanded to the roof (Fig. 11b) after withdrawal the face to 182 m. It is important to notice that compression zone emerged behind the tensile fronts of the overall damaged zone. This effect is natural and coincides with the coordination of tension-contraction of the intervals between adjacent bolts in Figure 8. The compression zone provides a room for dilatation of forefront sectors of the ground that follow the boundaries of damaged zone around the roadway.

Table 1 Mechanical properties of the rocks around the roadway.

Rock	UCS, MPa	Tensile strength MPa	Elasticity module, GPa	Peak strength at confined stress	
				10 MPa	20 MPa
Sandstone	63.0	3.0	23.0	290	360
Shale	48.1	0.5	13.0	117	133
Argillite	51.7	2.7	29.8	285	353

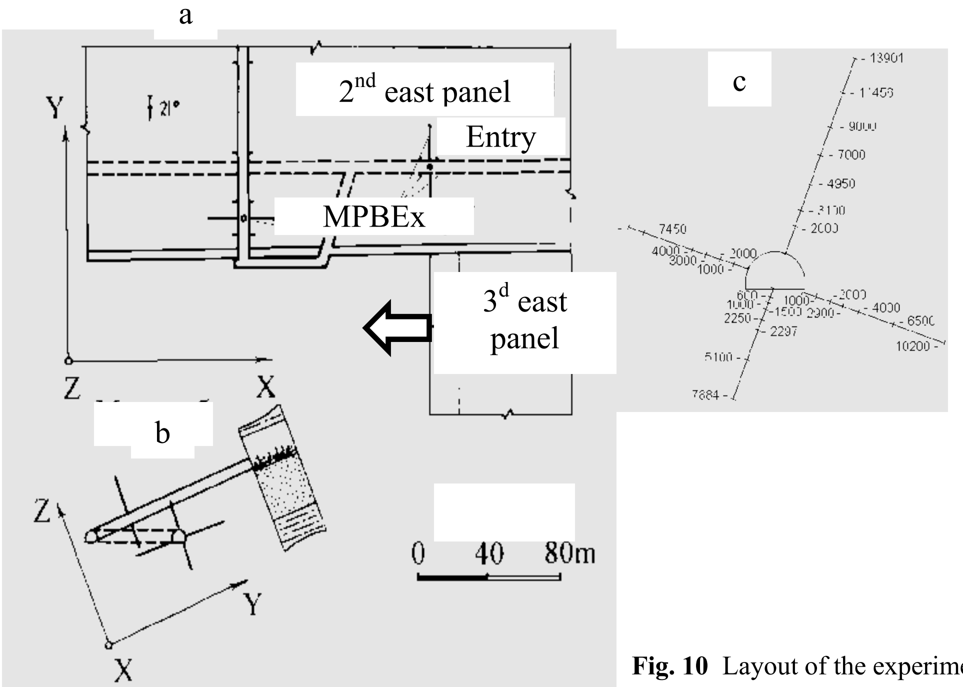

Fig. 10 Layout of the experimental site.

Figure 12 demonstrates the evolution of the damaged zone which expanded consequently in time and space. Position 1 indicates the zone boundary before the influence of the adjacent longwall. Dimensions of the damaged zone were 2.9 m in the floor, 2.7 m in the left side and the roof of the roadway, and 1.3 m on the right side. The adjacent longwall had disturbed stress state of the rock mass that induced consequent development of the damaged zone to the floor and to the right side of the roadway (position 2) then to the left side (position 3) and finally to the roof that indicated with position 4. Therefore rock mass self-organized the process of irreversible movement in the form of ground compression-tension (close cooperation) and sequential expansion of the damaged zone (distant cooperation) in time and space. Apparently, if this cooperation were blocked, the dimensions of the damaged zone would be smaller.

It is important that the patterns of the dissipative structures succeeded each other discontinuously in time and in space. This significant peculiarity has occurred both during the landslide progress and disintegrating zone development around the underground opening. The cluster mosaic shifted abruptly as indicated in Figure 7 likely the boundaries of the damaged zone, which expanded with discrete increments (Fig. 12). Such irreversible behavior of the ground is consistent with the bifurcations of dissipative structures that emerge discontinuously too (Glensdorf et al., 1971; Haken, 1981). Factually, the cluster mosaic bifurcates under random fluctuations of ground pressure, strength of the rock mass, its humidity, or temperature.

Paradoxically, these bifurcations occur during continuous changing of the irreversible ground movement as in kaleidoscope, incessant rotation of which produces images that replace each other discontinuously. Therefore, velocity of the ground movement as its derivative cannot serve as an indicator of the bifurcation. We found empirically that only monitoring of incremental irreversible displacement in diapason between 2 and 10 standard errors of measurement provides reliable unveiling of the dissipative structures.

Szafarczyk and Gawalkiewicz (2016) published results of landslides monitoring that may serve as a good independent confirmation of this diapason (Fig. 13). Standard error of the ground strain measurement was 0.28 mm/m and maximum registered strain was 0.7 mm/m or 2.5 times more. The arrow indicates general direction of the gravity gradient. It can be seen that there is not apparent correlation between the directions of maximal tensile strain and the gradient of the gravity. It means that Polish authors could delineate a ground clusters structure using incremental vectors of ground movement.

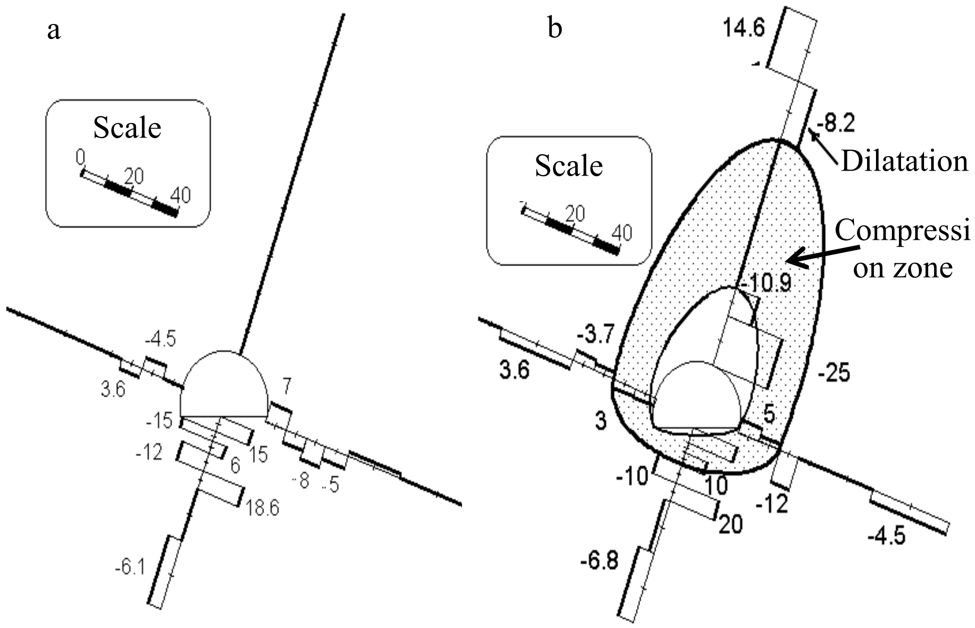

Fig. 11 Progress of surrounding rock deformation after withdrawal of the longwall face to 25 m (a) and 182 m (b).

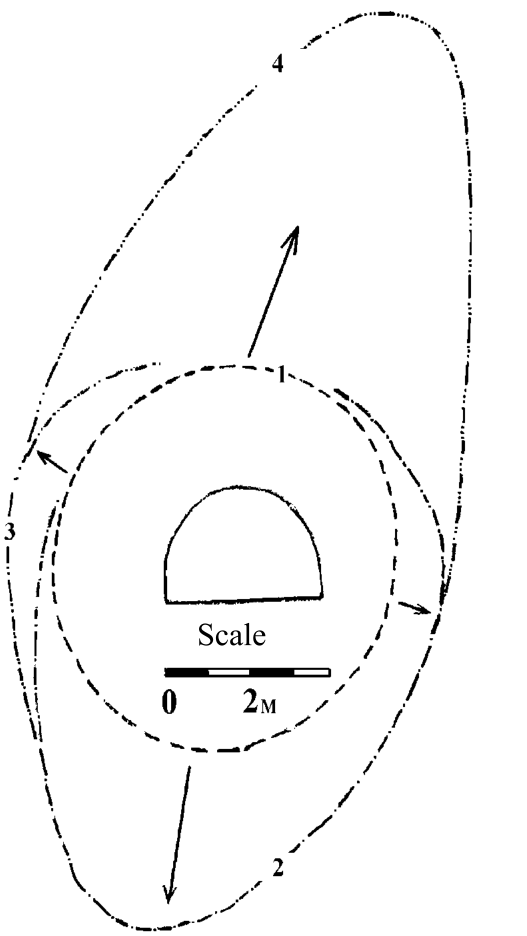

Fig. 12 Successive development of damage zone boundaries

Maximum strain of 34 mm/m has been registered during another case of slow landslide monitoring that was conducted in approximately same geographical and geological conditions. Strain distribution depicted in Figure 14 and demonstrates strong correspondence between directions of the strains and the gravity gradient because maximal strain is 121 times more than error of measurements. Ground displacement was integrated during such a long period that hid possible dissipative structures.

7. DISCUSSION

Self-organization of the irreversibly moving ground has theoretical and practical importance. In theoretical aspect, we for the first time proved that even deteriorating rock mass is capable to create the structures which organize and facilitate their irreversible movement to spend minimum potential energy for the same amount of the irreversible integral movement of the rock mass. This condition is governed by the second law of thermodynamics. Put it simply, the rock mass tends to move by the easiest way producing minimum excess entropy. We discovered specific patterns of the structures that promote transition to such the way, namely rock mass disintegrated into short-living clusters comprised rock blocks and fragments which converge, diverge, slide relatively each other, and create vortex patterns during the irreversible movement of the ground. It was found that such pattern is mandatory condition for development of irreversible movement of a rock mass or ground due to close interaction of the blocks and fragments and distant cooperation of the clusters. Therefore it is practically important that restriction of such self-organizing behavior enforces the rock mass to choose another and more energy-expensive way for the irreversible movement.

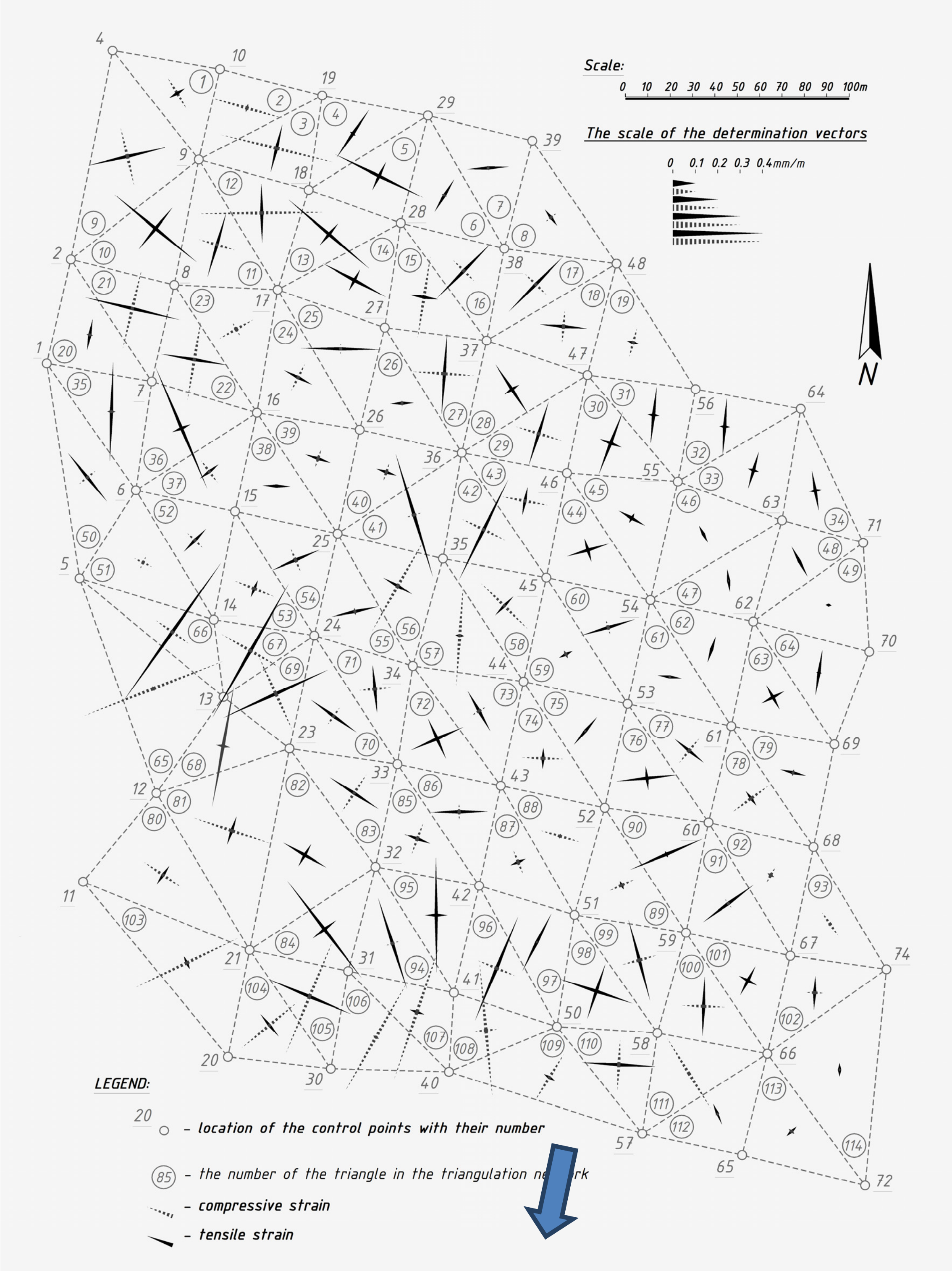

Fig. 13 Distribution of incremental strain during a slow landslide progressing: case 1, (Szafarczyk and Gawalkiewicz, 2016).

For example, the close interaction of the blocks and the distant cooperation of the clusters should be restricted to maintain the stability of underground constructions or natural ground slopes. Technically, we should restrain the alternative movement of adjacent blocks and clusters and prevent the sequential development of the damaged zone around underground constructions forcing simultaneous and concurrent expanding of the zones. To do this, we should constrain all components or degrees of rock mass freedom.

There is a prevailing component of ground movement usually. A sliding ground tends to move along a maximal gradient of gravity. Surrounding underground cavity rock mass moves into the opening: the roof moves along the gravity, the floor heaves in opposite direction, and the sidewalls move transversely to the gravity.

The most attention is usually paid to prevent general trend of ground displacement in 3D space. However, the other two collateral directions are considered as minor or peripheral and remain

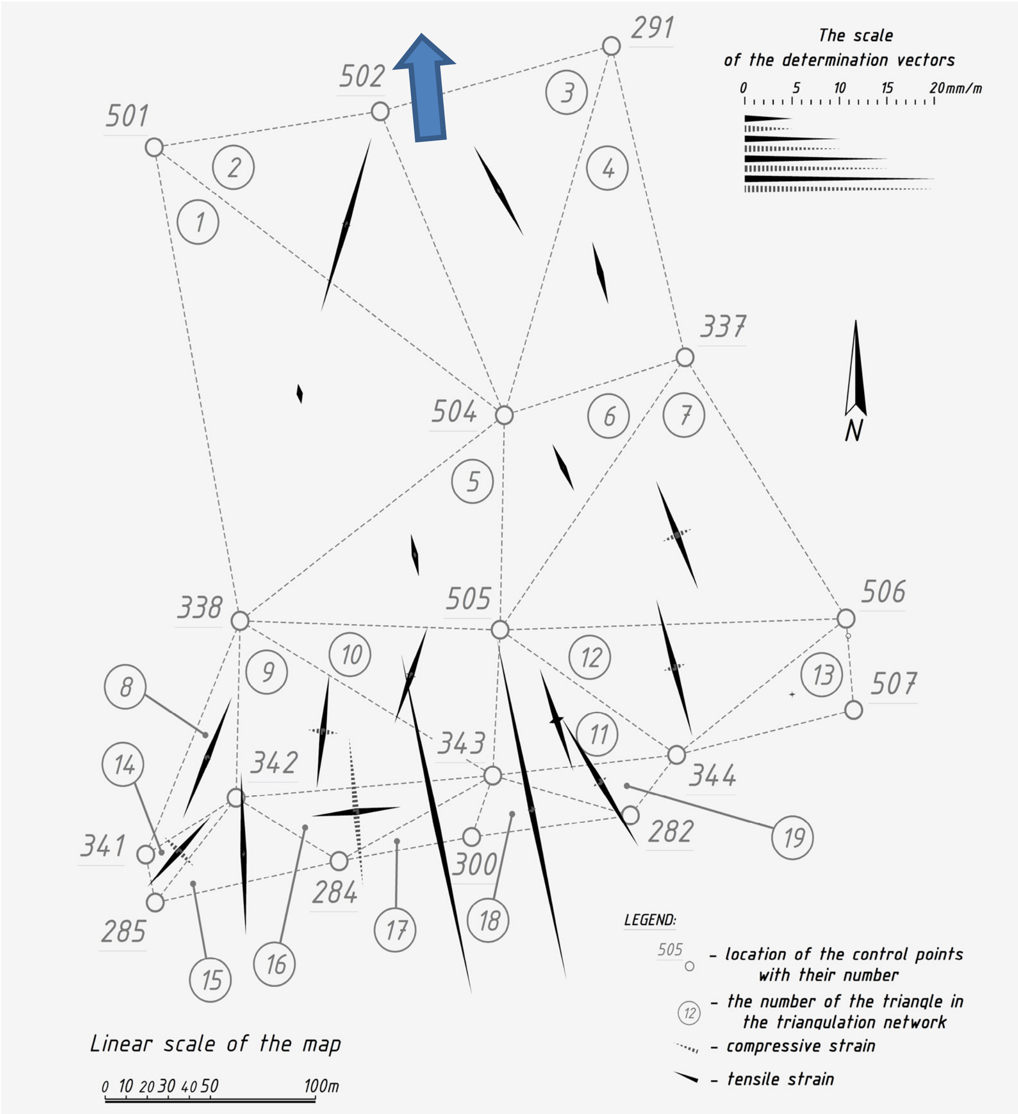

Fig. 14 Distribution of incremental strain during a slow landslide progressing: case 2, (Szafarczyk and Gawalkiewicz, 2016).

unprocessed. Meanwhile, we should pay much more attention for ground reinforcement in the transversal directions. Soil nails, retaining walls, dowels, geotextile and other mechanical devices of ground reinforcement are oriented along the general irreversible movement of the landslide and against the motion of the ground (Choi and Cheung, 2013). The piles are oriented mostly vertically and prevent ground movement passively resisting shear deformation of the ground (Hazarika et al., 2011). Rock bolts are oriented in the roof of an underground opening against the gravity or transversely to it against the sloughed sidewalls (Kent et al., 2014). Improving surface and subsurface drainage, preserving vegetation and the other measures invest in resistance and blocking of the general direction of landslides movement but do not restrain the other two degrees of freedom that are transversal to the first one.

Therefore we propose to restrict these degrees of freedom as much as possible. For instance, in the case of a landslide, it is possible to restrain all three degrees of freedom (Fig. 15a). This task can be solved with three cable systems: cable system 1 oriented approximately against the direction of integral ground movement, whereas system 2 and 3 are transversal to the system 1. Moreover, the all three systems of the cables are approximately mutually perpendicular to each other. All cable bolts should be installed and fixed in the competent bed of the landslide and must be pretensioned. The long cables having a length of 10 m and more exceed the average size of the ground block by several times. Therefore the long cables can restrain both close cooperation of the blocks and distant interaction of the clusters because the set which consists of the three cable systems restricts degrees of freedom in 3-dimensional space.

All mentioned above reinforcing systems can be installed through the holes which are drilled from the ground surface. However, an underground opening is congested and crowded, hence there is not the sufficient room and possibility to reinforce the surrounding rock mass is restricted. A way to restrain degrees of freedom in 3D space is to vary the inclination of the rock bolts (Naprasnikov et al., 1999) or pretensioned cables with reference to the gravity (Fig. 15b). This technique may reduce the degrees of freedom and noticeably prevent close interaction of the blocks because the inclination of the bolts creates collateral tightening components which restrict transversal degrees of freedom for the rock mass.

The distant interaction of the clusters in the roof and floor of an underground opening can be restrained with the props that should be installed under heads of the selected rock bolts and cables, for example, the bolts that are installed at the centerline of a roadway. The best effect provides a combination of two or three rock bolts whose heads are close to each other and which are supported by the prop (Fig. 15c).

Pretensioned truss bolts are effective device to restrain degree of freedom along stratification (Cox, 2003). However, the truss bolts create retaining forces in vicinity of the ground surface, whereas distant interaction of the clusters occur at least to the depth of 10 m from a roadway lining. Kent et al. (2014) reported the successful experience of entry sidewall stabilization using webbing attachments that restricted relative movement of the rock bolt heads on the side surface of an entry. It is impossible to restrain the blocks and clusters interaction completely and in whole volume of a ground where irreversible deformations may occur but any intentional measure will reduce the negative effect of their cooperation.

Requirement to restrain all degrees of freedom is absolute and much more capacious, versatile and potential than it appears at the first glance. Degrees of freedom should be restrained literally: translational and rotational degree of freedom in all directions. Such terms provide a wide range of possible means, methods, devices and technologies that may facilitate restriction of degree of freedom both along direction of active ground movement and in the collateral or transversal directions. The moving ground usually contracts along the collateral directions what reflects balance of mass. This contraction provides additional degree of freedom that accelerates process of irreversible ground movement in a back feed manner. Therefore designers should construct such gadgets, mechanisms and reinforcing systems which not only resist against active ground movement but compensates collateral contraction of the moving ground. For example, we developed a helicoidal rock bolt, which restricted both translational and rotational degree of freedom along direction of active ground movement, and instantaneously, caused expansion of the borehole – and consequently rock mass – along normal to this direction. This effect assisted to maintain lateral pressure in the moving rock mass and enhanced longwall entry stability (Nazimko et al., 2008). Importantly, the helicoidal bolts transform the potential energy of ground pressure to generate collateral expansion.

Another practical implementation of the new findings concerns the cases when there is a need to disintegrate the rock mass, for example during its hydro-fracturing. This is out of the scope of this paper but preliminary analysis indicated that surrounding rock mass disintegrates by separate stages in time and portions in space. Specifically, examination of micro-seismic events demonstrated that process of the disintegration occurs by turn: it comes back to the previously fragmented rock clusters several times and repeats crumbling of the rock blocks by pieces, one after other, what minimizes energy expenditure for the same rate of rock mass disintegration. That direct manifestation of rock mass self-organization and forming of a structure in time and space is usually unnoticed because of strong stochastic noise occurrence.

There are other two theoretical issues which were raised. First, two-dimensional strain state of the ground and rock mass is an ideal state which is impossible to reach in reality because this state is extremely energy-expensive. The rock mass volume or ground body will find a way to get out of this state through random fluctuation. Glensdorf et al. (1971) have proven that any thermodynamic system which is in the non-equilibrium state may bifurcate and shift to an essentially different state under triggering of a subtle fluctuation. The real ground body or a rock mass has infinite sources of such fluctuation, namely defects, fractures, inhomogeneity, non-uniformity. It does mean that 2D modeling conceals an intrinsic error which overestimates bearing capacity of a system modeled. In reality, surrounding rock mass collapsed earlier under the same initial and boundary conditions because there are more degrees of freedom in natural prototype in comparison to those simulated on a computer in 2D state.

Second issue is less obvious but more important from theoretical point of view. Is it applicable to use well-known constitutive models for replication such specific irreversible behavior of the rock mass as the cluster interaction? This is discussion for another paper but preliminary attempts, which we have made, demonstrated that popular models (for example finite element methods, finite difference methods) are insensitive to the cluster behavior and cannot reproduce the close interaction of adjacent blocks or rock lumps and the distant cooperation of the clusters. This issue is very important because amount of energy which irreversibly moving rock mass dissipates may differ several times depending on the way that it chooses. This theoretical issue generates a big practical effect, namely, using of the relevant methods and specific technologies may change the way of irreversible movement what essentially reduces convergence of roof and floor in an underground opening or diminishes probability of a landslide.

Our findings open wide scope for prospective investigation of irreversible behavior of a discrete medium not only in rock mechanics, but in metallurgy; mineral processing; transport, storage and warehousing of bulk cargo; micro-technology. For example we found that irreversible movement of metallic powder during pressing, extrusion or metal microcrystals stirring during drawing wire through a die obey the same laws of cluster interaction (Nazimko et al., 2002a). Non-reversible cluster structures of fine coal slime has been observed during process of its dewatering in filter-presses (Garko-

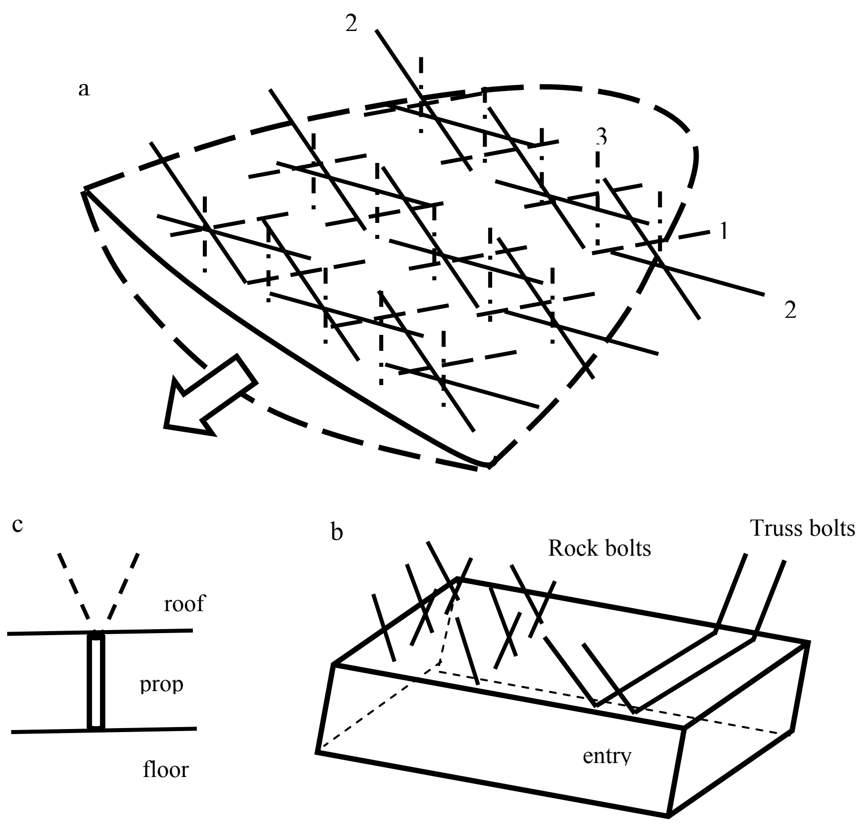

Fig. 15 Reinforcement patterns that reduce degree of freedom for ground.

venko and Nazimko, 2003). Noticeably, we should suppress the fragment and cluster cooperation when there is a need to increase stability of the disintegrating medium and to the contrary, support and promote the self-organization to activate disintegration, nonreversible movement, and minimize energy consumption.

8. CONCLUSION AND FUTURE RESEARCH

8.1. NEW FINDINGS

It was for the first time proved that even deteriorating, rock mass is capable to create the dissipative hierarchical structures which self-organize and facilitate their irreversible movement during accumulation of the damage to spend minimum potential energy for the same amount of the irreversible integral movement of the rock mass. These structures are triggered by random fluctuations and are a product of both the close interaction of adjacent blocks or ground fragments and the distant cooperation of the block clusters. The ground fragments create short-lived clusters that move as a whole aggregate body, which may eventually reintegrate into other clusters and blocks. The cluster pattern rearranges during progress of the irreversible ground moving. This process of the reorganization might be followed by cutting of the intact ground or rock blocks because the boundary of a cluster-ancestor may not coincide with the boundary of the cluster-offspring.

The blocks converge, diverge, slide relatively each other, and create vortex patterns during the irreversible movement of the ground and the rock mass, what evolves the dissipative structures in time and space. These structures facilitate the accumulation of degrees of freedom for a ground body to separate from the stable rock mass and develop a landslide or roof sag and even a fall in an underground opening. These patterns of nonreversible ground motion can be unveiled with incremental fields of ground movement. These increments should be as small as possible however not to be less than the error of measurement.

The complete spatial randomness of the incremental vectors length and direction decays linearly as process of the irreversible movement progresses and the disintegrated ground accumulates sufficient degrees of freedom for dilatation. Eventually, versatile patterns of the dissipative structures degrade to a simple picture of straight-forward flow of debris.

The patterns of ground irreversible movement and the dissipative structure vary in space and in time. The adjacent blocks and clusters promote their cooperation giving the way one after the other, moving in turn, alternatively. The anti-phase pattern of incremental block movement prevails and is the most important peculiarity of the irreversible behavior of the ground and a rock mass. A block delayed when the adjacent block accelerated and vice versa, what demonstrates the close interaction of the ground fragments. In particular, this close cooperation of the adjacent blocks makes impossible plane strain state in vertical cross section of an underground elongated roadway because random blocks displace along its axis. Therefore, 2D simulation of ground movement around underground-elongated roadway overestimates stability factor of this roadway.

An apparent distant cooperation manifested during the development of a damaged zone around an underground roadway when this zone sequentially expanded to all direction not at the same time but in turn. Possibility of synchronous active irreversible movement of surrounding ground in all directions (from the roof, sides, and floor) is miserable because it is not consistent with the second law of thermodynamics (1). The damaged zone expanded to the floor then to the sides and finally to the roof of the roadway in the case. Such distant interaction reflected self-organization of the damaging rock mass that was governed by the thermodynamic law of the irreversible processes: an open thermodynamic system that is far from the equilibrium tends to create structures and self-organizes to produce minimum excess of entropy.

Extant techniques restrain basically one prevalent component of the irreversible ground movement in 3D space. The other two collateral transversal components were usually ignored. However, blocking of these transversal components can prevent the development of a dangerous irreversible movement of the ground and increase stability of the ground.

New pattern of self-organization described in this paper is relevant for the wide scope of discrete media. One should suppress the fragment and cluster cooperation when there is a need to increase stability of the disintegrating medium and to the contrary, support and promote the self-organization to activate disintegration and nonreversible movement, what minimize energy consumption.

8.2. FUTURE RESEARCH

Extant geomechanical models of a ground volume or a rock mass apply the constitutive sub-models that reproduce the irreversible behavior of a rock sample, whereas the size of the simulated volume exceeds the sample sizes significantly. Such approach does not guarantee that behavior of the model as a whole will correspond to the behavior of the real object after the model transits the peak strength of the ground and the irreversible ground movement will develop. This puts a need to develop additional methods and techniques that can portray both the close interaction of the adjacent ground fragments and distant cooperation of their clusters during development the post-peak deformation and irreversible stage of ground movement.

A special procedure should be developed for correction of the results of simulation in plane strain state which may disappear in reality when the ground transits over peak strength.

Present methods, devices, and technologies should be modified to suppress close and distant interaction of the ground fragments and clusters during irreversible movement of the ground and rock mass. It is necessary to restrain all degrees of freedom of the ground as much as possible including both translational and rotational degrees.

Our findings open wide scope for prospective investigation of irreversible behavior of the ground and rock masses, its patterns, and their parameters, namely, sizes and dimensions of the clusters in 3D space, periods of patterns bifurcation, effects of support type and its bearing capacity on the irreversible behavior of the dissipative structures, impact of stress and ground pressure level and its rate, for example speed of a longwall advance. In addition, new findings are the basis for reexamination of such popular technological process as hydro-fracturing which is widely used during extraction of oil, natural gas, coal-bed methane, and shale gas.

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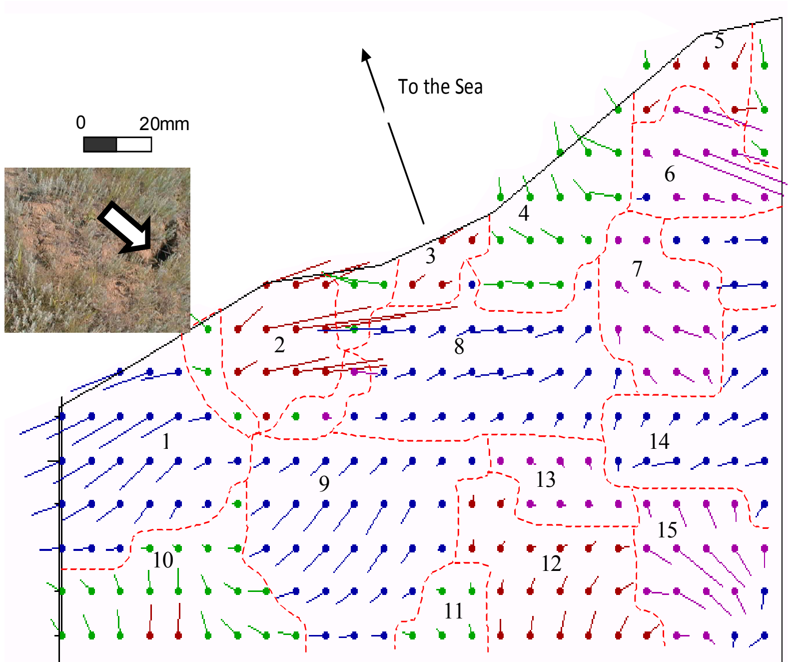

Fig. 3 Distribution of incremental sliding.

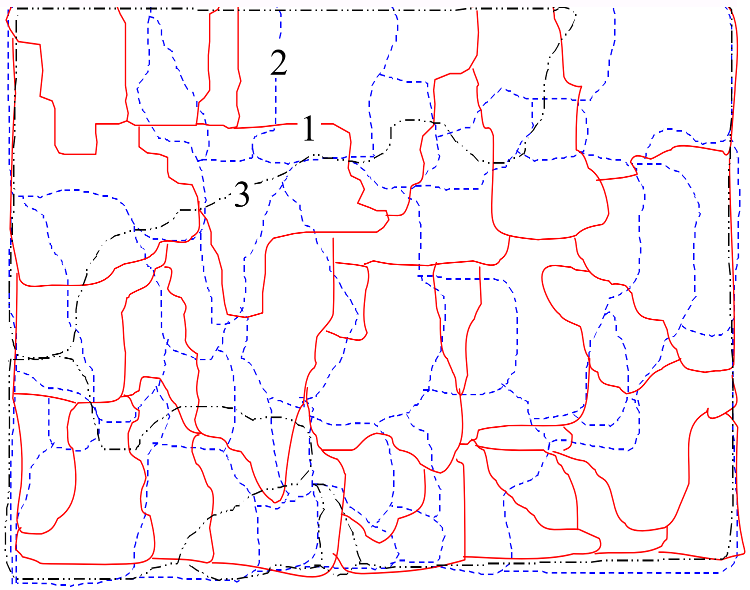

Fig. 7 Overlapping of cluster distributions: red (1 – solid), blue (2 – intermitted) and black (3 – intermitted with point) boundaries correspond to 7th, 8th and 9th stages of modeling.

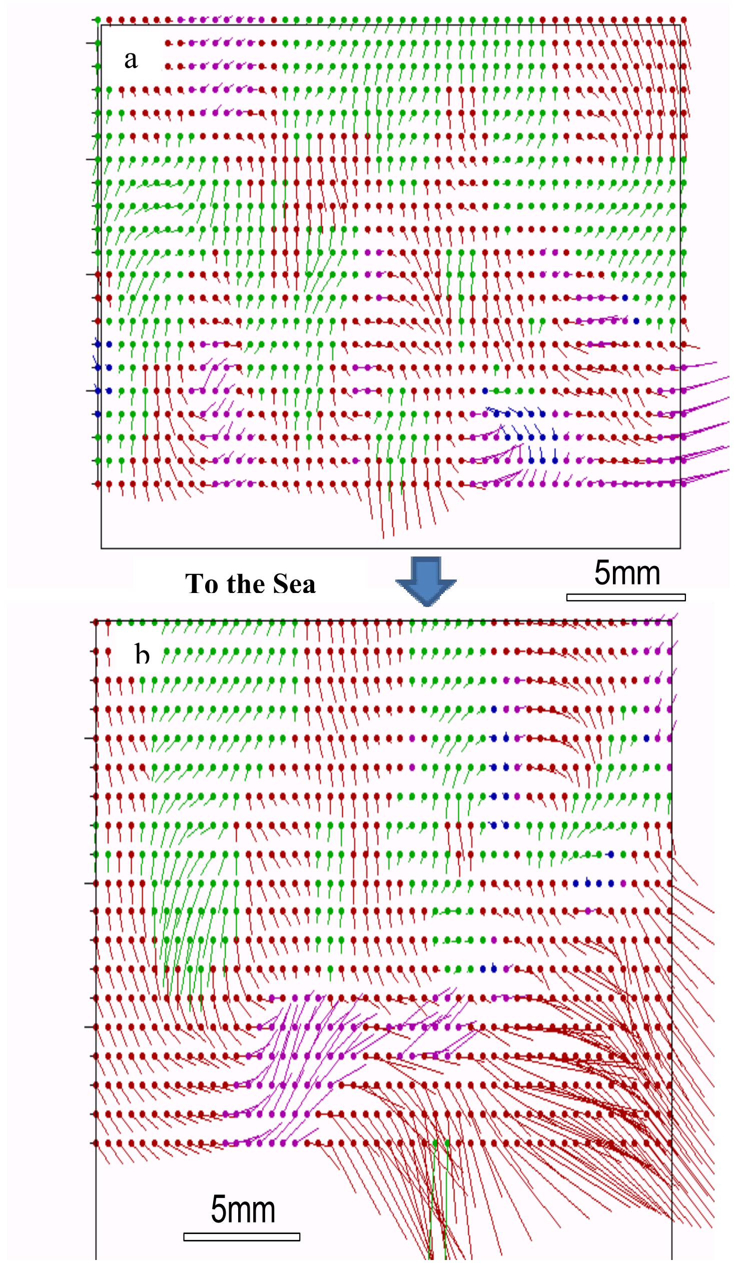

Fig. 5 Displacements distribution at stage 7 (a) and 10 (b).