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INVESTIGATION OF A ROOF FALL AS AN IRREVERSIBLE PROCESS OF ROCK MASS SELF-ORGANIZATION

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Внаслідок підвищеного гірського тиску і нестачі міри свободи масив навколо виробки повинен розділятися на сегменти (кластери), які вимушені зсуватися з поворотом один за іншим в просторі і у часі. Кластери повинні звільняти один одному місце змінюючи швидкість зсування і напрям, щоб мати можливість зміщатися в утворену виробкою порожнину. Границі сегментів, що знову утворилися не співпадають з попередніми границями сегментів-предків. Обвалення покрівлі - результат специфічної поведінки сегментів. Запропоновані практичні рекомендації по управлінню станом масиву гірських порід навколо підготовчої виробки на основі вивчення процесу формування і зсування кластерів.

В результате повышенного горного давления и недостатка степени свободы массив вокруг выработки должен разделяться на сегменты (кластеры), которые вынуждены сдвигаться с поворотом один за другим в пространстве и во времени. Кластеры должны освобождать друг другу место изменяя скорость сдвижения и направление, чтобы иметь возможность смещаться в образованную выработкой полость. Границы вновь образовавшихся сегментов не совпадают с предыдущими границами сегментов-предков. Обрушение кровли - результат специфического поведения сегментов. Предложены практические рекомендации по управлению состоянием массива горных пород в окрестности подготовительной выработки на основе изучения процесса формирования и сдвижения кластеров.

INTRODUCTION

Underground opening stability is the most urgent issue in rock mechanics. Extensive efforts have been undertaken to investigate the problem [1-4]. Recent findings have demonstrated that proper understanding of rock mass stability may be achieved through a thorough studying of its irreversible behavior [5-7]. Rock mechanics specialists have realized long before that disintegration of rock mass surrounding an underground opening does not imply failure of this opening. A new Austrian method for driving a tunnel is a typical example of such an approach [8]. This technique employs two stages of drivage. In the first stage, temporary yield support is installed while in the second stage, permanent heavy support is erected after the disintegration of some portions of the surrounding rock mass. The trick is to detect a relevant lag between installation of both kinds of supports. It should be stressed that there is no definite and intelligible procedure for the determination of lag time and for selection of proper support parameters. This technique remains essentially an art and depends on individual experience.

Lack of knowledge causes dangerous events like roof falls followed by fatalities [9]. Therefore more attention should be paid to the investigation of irreversible behavior of rock mass to better understand the complex stability problem. In this paper the results of a detail investigation of the irreversible kinetics of rock mass movement around a rectangular underground opening are reported.

PROCEDURE AND TECHNIQUES OF INVESTIGATION

Despite of modern sophisticated computer programs, physical modeling and underground measurements remain the most effective and reliable method to study the irreversible processes around an underground opening where extensive destruction of rock mass has occurred as a result of intensive ground pressure or poor ground conditions. Consequently a plaster sand physical model was used to investigate the kinetics of ground movement and deformation around a rectangular opening. The scale of modeling was 1:35,8 in which the height, width and thickness of the model were 380 mm, 350 mm and

19 mm, respectively (Fig. 1). A mixture of sand, plaster, chock and water in the proportion of 92,26:2,77:1,37:3,6 by weight produced a shale-like rock material according to the following standard similarity criteria,

$$N_m = \frac{l_m \, \gamma_m}{L_n \, \gamma_n} N_n, \qquad (1)$$

where γ_m, γ_n – density of material in a model and in a natural prototype, respectively;

l_m, L_n – linear dimensions of a model and the prototype, respectively;

N_m, N_n – strength of synthetic material and natural rock, respectively.

The mixture was poured into the model frame in layers separated by mica. Mica was distributed over the top of the layer being made in

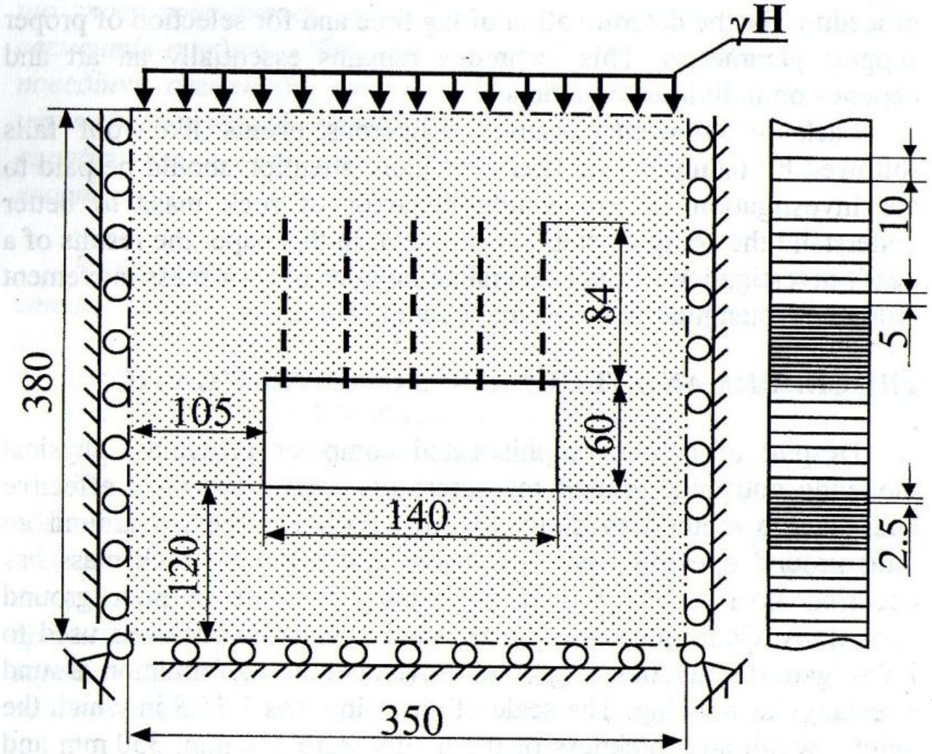

Fig. 1. Front view of the physical model.

the amount of 0,15 mg/cm^2. The front and the rear sides of the model were restrained by a thick (14 mm) glass plate attached to the frame. Thickness of the rock layers ranged from 2,5 mm to 10 mm or from 0,089 m to 0,358 m in the natural prototype. Each layer was compressed by a pressure of 15 kPa. After completion, monuments were marked on the front side of the model and the whole model was consolidated through vibration by a pressure of 89,8 kPa for 15 minutes. The frequency of vibration was 50 cycles per second and its magnitude was ±3 mm. The vibrator had a power of 0,5 kW. The amount of compressive pressure for consolidation was chosen to be approximately 3 times more than that applied to the upper boundary of the model during testing. Such consolidation provided a uniaxial compressive strength of the synthetic material 0,67 MPa or 40 MPa for natural prototype (i.e. shale). Cohesion between adjacent layers was 0,055 MPa. In addition, the process of consolidation increased the reliability of the final results because it prevented the consolidation of model body during testing in local spots where high stress concentration occurred, e.g. at the ribs of the opening. Instead of local consolidation, ribs sloughing and floor heave will likely occur as in an actual prototype. Local consolidation would cover up these effects and distort the final results because these effects occur in the vicinity of the opening.

The opening was 140 mm long by 60 mm high (5 m by 2,15 m in nature) and was excavated after consolidation in the lower portion of the model. Distances from the sides, top and bottom of the model to the opening were sufficient to minimize the boundary effects. The roof of the roadway was supported with 5 rock bolts. Steel wire (0,7 mm in diameter) was used to simulate rock bolts of 25 mm in diameter. The bolts length was 50 mm in the model or 1,8 m in natural prototype. Spacing between adjacent bolts was 25 mm (0,9 m in nature). The upper boundary of the model was loaded with a piston pressed by screws against the boundary. The applied pressure was increased from 27 kPa to 31 kPa during experiments. It must be noted that only the vertical active pressure was applied to the upper boundary of the model while the sides of the model reacted passively. The pressures applied during consolidation and testing of the model were controlled by the torque on the screws. A total of 12 stages of boundary loading were used and took 9,5 rotations of the loading screws. As a result, the piston pressed down into the model 16 mm. Finally, 10 of the 12 stages were found to have sufficient features to show qualitative changes in the model behavior. Roof fall occurred after the 8th stage of loading. One stage corresponded approximately to one turn of screws or 1,7 mm of piston movement.

Displacements of the monuments on the model during testing were recorded by a digital camera and processed by a special software [10]. In order to investigate the kinetics of ground movement, the distributions of vertical and horizontal components of displacements, displacement vectors, and normal, tangential and volumetric strain were analyzed. The distribution of measurement accuracy is depicted in Fig. 2. It may be considered as a normal distribution with a standard deviation of accuracy of 14 mm (or 0,39 mm in the model). Displacement more than 0,034 m and more than 0,02 m may be

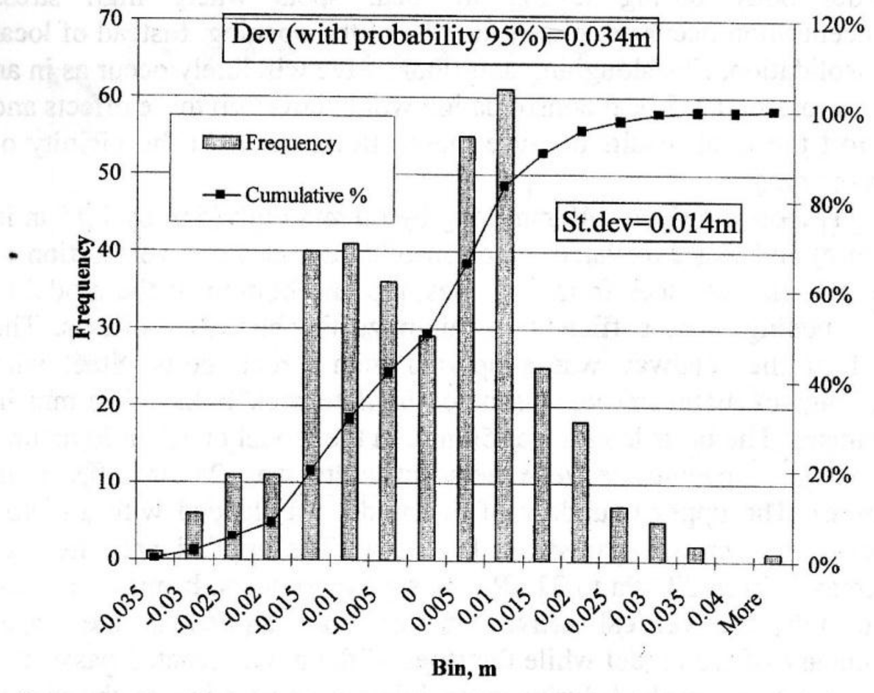

Fig. 2. Histogram of error distribution.

considered as determined with confidence 95% and 85% correspondingly.

In addition, ultrasonic sounding of the model was used to examine model integrity and density. An ultrasonic transducer and a transceiver were mounted opposite to each other on the front and the back sides of the model, respectively. Ultrasonic oscillation with frequency 150 kHz was used. A shorter wave propagation time through the model body indicates denser and therefore more stressed material. A rectangular yellow grid was marked on the front side of the model for proper positioning of the transceivers.

To validate the modeling results, underground measurements were conducted in a coal mine roadway. Rock mass displacements in the roof, ribs, and floor were measured by leveling and borehole extensometers.

ANALYSIS OF DISPLACEMENT, STRAIN AND STRESS REDISTRIBUTIONS

Figure 3 demonstrates four critical states of the model during its testing. Position a corresponds to the initial state of the model, positions b and c describe the states of the model immediately before and after the roof fall. Position d refers to the same state of the model as position b but from the rear side. Positions I and II are the exploded views of two areas in the position d. Note position d shows the rear side of the model where monuments were absent and shows clear details of rock mass deformation.

Ultrasonic wave travelling time was measured at two points before testing, one at the center of the opening where it was empty between the glass plates and in the roof where it was filled with model intact body. The time was 34 microseconds at the empty site and 29 mcsec at the intact site.

Vertical displacements in the model during testing are depicted in Fig. 4. Positions *a, b, c, d, e, f* and *g* correspond to the stable states of the roof (stages 2,3,4,5,6,7 and 8) where position *g* was the state of the model immediately before the roof fall. Position *h* was the state of the

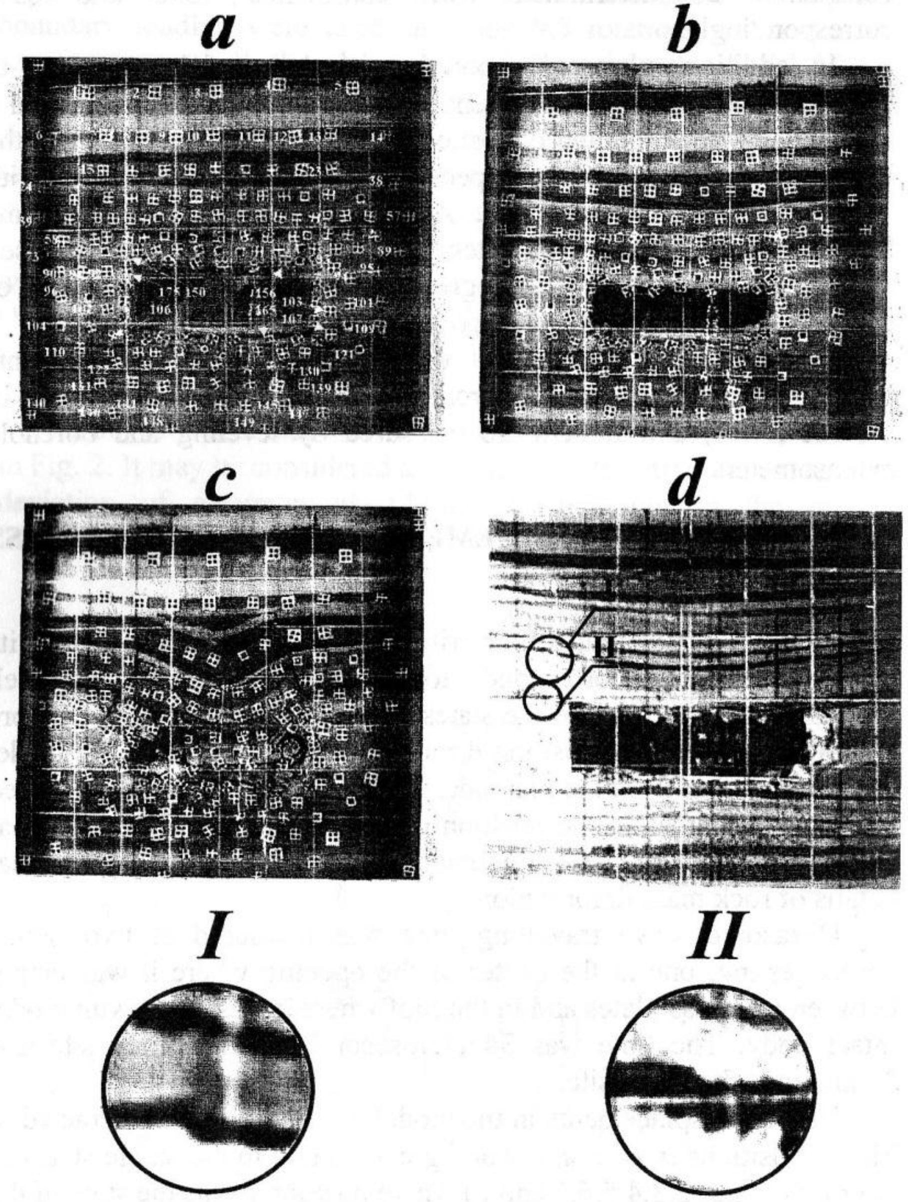

Fig. 3. Three stages of physical modeling during testing and two exploded views of rear side of the model.

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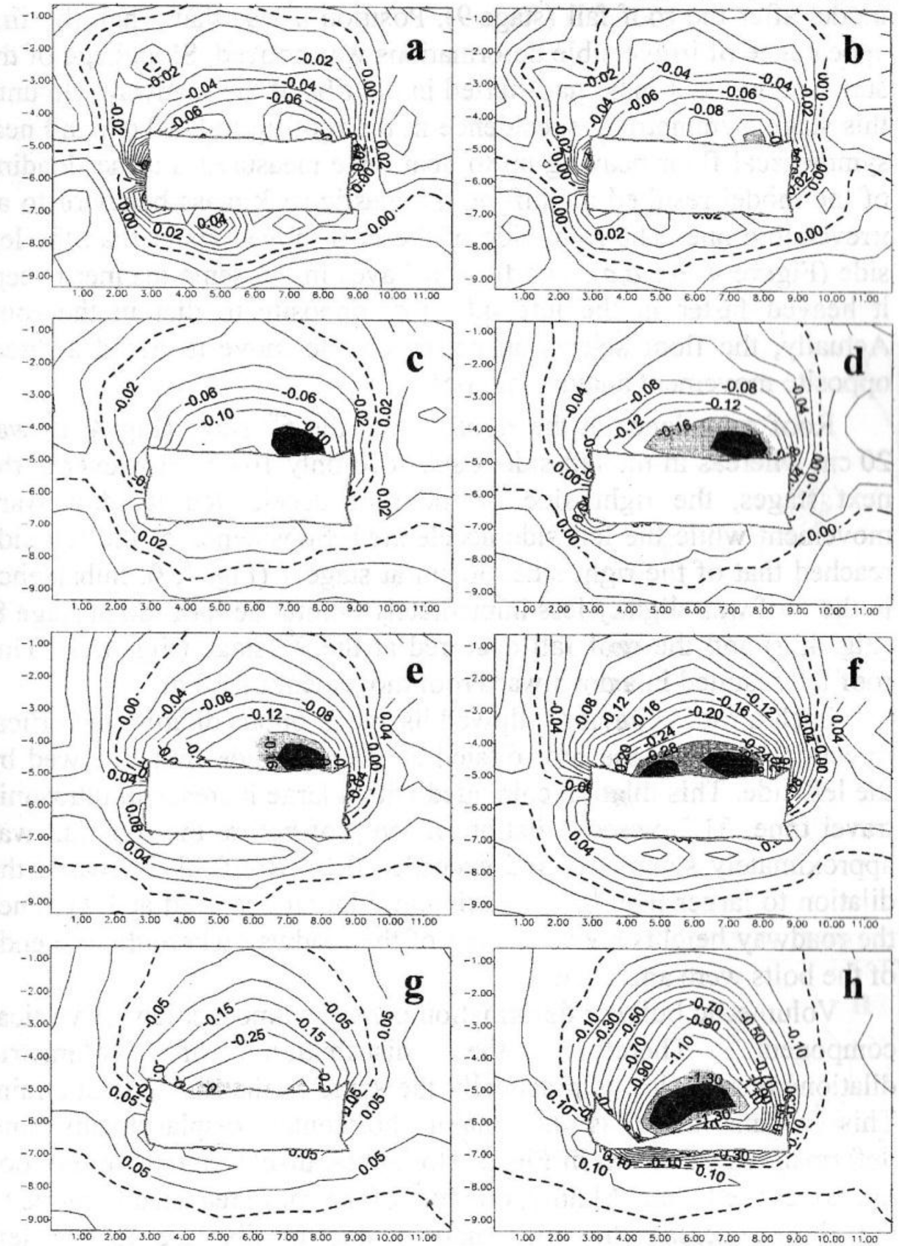

Fig. 4. Vertical subsidence (along Y-axis) distribution at various stages of model testing.

model after the roof fall (stage 9). Position *a* was that when the first appearance of irreversible deformations was noticed. Sloughage of the surrounding rock mass had started in the ribs of the roadway. Up until this stage, symmetrical subsidence in the roof up to 8-10 cm and near symmetrical floor heaving up to 6cm were measured. Further loading of the model resulted in shifting the elastic rock mass behavior to an irreversible one. The right side of the roof moved faster than the left side (Figure 4, *b,c,d,e*). The floor behaves in the same manner except it heaved faster in the left side, just opposite to that in the roof. Actually, the floor selects an easier way to move to avoid a direct opposite movement against the roof.

Roof subsidence at the right side at the 6th stage (Fig. 4, *e*) was 20 cm whereas in the left side it subsided only 10 cm. However at the next stages, the right side of the roof decelerated its downward movement while the left side accelerated. Subsidence of the left side reached that of the right side, 30 cm at stage 7 (Fig. 4, *f*). Subsidence in the roof was slightly less immediately before the roof fall at stage 8, (Fig. 4, *g*) and the roof fall occurred at the 9th stage (Fig. 4, *h*). This roof fall resulted in a downward roof movement of 1,5 m.

Such a roof behavior followed its synchronous dilation in vertical direction. Namely, the roof dilated at the right side first followed by the left side. This dilation coincided with a large increase in ultrasonic travel time, 31,2 mcsec. Dilation of the roof before the roof fall was approximately symmetric and exceeded 0,10. Roof fall increased the dilation to larger than 0,40. Maximum dilation occurred at 1.41 times the roadway heights above the top of the roadway where the top ends of the bolts were anchored.

Volumetric bulking deformation consists almost solely of vertical component. Therefore the distribution of volumetric dilation/compression is practically the same as that of vertical strain. This means there is no major horizontal displacements and deformations as shown in Fig. 5. Horizontal displacements in the roof did not exceed 2 cm. Mainly, one half of the roof area tried to move to the right whereas the other half tended to displace to the left (Fig. 5, *a,d,f,g*) although the areas of movement in the right and left sides were not distributed symmetrically. This situation is very

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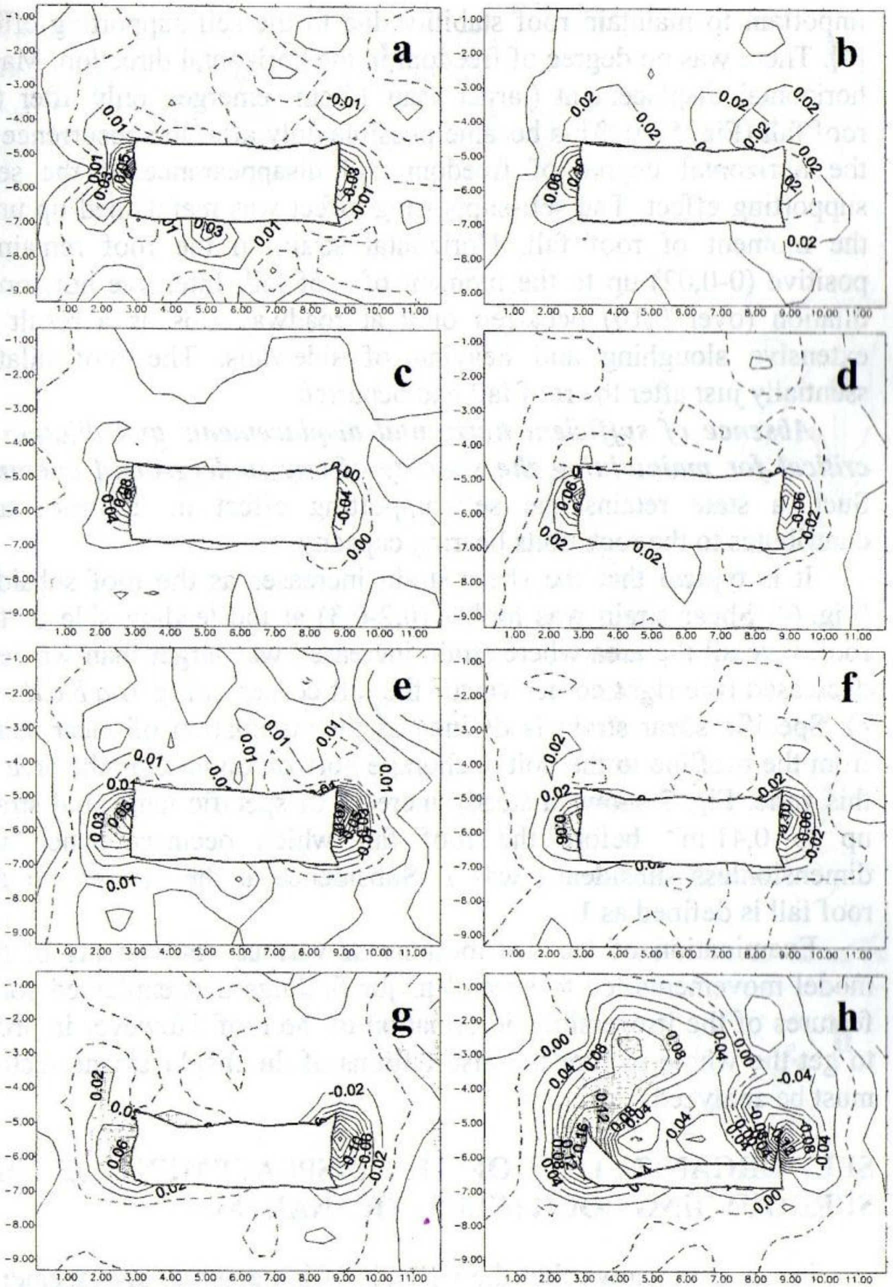

Fig. 5. Horizontal displacement (along X-axis) distribution at various stages of model testing.

important to maintain roof stability due to the self-supporting effect [7]. There was no degree of freedom in the horizontal direction. Major horizontal displacement (larger than 12 cm) emerged only after the roof fall (Fig. 5, *h*). This became possible only after the occurrence of the horizontal degree of freedom and disappearance of the self-supporting effect. The self-supporting effect was maintained up until the moment of roof fall. Horizontal strain in the roof remained positive (0-0,02) up to the moment of roof fall. Intensive horizontal dilation (over 0,10) occurred only at roadway ribs as a result of extensive sloughing and heaving of sidewalls. The roof dilated ssentially just after the roof fall had occurred.

Absence of sufficient horizontal displacements and dilation is critical for maintaining the stability of any underground opening. Such a state retains the self-supporting effect in the roof and contributes to the rock bolts bearing capacity.

It is typical that the shear strain increases as the roof subsides (Fig. 6). Shear strain was higher (0,2-0,3) at the leading side of the roof. Overall the area where strain increased was larger than where it decreased (the right corner versus the left corner in Fig. 6 *a,b,c,d* and *e*). Specific shear strain is defined as the summation of shear strain from the roofline to the bolt anchorage horizon divided by the area of this zone. Fig. 7 shows a steady increase of specific tangential strain up to 0,41 m^{-2} before the roof fall which occurred when the dimensionless subsidence was 1. Subsidence at the moment of the roof fall is defined as 1.

Examination of the distributions of various components of the model movements led to several major findings that explained some features of the irreversible deformation of the roof. However in order to get the whole picture the distributions of the displacement vectors must be analyzed.

SELF-ORGANIZATION OF THE DISPLACEMENT OF THE SURROUNDING ROCK (CLUSTER ANALYSIS)

It has been shown that the analysis of incremental displacements and strains is the best way to understand the irreversible geomechanical processes (6). The distributions of the vector

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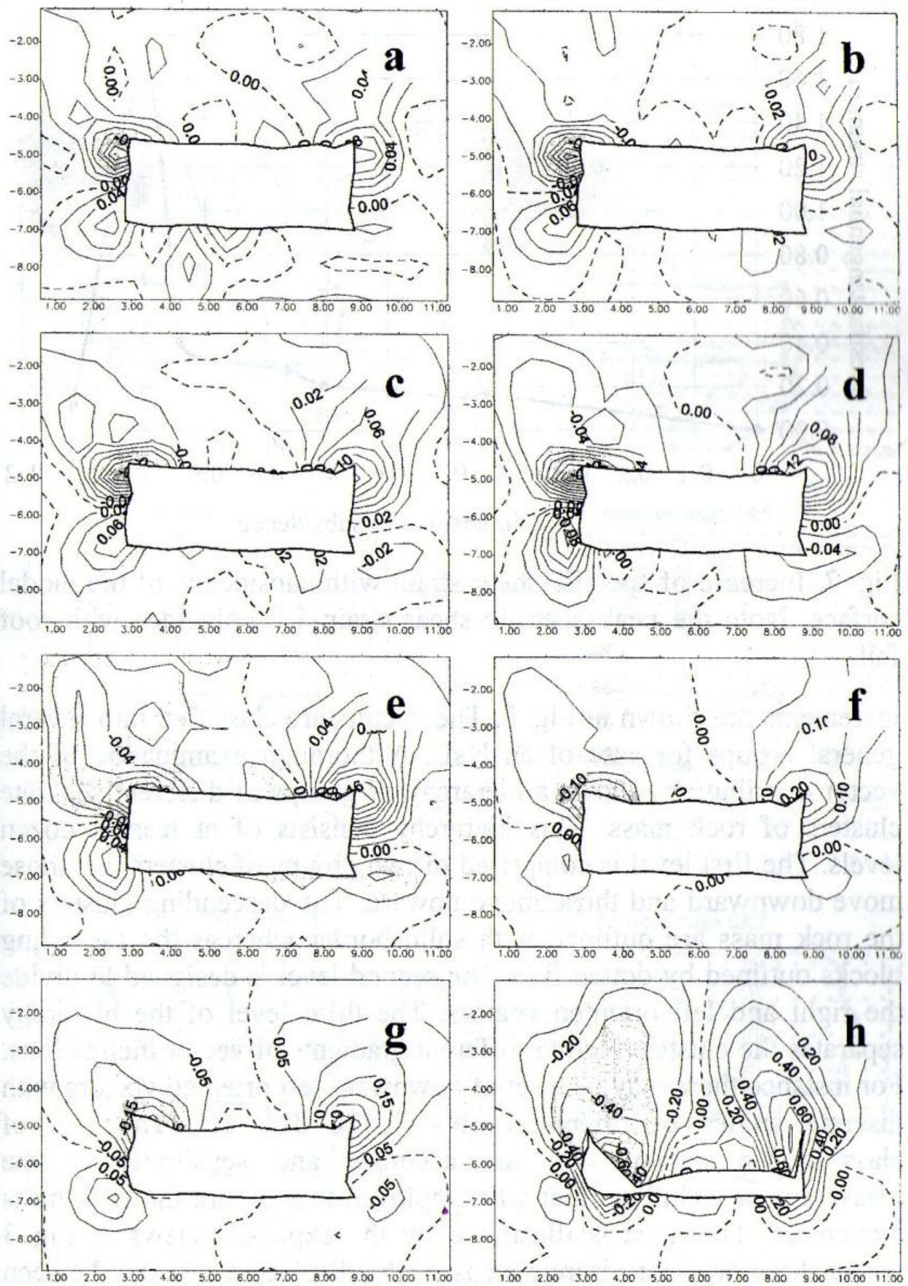


Fig. 6. Shear strain distribution at various stages of model testing.

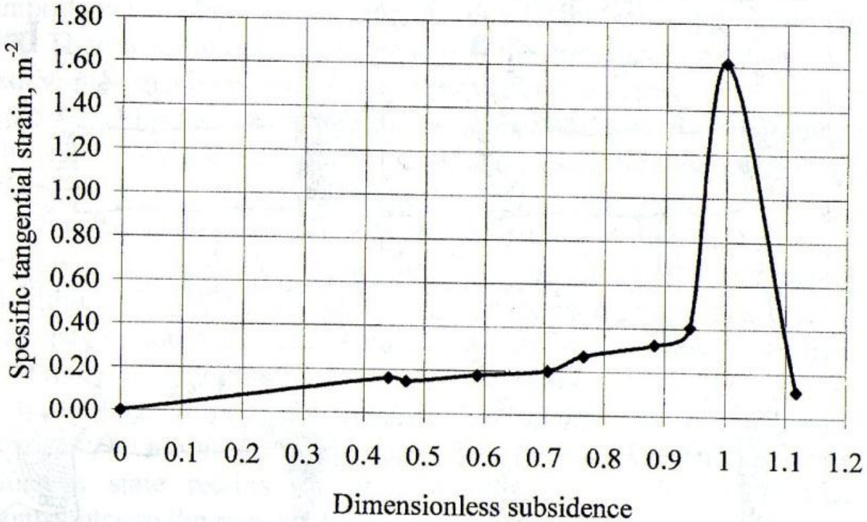
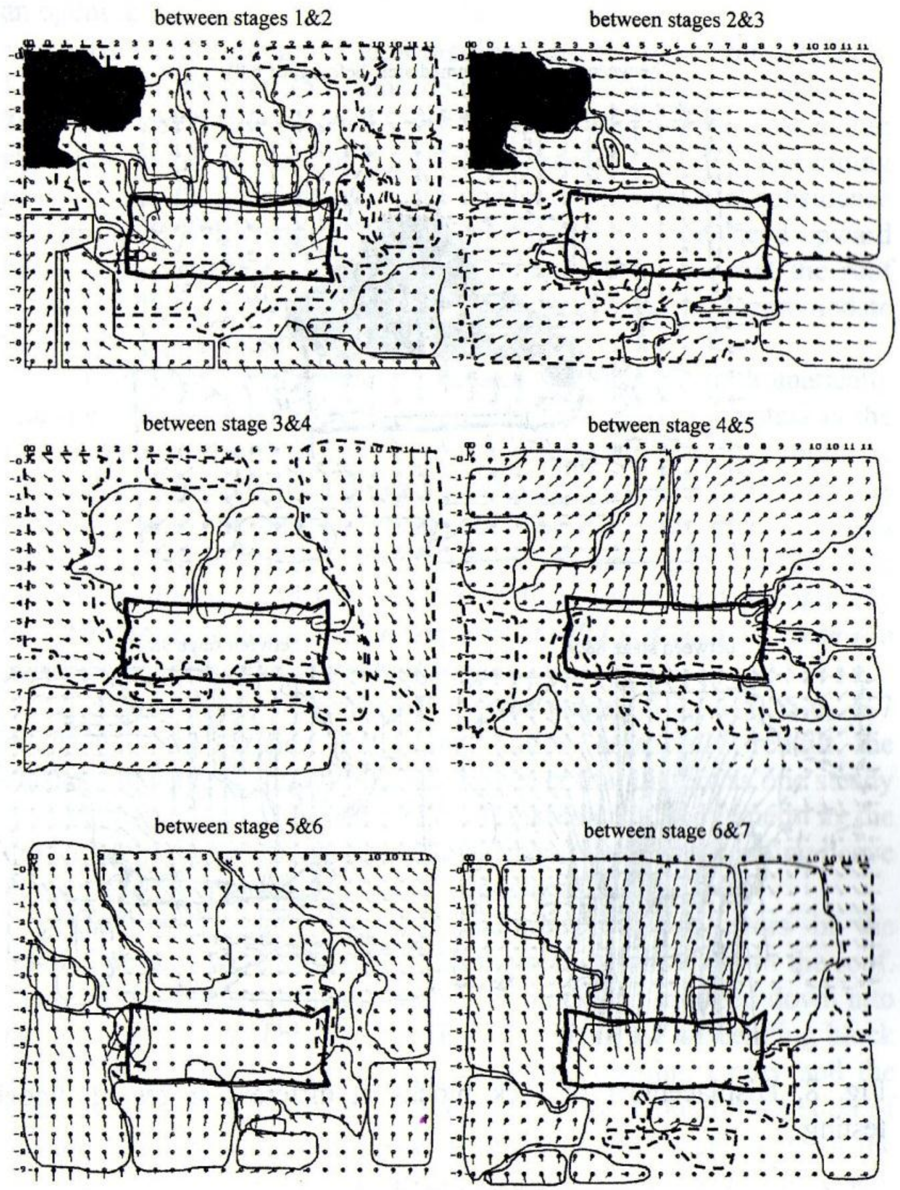


Fig. 7. Increase of specific shear strain with subsidence of the model surface. Note the peak specific shear strain 1.0 coincides with roof fall.

increments are shown in Fig. 8. The vectors are classified into several general groups for ease of analysis. A thorough examination of the vector distributions shows a hierarchy of groups of different separate clusters of rock mass. This hierarchy consists of at least a dozen levels. The first level is comprised of two groups of clusters, i.e. those move downward and those move upward. The descending clusters of the rock mass are outlined with solid border whereas the ascending blocks outlined by dotted line. The second level is designed to divide the right and left oriented vectors. The third level of the hierarchy separates the clusters having different gradients of vector inclinations. For instance there may be a set of downward left oriented vectors with discrete angles of orientation 0^0-10^0, 20^0-30^0, etc. The rate of classification depends on the accuracy and sensitivity of the measurement technique that was employed to measure the rock mass movement. This idea is illustrated by the exploded views in Fig. 3 where three or more discrete steps of the displacements may be seen between adjacent monuments. Fractal geometry [11] may be used to facilitate this cluster analysis. However a three level classification as a



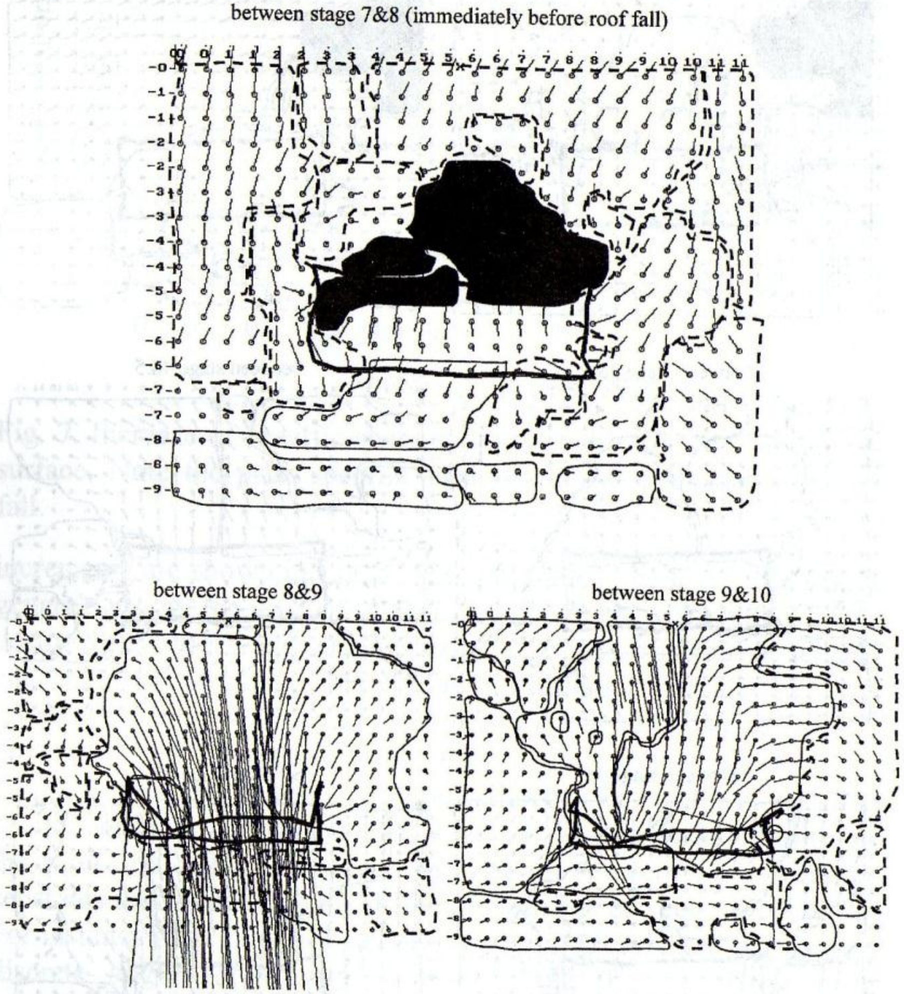


Fig. 8. Displacement of rock blocks at different stages of model testing.

first approximation was found in this research to be sufficient to discover the major behavior of the irreversible rock movement around an opening.

After the grouping of vector distributions, there are approximately 12 clusters in the roof (5 ascending and 8 descending) at the stages 1-2; 6 clusters in the roadway ribs (3 ascending and 3 descending clusters); and 5 clusters in the floor (1 ascending and 4 descending ones). It may be noted that the roof underwent incremental subsidence as a group of 8 descending clusters and the floor experienced upward heave by a single cluster. It is very important to note that the roof subsided by at least 8 different clusters that tried to accommodate their mutual movement.

Incremental displacements between stages 2-3 dramatically rearranged the cluster's organization. The two left-side clusters in the roof joined to form a new common ascending one. It should be stressed that the common ascending cluster was assembled from one ascending and one descending cluster. The right-side ascending and descending clusters in the roof united into one descending cluster. The clusters in the ribs and floor of the roadway rearranged dramatically too. ***The borders of new offspring clusters did not coincide with the previous borders of ancestral clusters.***

Incremental displacements between stages 3-4, 4-5, 5-6, 6-7 maintained this trend. Every distribution essentially rebuilt the cluster's mosaic. It should be noted however that there was one steady feature, namely the general trend of incremental movement in the immediate roof was downward displacement whereas ascending heave occurred in the immediate floor (except stages 5-6).

Stages 7-8 needs a special mention. Three clusters in the immediate roof were separated from the rest of rock mass in the roof. These three clusters formed a triangular block and dropped down into the opening cavity. This was the first time when the descending block of rock mass was positioned right over the opening cavity and the width of the block was slightly less than the horizontal dimension of the opening cavity. This means a favorable condition emerged for the roof fall. The rest of the surrounding rock mass shifted its movement upward accelerating the process of separation. In addition, the ribs of the opening diverged to give some degrees of freedom or room for the roof fall to occur. These were the symbolic behavior of rock mass immediately before the roof fall. Such an unusual behavior may be employed as an indicator of a possible hazardous event.

Roof collapse after the 8th stage occurred with two big clusters in asymmetric movement, the right-side being larger. Sometimes later, this asymmetry was corrected or compensated by the left-side movement and the roof clusters rearranged at the stage 10.

The behavior of the rock mass surrounding an opening may be generalized as follows. Any rock mass that has some cohesion and strength can not move into an opening cavity simultaneously and orderly due to the lack of degree of freedom. ***It must be divided into clusters, that are forced to move by turn***, one after another in space and in time. The crowded clusters have to yield to each other in order to keep moving into the opening cavity. This is why alternating acceleration/deceleration of vertical subsidence in the right and left side of the roof were measured.

UNDERGROUND EXPERIMENTS

Irregular pattern of adjacent roof blocks subsidence was found in an experimental section of a coal mine entry. "Yuzhno-Donbasskaya #1" coal mine is located 60 km from Donetsk , Ukraine and extracts bituminous coal from three contiguous seams using retreat longwall system. The head entry was driven at the depth 537 m and had an arched cross section of 15,5 m^2 (Fig. 9). The roof in this area was composed of sandy shale having a uniaxial compressive strength (UCS) of 30 MPa. Coal seam was 1,65 m thick and has an UCS of 20 MPa. Other laminated strata such as shale, coal and sand layers with UCS 20-50 MPa are shown in Fig. 9. The entry was normally supported by steel arches but the experimental section was equipped with rock bolts. The bolts, 1,25 m long, were spaced at 1 m in both directions. The experimental section was 8 m long in which seven fully grouted rock bolts were installed in every cross section of bolt rows (Fig. 10).

Fig. 11 shows the deflections of bolts heads as the coal face approaches. These deflections were monitored with the level Ni-025

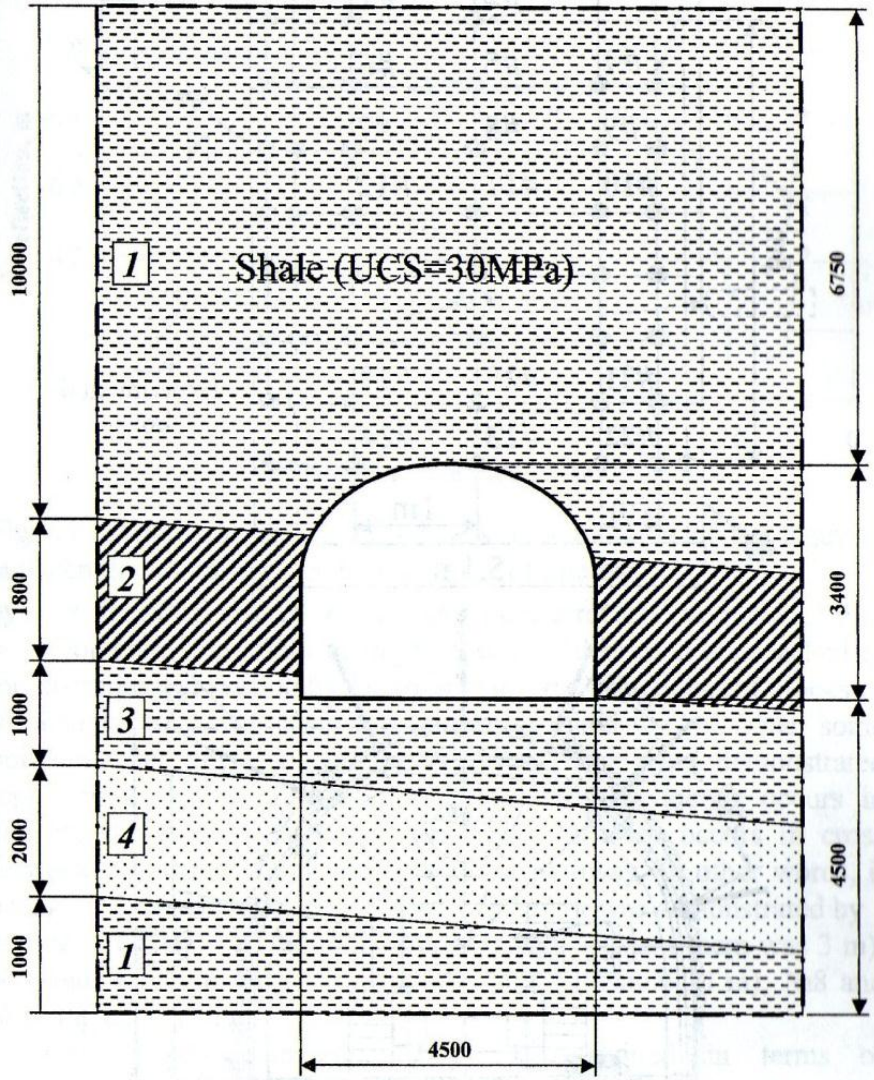


Fig. 9. Stratigraphic column for the instrumented sector of the underground roadway: 1 - shale (UCS=30MPa); 2 - coal (UCS=20 MPa); 3 - shale (UCS=27 MPa); 4 - sandstone (UCS=50MPa).

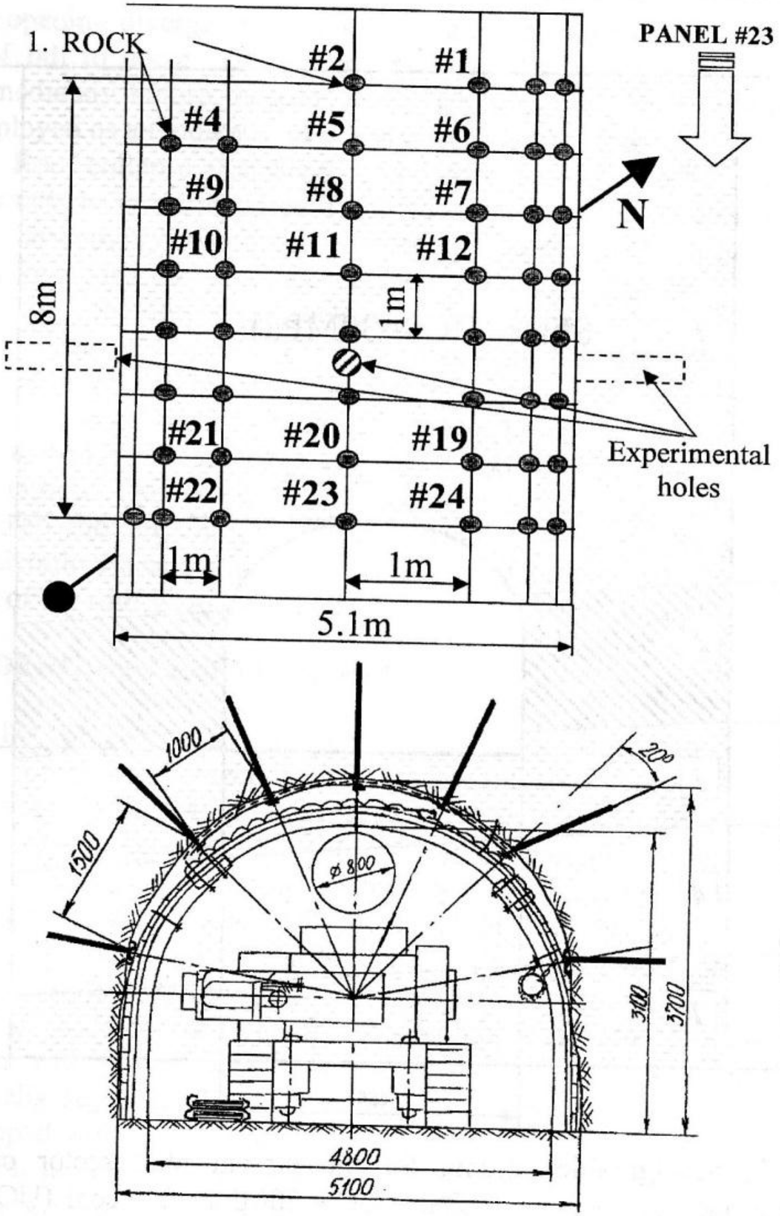


Fig. 10. Plan view (upper) and cross-section view (lower) of the instrumented sector of the underground roadway.

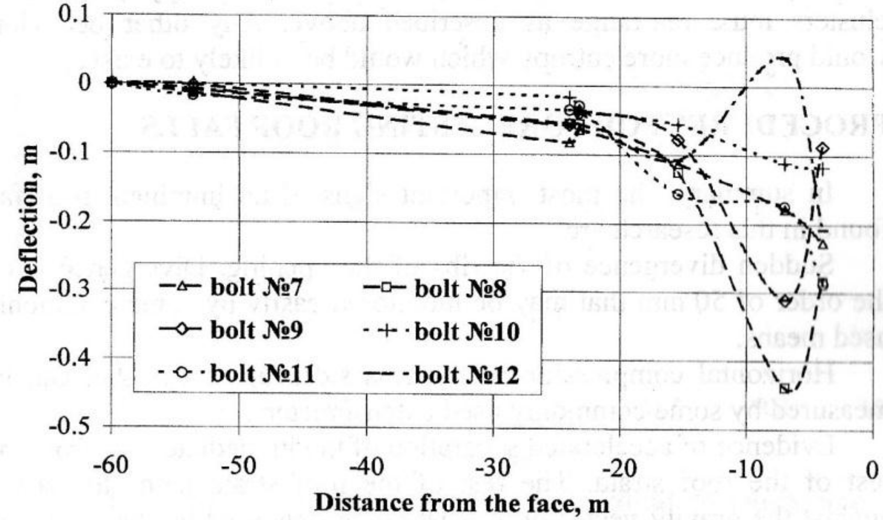


Fig. 11. Deflection of the bolts heads as a function of the distance between the retreating face and the bolts of interest.

by a professional surveyor with maximum error of leveling ±2,5 mm per kilometer. The effect of the face was evident as it approached to the instrumented section by 18-16 m. Almost all the adjacent blocks of reached up to 0,4 m when the face approached to 7 m. Then some bolts matched their subsidence, whereas other pairs demonstrated replacing of leader-outsider. Therefore, roof subsidence occurs in discrete blocks that move by turn. This behavior occurs in cross sections across and along the axis of the roadway. In other words, it occurs in 3-dimensional space. Such a behavior was demonstrated by the pairs of the bolts №9 and №12 (spacing between them was 3 m); №9 and №11 (spacing 1,5 m); №7 and №8 (spacing 1 m); №8 and №11 (spacing 1 m).

Cluster self-organization may be explained in terms of irreversible thermodynamics. The disintegrated rock mass surrounding a roadway may be treated as an irreversible system that puts (transmits) energy generated in remote rock mass under action of overburden strata through itself. Such a system must keep a state with minimum production of entropy. The entropy is a probabilistic measure of the geomechanical state of rock mass in the vicinity of a roadway. To maintain the minimum level of entropy production, clusters must rearrange as described above. Any other behaviors would produce more entropy which would be unlikely to exist.

PROCEDURES FOR FORECASTING ROOF FALLS

In summary, the most important signs of an imminent roof fall found in this research are:

Sudden divergence of the ribs of the opening. Divergence is on the order of 50 mm that may be monitored easily by some commonly used means.

Horizontal compression of the ribs sides up to 2% that can be measured by some commonly used extensometers.

Evidence of accelerated separation of the immediate roof from the rest of the roof strata. The rest of the roof strata tends to ascend against the gravity vector or at least holds steady while the separated immediate roof strives to subside.

Positioning of a separated rock mass directly over the cavity. The separated block does not overlap rock strata in the ribs sides of the roadway.

These four items of events provide abundant opportunities to develop a set of procedures for monitoring, forecasting and prevention of roof falls. It should be stressed that items 3 and 4 are well known indicators of possible roof fall occurrence. However they are not complete. The falls may or may not happen as field experience demonstrates.

Any procedures that employ a combination of the events will increase the reliability. The more indicators are used together the more reliable. The simplest approach is a simultaneous monitoring of horizontal and vertical convergence's at a suspected roadway sector. Fig. 12 shows an example of convergence progression. A roof fall is imminent when the sides of an opening switches to divergent while convergence of the roof and floor accelerates.

Simultaneous monitoring of horizontal convergence and strata separation in the roof is another option for prediction of roof fall. A roof fall is imminent when the horizontal divergence coincides with the initiation of roof separation.

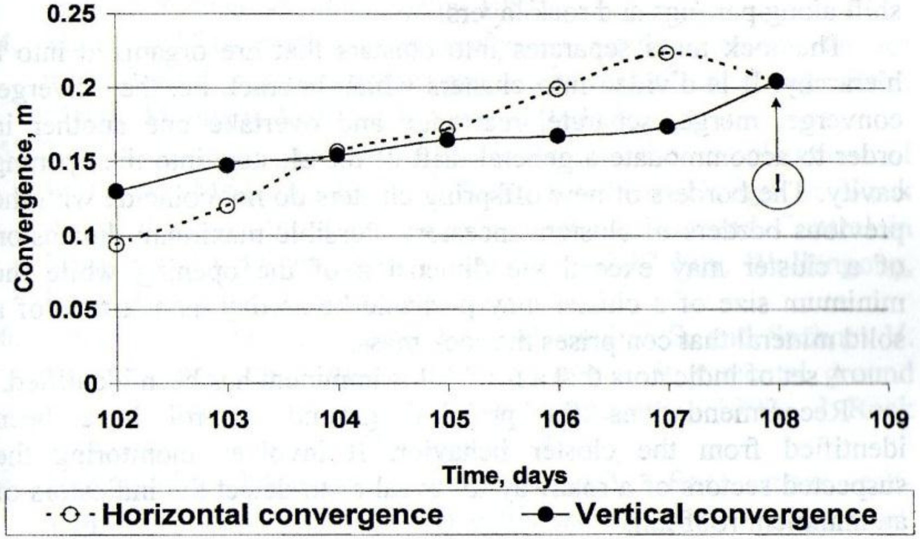


Fig. 12. Progression of roadway convergence. Roof fall occurs at (!).

CONCLUSION

Due to high ground pressure or poor geologic condition, the rock mass experiences irreversible deformation. Any rock mass that has some cohesion and strength can not move into an opening simultaneously and orderly. For the lack of degree of freedom, ***it must be divided into clusters that are forced to move by turn***, one after another in space and in time. The crowded clusters have to yield to each other and alter their movement velocity and direction in order to keep moving into the opening cavity. Such a behavior accounts for the uneven and irregular vertical subsidence and the movement of adjacent rock blocks in the roof, sides or floor of an opening. Such a movement causes changes in the horizontal displacement in the roof and the surrounding rock mass and destroys the symmetry of horizontal displacements with respect to the center line of the opening. That is why rock folds emerge in the roof and floor due to intensive ground pressure. Similar events are observed when the walls of a hole shift along partings and rock layers.

The rock mass separates into clusters that are organized into a hierarchy. It is divided into clusters which interact, i.e. they diverge, converge, merge, separate, rearrange and overtake one another in order to accommodate a general drift of the clusters into the opening cavity. The borders of new offspring clusters do not coincide with the previous borders of clusters-ancestors. Possible maximum dimension of a cluster may exceed the dimension of the opening while the minimum size of a cluster may probable be as tiny as a lettuce of a solid mineral that comprises the rock mass.

A set of indicators that a roof fall is imminent has been identified.

Recommendations for practical ground control have been identified from the cluster behavior. It involves monitoring the suspected sectors of a roadway to reveal or to detect the indicators of an imminent roof fall.

Horizontal displacements and dilation must be prevented in order to maintain the stability of an underground opening. Such a state retains the self-supporting effect of the roof and contributes to rock bolts bearing capacity.

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