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Snowmelt water breakthrough into coal mine

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Abstract. The paper addresses the mechanism of flood water inrush from a technogenic ground sinkhole into underground excavation. Basing on computer simulation it was demonstrated that an area of tensile stresses is formed in the zone affected by underground mining. A natural hydrofracture of rocks may develop from the sinkhole into the mine opening under the effect of tensile stresses and water hydrostatic pressure. Hazardous water inflow into underground mine opening may be associated both with direct hydrofracture crack egress into the opening and with preliminary intense filtration water inflow from the crack into the opening if the crack development slows down. On approaching the mine opening the fracture may stop growing due to local rock compression near the opening. The modeling has demonstrated that the actual picture of the catastrophic water inflow into the ventilation gallery cannot be explained by filtration mechanism only. The catastrophic water breakthrough may be caused by development of a major water-conducting crack growing from natural frost crack in the bottom of the sinkhole towards the mine opening.

Keywords: *underground mining, ground surface, sinkhole, floodwater, technogenic rock stresses, natural hydrofracture, filtration, water inrush.*

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1. Introduction

Emergency situations caused by spontaneous hydrological events show a continuous trend towards increasing frequency and scale of consequences [1]. Major economic damage from floods due to snow melting is inflicted on engineering constructions on earth surface. However, under certain conditions meltwater may affect safety of underground mining. There are a variety of mechanisms of this impact. As a rule, they are associated with general increase in rock mass water saturation and intensification of filtration.

Underground mining of solid mineral resources at small depths is sometimes accompanied by local sinking of earth surface with rupture of rock continuity referred to as technogenic ground fall-through. The fall-through is caused by a shift of undermined rock into the opening. In Russia design and construction of buildings in such cases are done in accordance with appropriate codes of practice to avoid adverse effects [2].

The surface sinkholes are often filled with water. In this case, besides the dangerous geomechanical impact on mining safety, the sinkhole becomes a source of hydrogeological hazard as a reservoir of water that can breakthrough into the underground mine opening. The water breakthrough into the underground opening may proceed by various mechanisms depending upon rock mass geological structure, features of its stress state and water pressure. Water inflow into the underground opening from a surface reservoir in a rather homogeneous and well-penetrable rock mass may proceed by a water filtration mechanism [3, 4]. Another mechanism of water penetration into the underground opening may take place in rock mass with horizontal layers. In this case rock undermining is associated with generation of vertical rock mass tension, bending and disclosing of layer contacts, water filling of the layer contacts, rupture of some layers due to critical bending deformation, which results in water penetration into the opening [5, 6].

If vertical pressure of overlying rock is about twice as high as natural horizontal stress (this situation is characteristic of sedimentary rock in regions with rather calm geodynamical environment), fields of tensile horizontal technogenic stress may be generated in the undermined rock. Tensile cracks may develop and become filled with water in such regions. This water as a factor of force may play an active role in crack development due to pressure on the crack sides. Such fracture cracks may become major canals for water breakthrough into openings both from surface and underground reservoirs [7].

In subarctic regions water breakthroughs may also be caused by generation of so-called frost cracks due to extremely low negative temperature. The generation of frost cracks descending into depth up to ten meters is characteristic of subarctic regions and is not associated with mining activities. These cracks may be considered natural objects affecting subsequent technogenic geomechanical and hydrogeological processes in the rock [8].

Another mechanism for water breakthroughs from the sinkhole to the opening related to both to crack generation

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and filtration flow is considered below on the example of the Yun-Yaga coal mine. As known, study of practical experience is the best way to understand specific mechanisms of events and to develop adequate methods for prediction of similar cases in future.

2. Water breakthrough from a sinkhole into a ventilation gallery at the Yun-Yaga mine

The now closed Yun-Yaga mine was used to extract coal from the Yun-Yaga coal deposit located in north-eastern part of the Pechora coal basin [9]. The climate of this region is subarctic with sharp temperature and pressure variations. Average temperature for a many-year period of observation is minus 6.3°C with absolute minimums of -42 to -52°C and maximums of +30 to +32°C.

The Yun-Yaga deposit is located in a region involving a zone of many-year frozen ground. The zone is 50-60% of the whole area, and there are multiple through taliks in the remaining portion, the zone maximum thickness is 180-200 m (average 50-70 m, predominant values up to 20-30 m), temperature ranges from -0.5 to -3.0°C. The through many-year taliks are as a rule located under large undrained lakes, the Yun-Yaga river, some streams and in a region of sinkholes.

The mine field geological structure has several water bearing sandstone layers located in roofs of coal seams under operation. The deposit natural hydrogeological conditions are impaired due to mine construction. The mine construction was accompanied by large water inflow (reaching 720 m^3/h). The underground water state underwent considerable change by the end of the construction. A large depression funnel was generated that reached and even went beyond the deposit outline involving the Yun-Yaga river-valley. The total decrease in the underground water level in main water-bearing horizons was 65 to 130 m.

A water breakthrough occurred from a rather small surface sinkhole into a ventilation gallery located at about 30m below the sinkhole. The sinkhole was formed in the area of influence of the excavation. However, the sinkhole had no hydrological connection with the ventilation gallery, which was explained by sufficiently plastic properties of the overlying rocks and rapid closing of induced cracks [10].

Water from the ventilation gallery penetrated further into the lava and the conveyor drift. Jumpers and water-resistant doors did not give effect due to water filtration through the surrounding rock mass and concrete partitions. Lack of power and flooding of the pumping stations led to flowage [11].

The breakthrough occurred during the period of high level of melt water (above 0.5 m) due to complete thawing of the overlying rock strata after their partial freezing in winter. The causes of the flood included limited water runoff and insufficient conveyance capacity of the hydrotechnical construction (bridge). The water breakthrough into the ventilation gallery began with weak dripping of water from the roof of the gallery, which turned into strong dripping with erosion and fall of loose roof rock and intense flow of water from the roof.

The coal seam thickness was 1.9 m and inclination was 10° (Figure 1). The immediate roof was a 1m siltstone layer of 40 MPa strength; the main roof was a sandstone layer about 14 m thick and 70-90 MPa strong. The overlying rock mass in weathering area was weakened by oxidation process and individual frost cracks.

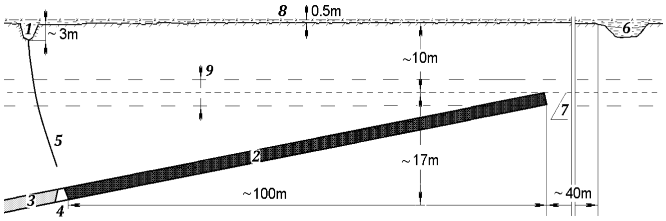


Figure 1. Scheme of water breakthrough in the Yun-Yaga mine: 1 –sinkhole; 2 – coal pillar; 3 – worked-out seam; 4 – ventilation gallery; 5 – water-conducting crack; 6 – river; 7 – coal seam egress under the bedrock, 8 – flood level at the event occurrence, 9 – natural talik

Check-up at the mine reported the following causes of the event:

a) absence of preventive activities such as sinkhole filling;

b) inadequate activities for isolation of the opening from the surface;

c) absence of hydrotechnical installations to prevent river overflow and water penetration into mining field at the seam egress under the overburdens;

d) insufficient conveyance capacity of the bridge over the river during water floods;

e) flood water rise higher than the maximum expected level, outflow beyond the protective pillar and breakthrough via the sinkhole into the ventilation gallery;

f) development of frost cracks;

g) development of a sinkhole in the earth surface along the frost cracks under the effect of flood water;

h) unfavorable complex of natural factors such as early and strong frost, deep freezing, small snow cover, short and violent spring water flood.

These causes were not supported by any calculations and were to a certain degree contradictory. For instance, a frost crack cannot be deeper than ten meters. The season-associated temperature variance has no effect at such a depth due to the talik impact. Development of the major crack should occur in another manner. Therefore, this event was considered abnormal and requiring a special examination.

3. Modeling of water breakthrough

An attempt was made to model the geomechanical and hydrogeological situation using the approach described in [12]. This approach assumes that the occurrence of a large water-supply crack is associated with the combined effect of technogenic pressure reduction of rocks and hydrostatic effect of water in the crack. The growing crack is actually a hydrofracture of the rock.

Since the initial geometric and geomechanical situation was not known in detail, different calculation schemes existed for the formulation of modeling problems. Each of the patterns included a rock mass up to 100 m deep and a 50-meter part of the excavations. On the part of the excavated seam (50 m in length) the resistance of the support to the movement of the overlying rocks was set by back pressure of 0.5 MPa. There was no back pressure in a small part of the excavation, including the ventilation gallery.

In the calculation the sinkhole was assumed to be an ellipsoid earth surface depression of about 3 m in depth, water pressure near the sinkhole bottom was 0.03 MPa. Since the sinkhole had no hydraulic connection with the mine opening and the permafrost was absent in the considered area, rock mass was assumed to be homogeneous elastic solid medium with 10^3 MPa modulus of elasticity and Poisson's ratio of 0.3.

Rock pressure in the virgin rock mass was specified by the academician A.N. Dinnik hypothesis that vertical stresses were determined by weight of overlying rock (about 0.6 MPa at a 30 m depth), while side stresses depended upon Poisson's ratio of the rock. They were 0.25 MPa in the case considered.

The conditions of the absence of permafrost in the considered area of rock mass were considered. It was due to technogenic influence of mining and the influence of sinkhole. For this reason, the rock mass was considered an elastic medium without internal stress sources.

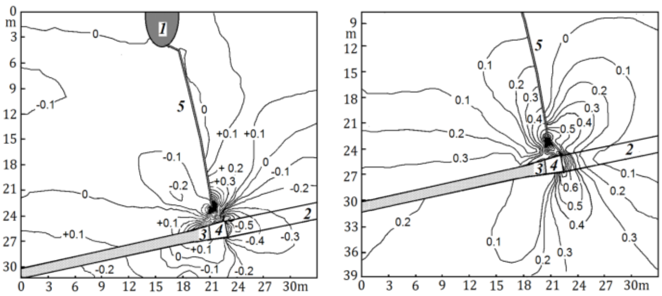
A variety of situations with initial crack starting from the sinkhole were considered including a small vertical frost crack beginning from the sinkhole bottom and a crack coming out from the sinkhole at an angle. As concerns crack growth two factors were considered, i.e. technogenic stress state of the rock mass and water pressure in the crack changing with depth by hydrostatics law.

Calculation of crack development was made by sequential steps according to the finite element method. Possibility of rock destruction at the crack end was assessed at each step by the Griffiths-Irwin criterion as described in. The vertical coordinate reflects the change in depth from the earth's surface. The horizontal coordinate defines the changes along the coal seam. If the criterion was met, a small length increment was specified along the direction of the highest tensile pressure of the rock. As a result of a sequence of calculation steps a trajectory was found for crack development from the sinkhole to the ventilation gallery due to rock natural hydrofracure.

4. Results and discussion

4.1. Stress-strain state and crack propagation

Figure 2 shows some results of stress calculation for a situation when a water-conducting crack approached the ventilation gallery (the distance from the crack end to the gallery was 2 m with a crack of 24 m in length). Figure 2a shows isolines of main stress which is the highest tensile stress leading to rock fracture. Figure 2b shows isolines of von Mises stress that allows assessment of the rock area of pre-destruction. Rock permeability is known to increase rapidly in this area [13].



(a) (b)

Figure 2. Stress distribution in the rock mass during crack propagation toward the mine opening: (a) – isolines of the maximum tensile stress (MPa); (b) – isolines of the von Mises equivalent stress (MPa): 1 – sinkhole; 2 – coal seam; 3 – worked-out seam; 4 – opening; 5 – crack

Analysis of the stress-strain state of the rock mass near the end of the crack and the ventilation gallery shows that the crack can reach the roof of the gallery under some conditions or stop in its development under other conditions (due to the features of the geometry of the opening and the local compression of the rock). The first case is the situation with dynamic break of water into the crack at once, the second case reflects the possibility of water filtration into the opening.

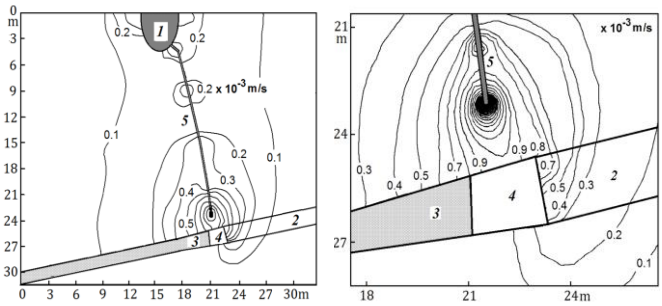
4.2. Filtration flow and water breakthrough mechanism

The problem of filtration theory is solved to analyze the features of the filtration flow into the ventilation gallery, including the water filtration directly from the surface and sinkhole together with the water filtration from the water-conducting crack. The filtration coefficient of siltstone 0.001 m/s was used in the calculation

As follows from the calculations, for a crack less than 20 m in length the filtration flow of water from the surface and from the crack to the rock mass is extremely low. The situation changes when the crack approaches the mine opening. In this case interaction between the crack and the opening begins (Figure 3).

Figure 3a shows the situation for a 24 m long crack. In the figure the isolines of values of the filtration rate (m/s) are shown. These values must be multiplied by a correction factor of 10^{-3}. As seen, the filtration flow of water is strongly limited by the end of the crack. Figure 3b shows isolines in the immediate vicinity of the opening. These isolines are constructed on a different scale for a different finite element mesh to verify the correct calculation and to more accurately estimate the amount of possible water flow into the hole.

The assessment showed that the water flow through the free surface of 15 m^2 can reach about 50m^3 per hour. Such an intense water flow may really cause washout of weak rock in the roof of the ventilation gallery and partial roof fall into the opening with the major crack start and water breakthrough in the opening to follow, which was the actual case.



(a) (b)

Figure 3. Distribution of filtration flow in the rock mass during crack propagation toward the mine opening: (a) – isolines of filtration flow rate (m/s) for a crack length of 24 m; (b) – enlarged view of filtration flow isolines in the vicinity of the mine opening: 1 – sinkhole; 2 – coal seam; 3 – worked-out seam; 4 – opening; 5 – crack

The modeling has demonstrated that the actual picture of the catastrophic water inflow into the ventilation gallery cannot be explained by filtration mechanism only. The catastrophic water breakthrough may be caused by development of a major water-conducting crack growing from natural frost crack in the bottom of the sinkhole towards the mine opening.

It follows from the modeling that the major water-conducting crack may be considered as natural hydro fracture of rock mass in the area of low technogenic stress. Hydrostatic pressure in the crack increases during water flood and the crack may grow to a considerable depth. This factor is of much importance for a case when the sinkhole occurs near the border of projection of the undermined seam portion to earth surface.

So, possibility of water breakthrough into the mine opening is associated in some degree with a sinkhole of earth surface. Note that probability of occurrence of a technogenic sinkhole on the earth surface under conditions of simple geometry of mine opening and absence of geological faults may be assessed using a rather simple formula based on statistical analysis of data concerning the sinkholes [14]. For the case considered probability of sinkhole occurrence may be calculated by a rough formula:

$$q = (H/S^{1/2}), \quad (1)$$

where H is the excavation depth; S is transverse section of the mine opening.

If $q < 8$, the sinkhole is practically unavoidable; if $q > 16$ the sinkhole is very rare; if $8 < q < 16$ probability of a sinkhole is about 0.5. However, these relationships can hardly help in assessing details and consequences of the sinkholes especially when they are filled with water. To make such a study computer modeling of stress state and hydrogeological state of the rock mass should be used. Timely modeling of possible situations with due consideration of geomechanical and hydrogeological factors could help to predict hazardous situations and to prevent water breakthrough in the mine opening [15].

It should be noted however that in real conditions of block structure of the rock mass the induced deformations can form a more complex picture as established in [16]. Here we use the idea of rock mass with rheological properties. In this case the induced cracks are closing over time.

As follows from our modeling, the major rapidly growing crack may stop to develop near the mine opening. In this case a heavy local filtration inflow into the opening may occur. In practice such a local water filtration inflow in loose rock often leads to washout and fall of the rock from the roof of the opening. In the case considered the rock mass failure area reached the end of the water-conducting crack, which resulted in a powerful stream of water into the opening.

4.3. Implications for prediction of water breakthrough

The conclusion may be made that if water penetration into mine openings proceeds by the crack-and-filtration mechanism, heavy dripping from the opening wall and roof should occur before the catastrophic breakthrough. Therefore, one may predict the critical situation with breakthrough of the major portion of water into the mine opening and take preventive measures beforehand to reduce hazardous consequences of the water breakthrough.

Assessment of possibility of water breakthrough into underground openings in subarctic regions should involve assessment of possible effect of permafrost, which in general prevents water penetration into underground mine openings. However, one has to take into consideration that taliks may be generated in the rock mass under the effect of mining at small depth. In addition, the presence of natural and artificial water reservoirs on the surface further contributes to the generation of taliks. In this case the poorest conditions for water breakthrough into underground openings at small depth are formed due to spring thawing of subsurface rock.

5. Conclusions

The meltwater-filled sinkhole changes dramatically rock geomechanical state and makes conditions for generation of a hydrofracture crack to mine opening. Hazardous water inflow into underground mine opening may be associated both with direct hydrofracture crack egress into the opening and with preliminary intense filtration water inflow from the crack into the opening if the crack development slows down. In loose rock, an intense filtration inflow of water, which manifests itself by a very intense dripping of water from the roof of the mine, can be an indicator of the approaching washout of the rock and the flood of water from the water-conducting crack.

Author contributions

Conceptualization: NAM; Data curation: VNO; Formal analysis: VNO, EVF; Funding acquisition: VNO; Investigation: EVF, NAM; Methodology: NAM, EVF; Project administration: NAM; Resources: VNO, EVF; Software: EVF; Supervision: VNO, NAM; Validation: NAM; Visualization: NAM; Writing – original draft: NAM, VNO, EVF; Writing – review & editing: NAM, VNO, EVF. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Еріген қар суларының көмір шахтасына енуі

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Аңдатпа. Мақалада техногендік жер бетіндегі опырылмадан жерасты қазбасына тасқын суларының басып кіру механизмі қарастырылады. Компьютерлік модельдеу нәтижесінде жерасты кен өндіру әсер ететін аймақта созылу кернеулерінің аймағы қалыптасатыны көрсетілді. Созылу кернеулері мен судың гидростатикалық қысымының әсерінен жыныстардың табиғи гидрожарықшақтануы опырылмадан жерасты қазбасына қарай дамуы мүмкін. Жерасты қазбасына қауіпті су ағымы гидрожарықшақтың тікелей қазбаға жетуімен де, сондай-ақ жарықшақтың дамуы баяулаған жағдайда жарықшақтан қазбаға дейінгі алдын ала қарқынды сүзгілік су келуімен де байланысты болуы мүмкін. Қазбаға жақындаған кезде жыныстардың жергілікті сығылуына байланысты жарықшақтың өсуі тоқтауы ықтимал. Модельдеу нәтижелері вентиляциялық штрекке болған апатты су басуды тек сүзгілік механизммен ғана түсіндіру мүмкін еместігін көрсетті. Апатты су прорывы опырылма түбіндегі табиғи аяздық жарықшақтан басталып, жерасты қазбасына қарай өсетін ірі су өткізгіш жарықшақтың дамуына байланысты болуы мүмкін.
Негізгі сөздер: *жерасты пайдалы қазбаларды өндіру, жер беті, опырылма (карсттық ойыс), тасқын сулары, тау жыныстарындағы техногендік кернеулер, табиғи гидрожарықшақтану, сүзгілеу (фильтрация), су басып кіру*.

Прорыв талых снеговых вод в угольную шахту

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Аннотация. В работе рассматривается механизм прорыва паводковых вод из техногенного провала земной поверхности в подземную выработку. На основе компьютерного моделирования показано, что в зоне влияния подземных горных работ формируется область растягивающих напряжений. Под действием растягивающих напряжений и гидростатического давления воды может развиваться естественный гидроразрыв горных пород от провала к горной выработке. Опасный приток воды в подземную выработку может быть связан как с непосредственным выходом трещины гидроразрыва в выработку, так и с предварительным интенсивным фильтрационным притоком воды из трещины в выработку в случае замедления развития трещины. При приближении к выработке рост трещины может прекращаться вследствие локального сжатия пород вблизи выработки. Моделирование показало, что реальная картина катастрофического притока воды в вентиляционную галерею не может быть объяснена только фильтрационным механизмом. Катастрофический прорыв воды может быть обусловлен развитием крупной водопроводящей трещины, растущей от естественной морозной трещины в днище провала в сторону подземной выработки.
Ключевые слова: *подземная добыча полезных ископаемых, земная поверхность, провал (карстовая воронка), паводковые воды, техногенные напряжения в горных породах, естественный гидроразрыв, фильтрация, прорыв воды*.

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