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NUMERICAL ANALYSIS OF THE POSSIBILITY OF NOXIOUS GASES INFILTRATION INTO A SHELTER LOCATED IN A GAS-BEARING COAL-ROCK MASS

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Abstract. Shelters in coal mines are used to protect miners during accidents associated with gassing of roadways, fires, explosions of methane-air mixture. Supporting of the shelter must provide the necessary level of tightness to prevent the penetration of noxious gases from the mine atmosphere or gas-bearing rocks. The purpose of this work is to study the possibility of noxious gases penetration into a shelter in case of its sealing failure for the early detection of weak constructional elements and to ensure safe conditions for people in the shelter during accidents. To achieve the goal, methods of numerical simulation of time-dependent processes of elastic-plastic deformation and gas filtration were used. A coal-rock mass with a roadway and an adjacent shelter with typical supporting elements were considered at a depth of 400 m and 1000 m.

The study of the stress state of the shelter support showed that under the considered conditions, in the case of a relatively small depth, hard steel and concrete constructional elements withstand the load without loss of their stability. With an increase in the depth of the shelter location, inelastic deformation of the concrete barrier between the shelter and the roadway occurs on a small area. The probable destruction of this zone will not lead to a violation of the entire barrier integrity, which makes it impossible to start mass exchange processes between clean air in the shelter and harmful combustion products in the roadway. The roof and walls of the shelter, covered with reinforced concrete and sealed, remain practically impermeable from the next day after their construction in both the first and second cases. But later, in the lower left corner of the shelter at a depth of 1000 m, methane from the coal seam begins infiltrating through the unsupported and unsealed floor.

The developed numerical model can be used with other basic data on mining and geological conditions to identify constructional elements of a shelter, which lose stability during operation and threaten the shelter's tightness. Timely strengthening of such weak elements will prevent the danger of noxious gases infiltrating into the shelter.

Keywords: time-dependent rock deformation, shelter, sealing failure, gas filtration, numerical simulation.

1. Introduction

Shelters in coal mines are used to protect miners from lack of oxygen and exposure to noxious gases during accidents associated with gassing of roadways, fires, explosions of methane-air mixture. They are also necessary for the work of rescuers who conduct reconnaissance and must remove injured persons from the accident site [1–3]. Such shelters are built in a niche adjacent to the roadway. The normative document [4] emphasizes that support of the shelter must ensure the required level of tightness and repair-free maintenance of the shelter during its operation. The shelter's tightness should be sufficient to prevent the penetration of fire gases from the adjacent roadway [5–7]. It is also necessary to ensure the supply of fresh air and its excess pressure of at least 50 Pa relative to the pressure in the roadway, which prevents the penetration of combustion products into the shelter.

The source of noxious gases ingress into the shelter can be not only the atmosphere of the adjacent roadway, but also coal seams and rocks, which in the conditions of coal mines of Ukraine have high gas content [8–12].

Gas penetration into the shelter is possible by:

- mass exchange between clean air in the shelter and harmful combustion products in the roadway, provided the barrier between the roadway and the shelter is significantly destroyed;
- infiltration of noxious gases through disturbed rocks and constructional elements from the sources of release (gas-bearing rocks and coal) in case of shelter sealing failure.

The processes of gas filtration [13–18] and mass exchange [19–22] were studied by many scientists in different countries of the world. On the basis of elastic-plastic mechanics and gas dynamics, a model of the coupled processes of gas filtration and deformation of heterogeneous coal was developed, the effect of coal heterogeneity on gas filtration and coal destruction was studied [15]. Simulation of gas filtration to wells in a coal seam, the permeability of which was increased by hydraulic fracturing [18], was performed. The effect of the type of support on filtration processes in the vicinity of a roadway, the movement of filtration flows during the operation of degassing wells, and the use of protective structures in the drift were studied [13, 18]. However, the possibility of methane filtration from a disturbed gas-bearing mass into a sealed underground structure with various types of support in case of loss of stability of some constructional elements has not been investigated before.

An important factor affecting the gas filtration process is the permeability of rocks and coal, which depends primarily on their stress state [23–26]. Therefore, a thorough study of stress fields in the layered, gas-bearing rock mass with the roadway and the shelter, the stability of their constructional elements is necessary in order to explore the possibility of the penetration of noxious gases into the shelter.

In view of the above, the purpose of this work was to study the possibility of noxious gases penetration into a shelter in case of its sealing failure for the early detection of weak constructional elements and to ensure safe conditions for people in the shelter during accidents.

2. Problem definition

To achieve the goal, the following tasks were fulfilled:

1) the time-dependent deformation of the coal-rock mass and elements of support was investigated;

2) the possibility of mass exchange between clean air in the shelter and harmful combustion products in the roadway was investigated;

3) the process of gas filtration from the sources of its release to the shelter in case of loss of stability of concrete constructional elements with their sealing failure was investigated.

For the calculations, a typical design of the shelter adjacent to the roadway, which is driven through the coal seam, is considered, figure 1. Both the roadway and the shelter are supported with frames, the astel of the walls and the roof is reinforced concrete, the shelter is separated from the roadway by a concrete barrier 200 mm thick. The floor of the shelter is located 700 mm above the floor of the roadway.

The simulation was performed under the conditions when the roadway is located at a depth of 400 m and 1000 m, the host rock is argillite, the coal seam has a natural gas content of 20 m3/t, seam methane pressure at a depth of 400 m is 3 MPa, at a depth of 1000 m it is 8 MPa. The properties of the rocks and support's materials used in the calculations are given in the table 1.

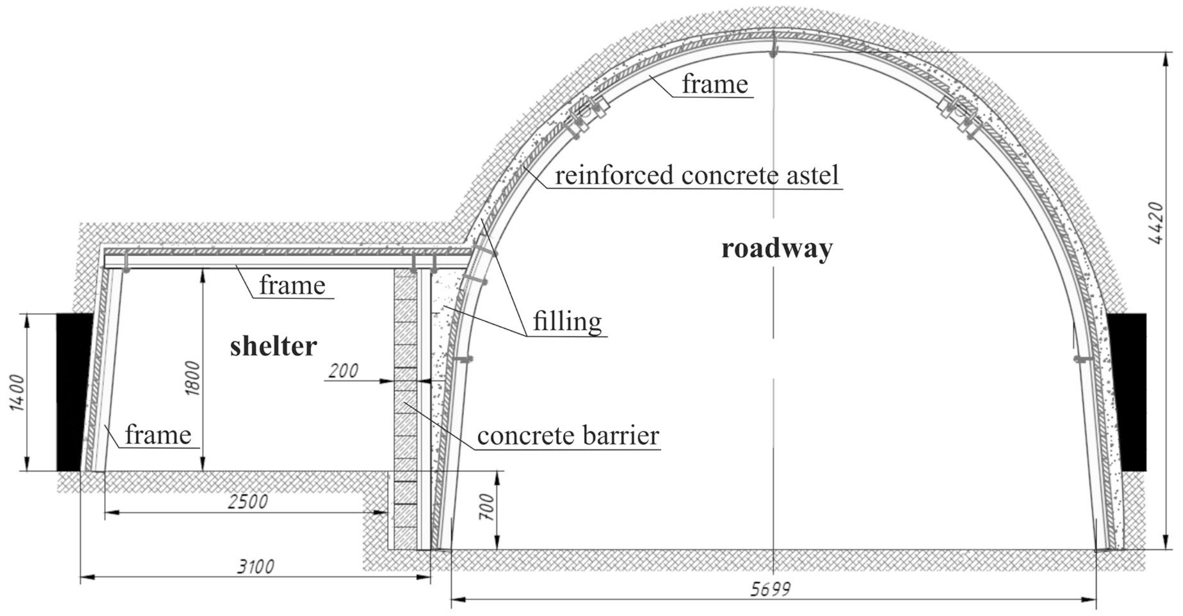


Figure 1 – A typical design of the shelter

Table 1 – The properties of the rocks and support’s materials

Rocks and materials	Ultimate strength σ_c, MPa	Modulus of elasticity E, GPa	Poisson's ratio, ν	Cohesion C, MPa	Friction angle ϕ, deg
Argillite	25	12	0.32	7	30.0
Coal	15	5	0.26	4.5	28.5
Steel	650	200	0.25	-	-
Concrete	40	20	0.2	11.5	30.0
Reinforced concrete	50	24	0.2	13.9	32.0
Backfilling	2	1,2	0.18	0.7	20.0

3. Methods

To solve the problem, numerical simulation of the following coupled processes was performed:

- time-dependent deformation of the rock mass and support’s elements;
- gas filtration from the sources of release to the shelter in case of loss of stability of concrete supporting structures with their sealing failure.

The stress-strain state of the rock mass in the vicinity of the roadway is described by the system of equations [13, 27]:

$$c_g \frac{\partial}{\partial t} u_i = \sigma_{ij,j} + X_i(t) + P_i(t), \qquad (1)$$

where c_g – damping coefficient, kg/(m^3·s); u_i – displacements, m; t – time, s; $\sigma_{ij,j}$ – derivatives of the stress tensor components for x and y axes respectively, Pa/m; $X_i(t)$ – projections of the external forces per unit volume of rocks, N/m^3; $P_i(t)$ – projections of forces due to gas pressure within the crack-pore space, N/m^3.

The initial and boundary conditions for this problem are:

$$\begin{gathered}\sigma_{yy}\big|_{t=0}=\gamma H;\quad \sigma_{xx}\big|_{t=0}=\lambda\gamma H;\\ u_x\big|_{t=0}=0;\quad u_y\big|_{t=0}=0;\\ u_x\big|_{\Omega_1}=0;\quad u_y\big|_{\Omega_2}=0,\end{gathered}\tag{2}$$

where γ – average weigh of the overlying rock seams, N/m^3; H – mining depth, m; λ – the side thrust coefficient; u_x, u_y – components of the displacement vector, m; Ω_1 – the vertical boundaries of the outer contour; Ω_2 – the horizontal boundaries of the outer contour.

Coulomb-Mohr criterion [28, 29] is used in mathematical description of rock transition into a disturbed state. The stress field is analysed using the geomechanical parameter Q*, which characterizes the difference of the principal stress tensor components:

$$Q^*=\frac{\sigma_1-\sigma_3}{\gamma H},\tag{3}$$

where σ_1, σ_3 – maximum and minimum component values of the principal stress tensor, Pa.

The gas filtration process in the disturbed area is described by the equation [14]:

$$\frac{\partial p}{\partial t}=\frac{k_{tech}}{2\mu_g m}\left(\frac{\partial^2 p^2}{\partial x^2}+\frac{\partial^2 p^2}{\partial y^2}\right)+q(t),\tag{4}$$

where p – gas pressure, Pa; k_{tech} – filtration permeability caused by mining operations, m^2; μ_g – gas viscosity, Pa·s; m – rock porosity, %; q – gas release function, that simulates methane desorption.

The permeability k_{tech} of rocks and concrete, depending on their stress state, is determined by the equations obtained by the authors earlier [13, 27].

The initial and boundary conditions are:

$$p\big|_{t=0}=p_0;\quad p\big|_{\Omega_3}=p_{at};\quad p\big|_{\Omega_4}=p_{sh};\quad p\big|_{\Omega_5(t)}=p_0,\tag{5}$$

where p_0 – seam pressure, Pa; Ω_3 – unsealed roadway contour; p_{at} – air pressure, Pa, p_{at} = 0.1 MPa; Ω_4 – unsealed shelter contour; p_{sh} – pressure in the shelter, Pa, $p_{\mathrm{sh}}=p_{\mathrm{at}}+50$ Pa; $\Omega_5(t)$ – the time-dependent boundary of the filtration area.

We assumed that the tightness of the constructional elements is broken if they exceed the strength limit. Then the next boundary condition, which is set at each time step after the calculation of the zone of inelastic deformations, is added to conditions (5):

$$p\big|_{\Omega_6} = p_{sh}, \tag{6}$$

where Ω_6 – elements of concrete support with broken tightness.

Problem (1), (4) with boundary and initial conditions (2), (5) and (6) are solved using the finite element method [30–32] with the help of authors' software. At each time step, the stress field and the zone of inelastic deformations are calculated; the permeability in the filtration area is calculated on the basis of the obtained data; then the places of sealing failure and the parameters of the gas filtration process (pressure, filtration speed and the amount of gas penetrating the shelter) are determined.

4. Results and discussion

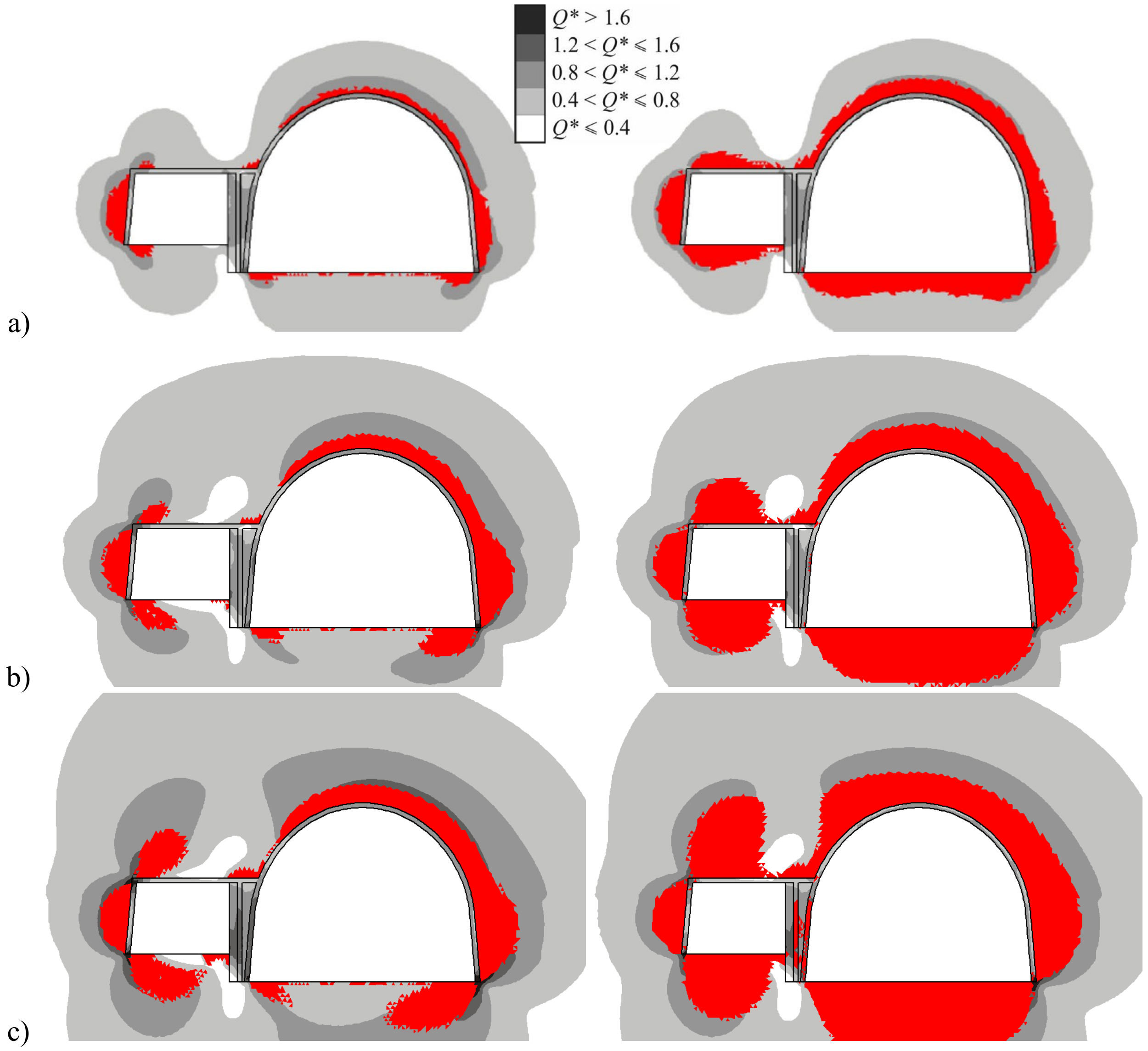
Analysis of the stress fields in the coal-rock mass and stability of the constructional elements of shelter.

In a series of numerical calculations, the stability of the roadway and the shelter at depths of 400 m and 1000 m was investigated. Figure 2 presents the results of calculation of Q* parameter values and the zones of inelastic deformations, which are shown in red, in rocks and support at different time points.

It is clearly seen that over time the area of increased difference of the principal stress tensor components (Q* parameter) expands around the roadway and the shelter. This parameter is a relative value, so its distributions at different depths are almost the same. Small differences are caused by the different intensity of the inelastic deformation process at depths of 400 m and 1000 m. In one day, the zone in the roof of the shelter, where Q* > 0.4, spreads by 1.5 m, reaches 4.9 m in 3 days, and in 10 days it is already 6 m deep. An increase in Q* parameter values leads to an increase in both the intensity of cracking and the filtration permeability of the host rocks around the roadway.

The zone of inelastic deformations, where the strength limit of the rock is exceeded, also grows over time around the roadway and the shelter. But, as can be seen in figure 2, in the case when H = 400 m, it is much smaller. Figure 3 shows the graphs of the increase in the area of the zone of inelastic deformations in the rocks around the roadway with the shelter and in their support at different depths. If H = 1000 m, at different time points, the area of the zone of inelastic deformations is 2.3-3.2 times larger than at a depth of 400 m.

Regarding the stress state of the support for the shelter, in the case of a relatively small depth of its location, we can see that over time Q* parameter values in the supporting elements increases, but hard steel and concrete elements withstand the load without loss of stability (figures 2a–2c, left side).



a) $t = 1$ day; b) $t = 3$ days; c) $t = 10$ days

Figure 2 – Distributions of Q^* parameters values and zones of inelastic deformations in rocks and supporting elements: $H = 400$ m (left side); $H = 1000$ m (right side)

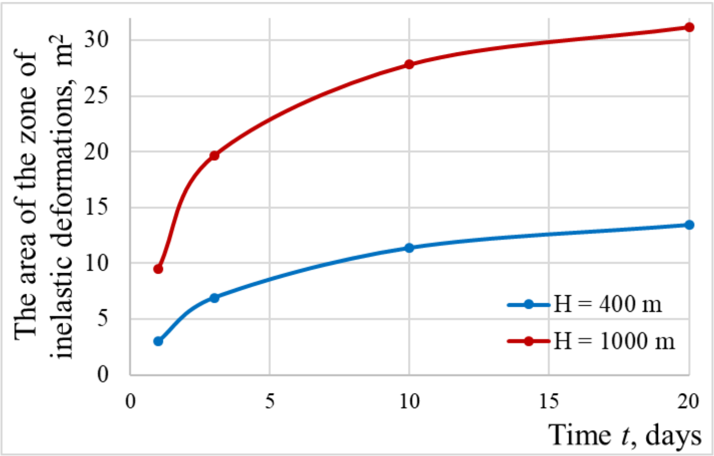
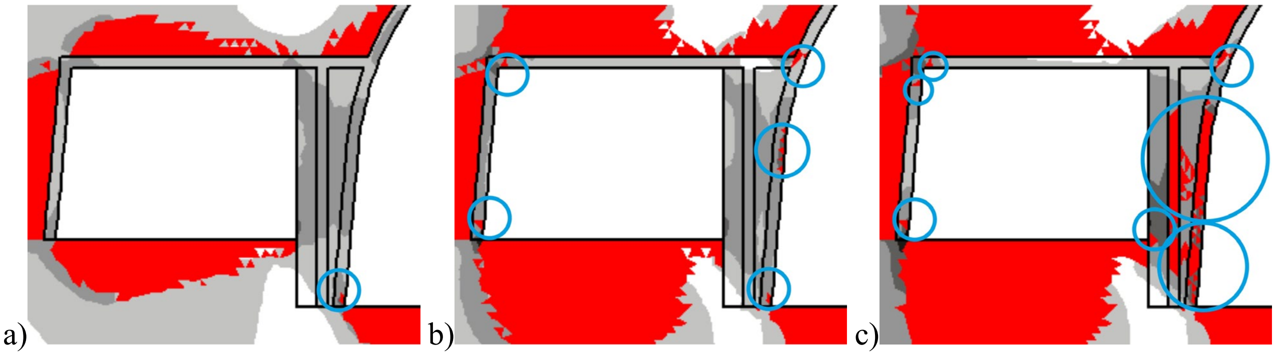


Figure 3 – Time change of the rock area with inelastic deformations

Under these conditions, the concrete barrier, which is part of the construction of the partition between the roadway and the shelter, is elastically deformed and performs its function of supporting the rock arch. But at H = 1000 m, some supporting elements begin to lose their stability in one day, and at each time step, there are more and more such elements. Enlarged fragments of the calculation area with the shelter are shown in figure 4.



a) t = 1 day; b) t = 3 days; c) t = 10 days

Figure 4 – Distributions of Q^* parameters values and zones of inelastic deformations in supporting elements of shelter, H = 1000 m

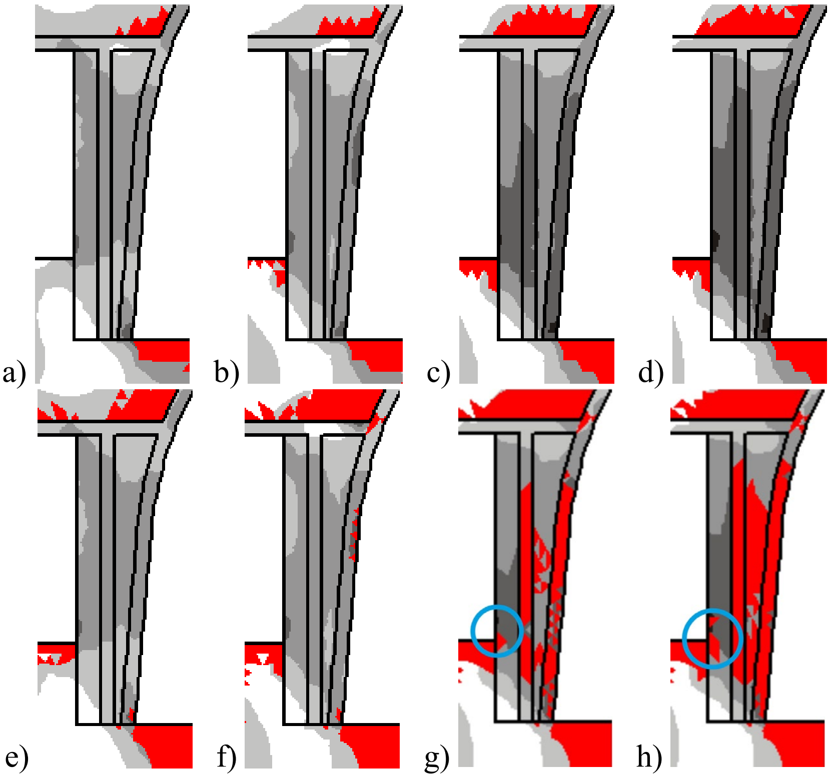
After 10 days (figure 4c), even the 200 mm thick concrete barrier, which separates the shelter from the roadway, begins to fracture. That is, with an increase in the depth of mining operations, the support of the roadway and the shelter needs reinforcement.

Ingress of noxious gases into the shelter in case of its sealing failure.

The source of noxious gases is the atmosphere of the adjacent roadway. The pressure differential causes the start of process of gas filtration through disturbed rocks and support. If the air pressure in the roadway is equal to atmospheric pressure, then the excess pressure in the shelter will prevent the penetration of noxious gases from the roadway through disturbed host rocks. The air pressure in the adjacent roadway can increase significantly during the explosion of the methane-air mixture [33]. But this is a short-term increase for a time that is incomparably shorter than the time required for the development of a slow filtration process.

If the partition between the roadway and the shelter is significantly fractured, the development of mass exchange processes between clean air in the shelter and harmful combustion products in the roadway is possible [19]. Mass exchange occurs due to the diffusion of gases, as well as mechanical mixing, in the direction of the phase with a lower concentration of the component [20–22]. Therefore, the integrity of the concrete barrier is a guaranteed protection against ingress of combustion products into the shelter during an explosion.

We considered the possibility of concrete barrier disintegration, which is the main element of the partition between the roadway and the shelter (figure 1), at depths of 400 m and 1000 m (figure 5).



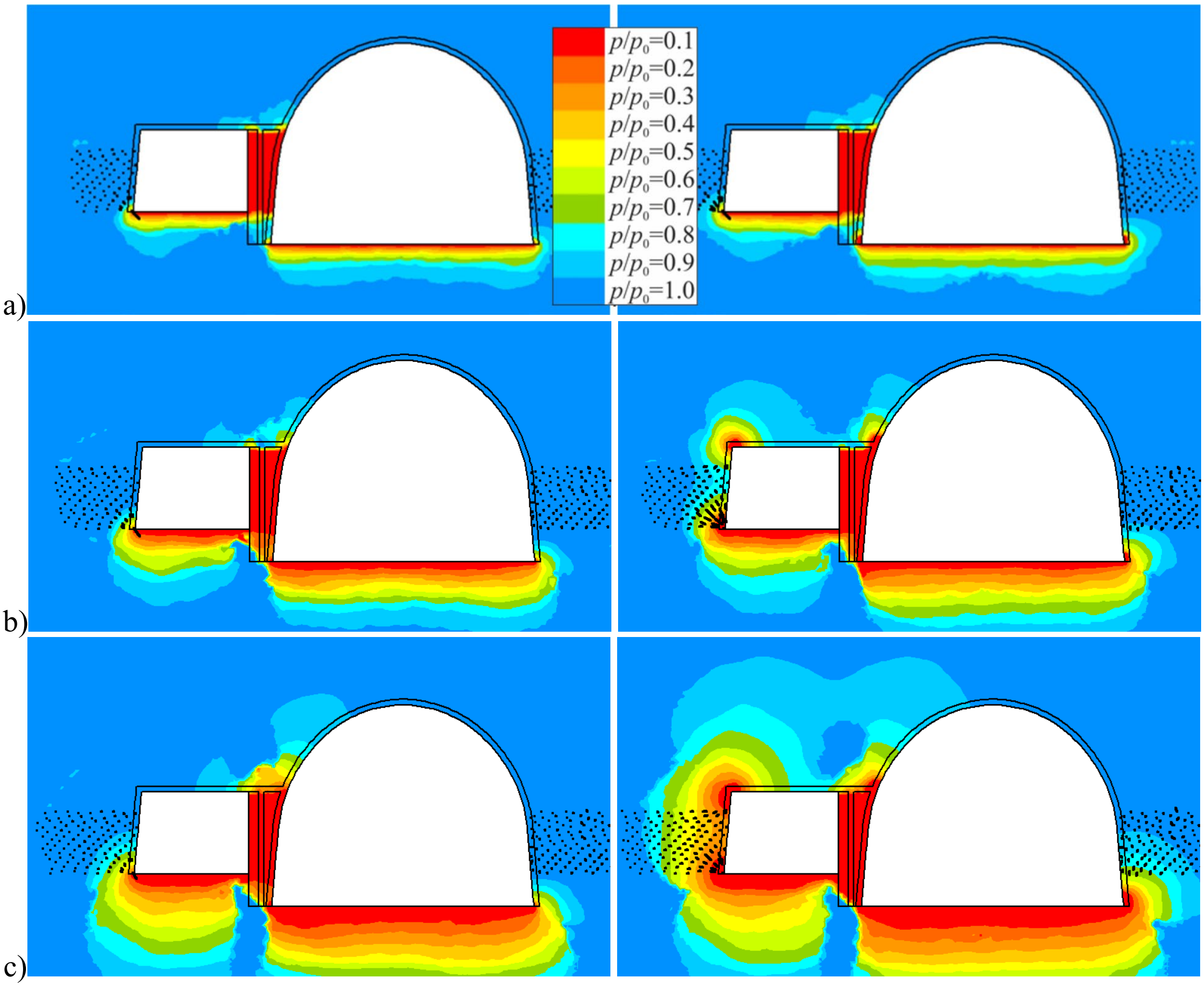
a) t = 1 day, H = 400 m; b) t = 3 days, H = 400 m; c) t = 10 days, H = 400 m;
d) t = 20 days, H = 400 m; e) t = 1 day, H = 1000 m; f) t = 3 days, H = 1000 m;
g) t = 10 days, H = 1000 m; h) t = 20 days, H = 1000 m

Figure 5 – Zones of inelastic deformations in the concrete barrier and other elements of the partition between the roadway and the shelter

The hard concrete barrier withstands the load and maintains its integrity in both cases at the considered depths of mining operations. A small zone of inelastic deformations occurs in the lower part of this constructional element, from the inner side, figures 5g and 5h. But the inelastic deformation of the concrete barrier occurs in a small area and the probable destruction of this zone will not lead to a violation of the entire barrier integrity. In the considered cases, with the assumed boundary, initial, mining and geological conditions, with given properties of rocks and materials, harmful combustion products do not penetrate into the atmosphere of the shelter from the roadway.

The source of noxious gases is the coal seam. Methane pressure in the coal seam is significantly higher than the air pressure in the shelter [34], therefore, if there is a permeable area around the shelter and if its sealing is failed, methane from the coal seam can penetrate into the shelter. The process of methane filtration from the coal seam to the shelter was investigated, figure 6 shows distributions of methane pressure values, figure 7 shows the trajectories of its filtration at different time points at depths of 400 m and 1000 m.

According to the typical support scheme (figure 1), the floor of the roadway and shelter is not sealed, and therefore the pressure of the gas contained in the fracture-pore space of the disturbed rocks in the floor gradually drops. If there were sources of methane release under the shelter (coal seams or gas-bearing sandstones), methane from them would be filtered into the atmosphere of the shelter and the roadway.

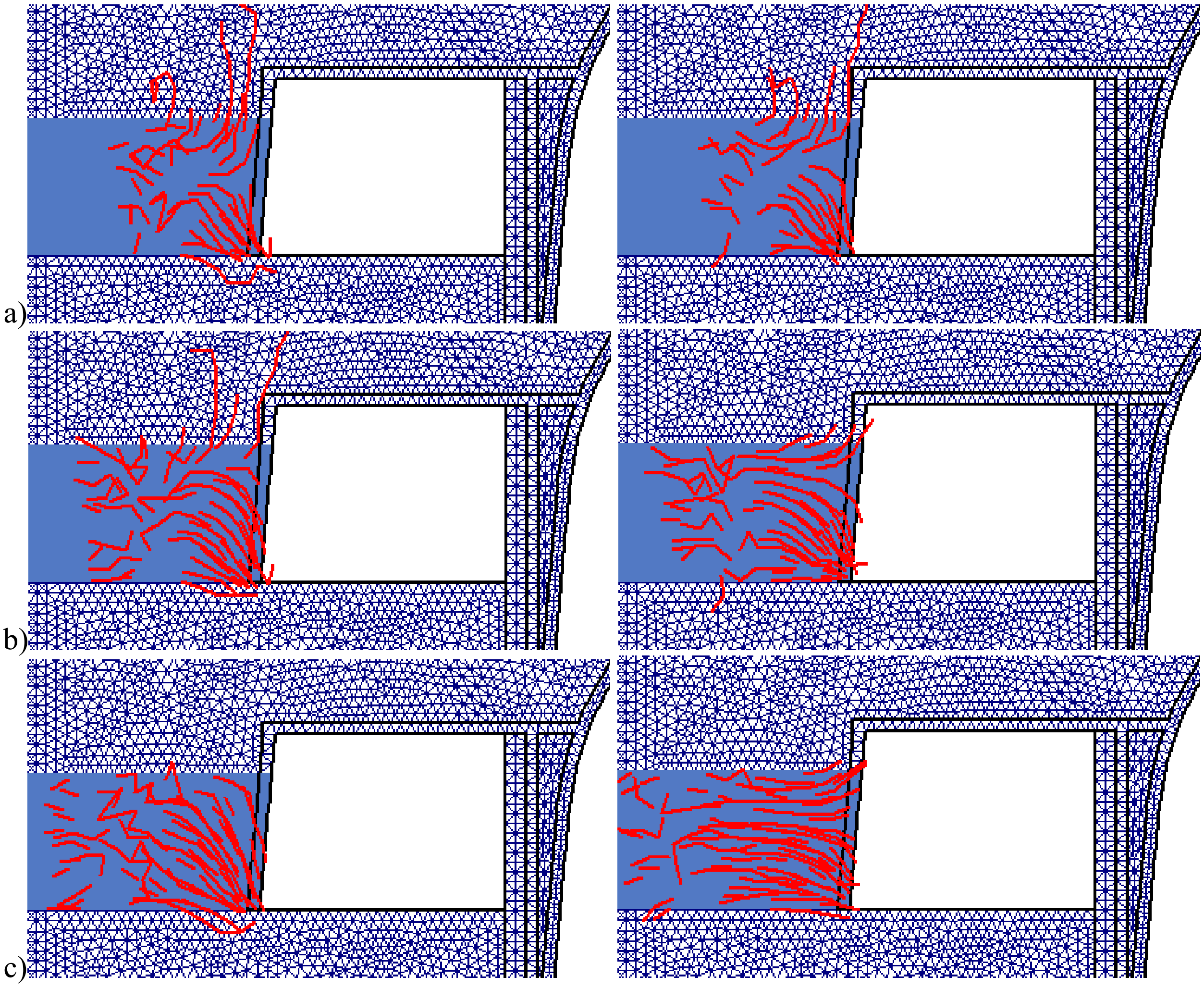


a) t = 1 day; b) t = 3 days; c) t = 10 days

Figure 6 – Distribution of gas pressure values and directions of its filtration: H = 400 m (left side); H = 1000 m (right side)

The roof and walls of the roadway and the shelter, covered with reinforced concrete and sealed, remain practically impermeable from the next day after their construction in both the first and second cases (figure 6a). But in the lower left corner of the shelter there is methane ingress from the coal seam through the unsupported and unsealed floor (figure 7a).

At a depth of 400 m, this situation remains unchanged throughout the research period, which was 20 days. Trajectories of methane filtration do not cross the side surface of the shelter, in the immediate vicinity of it, the directions of movement of the filtration flow are directed parallel to the shelter surface. Methane from the coal seam ingresses into the shelter only through disturbed rock in the lower left corner (figures 6a-6c, left side, and figures 7a–7c, left side).



a) t = 1 day; b) t = 3 days; c) t = 10 days

Figure 7 – Trajectories of methane filtration: H = 400 m (left side); H = 1000 m (right side)

With the loss of stability of some concrete supporting elements at a depth of 1000 m and the violation of their tightness (figures 4b and 4c), a new path appears for the ingress of noxious gases into the shelter, where air pressure is much lower than methane pressure in the coal seam. Methane pressure drops behind the concrete astel in the places where its tightness is broken (figures 6b and 6c, right side). Trajectories of methane filtration cross the surface of the shelter's wall both in its upper and lower parts (figures 7b and 7c, right side). At the same time, the average rate of methane filtration increases by 3.5–3.9 times (figure 8); gas release into the shelter increases by 2.7–4 times at different time points (figure 9).

The typical support, which includes the steel frames, the concrete barrier, the reinforced concrete astel for the walls and roof (figure 1), does not ensure the stability of the shelter and its tightness at great depths. It requires strengthening with rock bolts [35], increasing the thickness of concrete structures in weak places identified by numerical simulation, and sealing the floor of the shelter to prevent ingress of noxious gases through disturbed rocks.

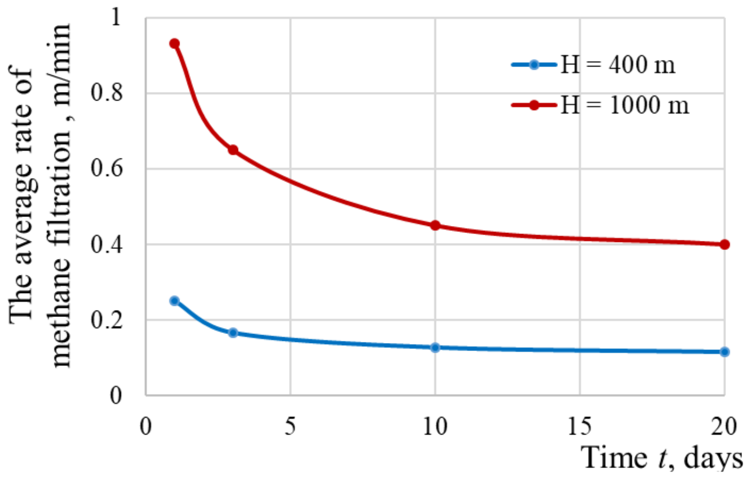


Figure 8 – The average rate of methane filtration in the filtration area

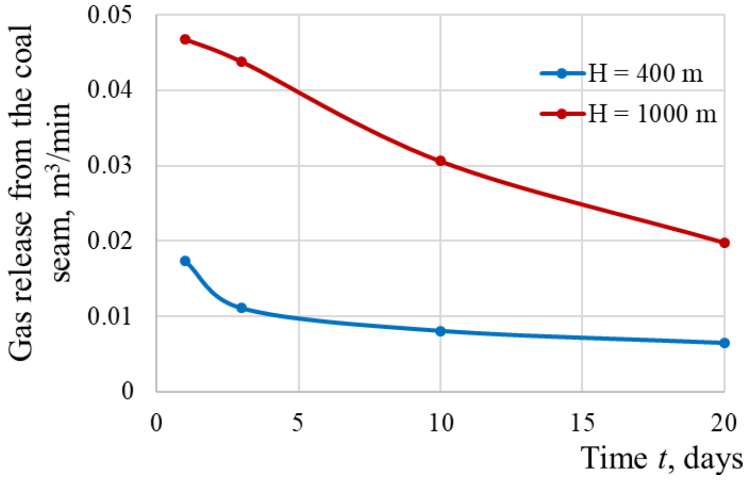


Figure 9 – Gas release in the shelter

6. Conclusions

Numerical simulation of the coupled processes of time-dependent elastic-plastic deformation and gas filtration was made. The coal-rock mass with the roadway and the shelter, as well as their supporting elements at depths of 400 m and 1000 m were considered.

The study of the stress state of the support in the shelter showed that under the considered conditions, in the case of a relatively small depth, the difference of the principal stress tensor components in the supporting elements increases, however hard steel and concrete constructional elements withstand the load without loss of their stability. The concrete barrier, which is part of the construction of the partition between the roadway and the shelter, is elastically deformed and performs its function of supporting the rock arch under these conditions.

With an increase in the depth of the shelter location, inelastic deformation of the concrete barrier between the shelter and the roadway occurs on a small area. The probable destruction of this zone will not lead to a violation of the entire barrier integrity, which makes it impossible to start mass exchange processes between clean air in the shelter and harmful combustion products in the roadway. The roof and walls of the shelter, covered with reinforced concrete and sealed, remain practically impermeable from the next day after their construction in both the first and second cases. But later, in the lower left corner of the shelter at a depth of 1000 m, methane from the coal seam begins infiltrating through the unsupported and unsealed floor.

According to the performed calculations, the typical support, which includes the steel frames, the concrete barrier, the reinforced concrete astel for the walls and roof, does not ensure the stability of the shelter and its tightness at great depths. It requires strengthening with rock bolts, increasing the thickness of concrete structures in weak places identified by numerical simulation, and sealing the floor of the shelter to prevent ingress of noxious gases through disturbed rocks.

The developed numerical model can be used with other basic data on mining and geological conditions to identify constructional elements of a shelter, which lose stability during operation and threaten the shelter's tightness. Timely strengthening of such weak elements will prevent the danger of noxious gases infiltrating into the shelter.

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ЧИСЕЛЬНИЙ АНАЛІЗ МОЖЛИВОСТІ ПРОНИКНЕННЯ ШКІДЛИВИХ ГАЗІВ В КАМЕРУ-СХОВИЩЕ, РОЗТАШОВАНУ В ГАЗОНОСНОМУ ВУГЛЕПОРОДНОМУ МАСИВІ

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Анотація. Камери-сховища у вугільних шахтах використовуються для захисту гірників під час аварій, пов'язаних із загазованістю гірничих виробок, пожежами, вибухами метано-повітряної суміші. Кріплення камери-сховища має забезпечувати необхідний рівень герметичності для запобігання проникненню в неї шкідливих газів із шахтної атмосфери або з газоносного масиву. Мета роботи – дослідження можливості проникнення шкідливих газів в камеру-сховище у разі порушення її герметичності для завчасного виявлення слабких елементів конструкції і забезпечення безпечних умов перебування людей в камері-сховищі під час аварій. Для досягнення мети використовувались методи чисельного моделювання залежних від часу зв'язаних процесів пружно-пластичного деформування і фільтрації газу. Було розглянуто вуглепородний масив з гірничою виробкою і прилеглою до неї камерою з типовими елементами кріплення на глибині 400 м і 1000 м.

Дослідження напруженого стану кріплення камери-сховища показало, що за розглянутих умов, у випадку відносно невеликої глибини міцні сталеві і бетонні елементи кріплення витримують навантаження без втрати стійкості. Із збільшенням глибини розташування камери-сховища на малій площі відбувається непружне деформування бетонної перегородки між камерою і виробкою. Ймовірне руйнування цієї зони не призведе до порушення цілісності всієї перегородки, що унеможливлює розвиток масообмінних процесів між чистим повітрям в камері-сховищі і шкідливими продуктами горіння в виробці. Покрівля і боки камери, вкриті залізобетонною затяжкою і загерметизовані, через добу після їх спорудження залишаються практично непроникними і в першому і в другому випадках. Але згодом в лівому нижньому кутку камери-сховища на глибині 1000 м починається просочування метану з вугільного пласта через незакріплену і незагерметизовану підошву.

Розроблену чисельну модель можна використовувати і з іншими вихідними даними щодо гірничо-геологічних умов для виявлення елементів конструкції кріплення камери-сховища, які втрачають стійкість в процесі експлуатації і загрожують герметичності камери. Завчасне посилення таких слабких елементів дозволить уникнути небезпеки просочування шкідливих газів всередину камери.

Ключові слова: деформування порід в часі, камера-сховище, порушення герметичності, фільтрація газу, чисельне моделювання.