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THE DEFORMATION DYNAMICS OF THE EXPERIMENTAL ADIT'S MATERIAL DURING A COAL DUST EXPLOSION

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The purpose of this paper is to improve the mechanism that forms an explosive environment within the workings' space from the accumulated coal dust, based on determining the dynamic deformations under the influence of an explosion in the material that contains the examined working. To simulate the dynamic changes in the stressed-deformed state of the rock mass with an experimental adit inside when under the impact of explosive loads, a modern method of finite differences of mathematical-computer modeling has been used. During the research, the mathematical model has been adapted for studying the stressed-strained state of the rock mass that hosts the created experimental adit at the imitation of a dust blast. Additionally, the model takes into consideration the peculiarities of the direct impact of explosion products on the working's wall, as well as their indirect action. The data were acquired on the propagation of the progressive front of seismic waves inside mining rocks that host the experimental working. The parameters of speed and acceleration of the seismic wave components have been established that occur ahead of the shock front, which moves in the gas environment of a mining working during the explosion of a dust-air mixture.

This paper reports data on the dynamic processes occurring in a mining massif and on the surface of the experimental working at the chain explosion of a dust-air mixture. The simulation results have made it possible to confirm the hypothesis about the loosening of dust accumulations under the influence of seismic waves, which emerge significantly ahead of the explosion front moving along the working. The modeling results provide an opportunity to improve the systems of protection or localization of the dust-air or dust-gas-air explosions. The existence of seismic waves ahead of the shock front makes it possible to prepare in advance the means for localizing dust explosions

Keywords: explosion, explosive dust-air environment, seismic waves, experimental adit, computer modeling

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1. Introduction

Methane and coal dust explosions remain one of the common and most difficult consequences of underground accidents. Over the last 40 years, there has been no significant reduction in the number of explosions in Ukraine (Fig. 1).

In addition, there was an increase in the load on longwalls while the intensification of layers' processing led to a greater methane release at extracting sites, as well as to an increase in the dust fraction in the volume of coal chipped off a layer. Thus, there are objective conditions for the growth of the threat of gas-dust explosions inside the mining workings of coal mines both in Ukraine and other coal-mining countries, as well as in other industries [1, 2]. Most of the dust explosions inside underground workings are complicated by fires, for example, an accident of this kind in 1992 at the Donetsk mine named after O. O. Skochyns'kyi has lasted up to now, covering an underground area of more than two square kilometers. As a result, the environmental stability of a significant subsoil volume is disrupted, the discharge from the isolated space to the surface of toxic fire gases and water that is contaminated by the products of coal coking amount to millions of cubic meters.

In this regard, the task of improving the techniques and means to prevent and effectively localize gas and coal explosions dust remains relevant both in terms of industrial and environmental safety. To devise more effective technologies to combat such emergencies, it is necessary to elucidate in detail the mechanism that forms the conditions for the occurrence of a dangerous environment. The most efficient tool to address this issue is to conduct experimental explosions at the experimental facilities such as adits [2–4].

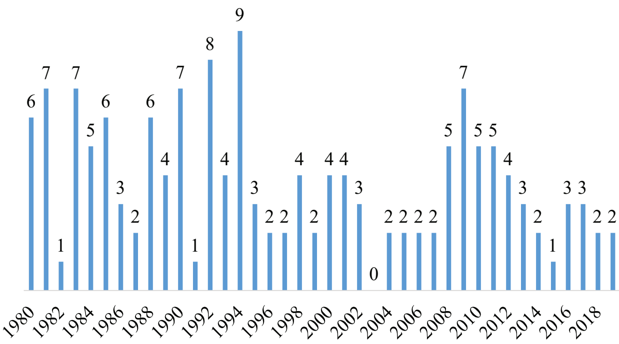


Fig. 1. The dynamics of the number of explosions of gas and dust at the coal mines of Ukraine (data on 2014–2019 refer to the enterprises controlled by Ukraine)

As evidenced by the results of investigating the circumstances and causes of accidents related to the explosions of coal dust, the conditions that preceded the emergence of an emergency were mostly normal. Airing the workings, the condition of spark explosion protection of electrical equipment, compliance with safety requirements for DEO (drilling explosive operations), the availability of explosion localization means met the requirements of safety rules. Inside the facilities, there were no explosive concentrations of coal dust and air. The base of the workings, walls, and ceilings contained the accumulation of dust but they did not have oxygen in their composition that would be sufficient for the deflagration or detonation combustion. The sources of ignition of the combustible environment are most often the drilling blasting, malfunction of electrical equipment, heating of metallic parts or rocks [4, 5].

2. Literature review and problem statement

Modern theories of the emergence and development of a dust blast consider an environment that has a mixture of dust and methane that is enough for combustion under a deflagration or detonation mode. The reaction occurs at a speed close to the speed of sound in the air; this is the so-called fire front in which, due to a sharp increase in the temperature of the oxidation products, the pressure intensively increases. A combustion zone propagates towards the accumulation of a combustible substance. The displacement of gas volumes adjacent to the source of combustion leads to the formation, ahead of the fire front, the so-called shock front, in which the gas environment's compression is close to the hydrostatic one in character [5]. The initiation of an explosion is similar to the ignition of fuel in the diesel engine of internal combustion, due to high pressure or at the expense of infrared radiation, which is generated by the fire front. To this end, it is required that the working's environment should contain a suspended air-dust mixture with a combustible concentration of coal dust [6]. However, actual workings have no such suspensions, only solid clusters, in which the dust content level is much larger than needed for a burning flame. It is unknown how, in a few milliseconds, a combustible dust-air mixture is formed within the working's space. Earlier, we put forward a hypothesis about the participation of seismic waves in it [7]; however, it needs confirmation.

We did not find any studies that could elucidate the mechanism of the direct and indirect interaction between the shock wave of an air-dust explosion and the working's walls. This issue is subject to investigation.

The front of elevated pressure propagates ahead of the explosion fire front; it has a relatively small length that is about several meters. This leads to the compression of dust clusters and, rather than contributing to the further evolution of an explosion, decelerates it. However, the actual pattern of an accident testifies to the opposite; the dust explosion propagated over a network of workings like blowing up a detonation cord. We have not found any explanation for such a contradiction in the literary sources. This implies the insufficient examination of the mechanism that initiates and spreads in the underground mining workings the explosions of a mixture of coal dust with air or a gas-air mixture (hybrid air suspensions).

It is impossible to purposefully reproduce the conditions for such an accident under actual mining conditions because of the catastrophic devastating effects of this kind of experiment, which is why researchers apply special structures such as shock pipes or adits. The data acquired from experimental explosions at man-made facilities testify to the uneven nature of a flame propagation along the length of the experimental working.

Thus, at the Polish experimental mine "Barbara", experimental drifts, arranged between thick rock walls, had a total length of 200 m of the round, and 400 m of the vaulted, type. The corresponding areas of the intersections were 5 and 7.5 m^2. Coal dust was placed on the bed, as well as in special gutters on the working's sides. The explosion was carried out by blasting a stoichiometric mixture of air and methane, which was created in the dead-end part of the adit [8].

The experimental explosions of coal particles, performed by Polish colleagues, may serve an example: first – conditional size d=25, ash content n=60 %, load q=1,200 g/m^2); second – d=85, n=70 %, q=300 g/m^2. The speed of flame propagation in the experimental working changed in a wide range, decreasing from 320 to 160 m/s, or increasing from the level of 160...240 to 720...1,130 m/s. This opposite nature of the process was explained by researchers by the difference in the type of coal, its mass, humidity, ash content, and the dispersity of dust particles. The initial wave formed by the explosion had an amplitude of 320 m/s and a length of about 40 m. At the adit section of 40...280 m, the amplitude of the waves was very diverse but the length was 20...40 m. In the last section (longer than 320 m from the dead-end), they observed the increased length of the waves, to 80...100 m. The results of the experiments do not provide explanations of how the clusters on the bed and in gutters give rise to an explosive suspension. Note that a blast wave passes the working's section of length 10 m over 0.01....0.06 s. To ensure that a dust particle from the bed, in a state of rest, reaches the adit's middle during this time along the shortest path, it should acquire the average movement speed of not less than 20...100 m/s. The source of such accelerations is unknown.

A large body of scientific work addresses the processes occurring during explosions inside mining workings. Study [8] simulated the gas explosion parameters and the virtual flame movement within underground voids. Paper [9] established the effective parameters of the macro kinetics of hydrocarbon combustion under a deflagration and detonation mode in the numerical calculation of emergency explosions in mining workings to suppress the shock wave in the workings' voids. The mechanism of dust explosion as a combination of multiphase, turbulent, chemically reacting flows at burning a combustible aerosol was considered in [10]. However, the cited studies did not tackle the processes of dynamic vibrations in the rocks that surround mining workings, which affect the formation of an explosive environment inside a working's space.

The methods of finite elements are intensively used to assess the stressed-strained state of a mining massif. Paper [11] numerically modeled the axisymmetric problem of explosive impact on the gas-saturated mountain rock in order to intensify its degassing. However, the phenomena of fluctuations in a working's walls were not considered. Close to such a statement is to determine the safe parameters of drilling-explosive operations based on the estimation of the influence of seismic explosion waves on an array of rocks [12]. However, the authors solved a two-dimensional boundary-value problem, which was reduced to solving the spatially-one-dimensional differential equations. This solution is not acceptable when considering mechanical systems of complex asymmetrical shapes, which are qualitatively different from the cylindrical or flat shapes.

We found no research into the dynamics of the stressed-strained state at the three-dimensional mining facilities of complex configurations and its influence on the phenomena on a working's walls where coal dust is accumulated. This requires the improvement of known methods for numerical modeling in order to solve the tasks that we set in a four-dimensional (x, y, z, t) statement.

Based on the assumption that seismic waves propagate in the rock environment faster than the shock waves in the air [7], one should model their dynamics at an experimental structure. It may be possible that the fluctuations of a working's walls lead to the movement of dust particles while loosening the clusters and lift the particles into the air. This might help form an explosive concentration in the air before the approach of the compression (shock) and fire fronts.

3. The aim and objectives of the study

The aim of this study is to improve the mechanism that forms, within a mining working's space, the explosive environment from the accumulations of coal dust, based on elucidating the dynamic deformities in the material that hosts an experimental working, under the action of an explosion.

To accomplish the aim, the following tasks have been set:

– to establish, based on the generalization of existing theoretical representations and results of experimental studies, transitional provisions for uncovering the unexplored sides of the process of an explosion in experimental workings;

– to improve a mathematical model for studying the dynamics of the stressed-deformed state of the rock array of a structure that hosts an experimental adit, under the influence of normal and indirect influence of dust explosion;

– to acquire data on the dynamic processes occurring at the surface of the experimental working and in the array that surrounds it during the explosion of a dust-air mixture;

– to test the validity of a hypothesis about the loosening of dust accumulations under the influence of seismic waves in order to create an explosive dust-air medium inside a working.

4. Substantiating the procedure for examining the dynamics of deformations in the material that hosts an experimental working under the action of a dust explosion

For a more detailed elucidation of the mechanism that forms a combustible environment in the workings, which contributes to the occurrence and propagation of an air-dust explosion, we modeled changes in the stressed-strained state (SSS) of the rock array, in which an experimental adit was constructed, under the influence of dynamic loads. To this end, it is advisable to apply a modern finite-difference method of mathematical-computer modeling [13]. When modeling this process, we considered an experimental structure whose geometry is schematically shown in Fig. 2, similar to the adits at "Barbara" mine, MakNDI (Makeyevka State Research Institute for Mining Safety in the Mining Industry) and others.

When building a model, the following assumptions and initial conditions were accepted.

1) the process of dust explosion propagation along a linear mining working was simulated by means of the consecutive blasting of a chain of charges of an explosive substance, which are located at a distance of 1 m. The propagation speed of the detonation along the working is V_f=400 m/s;

2) in each section of the chain, an explosion is consistently executed, equivalent to blasting four kilograms of TNT;

3) when modeling the explosion, we do not take into consideration its chemical and gas-dynamic nature but consider its result in the form of the assigned pressure curve on the wall of the working;

4) the medium accepted for the location of a working is a material with the averaged mechanical characteristics of sedimentary rock. The length of the structure is 50 m;

5) the thickness of the environment layer surrounding the working is 6 m, under the assumption that the oscillatory waves reflected from the outer boundary of the layer did not significantly influence the qualitative pattern of the movement of the working's walls;

6) the rock material is homogeneous, isotropic, and solid, without cavities and cracks.

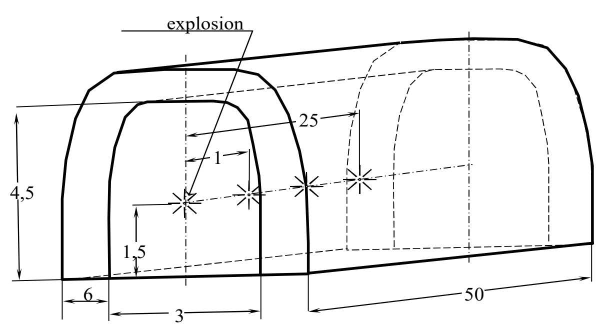


Fig. 2. Schematic showing the structure of the experimental working and surrounding array

In a statement for a single element of the solid, deformed body, in the original state at the original time t=0, as shown in Fig. 3, the separate element of a given body is marked by Ω_0 and the boundary Γ_0. The current body configuration at a specific time t is indicated by Ω, and the boundary – by Γ. When the body moves from position Ω_0 to position Ω, an arbitrary point X, which in the initial state belongs to the region Ω_0, would belong to the region Ω.

The fundamental equations describing the dynamic interaction of solid bodies were obtained by taking into consideration the locking laws or balance laws.

In a given statement, the equation of pulse preservation is recorded in the following form:

$$\sigma_{ij,j}+\rho\cdot f_i=\rho\cdot\ddot{x}_i, \tag{1}$$

where σ_{ij} is the Cauchy stress tensor; ρ is the density of the material; f_i is the forces acting on the body; $\ddot{x}_i$ is the body acceleration point.

A mass preservation law is written in the following form:

$$\rho\det(J)=\rho_0, \tag{2}$$

where ρ_0 is the initial density of the material; $\det(J)$ is the determinant of the tangent rigidity matrix (Jacobian).

The equation for energy conservation law includes the amount of the kinetic and internal energies, which should equal the amount of work of the external forces.

$$P^{\text{int}}+P^{kin}=P^{ext}+P^{heat}. \tag{3}$$

The kinetic energy is calculated from:

$$P^{kin}=\frac{\mathrm{d}}{\mathrm{d}t}\int_{\Omega}\frac{1}{2}\rho v\cdot v\mathrm{d}\Omega, \tag{4}$$

the amount of internal energy is determined from the following expression:

$$P^{ext}=\int_{\Omega}v\cdot\rho b\mathrm{d}\Omega+\int_{\Gamma}v\cdot t\mathrm{d}\Gamma. \tag{5}$$

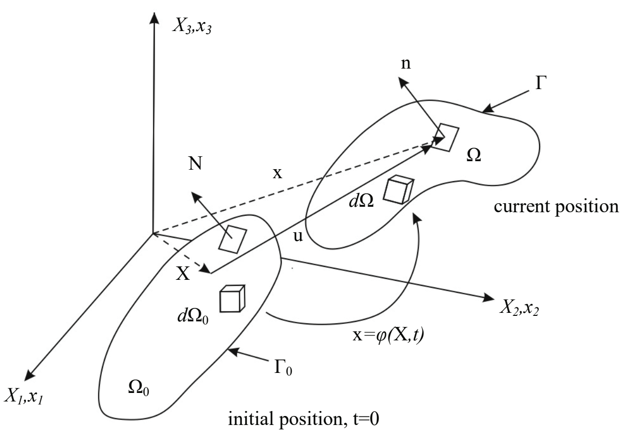


Fig. 3. The initial (Ω_0) and current (Ω) states of the non-deformed solid body

In the absence of sources of thermal heating, the equation of energy conservation is recorded, according to works [14, 15], in the following form:

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_{\Omega}(\rho w^{\text{int}}+\frac{1}{2}\rho v\cdot v)\mathrm{d}\Omega=\int_{\Omega}v\cdot\rho b\mathrm{d}\Omega+\int_{\Gamma}v\cdot t\mathrm{d}\Gamma. \tag{6}$$

The transformed equation of energy conservation for the deformed solid body is recorded in the following form:

$$\rho\frac{\mathrm{d}}{dt}w^{\text{int}}=\sigma_{ij}D_{ij}, \tag{7}$$

where D_{ij} is the magnitude of the rate of the growth of deformations, determined from the following expression:

$$D_{ij}=\frac{1}{2}\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}\right).$$

At the body's boundary Γ_f, the boundary conditions are described by the following equation:

$$\sigma_{ij}n_j=t_i(t), \tag{8}$$

where n_j is the externally directed normal to the boundary of a solid body.

For the boundary conditions describing the deformation at the boundary of a solid body, the following equations are written

$$x_i(X,t)=\overline{x}_i(t). \tag{9}$$

If there is no contact between the bodies, the resulting boundary conditions are:

$$\left(\sigma_{ij}^{+}-\sigma_{ij}^{-}\right)n_j=0. \tag{10}$$

Under the condition that the body may execute displacements δx_i, the state of the solid deformed body is described by the equation that expresses the balance of possible operations:

$$\int_{\Omega}\left(\rho\ddot{x}_i-\sigma_{ij,j}-\rho f_i\right)\delta x_i\mathrm{d}\Omega+\int_{\Gamma}\left(\sigma_{ij}n_j-t_i\right)\delta x_i\mathrm{d}\Gamma+$$
$$+\int_{\Gamma}\left(\sigma_{ij}^{+}-\sigma_{ij}^{-}\right)n_j\delta x_i\mathrm{d}\Gamma=0. \tag{11}$$

Equating the number of possible operations to zero, considering the required transformations, equation (11) takes the following form:

$$\int_{\Omega}\rho\ddot{x}_i\delta x_i\mathrm{d}\Omega+\int_{\Omega}\sigma_{ij}\delta x_{i,j}\mathrm{d}\Omega-\int_{\Omega}\rho f_i\delta x_i\mathrm{d}\Omega-$$
$$-\int_{\Gamma_f}t_i\delta x_i\mathrm{d}\Gamma-\int_{\Gamma_c}t_i^c\delta x_i\mathrm{d}\Gamma. \tag{12}$$

The equation for interpolating the parameter distribution in the inner space of the finite element (FE) is recorded in the following form

$$x_i(X,t)=x_i\left(X(\xi,\eta,\zeta),t\right)=\sum_{j=1}^{m}\varphi_j(\xi,\eta,\zeta)x_i^j(t), \tag{13}$$

where ϕ_j is the function of the parametric coordinates' form (ξ, η, ζ); m is the number of nodal points defining the space of FE; x_i^j is the coordinate of a nodal point based on one of the three coordinate axes.

The potential energy for FE is written in the form of the following equation

$$\delta\pi_e=\int_{\Omega_e}\rho\ddot{x}_i\Phi_i^e\mathrm{d}\Omega+\int_{\Omega_e}\sigma_{ij}\Phi_{i,j}^e\mathrm{d}\Omega-$$
$$-\int_{\Omega_e}\rho f_i\Phi_i^e\mathrm{d}\Omega-\int_{\Gamma_{ef}}t_i\Phi_i^e\mathrm{d}\Gamma, \tag{14}$$

where $\Phi_i^e=(\varphi_1,\varphi_2,...,\varphi_k)_i^e$.

For the FE ensemble, the principle of possible displacements must be observed, which allows us to write the energy conservation equation for the entire body divided by FE

$$\sum_{e=1}^{en}\left(\begin{array}{l}\int\limits_{\Omega_e}\rho\ddot{x}_i\Phi_i^e d\Omega+\int\limits_{\Omega_e}\sigma_{ij}\Phi_{i,j}^e d\Omega-\\-\int\limits_{\Omega_e}\rho f_i\Phi_i^e d\Omega-\int\limits_{\Gamma_{ef}}t_i\Phi_i^e d\Gamma\end{array}\right)=0. \quad (15)$$

In the matrix form, equation (15) is written in the following form:

$$\sum_{e=1}^{en}\left(\begin{array}{l}\int\limits_{\Omega_e}\rho\mathbf{N}^t\mathbf{N}\mathbf{a}_e d\Omega+\int\limits_{\Omega_e}\mathbf{B}^t\sigma d\Omega-\\-\int\limits_{\Omega_e}\rho\mathbf{N}^t\mathbf{b}d\Omega-\int\limits_{\Gamma_{ef}}\mathbf{N}^t\mathbf{t}d\Gamma\end{array}\right)=0, \quad (16)$$

where $\mathbf{N}$ is the interpolation matrix; σ is the stress vector; $\mathbf{B}$ is the matrix of stiffness; $\mathbf{a_e}$ is the vector of nodular accelerations; $\mathbf{b}$ is the load vector; $\mathbf{t}$ is the vector of traction forces.

The velocities of the FE nodes when applying an explicit integration method are determined from the following formula:

$$v^{n+\frac{1}{2}}=\left(u^{n+1}-u^n\right)/\Delta t^{n+\frac{1}{2}}\Rightarrow u^{n+1}=u^n+\Delta t^{n+\frac{1}{2}}v^{n+\frac{1}{2}}. \quad (17)$$

The FE nodes offsets are determined from the following expression:

$$x^{n+1}=x^0+u^{n+1}. \quad (18)$$

The principal formula for determining the acceleration of the FE nodes as a time-derivative takes the following form:

$$a^n=\left(v^{n+\frac{1}{2}}-v^{n-\frac{1}{2}}\right)/\Delta t^n\Rightarrow v^{n+\frac{1}{2}}=v^{n-\frac{1}{2}}+\Delta t^n a^n. \quad (19)$$

Then, by using these formulae, equation (16) is written in the following form:

$$Ma^n=F^n;\quad F^n=\sum_{e=1}^{en}\left(F_e^{ext}-F_e^{\text{int}}\right)^n. \quad (20)$$

The accelerations of points are determined based on the system of linear algebraic equations:

$$a^n=M^{-1}F^n. \quad (21)$$

The critical step for time is determined based on the Courant-Friedrichs-Lewy criterion from the following expression:

$$\Delta t\le\Delta t_{crit}=\min\frac{l_e}{c_e}, \quad (22)$$

where c_e is the parameter defined by the following formula:

$$c_e=\sqrt{\frac{E_e}{\rho_e}},$$

l_e is the characteristic spatial grid pitch.

When simulating the pressure of an explosion, a special empirical curve was used [14], which is shown in Fig. 4.

The parameters of a given curve depend on the scalable distance from the wall to the explosion site, which is determined from the following formula:

$$Z=R\cdot M^{\frac{1}{3}}, \quad (23)$$

where R is the distance from a wall to the explosion site; M is the TNT mass equivalent.

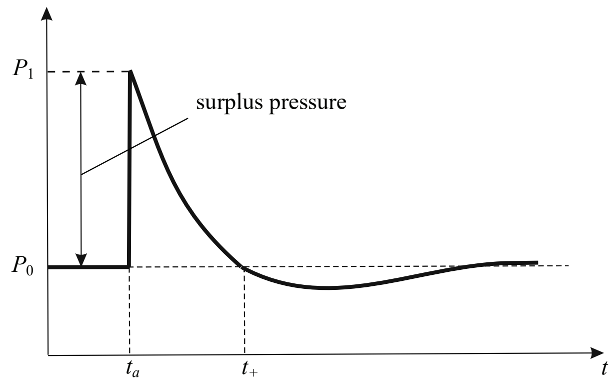


Fig. 4. The curve of explosive pressure on the surface of a working's walls

The parameters of the curve in Fig. 5 are determined by using a special nomogram acquired empirically [14].

At the indirect contact between the front of an explosive wave and the working's wall surface, the pressure is weakened. The weakened pressure is determined from the following formula

$$P_{eff}=P_{ref}\cos^2\theta+P_{inc}\left(1+\cos\theta-2\cos^2\theta\right), \quad (23)$$

where θ is the angle between the facet of the surface finite element and the line drawn from the point of the explosion site at right angle and the shortest distance from the explosion site to the center of the facet; P_{inc} is the pressure caused by an incident shock wave, determined from the following formula:

$$P_{inc}=P_s\left(1-\tau\right)e^{-a\tau};\quad \tau=\frac{t-t_a}{t_+-t_a}, \quad (24)$$

P_{ref} is the pressure of the reflected shock wave, determined from the following formula:

$$P_{ref}=P_r\left(1-\tau\right)e^{-\beta\tau}. \quad (25)$$

The parameters included in these formulae are determined based on empirical nomograms [14].

The material used is a perfectly elastic material, whose mechanical properties correspond to the averaged characteristics of sedimentary mountain rock (Table 1). We took into consideration that there is no negative influence of crack formation in man-made structures, which leads to the scattering and attenuation of seismic waves.

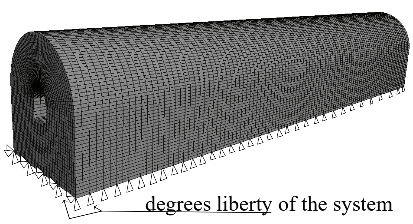
Fig. 5, *a* shows the finite-element diagram demonstrating the boundary conditions. To solve the dynamics problem using an explicit method of finite elements, we selected a hexahedral FE of the Lagrange type [16], which is shown in Fig. 5, *b*. A given FE is designed to simulate fast-flowing dynamic processes for solid bodies; it is used for all elements of the model.

Table 1

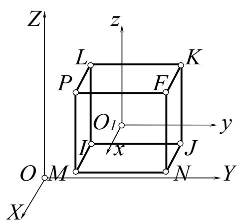
Averaged mechanical characteristics of mountain rock

Parameter	Measurement unit	Magnitude
Elasticity module	MPa	6×10^4
Density	kg/m^3	2,900
Poisson coefficient	–	0.275

We used the developed virtual model of a structure to obtain the dynamic pattern of change in the stressed-strained state of the massif that hosts an experimental working where a chain of explosions was performed. Data on the environment displacement and the rate of this process have been obtained.



a



b

Fig. 5. Model representation of the experimental explosions structure: *a* – a finite-element diagram; *b* – the shape of a finite element

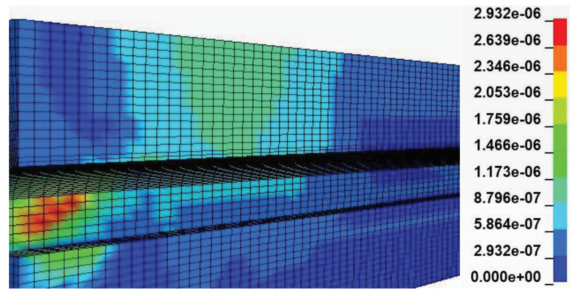
5. Results of studying the dynamics of walls in the experimental working and the surrounding environment during coal dust explosion

The possibilities of the procedure have made it possible to examine patterns in the change of rock SSS in different projections and scales. The limited dimensions of the experimental structure determine the emergence of waves reflected from the side walls and ends, which results in a complex interferential pattern that is difficult to decipher.

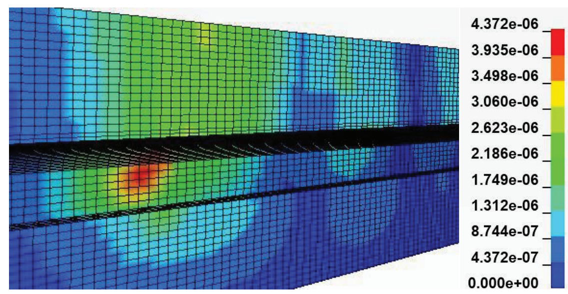
To analyze the state of rocks located ahead of the source of increased pressure (explosion) and minimize the impact of interference, our further study considered only the first five-six explosions ($0<t>25$, s·10^{-4}).

The vertical cross-section of the experimental structure clearly indicates (Fig. 6) that a displacement zone is formed, after the second explosion of the chains of explosions (Fig. 6, *a*), in the roof and in the bed. It is located 15 m ahead of the source of the explosion, has a length of about 10 m with a maximum amplitude of around $1\cdot10^{-6}$ m.

Further explosions ensured an increase in the number of waves ahead of the source, so, after the fifth explosion (Fig. 6, *b*), three waves formed at a distance from the source of, respectively, 10, 20, 25 m; of length, 5, 2.5, 2.5 m; the size of shifts is, accordingly, (2,5; 1; 1)$\cdot10^{-6}$ m. This means that the surface of the working is exposed to shakes even before the flame or shock fronts reach this place. As a result of shaking, the coal dust resting in the roof or on the floor is capable of transferring from solid clusters to the loose state with a part of it discharged into the air. Such particles, while easily mixing with air, form a combustible mixture – a raw material for a non-fading explosion.



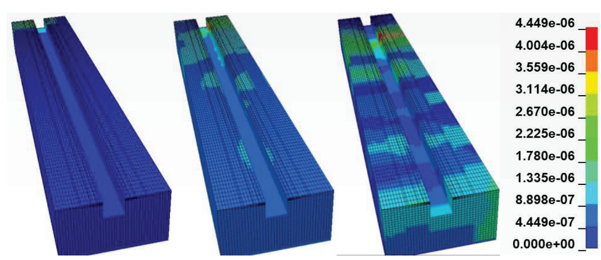
a



b

Fig. 6. The distribution of deformations (shifts) in the vertical cross-sections of the rock surrounding an adit after explosions: *a* – second (t=10·10^{-4}, s); *b* – fifth (t=24·10^{-4}, s)

A similar pattern is observed in the horizontal cross-section of the structure (Fig. 7).



a *b* *c* *d*

Fig. 7. The distribution of deformations in the horizontal cross-section of the rocks surrounding an adit at the following moments from the onset of the explosion (t), s·10^{-4}: *a* – 4; *b* – 14; *c* – 24; *d* – an absolute deformation scale, m

The results of the analysis show that the waves of shifts of seismic nature in mountain rocks are ahead of the shock and fire fronts that propagate through the gas environment in the experimental working's space. After the fifth explosion in the chain of explosions, the entire volume of the structure experiences shifts (Fig. 7, *c*), this means that the dust contained on the working's walls can enter the suspended state in the air, thereby forming an explosive environment.

The shift is functionally associated with speed, but the second is more indicative of the probability of dust formation (Fig. 8).

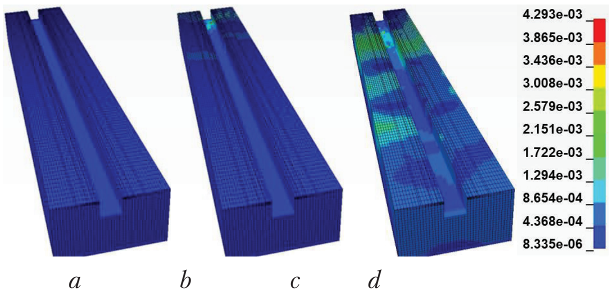


Fig. 8. The distribution of shift rates of the rocks surrounding a working in the horizontal cross-section at the following moments from the onset of the explosion (t), s·10^{-4}: a – 4; b – 14; c – 24; d – a rate scale, m/s

In the initial period, the state of the working's walls (Fig. 8, *a*) was relatively calm but, after a few explosions, vibrations occur at the section equal to half the length of the structure (Fig. 8, *b*). The whole structure is then susceptible to shocks and oscillations (Fig. 8, *c*). The distance from the source of explosions is, in this case, up to 40 m, that is, over the entire length of the working, ahead of the combustion front, there are conditions for the transfer of coal dust from solid clusters to the loose or air-suspended state.

6. Confirming a hypothesis about the influence of seismic waves on the formation of an explosive dangerous dust-air medium in a working

Of interest is to study the movement dynamics during the explosion of a single point on the wall of a working; this highlights the nature of the behavior of coal dust particles located in this place. We investigated the nature of change in the speed of the shift of the experimental working's wall in the course of development of a coal dust explosion at the section, taken as an example, located 17 m from the source of initiation (Fig. 9). The section moved together with the source of the explosion, remaining at a constant distance from it. The chart shows the processes taking place along the contour of the working ahead of the explosion front that moves along it. We have observed qualitative similarity to experimental explosions at the mine "Barbara".

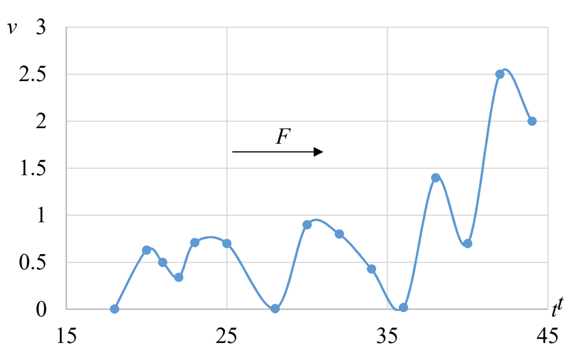


Fig. 9. The character of change in the speed (v·10^{-3}, m/s) of a shift of the experimental adit's wall during the development (t, s·10^{-4}) of a coal dust explosion at the section located 17 m from the source of initiation, F is the direction of the explosion front motion

7. Discussing the results of studying the dynamics of deformation of the experimental adit's material during a coal dust explosion

Based on the analysis and generalization of existing theoretical results and the results of experimental studies, it has been determined that they do not give an idea about those dynamic geomechanical processes that take place in experimental workings during the explosion of a dust-air mixture. The speed, amplitude of waves, and other parameters of the environment dynamics are unknown. That restrains the substantiation and construction of means and techniques to prevent, localize dust explosions, and to protect miners from the related negative factors.

To elucidate the mechanism that forms an explosive dangerous situation in experimental structures, we have refined a mathematical model to study the dynamics of the stressed-strained state of a rock array that hosts an experimental adit. In the model, an experimental structure is represented as a continuum of hexahedral finite elements geometrically similar to the state of an actual structure (Fig. 5). The physical-mechanical properties of the elements correspond to the indicators of the actual sedimentary rocks (Table 1). The propagation of an explosion is simulated by blasting a chain of explosives, which are located at a distance of 1 m; the rate of detonation propagation along a working is 400 m/s. The distribution of the kinetic energy in the finite elements during a dust explosion is described by expression (14). The features of both normal and indirect impact of an explosion were taken into consideration; expressions (24), (25). This makes it possible to bring the process of modeling an explosion to the actual process. This is a new perspective as regards the results of our experimental explosions in experimental adits; there is the possibility to model a wide range of the mining-geological and mining-technical conditions for building and exploitation of underground mining workings. The limitation of this study, as well as the experiments in experimental workings, is the difference in the physical and mechanical properties between the cracked actual and solid man-made environments. However, in the future, the proposed procedure will be adjusted to reflect this difference.

The use of an improved approach to modeling has made it possible to obtain data on those dynamic processes that occur on the surface of an experimental working and in the surrounding array during the explosion of a dust-air mixture. We have established that the speed of seismic wave propagation is significantly larger compared to that of the shock front. As early as after the second explosion in a series of explosions (Fig. 6), a zone of shift forms in the roof and the bed. It is located 15 m ahead of the primary source of the explosion, with a length of about 10 m at a maximum amplitude of around $1 \cdot 10^{-6}$ m. After the third explosion, over about $15 \cdot 10^{-4}$ s, the seismic waves reach the end of the working at 50 m from the source. Further explosions led to an increase in the number of waves ahead of the source; after the fifth explosion, three waves formed at a distance from the source of, respectively, 10, 20, 25 m, of length 5, 2.5, 2.5 m with a magnitude of the shifts, accordingly, of $(2{,}5; 1; 1) \cdot 10^{-6}$ m. A similar pattern was observed in the horizontal cross-section of the structure (Fig. 7). In the future, it is necessary to consider the impact of the waves reflected from the external walls and ends of the structure on shifts of the experimental working's walls.

The results obtained have made it possible to assess the validity of the hypothesis about loosening the dust accumulations under the influence of seismic waves to form an explosive dust-air medium in a working. The dust particles that are at rest before the explosion receive, under the influence of seismic waves, the pulse of movement, which knocks them out of clusters on the roof, bed, and walls of the working. When the shock front approaches a cluster, the amplitude (Fig. 6, 7) and speed (Fig. 8, 9) of the oscillatory shifts of the working's walls grow. The speeds of the oscillatory shifts reach $(0.5...2.5)\cdot10^{-3}$, $m\cdot s^{-1}$, and the duration of the wave – $(5...7)\cdot10^{-3}$ s. In the future, it is planned to consider the process of moving a dust particle from a cluster to the air, as well as forming an explosive dust-air mixture.

The advantage of a given modeling method is the ability to vary the input data on geometry, environment properties, explosion parameters, etc. in a wide range. The result is a significant array of convenient information to analyze.

In a given statement of modeling, our study could be useful to investigate explosions conducted in experimental structures. To reproduce the processes occurring in actual underground workings, in the future we plan to clarify the physical and mechanical properties of stratified mining rocks, taking into consideration the natural and artificial fissuring, mining-technical conditions for workings, and so on.

8. Conclusions

1. Explosions of gas-dust environments in the mining workings of coal mines remain one of the most severe accidents in terms of their results and scale, which negatively affect the state of a mine's ecosystem and the level of its anthropogenic safety. There are objective causes of increased danger of explosions in the workings of coal mines, associated with the increased depth of the development of coal layers and the growth in the gas content of a mining massif.

2. This work provides a new perspective on conducting experimental explosions in experimental adits; there is the possibility to represent a wide range of mining-geological and mining-technical conditions for mining workings. This has been made possible by using the improved mathematical model of the dynamics of the stressed-strained state of a rock array that hosts an experimental adit during a dust explosion. In the model, an experimental structure is represented as a set of hexahedral elements that is geometrically similar to the actual structure; their physical and mechanical properties correspond to the indicators of actual sedimentary rocks. The features of both the normal and indirect influence of a wave-shaped explosion have been accounted for. This makes it possible to bring the process of modeling an explosion to the actual one.

3. We have obtained data on the dynamic processes, and their parameters, occurring in mining rock and on the surface of the experimental working during the chain explosion of a dust-air mixture. It has been established that the speed of seismic wave propagation is significantly larger than that of the shock front. Over approximately $15\cdot10^{-4}$ s, the seismic waves reach the end of a working at 50 m from the source, while the shock front moves 3 m. At 15 m ahead of the primary source of the explosion, a zone of the rock shifts forms along a contour of the working; it has a length of about 10 m at a maximum amplitude of about $1\cdot10^{-6}$ m. Subsequently, there is an increase in the number of such waves; in $24\cdot10^{-4}$ s, ahead of the explosion source, three waves formed at a distance from the source of, respectively, 10, 20, 25 m, of length 5, 2.5, 2.5 m, with the size of the shifts is, accordingly, $(2.5; 1; 1)\cdot10^{-6}$ m.

4. The results obtained have confirmed the hypothesis about the possibility of loosening the dust accumulations under the influence of seismic waves, which are significantly ahead of the front of the explosion. The speeds of the oscillatory shifts reach $(0.5...2.5)\cdot10^{-3}$, $m\cdot s^{-1}$, and the duration of a wave is $(5...7)\ 10^{-3}$ s. Dust particles, under the influence of the seismic waves, receive the pulse of movement, which knocks them out of the clusters on the walls of the workings into the air stream. The lofted dust particles form a cloud in which the content of dust reaches an explosive concentration that leads to the further generation of an explosion.

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FORECASTING A MOISTURE MODE OF THE DRAINAGE LAYER IN A ROAD STRUCTURE UNDER THE ACTION OF LOADING

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The processes forming the humidity mode of the drainage layer of a road structure under the action of excess load have been investigated. The stressed-strained state was determined based on a numerical experiment using the software-calculation suite SCAD Office. The numerical modeling of the examined structure involved the static load of the A_2 group for a road of category II. A series of numerical experiments were performed, which included an increase in the rated load by 10–50 % when overwetting the drainage layer and the earth bed. The distribution of the isofields and isolines of normal stresses and deformations in the volumetric elements was derived, which made it possible to determine the thickness of the soil layer of the earth bed, 0.67 m, from which water is squeezed out under the influence of excess loading.

Based on the approach for determining the parameters of soil subsidence at its drying or freezing, the dependences were established for the relative subsidence of soil, the coefficients of linear subsidence and compaction of soil under the influence of excess load. The proposed dependences integrate such indicators as the deformation below a drainage layer, the depth of stress spread, at which water is not squeezed out from soil, the optimum humidity, and the full moisture content of the soil.

Based on the results of numerical experiments and soil subsidence parameters, the amount of water squeezed out from a layer of soil under the influence of excess load has been determined, which is 5.4 liters per m^2. The results obtained make it possible to adjust the value of the total specific excess water flowing into a drainage structure. Taking into consideration the squeezing out of water from an earth bed from a soil layer under the influence of excess load from a wheel of 86.25 kN, the general specific excess could vary in the range from 35.4 to 22.4 liters per 1 m^2. Increasing it by 18–32 % would change the humidity mode of the road bed and reduce the overall elasticity module

Keywords: stressed-strained state, road structure, drainage layer, water squeezing, excess load

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1. Introduction

Increasing the traffic intensity of heavy-weight automobiles predetermines the continuous growth of loads, motion speeds, and, accordingly, the stricter requirements for the strength and stability of road structure. Note that the adverse situation arises when a large weight of the cargo leads to irreversible deformations in both the asphalt-con-