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Satbayev University

ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН
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NEWS

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Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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SUBSTANTIATION OF DESIGN PARAMETERS OF COAL DUST EXPLOSION CONTAINMENT SYSTEM

Abstract. The aim of the paper is to identify the qualitative and quantitative parameters of seismic waves and accelerations on the mine working contour after an explosion of the gas-and-dust mixture. Information about the formation of seismic waves in the rock mass accommodating the mine working was received using modelling in order to improve the means of containment of explosion of further developed dust-air mixture. The parameters of seismic waves, such as propagation velocity and acceleration, amplitude, and frequency of oscillations of mine working walls, were established for the conditions of the experimental structure, which allows to scientifically substantiating the design parameters of the systems protecting the miners against explosion. The energy of the explosion propagates in the rock mass in the form of a series of peak-like pulses and oscillations with smaller amplitude. Modulus of acceleration is an informational indicator, which suits the most for registration by seismic sensors responding, specifically, to the most powerful peak pulses formed by seismic waves. By revealing the qualitative and quantitative indicators of seismic wave propagation on the mine working contour and in the rock mass, the parameters of seismic sensors of the systems protecting the miners against explosion can be substantiated.

Key words: seismic sensors, explosion containment, mine working, air dust mixture

Introduction. Several explosions of gas-and-dust mixtures in the coalmines of Ukraine had unacceptably severe consequences. This type of accident is characterized by the spread of explosion for several kilometres along the network of mine workings, reaching neighbouring mining sites. Several explosions happened in the workings of Zasyadko mine lease enterprise in 1999, 2001, 2002, 2007 and as a result, 265 people died and 369 were injured. Accidentsat Skochynskyi mine: 114 people died and 87 were injured in 1991, 1998, 2014. In 1992, 63 people died and 53 were injured at Sukhodolska-Skhidna mine, and 28 and 2 people, respectively, in 2011. In 1994, 30 people died and 27 were injured at Slavianoserbska mine; at Barakov mine, 80 and 7 people, respectively, in 2000; 37 people died and 12 were injured at Krasnolymanska mine in 2004; 8 people died and 28 were injured at Stepova mine in 2017. The data above determine the relevance of the issue of protection of miners from the threats of dust explosions, such as those propagating through the network of mine workings.

Analysis of Recent Research and Publications. The explosions of methane-air and composite gas-and-dust-air mixtures are studied in laboratory settings and at explosive research plants. However, a complete theory that would reveal the mechanism of formation and progress of the explosion does not exist [1].

The ability of dust of different coal strata to explode is evaluated using laboratory instruments, mainly, calorimeters. It is confirmed that as the particle size of coal dust decreases, its burning rate increases.Particles of coal dust with a size of 44 μm and 37 μm have a higher burning rate when compared to other sizes [2]. The analysis of laboratory experiments proved that dust with a fractional composition of 63…94 μm possesses the most explosive properties[3]. This may be due to the polymodal composition of dust deposits, which leads to the simultaneous reaction of different fractions of fuel [4]. The Indian scientists found that minimum ignition temperature decreases with the concentration of coal dust until it reaches the stoichiometric concentration. [5]. Laboratory studies have shown that the overall pressure ratio was doubled when 6% of the methane mixture was added to 30 g/m^3 of coal dust, and it increased by 60% when the ignition source power of 10 kJ was used instead of 1 kJ. [6]. There have been attempts to investigate the use of an increased volume chamber (38 l) to test coal dust explosions[7]. Complex researches, a combination of computer modelling and calorimetric experiments, have been used to study the influence of the nature of air currents on the nature of explosive combustion of coal airborne dust. [8]

The addition of inert materials can significantly reduce the explosive properties of the mixture, until it burns out. This is achieved, for example, by a water curtain, which removes dust from the air stream, thereby reducing its accumulation in the ventilation networks of mines [9]. Another way to reduce the explosiveness of gas-and-dust mixtures is to add a sufficient amount of non-combustible components, such as shale powder [10]. The shale barriers and water curtains are the most common ways of explosion protection of mine workings. They consist of easily collapsible or overturning tanks with liquid or dispersed solid extinguishing agents, which are installed on shelves or suspended under the roof across the mine workings [10, 11]. The disadvantage of the known means is the inertia inherent in the mechanical circuit "extinguishing agent - tank - curtain drive - air compressed with shock front." This shortcoming is partially eliminated in automatic explosion containment systems, which use the energy of compressed gas or liquid for the rapid formation of a protective cloud in the void of emergency working [12]. The issue of increasing the response of the device for containment of coal dust explosions remains relevant. During the experimental explosions, the Polish researchers recorded the velocity of the fronts, mainly 300…700 m·s^{-1} [13], where the highest recorded velocity of the shock front along the mine working in the conditions of experimental mine galleries in some cases did not exceed 1,800…1968 m·s^{-1} [4]. It is significantly smaller in real-life conditions due to uneven dust deposition, dehydration of mine workings, etc. Geophysical studies of the velocity (m·s^{-1}) of seismic waves in sedimentary rocks (sandstones, shales, limestones) have established that it is in the following ranges: for p-waves (V_P): 1,500…6,000; s-waves (V_S): 600…3,500. [14].

The authors suggested the use of a higher velocity of seismic waves relative to the shock front for early detection of explosions and activation of explosion warning and suppression systems, and proposed a coal dust explosion containment system (DECS) (Fig. 1) [15]. Seismic sensor D_D is embedded into the wall of the mine working at a distance L_2 from pipeline 6, which exceeds the radius L_1 of seismic sensors response to rock oscillations by several times. Another sensor D_O is embedded into the wall of mine working next to the exhaust pipeline 6. Electrical cables for transmitting signals from seismic sensors are connected to the amplifier 7. The cables for transmission of control signals from amplifier 7 are connected: to the valves with electric drives 2 and 5, the means of sound and light alarm 8, as well as the lock 9, which holds the barrier 10 suspended under the roof. The possibility of lowering barrier 10 is implemented by means of a hinge 11, which connects the barrier with the side rocks. When coal dust explodes, a shock front of compressed air is formed in the mine working. The flame front behind the shock front moves at a distance of several meters with the detonation combustion of the air dust mixture. The explosion front propagates through the mine working with a velocity not less than the sound velocity in the air, Vf =330 m.s^{-1}. Part of the energy of the shock front is transmitted to the rocks surrounding the mine working, they form seismic waves that propagate in the rock mass with a velocity of Vs = 2,500…3,000 m.s^{-1}, which is several times the velocity of the shock front. However, due to natural and man-made fractures of rocks, seismic waves are scattered and absorbed, thus the radius of propagation is limited, and at a certain distance greater than L_1 from the shock front their power is insufficient to excite the seismic sensor. The additional sensor Dd is triggered a few seconds before the seismic waves reach the main sensor, D_o. The signal from the additional sensor D_d is sent via cable to amplifier 7, where the command is generated to turn on the sound and light alarm 8, as well as to trigger the locks 9 holding the barrier 10. Light and sound alarms alert people about the presence of explosion and the need to activate self-rescuers and proceed to shelters or take safe positions behind barrier 10. The miners will have more than five seconds to do so; this amount of time cannot be provided by the known means of combating coal dust explosions. The issue of substantiation of the DECS main technical parameters, e.g., distance L_2 of placement of the additional sensor D_d from the main one, D_o, establishment of radius where the sensor will respond to seismic waves L_1, remains unresolved. It is equally important to establish the frequency range and amplitude of seismic oscillations to which the sensor has to respond. The sensor has to be capable of separating explosions from other types of oscillations of the rock mass, such as blasting, transport and other

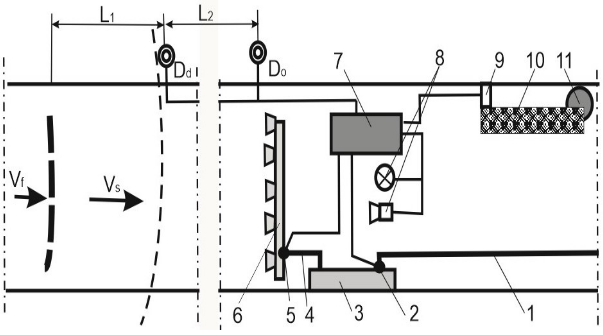


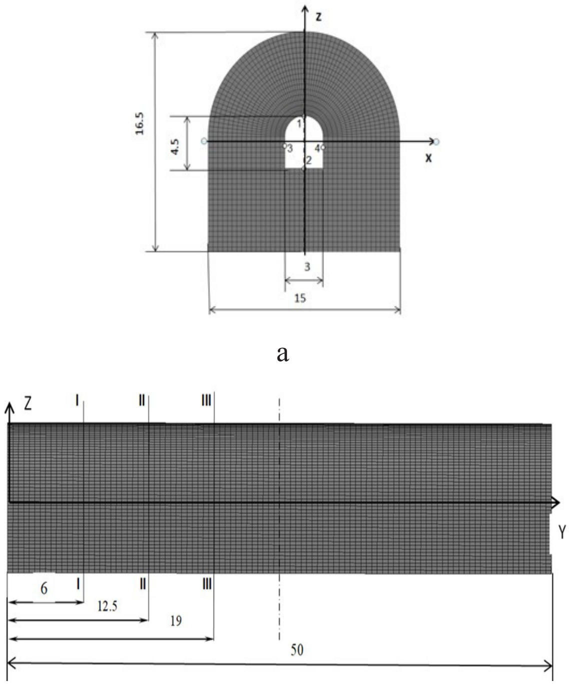
Fig. 1. Coal dust explosion containment system: 1 - pipeline for compressed gas supply; 2,5 - electrically driven valves; 3 - tank with fire extinguishing agent; 4,6 - pipeline; 7 - amplifier; 8 - sound and light alarm; 9 - lock; 10 - barrier; 11 - hinge; D_d, D_o - additional and main seismic sensors; L_1 - radius of sensor response to seismic waves; L_2 - distance between the sensors; V_f, V_s - velocity of propagation depending on the explosion front and seismic waves

Metods. The aim of the paper is to identify the qualitative and quantitative parameters of seismic waves and accelerations on the mine working contour after explosion of gas-and-dust mixture, in order to substantiate the parameters of sensitive elements of the miners' protection system. The research method is modelling with the help of finite-difference mathematical-computer modelling of four-dimensional (*x,y,z,t*) dynamic process of formation and propagation of seismic waves from explosion in experimental virtual mine working.

Based on the required accuracy of calculations and taking into account the limitations of computer technology, the authors created a virtual structure that has the shape of a vault, 3 m wide, 4.5 m high. The length of the structure is 50 m. It is covered with a six-meter layer of rock with physical and mechanical properties close to sandstones: modulus of elasticity: 6×104, MPa; Poisson's ratio: 0.275; density: 2,900 kg/m^3. The structure's lower surface has a rigid connection with the ground, the rest is free. Spatially developing explosion of coal dust was simulated by a series of consecutive detonation of explosive charges (explosives) each weighing four kilograms, with an interval of $2.5.10^{-3}$ s. This corresponded to the supersonic velocity of the shock front 400 $m.s^{-1}$. The modelling technique is given in more detail in [16].To determine the parameters of velocities and accelerations, the parameters of the motion of four points were fixed using the contour of the vaulted shape (Fig. 2a). In order to do so, three measuring boundaries along the length of the working at distances 6; 12.5; 19 m from the source of the explosion (Fig. 2b), as well as at the ends of the mine working, were selected.

During the study, the result of the explosion of the first several explosive charges was considered. This measurement method was adopted in order to avoid distortion caused by the reflection of waves on the surface of the structure and its ends when the oscillations reach these surfaces. The advantage of this method of explosion modelling is not only the ability to obtain indicators of absolute and relative deformations of the walls and rocks surrounding it, but also the ability to estimate the dynamic parameters of deformations, namely velocity and acceleration, their amplitude, frequency, phase, moduli, etc.

Results. A feature common to all velocity components relative to the coordinate axes is the presence of two stages, caused by the explosion of the specifically primary explosive, which is characterized by lack of synchrony and in-phase motion of control points 1-4 on the walls (Fig. 3). The duration of the first stage is approximately 0.025… 0.04 s. In the transverse directions x and z, the velocities of the points had an oscillating tendency with an amplitude from ± (2…6) e^{-03} to ± (10…12)e^{-03}, $m.s^{-1}$. In the longitudinal direction y, besides the oscillations, there is a clear tendency for the predominance of velocities towards the direction of the explosion. The maximum deviation V_y was observed after (0.1… 0.12) $e^{-0}3$, s, it was about (-5 e-03), $m.s^{-1}$.

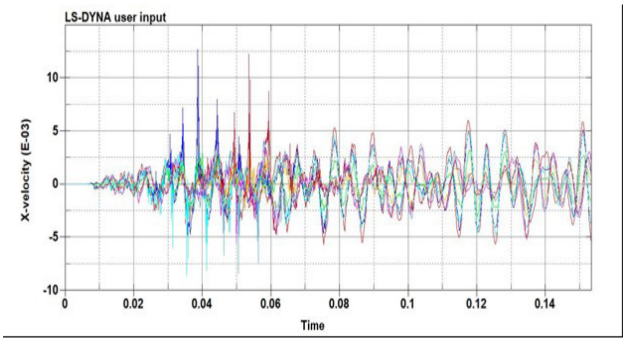


a

b

Fig. 2. Construction of a virtual structure (a - vertical cross-section; b - side view): I-I, II-II, III-III - boundaries of measuring the movement of points 1, 2, 3, 4 on the mine working contour

At the first stage, single peak jumps of individual points were observed, but the general picture indicates a tendency to zero total deviation of points from the initial state. That is, s-waves prevail. The secondary stage of velocity dynamics is characterized by a more orderly nature of motion. All control points on the mine working surface oscillate synchronously and in phase. In the transverse directions, horizontal x and vertical z, the amplitude of oscillations does not exceed ±(2…4)*e^{-03} and ±(1…2)*e^{-03}, $m.s^{-1}$, respectively. This difference is due to the design features of the structure. In the longitudinal direction y, in addition to the oscillating motion, the motion towards the propagation of the explosion along the mine working is traced first, and then in the opposite direction. This is a manifestation of p-waves.



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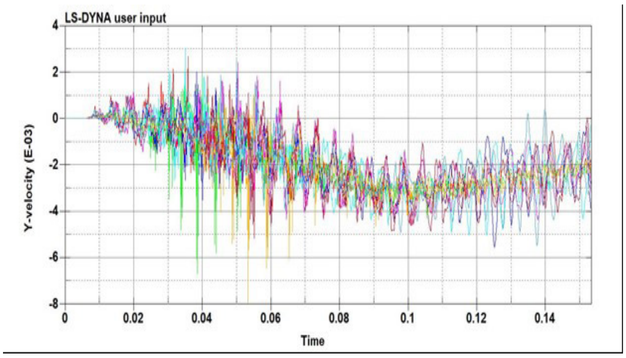

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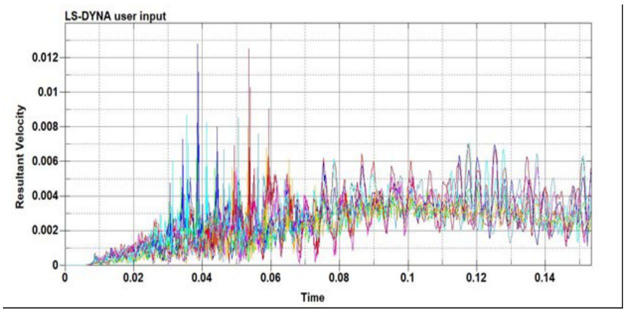
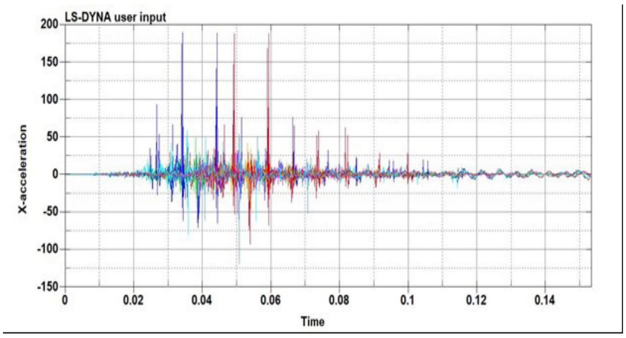


c)

Fig. 3. Velocity (m·s-1) of movement of the points of the mine working contour in the horizontal V_x (a) and longitudinal V_y (b) directions and the modulus of velocities (c) at a distance of 19 m from the source of the explosion; colours of trajectories of points according to Fig. 1a: 1 - red; 2 - green; 3 -dark-blue; 4 - blue

Waves of the secondary stage are inherently inertial self-oscillations of the structure, which are the consequences of external impact, specifically the detonation of explosive charges. This is confirmed by the dynamics of accelerations (Fig. 4).



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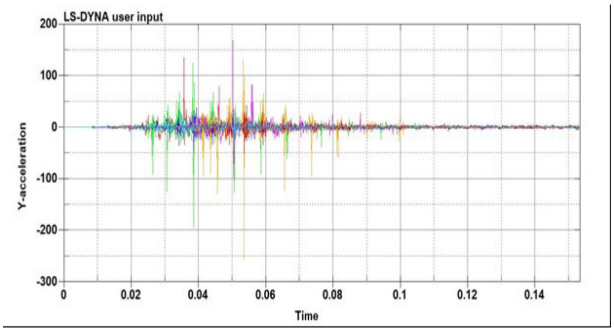

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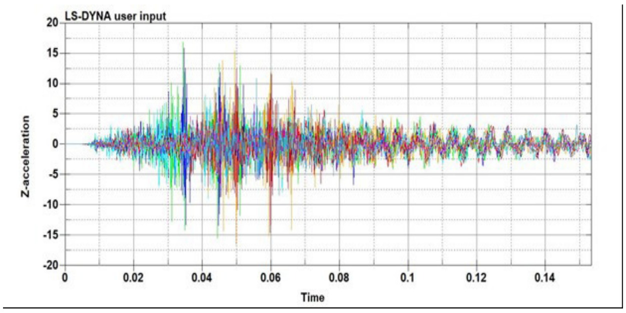

c)

Fig. 4. Acceleration (m·s^{-2}) of the points of the mine working contour in the horizontal D_x (a), longitudinal D_y (b) and transverse D_z (c) directions at a distance of 19 m from the source of the explosion; colours of trajectories of points 1-4 as in Fig. 3

These data indicate that the acceleration of control points on the surface of the experimental mine working occur only under the influence of the energy of explosions. The subsequent oscillatory process is due to the inertial redistribution of energy, and has a rapidly decaying nature. The design of the experimental structure (see Fig. 2) limits the movement of the particles of the medium in the horizontal directions x and y, and meet the conditions that exist in real-life mining to a certain degree. There are individual peaks with an amplitude of ±100…200 m·s^{-2} in these directions, but the main part of the harmonics has parameters up to ±25 m·s^{-2}. The duration of excitation of rock thickness particles is up to 0.045 s after the explosion, followed by attenuated acceleration of oscillations.

In the vertical direction z, the possibility of movement of particles of the medium is less limited, because the upper part of the structure has no restrictions in terms of motion. This confirms the nature of the accelerations in the vertical direction (see Fig. 4c), they are characterized by a smaller amplitude of peak oscillations (up to ±15 m·s^{-2}), the main part of the harmonics has ± 5 m·s^{-2}, but the duration of oscillations reaches 0.07 s.

In real-life mine conditions, when choosing means of monitoring the oscillations of the rock mass under the action of explosions of gas-and-dust mixtures, it is difficult to install such a device that senses oscillations in certain directions. Therefore, it is advisable to consider a more versatile indicator, i.e. the dynamics of the modulus of acceleration (Fig. 5).

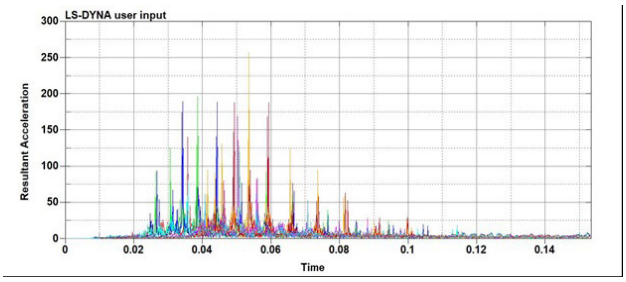

Fig. 5. Moduli of accelerations (m·s^{-2}) of the points of the mine working contour, the rest of the data are similar to those in Fig. 3

Unlike the modulus of velocity (see Fig. 3c) the modulus of acceleration tends to fade in the second stage, which allows to identify a single explosion relative to other types of earthquake. 0.02 s after a single explosion at a distance of 19 m from the explosive charge, the beginning of the acceleration of the indicator the points of the mine working contour (see Fig. 5) was observed. Within the time frame from 0.02 to 0.08 s up to 15…18 peaks with an amplitude of 50…250 m·s-2, i.e. with a frequency of about 300 Hz, occurred. These are the most powerful pulses that could move in the rock mass at the greatest distance from the source of the explosion. The bulk of the oscillations had an amplitude of 10…25 m·s-2, and propagated over a much shorter distance. This pattern of rock shifts is typical of the conditions of drilling and blasting of methane. The seismic sensor emits a single signal lasting up to 0.05 s. In contrast, during the propagation of the explosion front of the gas-and-dust mixture in the rock mass, the train of such oscillations is felt. A signal receiver needs to be set to receive about ten pulses for a short time, up to, e.g., 0.3…0.5 s, which automated systems must identify as gas-and-dust explosion.

The nature of the motion of seismic waves during the formation of a gas-and-dust explosion (Fig. 6) and its movement with the velocity of about 400 m.s^{-1} along the mine working is considered in the research. The modelling results indicate a gradual increase in the velocity of seismic waves with the development of a gas-and-dust explosion from 0 at the place of initiation to 2,600 m.s^{-1}when hypocentre of explosion moves to 20 m. With further movement of the explosion front, the velocity of the seismic wave remained almost constant at the level of 2,600 m.s^{-1}. The obtained results confirm the statement made by the authors about the expediency of using seismic waves to detect gas-and-dust explosions at the early stages and to create conditions for containment of threats to miners [16].

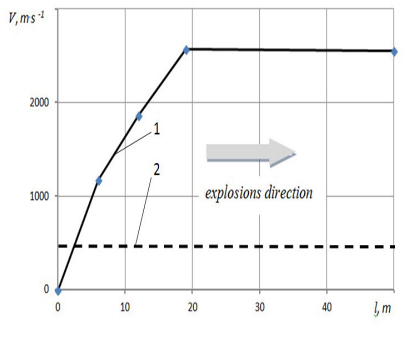

Fig. 6. Dynamics of change of velocities of seismic (1) and shock (2) waves directed along the length of experimental mine working

They allow to substantiate the time parameters of DECS, specifically the size of the required tju and the available tav time to ensure the protection of miners. The value of the required time tju consists of the intervals required for: person's reaction to light and sound alarms tr, activation of personal self-rescuer ti, finding shelter in protective niches or other places ts, etc. Some types of the actions above can be performed sequentially, while others can be performed simultaneously. In real-life conditions, their duration is influenced by several various factors. In the first approximation, we can assume that the total value of tju =$t_R+t_I+t_s$ can be from three to six seconds. The available time tavis determined by the DECS technical parameters, specifically by the interval from the registration of the explosion to the activation of alarm and protective devices, and the creation of safe conditions for people. The safety condition is the that tav must exceed t_{ju}. The available time for the system shown in Fig. 1 can be determined based on the established parameters of seismic and explosive waves. Thus, the time from the registration of the explosion by the additional sensor D_d (see Fig.1) to the activation of the valve 5 feeding the extinguishing agent to the sprinklers 6 is determined by the length of the explosion front from the moment of registration to the protective device with the velocity of Vf, and is $t_1=(L_1+L_2)$/Vf. When determining the tav, the loss of time tin for the activation of the DECS electrical and mechanical elements should be considered. These losses can be about a few tenths of a second.

There are two main DECS modes of operation. In the first mode, the system not only blocks the propagation of the explosion along the mine working, but also reduces such threats as pressure, toxic gases, high temperatures, etc. for the miners.Thus, to ensure the safety of miners, the following condition must be met:

$$t_{av}>t_{ju}, \text{ or } (L_1+L_2)/V_f-t_{in}>t_r+t_i+t_s. \quad (1)$$

In the inequality above, some indicators are constants (Vf,L1,tin), others (tr,ti,ts) can be practiced until they become automatic and minimal. The parameter of inequality, which could be actually adjusted, is the indicator L_2 which is a DECS constructive parameter.

As an example, let's consider an option of the system with the following parameters: V_f=400 m.s^{-1}; L_1=600 m; L_2=1,800 m;tin=0.5 s; (t_r+t_i+ts)=5 s. After substitution, we obtain tav=(600+1,800)/400-0.5=5.5 s, t_{ju}=5 s, i.e. the requirement tav>tju is met.

In the second mode, DECS can be used as a means of containment of explosions in the unattended mine workings ($t_r+t_i+t_s=0$), then inequality (1) takes the following form:

$$(L_1+L_2)/V_f>t_{in}. \quad (2)$$

This determines that the available time must exceed the time required for the activation of hydro-pneumomechanical elements, i.e. the formation of a cloud that stops the fire and the installation of a barrier occurs before the approach of the explosion front. Given that the duration of tin for the activation of the DECS electrical and mechanical elements is about 0.5 s, less sensitive seismic sensors may be used. For example, when $L_1 = 200$ m, and the additional sensor is installed closer ($L_2 = 300$ m), the available time tavwill be 1.25 s, which is much longer than the time required to get the DECS into operation.

The studies have shown the validity of the hypothesis underlying the coal dust explosion containment system in terms of the possibility to use seismic waves for early detection of an emergency situation. Rough calculations indicate the technical possibility of increasing the level of protection of miners from the effects of threats of dust explosion in the mine workings.

Conclusions. Computer modelling of the energy dissipation process of coal dust explosions give a qualitative and some quantitative idea of the mechanism of propagation of velocities and accelerations of seismic waves on the periphery of the experimental mine working. These data can be used to test the means of containment of coal dust explosions, but in order to use them in real-life conditions, the radius of sensor response to seismic waves (L_1) should be additionally determined in mine conditions. Preferably, the sensor has to respond structurally to the moduli of acceleration of train of seismic waves, so that to distinguish the dust explosion from other drivers of seismic oscillations of the rock mass.

Information on the formation of seismic waves in a rock mass accommodating a mine working was further developed, which became the basis for improving the means of containment of explosions of air dust mixture. The parameters of seismic waves, such as propagation velocity and acceleration, amplitude and frequency of oscillations of mine working walls, were established for the conditions of the experimental structure, which allows to scientifically substantiating the design parameters of the systems protecting the miners against explosion. The energy of the explosion propagates in the rock mass in the form of a series of peak-like pulses and oscillations with smaller amplitude. Modulus of acceleration is an informational indicator, which suits the most for registration by seismic sensors responding, specifically, to the most powerful peak pulses formed by seismic waves. By revealing the qualitative and quantitative indicators of seismic wave propagation on the mine working contour and in the rock mass, the parameters of seismic sensors of the systems protecting the miners against explosion can be substantiated.

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КӨМІР ШАҢЫНЫҢ ЖАРЫЛЫСТАРЫН ОҚШАУЛАУ ЖҮЙЕСІНІҢ ҚҰРЫЛЫМДЫҚ ПАРАМЕТРЛЕРІН НЕГІЗДЕУ

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ОБОСНОВАНИЕ КОНСТРУКТИВНЫХ ПАРАМЕТРОВ СИСТЕМЫ ЛОКАЛИЗАЦИИ ВЗРЫВОВ УГОЛЬНОЙ ПЫЛИ

Аннотация. Целью работы является раскрытие качественных и количественных параметров сейсмических волн и ускорений на контуре горной выработки, в которой произошел взрыв газопылевой смеси. Для усовершенствования средств локализации взрывов пылевоздушной смеси дальнейшего развития получили сведения по формированию сейсмических волн в горном массиве, вмещающем горную выработку. Для условий экспериментального сооружения установлено параметры сейсмических волн, такие как скорость и ускорение распространения, амплитуда и частота колебаний стенок горной выработки, что позволяет научно обосновать конструктивные параметры систем защиты горнорабочих от действия негативных факторов взрыва. Энергия взрыва распространяется в горном массиве в виде серии пикообразных импульсов и колебаний с меньшей амплитудой. Наиболее пригодным для фиксации, информативным показателем, на который должны реагировать сейсмические датчики является модуль ускорения, а, точнее, на наиболее мощные образованные сейсмическими волнами пиковые импульсы. Раскрытие качественных и количественных показателей распространения сейсмических волн по контуру горной выработки и в горном массивы позволяет обосновать параметры сейсмических датчиков системы защиты горняков от негативных факторов взрыва.

Ключевые слова: сейсмические датчики, локализация взрыва, горная выработка, пылевоздушная смесь.

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