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Earth and Planetary Sciences: Earth-Surface Processes

Application of a Numerical Model for Forecasting the Consequences of an Explosion

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ABSTRACT
The study presents an investigation of the consequences of explosive impacts during blasting operations at the Zhairem deposit using numerical modeling in the Ansys LS-DYNA software package. Based on literature data and the physico-mechanical properties of rock materials, two modeling scenarios were implemented: the explosion of a single blast hole and a group of blast holes. Dependencies of internal and kinetic energies, displacements, velocities, and accelerations of the rock mass, as well as the distribution of stresses and pressures within the rock, were obtained. It was shown that the maximum equivalent stress during the explosion of a single hole reaches 923.73 MPa, corresponding to the zone of intensive rock mass destruction. For a group of blast holes, energy release increases by several orders of magnitude, reaching 1.2×10^9 J. Characteristic phases of energy transformation and blast wave dynamics were identified, allowing the assessment of hazardous zones and potential consequences of unauthorized explosions. The results of the study can be used to improve the safety of blasting operations and to predict the impact of air-blast overpressure on buildings and structures.

Keywords: blasting operations; numerical modeling; Ansys LS-DYNA; single blast hole; group of boreholes; air-blast wave; overpressure; equivalent stresses; blast dynamics; explosion consequences prediction.

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Introduction

As part of the literature review, modern domestic and foreign studies on the modeling, analysis, and prediction of explosion consequences were examined. The studied materials range from empirical relationships and regulatory methods to numerical models.

In their article [1], Qiang W. et al., based on collected data from accidental explosions (at a US plant in 2013, at the Tianjin port in China in 2015, and at the Beirut port in Lebanon in 2020), studied the consequences and effects of ammonium nitrate (AN) explosions based on the Chinese national standard GB6722-2014. The main focus is on calculating the TNT equivalent of various explosives and assessing the impact of the blast wave, considering distance and scaling.

In studies [2], the authors focused on the blast wave propagating from the source to the object. The article analyzes different mathematical models used to determine the magnitude of explosion pressure. Two cases of their application were analyzed. In the first case, the distance to the explosive was varied while the explosive weight was constant. In the second case, the explosive mass was varied at the same distance. The results showed that the difference in calculations for different cases is least noticeable at large distances.

Work [[3], [4], [5]] examines the propagation of hydrogen combustion products in numerical modeling. The model accounts for pressure distribution and made it possible to determine the maximum overpressure at control points. It was found that with an increase in explosion power, the maximum overpressure increases. This increase is associated with the combustion radius and the amount of destroyed materials.

Based on the literature analysis, it has been established that explosion parameters (pressure, radius, impulse) significantly depend on:

- physicochemical properties of the explosive materials (EM);
- density of the medium;
- cloud shape (in the case of a gas or vapor-air mixture);
- initiation mode;
- conditions of wave propagation.

Based on the relevance of the topic, the aim of this work is to determine the scale and nature of possible consequences using numerical sumalation.

Experimental part

The object of study in this research work is the Zhairem barite-polymetallic deposit, specifically the Dalnezapadny open-pit mine, where mining is carried out by open-pit method. It is located in the Zhan-Arka district of the Karaganda region within the Atasu ore district. The geographical coordinates of the deposit are: 48°17′ N latitude and 70°20′ E longitude (Figure 1).

The main activity of JSC "Zhairem Mining and Processing Plant" is the extraction and processing of polymetallic, manganese, and iron ores, as well as the production of zinc and lead concentrates. The leading economic sector in the region is represented by the Kazzinc company, which is controlled by the Glencore group [6].

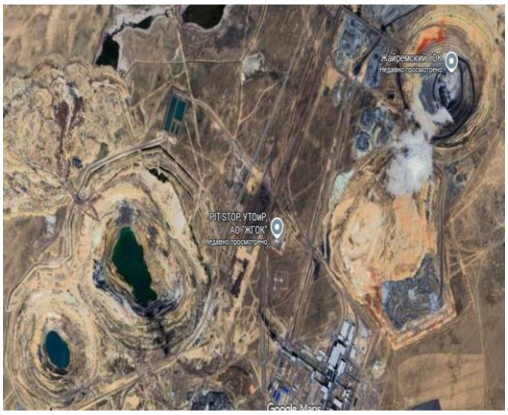

Figure 1 – Overview map of the study area

The collected data on drilling and blasting operations formed the initial basis for this scientific research. According to the drilling and blasting records, a consistent blast hole pattern of 5.2 x 5.7 m and a vertical drilling angle (90°) were used across the horizons.

In accordance with the deposit development plan, the following explosives are used in open-pit blasting operations: ANFO, Explo P, and Explo E 70. The effective energy relative to ANFO at a density of 0.8 g/cm³ is 2.30 MJ/kg, according to the stated characteristics [[7], [8], [9]]. These energy values are based on ideal detonation calculations at a limiting pressure of 100 MPa [[10], [11]].

To analyze the impact of explosions on the environment and structures, the LS-DYNA software package is used based on the aforementioned data. These methods allow for considering the complex geometry of objects and the heterogeneity of the medium, providing visualization of the dynamics of shock wave propagation in space and time.

In the numerical simulation, calculations were performed to analyze the physical processes of the explosion using the physico-mechanical characteristics of the rock from the deposit (Table 1).

Table 1 – Initial Parameters

Rock type	Rock mass
Rock density, kg/m³	2400
Young's modulus, MPa	19360
Poisson's ratio	0.25
Compressive strength, MPa	94.2
Explosive type	Anfo
Charge length, m	9.2
Stemming length, m	3.3
Explosive charge mass in the borehole, kg	150
Explosive density, g/cm³	0.8
Detonation velocity (D), m/s	42
Borehole diameter, mm	171
Effective energy, MJ/kg	2.30

Two variants of geometric models were considered in this study for a comprehensive assessment of blasting effects: a single borehole model for investigating the effect of an individual charge and a full block model for analyzing the interaction of charges and their overall impact on the rock mass (Figures 2–3). According to the drilling and blasting design parameters, the borehole diameter was 171 mm, with a spacing pattern of 5.5 × 5.5 m. The charge configuration consisted of 9.2 m of explosive column and 3.3 m of stemming.

The mathematical description of rock mass behavior was implemented using the MAT_PLASTIC_KINEMATIC (Type No. 3) material model. This model was selected because it effectively describes the elastoplastic behavior of the medium, taking into account isotropic and kinematic hardening. In addition, the model is computationally efficient for solid elements and allows consideration of strain rate effects.

To simulate the expansion process of detonation products of the explosive material (ANFO), the JWL (Jones–Wilkins–Lee) equation of state was used [[12], [13], [14], [15]]:

$$p = A\left(1 - \frac{\omega}{R_1 V}\right) e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right) e^{-R_2 V} + \frac{\omega E}{V}$$

In this equation, the parameters A, B, and E have the dimension of pressure, while R_1, R_2, ω, and V are dimensionless quantities. For modeling processes involving explosives, it is recommended to use the 'gram-centimeter-microsecond' unit system. Within this coherent unit system, pressure is expressed in megabars (Mbar) [[16], [17], [18]].

Option 1. Single-borehole model

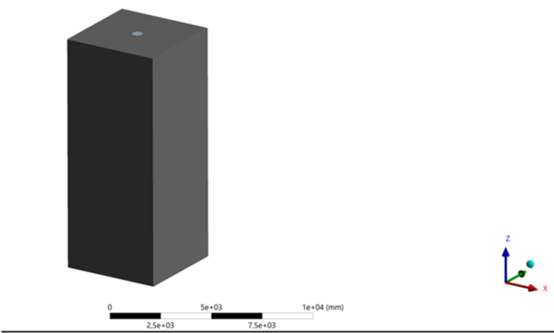

Figure 2 – Single borehole model

Option 2. Model of the entire block for analyzing the interaction of charges and the overall impact on the rock mass. According to the deposit's blast pattern passport, this model studied boreholes arranged in a staggered pattern with a 5.5 × 5.5 m grid and a delay interval of 42 ms (Figure 3).

The model shows dimension lines and values indicating the parameters of the block and the design of the blast holes. The block with a staggered arrangement of blast holes has the following dimensions:

- Length: 20 m;
- Width: 15 m;
- Height: 12 m;

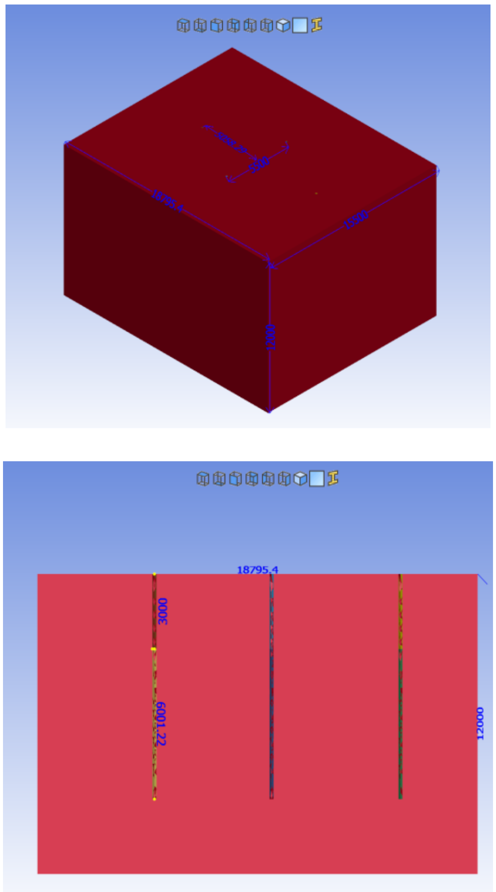

Figure 3 – Model of a full block of blast holes.

Results and Discussion

From the numerical modeling for Option 1, graphs of the internal energy, the kinetic energy of the system, and the velocity of the destroyed materials versus time were obtained (Figures 4-11).

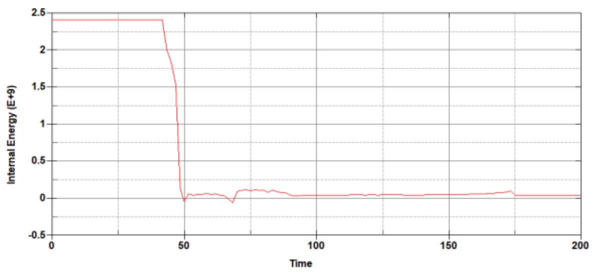

Figure 4 – Graph of internal energy variation

Analysis of the internal energy graph shows that characteristic phases of energy transformation can be identified. At the initial moment, a positive value of internal energy is observed. The main stage of energy absorption occurs in the interval from 0 to 50 ms, where the internal energy monotonically increases to a maximum value of 2.5×10^6 J, indicating an intensive process of plastic deformation and damage accumulation in the material. The subsequent phase from 50 to 200 ms is characterized by a monotonic decrease in internal energy to near-zero values. These internal energy dynamics correspond to a typical scenario of intense dynamic loading.

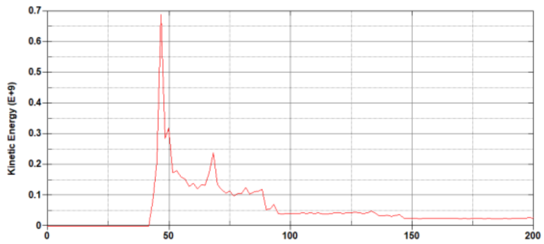

Figure 5 – Graph of kinetic energy variation

Based on the analysis of the kinetic energy dependence, a characteristic dynamic process of energy transformation under impulse loading is revealed. At the initial stage, an intensive increase in kinetic energy from zero to a maximum level of 0.65×10^9 J at T ≈ 42 ms is observed, which corresponds to the phase of active energy input and the transformation of external impact energy into mechanical motion. The subsequent monotonic decrease in kinetic energy continues in the interval of 50-200 ms.

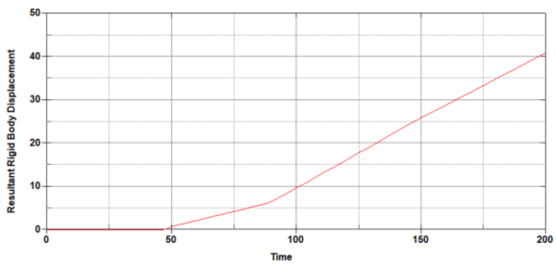

Figure 6 – Total displacement vs. time

From the graph of the velocity parameter versus time, a characteristic nonlinear development of the dynamic process under impulsive loading is observed. In the initial period, an intensive increase is recorded under the action of the external load.

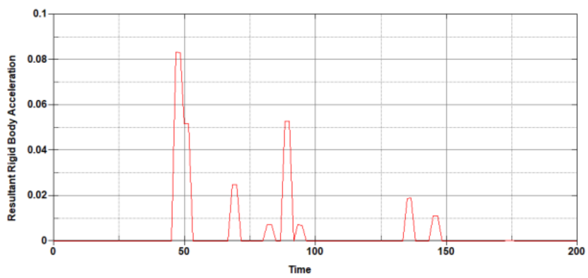

Figure 7 – Dependence of total acceleration on time

At the initial stage of the process, the acceleration remains near zero, indicating the absence of significant external influences. A sharp increase in acceleration, observed at T ≈ 40 ms, reaches an extreme value of $a_{max} \approx 0.083–0.084 m/s^2$ at T = 50 ms, corresponding to the primary impulsive loading on the structure. The subsequent dynamics are characterized by rapid attenuation, manifested as distinct peaks at T ≈ 90 ms (a ≈ 0.055) and T ≈ 140 ms (a ≈ 0.018). The amplitude of successive peaks decreases within the interval 100–150 ms.

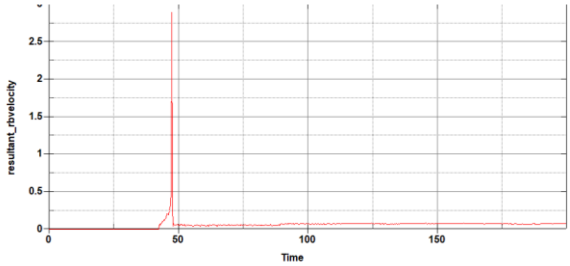

Figure 8 – Dependence of total velocity on time

The seismic effect is characterized by a sharp increase to a maximum value at the moment of detonation, followed by attenuation, manifested as a decrease in peak amplitudes within the 100–150 ms interval.

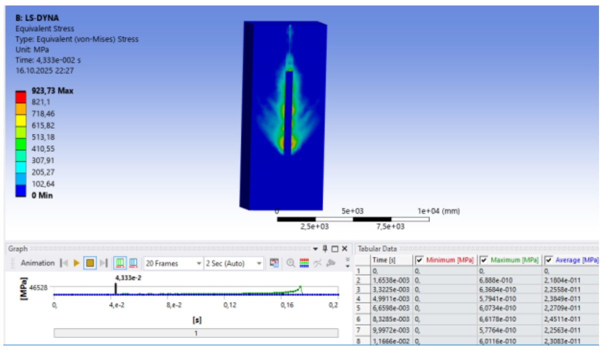

Figure 9 - Equivalent stress distribution in the rock mass after the blast

Also, from the simulation results, it was found that the maximum equivalent stresses under the blast impact at 42 ms reach 923.73 MPa near the borehole axis, which corresponds to the zone of greatest destruction of the rock mass. As the distance from the explosion source increases, the stresses decrease, reflecting the attenuation of the shock wave. Analysis of the destruction process allows for determining the boundaries of intensive impact zones for designing safe blasting operation parameters.

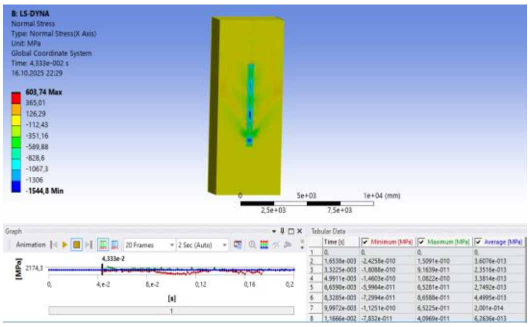

Figure 10 – Equivalent stress distribution in the rock mass after the blast

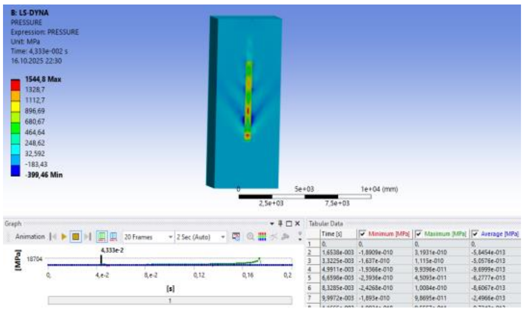

Figure 11 – Distribution of stress pressure in the massif after detonation

Analysis of normal stresses showed that during an explosion in the axial direction, alternating zones of compression and tension are observed with extreme values ranging from –1544.8 to 603.74 MPa. The main impact is concentrated along the borehole axis, where maximum rock compression occurs. The stress distribution indicates the formation of cracks as a result of tensile stresses in the peripheral zones.

When processing the results of Option 2, graphs of the energy, displacement, velocity, acceleration, as well as the distribution of stresses and pressure in the rock mass were obtained (Figure 12).

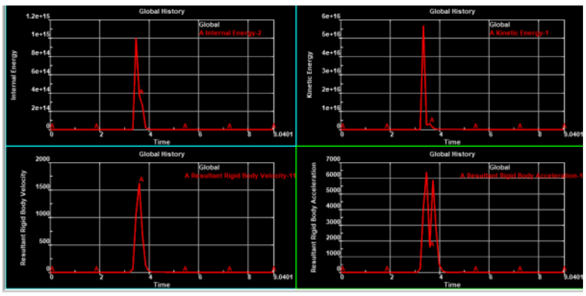

Figure 12 – Parameters of the rock mass under blast loading

The graphs from option 2 of the numerical simulation allow the following key features to be highlighted:

Graph No. 1. The main part of the explosion energy (J) is converted into internal energy over a very short period of time, which corresponds to the phase of intensive plastic deformation and rock fracture. After the shock wave passes, the system quickly stabilizes.

Graph No. 2. The peak of kinetic energy (J) occurs slightly later than the peak of internal energy, which is associated with the transition from deformation to movement of the rock mass.

Graph No. 3. The velocity impulse (m/s) confirms the development of high-speed movement of rock mass fragments at the moment of explosion. Rapid attenuation indicates the absence of prolonged displacement; the main response is impulsive, which is typical for the impact of a shock wave.

Graph No. 4. The acceleration (m/s²) confirms the presence of a powerful short-term impulse corresponding to the passage of the shock wave and the transfer of maximum force to the rock mass. Secondary oscillations indicate high-frequency vibration of the rock after the primary impact, which is characteristic of the seismic response during an explosion.

All four graphs demonstrate a typical picture of a short-term but extremely powerful dynamic process. In 2–3 ms, the main transfer of explosion energy to the rock mass occurs. Internal energy increases → then the energy transitions to kinetic → the rock acquires high velocities → and maximum accelerations.

The pressure distribution in the rock mass model at time t = 2.8722 ms after the 42 ms detonation time is shown (Figure 13). The pressure contours applied to the elements of the mass are displayed.

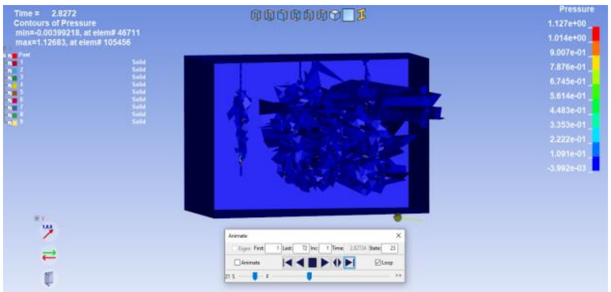

Figure 13 - Distribution of pressure in the rock mass

The distribution scale shows pressure amplitudes in the range: max = 1.127e+00 Pa, min = –3.992e–03 Pa. At a time of about 2.87 ms, the shock wave has already formed a region of high pressure in the central zone. At the periphery, the pressure remains low, indicating incomplete propagation of the wave at the early stage of the process.

The summarized simulation results for both options are presented in Table 2.

Table 2 – Comparative analysis of simulation results

Parameter of comparison	Single borehole (Option 1)	Group of boreholes (Option 2)
Total energy release	1.2×10^3 J	1,2×10^9 J
Max. internal energy	2.5×10^6 J	Several orders of magnitude higher (intensive plastic deformation)
Max. kinetic energy	0.65×10^9 J	Exceeds the values of a single borehole (transition to mass movement)
Max. equivalent stresses	923.73 MPa	Characterized by the interaction of stress fields of adjacent charges
Max. acceleration of the rock mass (a_max)	≈0.084 m/s²	Short-term impulse and force transfer to the entire block
Max. pressure	Concentrated along the borehole axis	Up to 1.127 Pa (at time t = 2.87 ms)

The analysis of the results allows for a well-founded practical interpretation to be formulated:

- seismic safety and vibration impact;
- stability of structures and failure zones;
- assessment of hazardous zones based on flyrock and pressure;

The quantitative indicators obtained in Ansys LS-DYNA are the basic data for designing safe blasting operation parameters and developing measures for the protection of buildings and structures [[19], [20]].

Conclusion

Based on the conducted research on forecasting the possible consequences of an explosion of a single borehole and an entire block, the following conclusions can be drawn:

The analysis of the equivalent stress distribution and plastic deformation zones (up to 923.73 MPa) makes it possible to optimize the blast hole pattern. The obtained data on the crushing zone radius provide the opportunity to reasonably change the distance between charges to achieve the required quality of rock mass fragmentation while simultaneously reducing the specific consumption of explosives.

The obtained dependences of peak accelerations and displacement velocities of the rock mass serve as a tool for assessing seismic safety. This makes it possible to predict the degree of vibration impact on buildings and structures located near the work zone and, if necessary, to adjust the mass of simultaneously blasted charges.

Modeling the dynamics of the air shock wave and rock flyout zones allows for establishing the boundaries of hazardous areas. This is critically important for protecting mining and transport equipment and personnel, as well as for preventing the impact of overpressure on infrastructure facilities.

Thus, the developed numerical model is an effective tool for the operational management of blasting operation parameters, ensuring a balance between blast productivity and industrial safety.

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Жарылыс салдарын болжау үшін сандық модельді қолдану

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ТҮЙІНДЕМЕ
Ғылыми жұмыста Ansys LS-DYNA бағдарламалық кешенінде сандық модельдеуді қолдана отырып, Жәйрем кен орнында жарылыс жұмыстары кезіндегі жарылыс әсерінің салдарын зерттеу ұсынылған. Әдеби деректер мен тау жыныстарының физика-механикалық қасиеттері негізінде екі модельдеу нұсқасы орындалды: жеке ұңғыманың жарылысы және ұңғымалар тобының жарылысы. Ішкі және кинетикалық энергиялардың, қозғалыстарына, жылдамдықтары мен массивтің үдеулері, сондай-ақ тау жыныстарындағы кернеулер мен қысымдардың таралуына тәуелділіктер алынды. Жеке ұңғыманың жарылысы кезінде эквивалентті кернеудің ең жоғарғы мәні 923,73 МПа-ға жететіні көрсетілді, бұл массивтің қарқынды бұзылу аймағына сәйкес келеді. Ұңғымалар тобы үшін энергия бөлінуі бірнеше есе артып, $1,2 \times 10^9$ Дж шамасына дейін жетеді. Энергияның түрлену фазалары және соққы толқынының динамикасы анықталып, қауіпті аймақтарды және рұқсат етілмеген жарылыстардың ықтимал салдарын бағалауға мүмкіндік береді. Зерттеу нәтижелері жарылыс жұмыстарының қауіпсіздігін арттыруға және соққы ауа толқынының ғимараттар мен құрылыстарға әсерін болжауға қолданылуы мүмкін.

Түйін сөздер: жарылыс жұмыстары; сандық модельдеу; Ansys LS-DYNA; жеке ұңғыма; ұңғымалар тобы; соққы ауа толқыны; артық қысым; эквивалентті кернеулер; жарылыс динамикасы; жарылыс салдарын болжау.

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Применение численной модели для прогнозирования последствий взрыва

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АННОТАЦИЯ
В научной работе представлено исследование последствий взрывных воздействий при ведении взрывных работ на Жайремском месторождении с использованием численного моделирования в программном комплексе Ansys LS-DYNA. На основе литературных данных и физико-механических свойств горных пород выполнено моделирование двух вариантов: взрыва одиночной скважины и группы скважин. Получены зависимости внутренних и кинетических энергий, перемещений, скоростей и ускорений массива, а также распределения напряжений и давлений в горной породе. Показано, что максимальные эквивалентные напряжения при взрыве одиночной скважины достигают 923,73 МПа, что соответствует зоне интенсивного разрушения массива. Для группы скважин энерговыделение возрастает на несколько порядков, достигая $1,2 \times 10^9$ Дж. Установлены характерные фазы преобразования энергии и динамики ударной волны, что позволяет оценить опасные зоны и возможные последствия несанкционированных взрывов. Результаты исследования могут быть использованы для повышения безопасности взрывных работ и прогнозирования влияния ударной воздушной волны на зданий и сооружени.

Ключевые слова: взрывные работы; численное моделирование; Ansys LS-DYNA; одиночная скважина; группа скважин; ударная воздушная волна; избыточное давление; эквивалентные напряжения; динамика взрыва; прогнозирование последствий взрыва.

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