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Managing the rock mass destruction under the explosion

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Managing the rock mass destruction under the explosion

Abstract

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Keywords

rock mass management, drill-blasting, explosives, charging cavity, rock mass destruction zones

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RESEARCH ARTICLE

Managing the rock mass destruction under the explosion

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Abstract

Using the theory of elasticity and the main provisions of the quasi-static-wave hypothesis of the mechanism of the destruction of a solid medium under the action of an explosion, analytical modelling of the parameters of the formation of crumpling zones and crushing of the rock mass around the charging cavity during its explosive loading was carried out. Analytical models of the radii of the crumpling, intensive fragmentation and fracturing zones formed around the charging cavity in the rock mass during its explosive loading, taking into account the pressure of the explosion products, the limit of tensile-compressive strength of the rocks, their structural composition, fracturing and compaction under the action of rock pressure, were developed. Based on the change in the stress-strain state of the rock mass under the action of the explosion, numerical modelling of the radii of the zones of crumpling, intensive fragmentation and fracturing was performed using the finite element method. According to the simulation results, the power dependence of the change in the radii of the crumpling and fragmentation zones of the rock mass was determined depending on the diameter of the charging cavity, the pressure of the explosion products, and the limit of rock compressive strength. By comparing the results of analytical and numerical modelling for rigid boundary conditions of a homogeneous non-cracked rock mass, the difference in the values of the radii of the defined zones was established as being 4, 8 and 6%, respectively. The resulting analytical models of the radii of crushing zones, intensive fragmentation and fracturing increase the accuracy of estimating the parameters of rock mass destruction by explosion by up to 50% and improve the parameters of drilling and blasting operations when carrying out mining operations, special purpose cavities and rocking of the rock mass.

Keywords: rock mass management, drill-blasting, explosives, charging cavity, rock mass destruction zones

1. Introduction

Ferrous metallurgy is one of the most developed industries in Ukraine. Its origin and formation took place on the raw material base of iron ores [1]. The extraction of iron ores is associated with the destruction of large volumes of solid rocks, which requires their preliminary crushing using drill-blasting. Drill-blasting technology needs constant improvement taking into account modern achievements in science and technology [2]. Today, one of the directions for improving the technology of conducting drill-blasting is increasing the safety of blasting operations and reducing their impact on the environment. This is possible due to the replacement of trinitrotoluene (TNT) containing explosives with emulsions of domestic production [3], which are absolutely safe in transportation [4]

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and storage [5], economically profitable [6] and environmentally friendly [7].

According to the Targeted Regional Program for the transition of ore and non-ore mining and dressing plants to TNT-free environmentally friendly explosives, new TNT-free explosives have been used since 2004. Already in 2011, the use of these explosives at open-pit mining enterprises reached 99%. Underground mining of iron ores is fully realized by drill-blasting using industrial explosives (IE), of which 58% are currently emulsions. The introduction of emulsion explosives (EE), which began in 2009 for underground works, revealed the imperfection of the existing methods of determining drill-blasting parameters. Officially operating methods do not consider the physicochemical features and detonation characteristics of EE, the structural construction of rocks, and their fracturing and compaction under the action of rock pressure, which leads to the use of incorrect parameters of drill-blasting operations with negative consequences.

Therefore, the special attention of scientists and industrialists is paid to the improvement and development of new methods of calculating drill-blasting parameters, which significantly increases the efficiency of creating underground infrastructure during ore extraction and the formation of special-purpose cavities. Therefore, the need to increase the efficiency of destruction of rocks by explosion using not only EE, but also all explosives is an urgent scientific and technical problem.

It is known that rock is a non-homogeneous solid body that has a complex structure, and the mechanism of its destruction is even more complex. In general, the mechanism of rock destruction by explosion is characterized by the short duration of the load and depends on many factors. Recently, the knowledge of the explosion process has expanded significantly, but today there is no generally accepted idea about the mechanism of destruction of rocks by explosion. This is related to the variety, complexity and rapidity of the phenomena that accompany the action of an explosion in a solid environment [8]. The phenomena of the explosion process include the detonation of the explosive charge, expansion of the charging cavity (hole or well), mechanical interaction of the explosion products with the mass of rocks, formation and propagation of shock waves, propagation and interaction of tension waves in the mass and its destruction, displacement of crushed material and flying pieces [9]. By analysing the hypotheses that explain the physical essence of the process of destruction of a rock mass by an explosion [10], modern views on the effect of an explosion in a solid environment under the joint action of explosion products and tension waves have been established.

Scientists from Ukraine, Poland, Serbia, Germany, Sweden, China, the USA, Australia, and other countries have studied the mechanism of rock destruction by explosion and have offered manufacturers a significant number of methods for calculating drill-blasting parameters for mining and rock mass based on the developed theories [11−16]. However, most of these methods have an empirical basis, which is based on the use of correction coefficients, and a minority is analytical, based on the determination of the destruction zones of rock mass. All theories and methods of calculating drill-blasting parameters are based on various patterns and ideas about the mechanism of rock mass destruction by explosion and do not take into account the detonation characteristics of modern EE. Therefore, based on the joint action of the explosion products and tension waves in the rock mass, it is necessary to improve the mathematical models [10] of the rock mass destruction zones by explosion depending on the detonation characteristics of drill-blasting and the physical and mechanical properties of the environment.

2. Materials and methods

The purpose of the study is to improve the calculation of the parameters of rock mass destruction zones by explosion, depending on the pressure of the explosion products in the charging cavity and the physical and mechanical properties of the rocks, by combining analytical and numerical modelling.

To meet the purpose, the following tasks were solved.

- the theories of determining the destruction zones of the rock mass around the charging cavity were generalized;
- the zones formed around the charging cavity under the action of the explosion due to the deformation and destruction of the environment were detailed;
- the regularity of the formation of crumpling zones, intensive fragmentation and crack formation, which are formed in the rock mass around the charging cavity under the action of the explosion, was revealed with the use of analytical modelling;
- numerical modelling of the destruction of the rock mass around the charging cavity was carried out, and the regularities of changes in the radii of the crumpling and crushing zones depending on the pressure of the explosion products and the physical and mechanical properties of the rocks were established.

3. Results and discussion

As a result of the explosion of an elongated explosives' charge in an unrestricted environment around the charge cavity, zones of crumpling, radial cracks and elastic deformations are formed. The analysis of the theories and methods of calculating the sizes of these zones established [10] that in order to determine the rational parameters of the drill-blasting according to various criteria of the destruction of the environment, the researchers established the regularities of the formation of only two zones, crumpling [17] and fracturing [18]. Also, all these theories and methods do not consider the zone of intensive fragmentation, the radius of which is decisive in determining the line of least resistance. Therefore, the mechanism of destruction of rocks around the charging cavity from the point of view of the types and criteria of destruction of the environment will be considered in more detail.

It is known that because of the detonation of the explosive charge due to the high pressure of the explosion products released at supersonic speed, a shock wave is formed in the condensed medium [19]. Within the radius of action of the shock wave, a compression zone is formed, in which the rock is destroyed into ultrafine particles, and a crumpling zone occurs. The thermoelastic loads can be the cause of one of the most probable mechanisms of rock destruction in this blast zone. As an alternative or additional factor, the mechanism [20] is considered due to the transition of the microstructure of the crystalline components of the rock to a state of instability. The reason is an oversaturation of the microstructure of the rock with linear and point defects. Exceeding the value of the critical concentration of defects leads to an excessive supply of internal energy with subsequent spontaneous (or forced) destruction of chemical bonds, especially during the release of rarefaction waves on the free surface. According to research [21], in the compression zone, the rock mass changes its structure and intensive fine-dispersed fragmentation of the rock into particles of up to 1 mm in size occurs. As it moves away from the charging cavity, the shock wave turns into a tension wave that propagates at the speed of sound. Behind the crumpling zone, a zone of rock crushing is formed, in which elastic–plastic deformations take place. According to the statements of Rzhevsky V.V. and Novik G. Ya., in this zone, the energy of the explosion is spent on overcoming the resistance of the shear rock, stretching and partially compressing it. Pokrovsky (2021) notes that after the formation of a compacted layer around the charging cavity (crumpling zone), a zone appears that is permeated with radial cracks in the form of rays, between which there are cracks perpendicular to the radii. These cracks occur when the pressure of the explosion products decreases, and there is a small displacement of the rock back to the centre of the explosion. Based on this, the crushing zone can be divided into two: intensive crushing, in which compressive tensions from the reduced pressure of the explosion products act, and directly the fracturing zone, where the rock will be deformed under the action of shear and tensile tensions.

Further, the tension wave turns into a seismic wave, which does not destroy the rock mass, but only shakes it, so a shaking zone appears behind the crack formation zone [22]. In the shaking zone, rocks are partially destroyed along natural cracks without crushing the rock mass into rock jointings. Based on the performed analysis of the rock destruction process by the action of the explosion, the final gradation of the zones formed around the charging cavity was carried out (Table 1).

The first three zones (Table 1) are of interest for solving the problems of rock crushing by explosion when calculating drill-blasting parameters – crushing, intensive fragmentation and fracturing. The fourth zone is important for considering the seismic effect of the explosion.

For the mathematical modelling of the explosion action, a parametric scheme was developed to determine the zones of crumpling, intensive fragmentation and fracturing [10], which are formed around the charge cavity during the detonation of the explosives charge (Fig. 1).

The mechanical tensions σ arising in the rock mass under the action of the explosion energy for the zone of crumpling, intensive crushing and fracturing are determined by the following relations:

$$\sigma = \frac{P_1 \cdot r^2}{R_{zm}^2 - r^2}, \mathrm{N/m^2} \tag{1}$$

$$\sigma = \frac{P_2 \cdot R_{zm}^2}{R_d^2 - R_{zm}^2}, \mathrm{N/m^2} \tag{2}$$

Table 1. Detailing of the zones that are formed around the charging cavity.

Zone	Wave	Deformations	Type of destruction
First	Shock	Plastic	Crumpling
Second	Tension	Elastic-plastic	Intensive fragmentation
Third			Fracturing
Fourth	Seismic	Elastic	Shaking

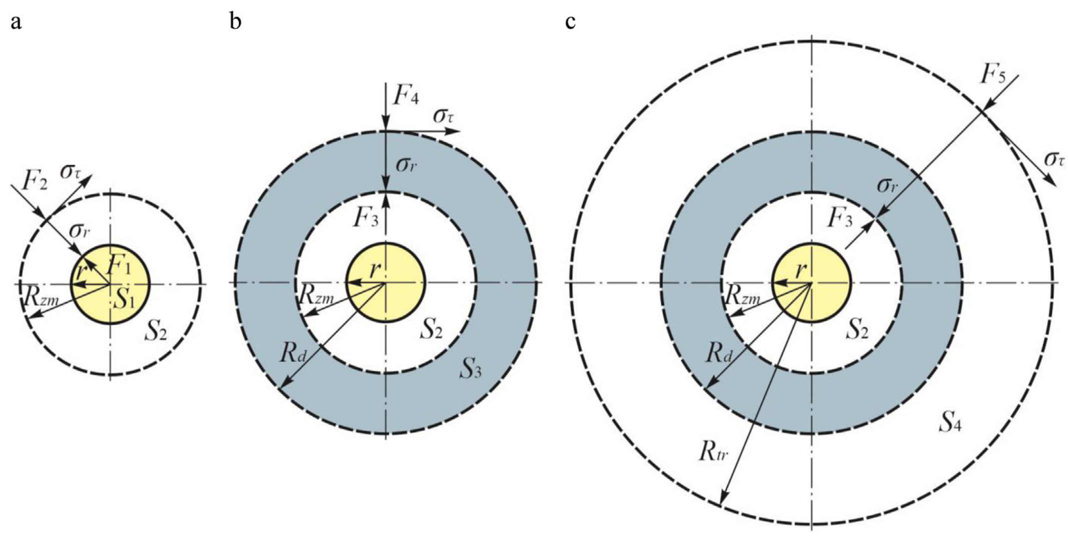


Fig. 1. Parametric schemes for determining crumpling zones (a), intensive grinding (b) and fracturing (c): S_1, S_2, S_3, S_4 are area of the charging cavity and corresponding zones, m^2; F_1, F_2, F_3, F_4, F_5, are active forces, N; σ_r is radial tensions, N/m^2; σ_τ is tangential tensions, N/m^2; r is radius of the charging cavity, m; R_{zm} is the radius of the crumple zone, m; R_d is the radius of the intensive fragmentation zone, m; R_{tr} is radius of the crack formation zone, m.

$$\sigma = \frac{P_2 \cdot R_{zm}^2}{R_{tr}^2 - R_{zm}^2}, \mathrm{N/m^2} \tag{3}$$

where P_1 is the pressure of the explosion products [23] corresponds to the expression with sufficient accuracy:

$$P_1 = \frac{\rho \cdot D^2}{8} \cdot K_{dz}, \mathrm{Pa} \tag{4}$$

where ρ is density of explosive, kg/m^3; D is explosive detonation speed, m/s; K_{dz} is coefficient that considers the change in the pressure of the explosion products on the walls of the charging cavity depending on the diameter of the explosive charge [24]:

$$K_{dz} = \left(\frac{d_z}{d}\right)^3 \tag{5}$$

where d_z is explosive charge diameter, m; d is diameter of the charging cavity, m. P_2 is reducing the pressure of the explosion products on the rock mass due to the increase in the contact area:

$$P_2 = \frac{P_1 \cdot r}{R_{zm}}, \mathrm{Pa} \tag{6}$$

Expressions (1)–(3) are the equations of the problem of G. Lamé [25], according to the theory of which in thick-walled cylinders under the conditions of internal pressure, the radial tensions σ_r at all points of the cylinder will be negative (compressive tension), and the tangential tensions σ_τ are positive (tensile tension), i.e. these are the main tension.

To determine the equivalent stress σ_{ekv} in the volumetric tension state, the Third theory of strength was used, which confirmed the reliability of the predictive parameters of the emission funnel radii in the conditions of real objects [26]. So, the main tensions are: $\sigma_1 = \sigma_\tau = \sigma$; $\sigma_2 = 0$; $\sigma_3 = \sigma_r = -\sigma$. According to the specified theory, the equivalent tension is equal to $\sigma_{ekv} = \sigma_1 - \sigma_3$; then for the crumpling zone $\sigma_{ekv} = \frac{2 \cdot P_1 \cdot r^2}{R_{zm}^2 - r^2}$, N/m^2; for the intensive fragmentation zone $\sigma_{ekv} = \frac{2 \cdot P_2 \cdot R_{zm}^2}{R_d^2 - R_{zm}^2}$, N/m^2; for the intensive fracturing zone $\sigma_{ekv} = \frac{2 \cdot P_2 \cdot R_{zm}^2}{R_{tr}^2 - R_{zm}^2}$, N/m^2. When forming zones of crumpling and intensive fragmentation, the condition of comprehensive compression applies $\sigma_{ekv} = \sigma_{st}$.

It is known from the theory of elasticity and plasticity that if the outer diameter of the cylinder is four times larger than the inner diameter, and the calculations assume a discrepancy of up to 6%, then the solution is not related to the shape of the outer contour, and the cylinder is in pure shear conditions, that is, for the zone of fracturing formation $\sigma_{ekv} = \tau_z$. Based on the above and taking into account the dynamic coefficient under shock loading, after the necessary transformations, analytical expressions of the radii of the zones were obtained

– crumpling

$$R_{zm} = 0.5 \cdot d \cdot \sqrt{1 + \frac{\rho \cdot D^2 \cdot K_{dz}}{2 \cdot \sigma_{st}}}, \mathrm{m} \tag{7}$$

– intensive fragmentation

$$R_d = R_{zm} \cdot \sqrt{1 + \frac{\rho \cdot D^2 \cdot d \cdot K_{dz}}{8 \cdot R_{zm} \cdot \sigma_{st}}}, \mathrm{m} \tag{8}$$

– fracturing

$$R_{tr} = R_{zm} \cdot \sqrt{1 + \frac{\rho \cdot D^2 \cdot d \cdot K_{dz}}{8 \cdot R_{zm} \cdot \tau_z}}, \mathrm{m} \tag{9}$$

where σ_{st} is compressive strength limit of rocks, Pa; τ_z is shear strength limit of rocks, Pa.

To increase the accuracy of the calculations of the radii of the specified zones, the coefficients of the rock structure, structural weakening of the rock mass, and rock compaction under the action of gravitational forces (rock pressure) have been introduced into the given formulas. With the necessary transformations, the formulas for calculating zone radii are as follows. With the necessary transformations, the formulas for calculating zone radii are as follows.

– crumpling

$$R_{zm} = 0.5 \cdot d \cdot \sqrt{1 + \frac{\rho \cdot D^2 \cdot K_{dz}}{2 \cdot \sigma_{st} \cdot K_{sp} \cdot K_s \cdot K_u}}, \mathrm{m} \tag{10}$$

– intensive fragmentation

$$R_d = R_{zm} \cdot \sqrt{1 + \frac{\rho \cdot D^2 \cdot d \cdot K_{dz}}{8 \cdot R_{zm} \cdot \sigma_{st} \cdot K_{sp} \cdot K_s \cdot K_u}}, \mathrm{m} \tag{11}$$

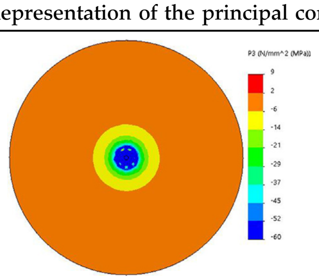
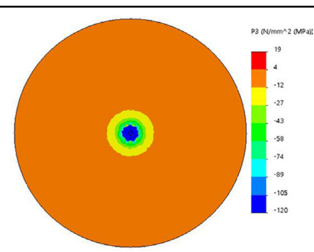
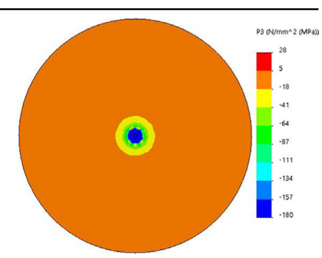
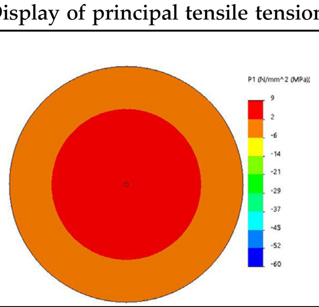
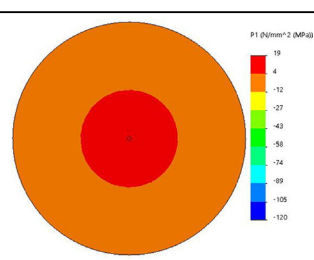
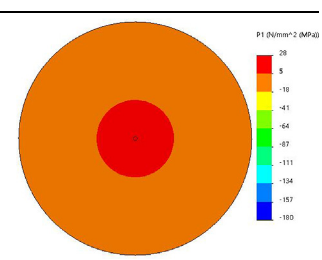
– fracturing

$$R_{tr} = R_{zm} \cdot \sqrt{1 + \frac{\rho \cdot D^2 \cdot d \cdot K_{dz}}{8 \cdot R_{zm} \cdot \tau_z \cdot K_{sp} \cdot K_s \cdot K_u}}, \mathrm{m} \tag{12}$$

where K_{sp} is rock structure coefficient [27], which depends on the properties of the rock mass: for viscous, elastic and porous rocks $K_{sp} = 2.0$; for dislocated, with variable deposition and fine fracturing $K_{sp} = 1.4$; for shale, with variable strength and layering, perpendicular to the direction of the charging cavity $K_{sp} = 1.3$; for massive, fragile $K_{sp} = 1.1$; for monolithic $K_{sp} = 1.0$; for fine-porous, non-dense $K_{sp} = 0.8$; K_s is coefficient of structural weakening of the rock mass, which is determined by one of the formulas given in the paper [10]; K_u is the empirical coefficient of rock compaction under the action of rock pressure [28], which is determined by the formula given in the paper [10].

In order to confirm the reliability of the obtained analytical models for calculating the radii of crumpling, intensive fragmentation and fracturing zones, numerical simulation was carried out using the

Table 2. Results of numerical simulation of rock mass destruction.

Compressive strength limit of rocks, MPa		
60	120	180
Representation of the principal compressive tension σ_3		
		
Display of principal tensile tension σ_1		
		

finite element method using the licensed software product of the SolidWorks Simulation engineering analysis system. For the numerical finite-element analysis of the mass destruction model around the charging cavity, the initial data were generated: geometric dimensions of the model, average values of physical and mechanical properties of rocks for all iron ore mines of Ukraine, and limit loads according to rigid conditions [29]. Computational experiments were carried out for rock compressive strength limits of 40–200 MPa, charging cavity diameters of 0.04–0.12 m, and explosion pressures of 1000, 1500, and 2000 MPa. The stiffness of the boundary conditions is given, taking into account the dynamic action of the explosion and the main provisions of resistance of materials [30], energy theory [31] and work [32]. As an example, the display of the main compressive tension σ_3 and tensile tension σ_1 of the model for rocks with a compressive strength of 60, 120, and 180 MPa, with a charging cavity diameter of 0.04 m and a pressure of the explosion products of 1000 MPa, which is given in Table 2, is considered.

According to the results of model measurements at a pressure of the explosion products of 1500 MPa, graphs were obtained (Fig. 2).

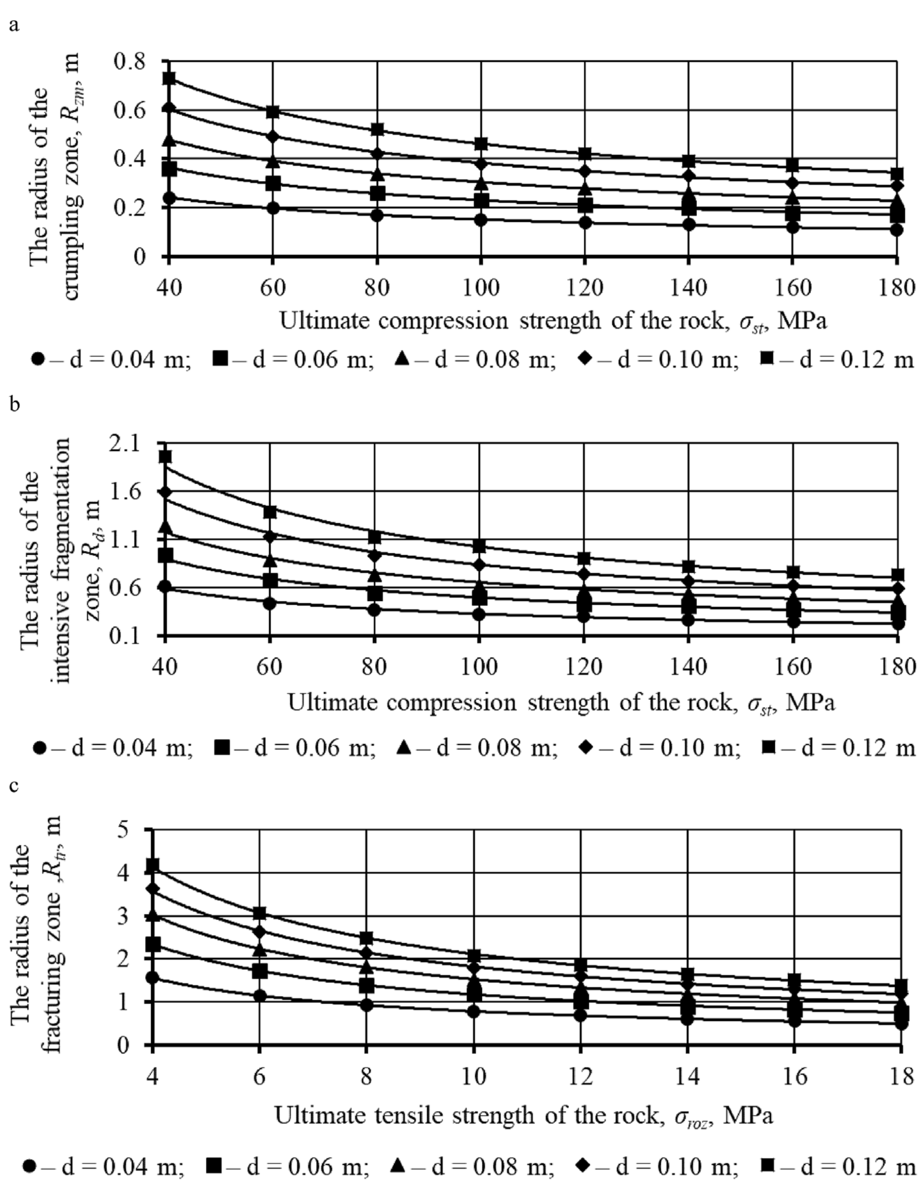


Fig. 2. Graphs of the dependence of the radius of the crumpling zone (a), intensefragmentation (b) and fracturing (c) from the tensile-compressive strength limit of rocks and the diameter of the charging cavity at a pressure of the explosion products of 1500 MPa.

Regression analysis established power-law dependences of zone radii changes.

− crumpling

$$R_{zm} = 0.372 \cdot d \cdot \rho^{0.499} \cdot D^{0.998} \cdot \sigma_{st}^{-0.501} \cdot K_{dz}^{0.499}, \mathrm{m} \tag{13}$$

− intensive fragmentation

$$R_{d} = 0.424 \cdot d \cdot \rho^{0.648} \cdot D^{1.296} \cdot \sigma_{st}^{-0.651} \cdot K_{dz}^{0.648}, \mathrm{m} \tag{14}$$

− fracturing

$$R_{tr} = 0.036 \cdot d \cdot \rho^{0.743} \cdot D^{1.486} \cdot \sigma_{st}^{0.747} \cdot \tau_{z}^{-1.494} \cdot K_{dz}^{0.743}, \mathrm{m} \tag{15}$$

By comparing the results of analytical evaluations with the results of numerical modelling, the discrepancy between the parameters of the zones of crumpling, intensive fragmentation and fracturing was established 4, 8 and 6%, respectively. This indicates the high reliability of the obtained results and the suitability of formulas (10)−(12) for determining the radii of the indicated zones, which improve the calculation of drill-blasting parameters during mining [27], special-purpose cavities [33] and ore rock mass cutting [34].

4. Conclusions

The analysis of ideas about the mechanism of the destruction of a rock mass by an explosion, as well as the theories of the formation of the radii of the zones that are formed around the charging cavity under the action of the explosion established that research tends to consider the physical mechanism of only two zones, crumpling and fracturing. The transitional zone of intensive fragmentation, within which the effect of the pressure of the explosion products continues, is not detailed. By analysing the deformation of rocks around the charging cavity from the point of view of the scheme and the criterion of the destruction of the medium, the zones formed around the charging cavity were detailed. These are zones of crumpling, intensive fragmentation, fracturing and shaking.

Analytical modelling of the mechanism of the formation of zones of crumpling and fracturing of the rock mass around the charging cavity under the action of the explosion obtained analytical models of the radii of the zones of crumpling, intensive fragmentation, fracturing, which are formed around the charging cavity in the mass of rocks during its explosive loading, taking into account the pressure of the explosion products, the strength of the rocks on stretching-compression, their structural composition, crumpling, intensive fragmentation, fracturing and compaction under the influence of rock pressure.

Numerical modelling of the destruction of rocks around the charging cavity, using the finite element method, established the power-law dependence of the change in the radii of the crumpling and fracturing zones depending on the diameter of the charging cavity, the pressure of the explosion products, and the compressive strength limit of the rocks. By comparing the results of analytical estimates of the radii of the crumpling, intensive fragmentation, and fracturing zones with the results of numerical modelling for hard boundary conditions, the difference in the values of the radii of these zones was established as 4, 8 and 6%, respectively. This indicates the high reliability of the obtained results and the suitability of the obtained analytical models for calculating the radii of these zones.

Author contributions

Conceptualization: M.K., O.K., I.S., V.S., Y.*P. and* A.S. methodology: M.K., O.K., I.S., V.S., Y.*P. and* A.S.; validation M.K., O.K., I.S., V.S., Y.P.; formal analysis, M.K., O.K., I.S., V.S., Y.P.; investigation: M.K., O.K., I.S., V.S., Y.P.; writing-original draft preparation, M.K., O.K., I.S., V.S., Y.P.; writing-review and editing: M.K., O.K., I.S., V.S., Y.P.; visualization, M.K., O.K., I.S., V.S., Y.P.; supervision, A.S.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

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Conflict of interest

The authors declare no conflict of interest.

References

[1] Kononenko M, Khomenko O, Kovalenko I, Savchenko M. Control of density and velocity of emulsion explosives detonation for ore breaking. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 2021;(2):69−75. https://doi.org/10.33271/nvngu/2021-2/069.
[2] Khomenko O, Kononenko M, Myronova I, Savchenko M. Application of the emulsion explosives in the tunnels construction. E3S Web of Conferences 2019;123:01039. https://doi.org/10.1051/e3sconf/201912301039.
[3] Krysin RS, Ishchenko NI, Klimenko VA, Piven VA, Kuprin VP. Explosive ukranit-PM-1: equipment and fabrication technology. Gornyi Zhurnal 2004;(8):32−7.
[4] Kholodenko T, Ustimenko Y, Pidkamenna L, Pavlychenko A. Ecological safety of emulsion explosives use at mining

enterprises. Progressive Technologies of Coal, Coalbed Methane, and Ores Mining 2014:255–60. https://doi.org/10.1201/b17547-45.

[5] Myronova I. Prediction of contamination level of the atmosphere at influence zone of iron-ore mine. Mining of Mineral Deposits 2016;10(2):64–71. https://doi.org/10.15407/mining10.02.0064.

[6] Kononenko M, Khomenko O, Myronova I, Kovalenko I. Economic and environmental aspects of using mining equipment and emulsion explosives for ore mining. Mining Machines 2022;40(2):88–97. https://doi.org/10.32056/KOMAG2022.2.4.

[7] Myronova I. The level of atmospheric pollution around the iron-ore mine. New Developments In Mining Engineering 2015;2015:193–7. https://doi.org/10.1201/b19901-35.

[8] Viktorov SD, Kazakov NN, Shlyapin AV, Lapikov IN. The impact of the explosion of a borehole charge on the granulometric composition in the upper area of unregulated crushing. Sustainable Development of Mountain Territories 2016;8(2):161–70. https://doi.org/10.21177/1998-4502-2016-8-2-161-170.

[9] Komir VM, Vorob'ev VV. Mechanism of explosive shattering of solid bodies and method of improving its efficiency. Sov Min Sci 1989;25(6):517–9. https://doi.org/10.1007/bf02528301.

[10] Kononenko M, Khomenko O. New theory for the rock mass destruction by blasting. Mining of Mineral Deposits 2021; 15(2):111–23. https://doi.org/10.33271/mining15.02.111.

[11] Dubinski J, Jura B, Janoszek T, Makówka J, Skiba J, Hildebrandt R, et al. In-situ experimental study on hydro borehole technology application to improve the hard coal excavating techniques in coal mine. Sci Rep 2023;13(1):1190. https://doi.org/10.1038/s41598-023-28501-7.

[12] Wang K, Zhang X, Du F, Li K, Sun J, Wang Y. Numerical study on damage response and failure mechanism of gas-containing coal-rock combination under confining pressure effect. Fuel 2023;(341):128683. https://doi.org/10.1016/j.fuel.2023.128683.

[13] Smolinski A, Wojtacha-Rychter K, Król M, Magdziarczyk M, Polański J, Howaniec N. Co-gasification of waste-derived-fuel and bituminous coal with oxygen/steam blend to hydrogen rich gas. Part A Energy 2022;254:124210. https://doi.org/10.1016/j.energy.2022.124210.

[14] Kuzmenko O, Dychkovskyi R, Petlovanyi M, Buketov V, Howaniec N, Smolinski A. Mechanism of interaction of backfill mixtures with natural rock fractures within the zone of their intense manifestation while developing steep ore deposits. Sustainability 2023;15(6):4889. https://doi.org/10.3390/su15064889.

[15] Mutke G, Dubiński J, Lurka A. New criteria to assess seismic and rock burst hazard in coal mines. Arch Min Sci 2015;3. https://doi.org/10.1515/amsc-2015-0049.

[16] Cioca IL, Moraru RI. Explosion and/or fire risk assessment methodology: a common approach, structured for underground coalmine environments. Arch Min Sci 2012;1. https://doi.org/10.2478/v10267-012-0004-7.

[17] Esen S, Onederra I, Bilgin HA. Modelling the size of the crushed zone around a blasthole. Int J Rock Mech Min Sci 2003;(40): 485–95. https://doi.org/10.1016/s1365-1609(03)00018-2.

[18] Torbica S, Lapcevic V. Rock breakage by explosives. European Int J Sci Technol 2014;3(2):96–104.

[19] Danilenko VV. Vzryv: fizika, tekhnika, tekhnologiya784. Moskva: Energoatomizdat; 2010. p. 121–8.

[20] Sobolev VV, Kulivar VV, Kyrychenko OL, Kurliak AV, Balakin OO. Evaluation of blast wave parameters within the near-explosion zone in the process of rock breaking with borehole charges. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 2020;(2):47–52. https://doi.org/10.33271/nvngu/2020-2/047.

[21] Andrievskij AP, Kutuzov BN, Matveev PE, Nikolaev YuI. On the crush zone formation in a rock massif under its blasting loading by column charges. Fiziko-Tehnicheskiye Probl Razrab Polezn Iskopayemykh 1997;1:39–44.

[22] Mosinets VN, Gorbacheva NP. A seismological method of determining the parameters of the zones of deformation of rock by blasting. Sov Min Sci 1972;8(6):640–7. https://doi.org/10.1007/bf02497586.

[23] Persson PA, Holmberg R, Lee J. Rock blasting and explosives engineering. Boca Raton, Fla: CRC Press; 1993. p. 560.

[24] Torbica S, Lapčević V. Estimating extent and properties of blast-damaged zone around underground excavations. Rem 2015;68(4):441–53. https://doi.org/10.1590/0370-44672015680062.

[25] Fesik SP. Spravochnik po soprotivleniyu materialov. Kiev: Budivel'nik; 1982. p. 280.

[26] Andrievskii AP, Kutuzov BN, Matveev PF, Nikolaev YI. Formation of the blast crater in a rock mass blast-loaded by column charges. J Min Sci 1996;32(5):390–4. https://doi.org/10.1007/bf02046160.

[27] Kononenko M, Khomenko O, Savchenko M, Kovalenko I. Method for calculation of drilling-and-blasting operations parameters for emulsion explosives. Mining Of Mineral Deposits 2019;13(3):22–30. https://doi.org/10.33271/mining13.03.022.

[28] Khomenko O, Kononenko M. Geo-energetics of Ukrainian crystalline shield. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 2019;(3):12–21. https://doi.org/10.29202/nvngu/2019-3/3.

[29] Dychkovskyi RO. Forming the bilayer artificially created shell of georeactor in underground coal well gasification. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 2015;5:37–42.

[30] Belyaev NM. Soprotivlenie materialov. Moskva: Fizmatgiz; 1962. p. 856.

[31] Anistratov YuI. Energeticheskaya teoriya rascheta tekhnologii otkrytykh gornykh rabot. Gornyy informatsionno-analiticheskiy byulleten 1996;(3):20–9.

[32] Pokrovskiy GI. Vzryv. Moskva: Nedra; 1980. p. 190.

[33] Falshtynskyi V, Dychkovskyi R, Khomenko O, Kononenko M. On the formation of a mine-based energy resource complex. E3S Web of Conferences 2020;201:01020. https://doi.org/10.1051/e3sconf/202020101020.

[34] Fedko MB, Muzyka IO, Pysmennyi SV, Kalinichenko OV. Determination of drilling and blasting parameters considering the stress-strain state of rock ores. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 2019;(1):37–41. https://doi.org/10.29202/nvngu/2019-1/20.