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Sustainable management of iron ore extraction processes using methods of borehole hydro technology

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Abstract: The development of rich iron ore deposits in the Kryvyi Rih Basin is carried out by underground methods at considerable depths. This mining method is characterised by high labour, capital and operating costs. In the paper, the experimental research on the establishment of rational parameters of borehole hydrotechnology for the sustainable management of iron ore extraction processes of martite ore deposits at considerable depths. Based on the experimental studies, mathematical expressions have been derived to calculate the rational parameters for borehole disintegration of martite ore masses using rotating water jets. Dependencies between the structural and morphological characteristics and the fracturing of martite ores, as well as the parameters of influence of water control, were identified. It was found that the use of borehole hydrotechnology ensures selective exposure of ore-forming minerals. As a result, the ore quality is improved and the silica mass fraction is reduced, which enables the production of the highest quality iron ore raw materials – superconcentrates. In addition, this technology is a combined ore preparation process that includes beneficiation, grinding, and classification of destruction products based on their particle size composition during their washing.

Keywords: axial pressure; borehole hydro-technology; enrichment; rich iron ores; rotating water jet; sustainable management; water monitor.

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1 Introduction

The economic potential of Ukraine's mining and metallurgical complex largely depends on the current state and prospects for sustainable development and transformative trends in the raw material base, equipment, and technology for extracting rich iron ores (Pysmennyi et al., 2020). Simultaneously, it has been established that nearly 80% of all explored iron-rich reserves are situated within the Ukrainian shield (Khomenko and Kononenko, 2019), specifically within the Kryvyi Rih iron ore basin (Kryvbas) (Smirnov et al., 2014). These reserves are developed using the gross underground method (Pysmennyi et al., 2022), reaching depths of 1,100 m–1,300 m (Pysmennyi et al., 2020), and employing various iterations of underground collapse systems (Kosenko, 2021). For the destruction of the ore massif, blasting (Kononenko and Khomenko, 2021) with fans of deep boreholes of different orientations (Kononenko et al., 2021) and planar undosed release of the ore mass through funnels (Pysmennyi et al., 2018) is used.

At the same time, approximately 51% of rich iron ore deposits have a uniaxial compressive strength of less than 40 MPa, 32% range between 40–60 MPa, 13% lie within the 60–80 MPa range, and a mere 4% exceed 80 MPa (Kononenko et al., 2022). In addition, it is known that 20 to 30% of the balance reserves of high-quality pure martite ores lie in the depths of Kryvbas (Tarasyutin, 2015). This creates extremely promising conditions for the organisation of extraction and production of high-quality iron ore concentrates ($\text{Fe} = 67\text{--}70\%$, $\text{SiO}_2 = 2.5\text{--}0.15\%$) (Tarasyutin, 2015). The resultant concentrates find application in producing of universally-utilised iron powders employed in electric steel smelting, powder metallurgy, and ferrite metallurgy (Yang et al., 2022). However, the structural and mineralogical attributes of high-quality martite ores do not allow for their effective preparation to beneficiation processes via physical methods

based on ore blasting (Khomenko et al., 2013) and mechanical grinding (Zhang et al., 2022).

Thus, with the transition of mining operations to deeper mine horizons (1,200 m–1,500 m), the problem of expanding the range of iron ore products are becoming more important and urgent (Tarasyutin, 2015). Achieving this necessitates enhancing the quality of extracted ore mass without escalating quantitative losses and costs (Nunna et al., 2021). Non-traditional mining geotechnologies (Zhang and Wang, 2023) present a viable approach to address this issue. Borehole hydrotechnology (Rochev, 2018) is one such technology, benefiting from the favourable low strength and stability of iron ore masses in the deep Kryvbas horizons (Tarasyutin, 2015). Notably, the implementation of a high-pressure water jet for rock mass destruction is perspective method.

Sustainable mining is founded on the report of the UN World Commission on Environment and Development (Zhuang et al., 2023), which asserts that sustainable development aims to fulfil present needs without constraining opportunities for future generations to satisfy their own needs. This entails technological advancement and conscientious management of environmental, social, and economic concerns (Ali et al., 2022; Miranda and Gorman, 2018; Polyanska et al., 2024). For mining organisations, it also places emphasis on worker and community safety.

The sustainable management of mining involves the implementation of tactics aimed at reducing the environmental effects of mining. This includes the evaluation, tracking, and improvement of various environmental performance indicators (Miranda and Gorman, 2018; Khomenko, 2012). It pertains to the conscientious extraction of mineral resources with minimal environmental impact, as well as the promotion of social advantages and long-term economic sustainability (Pazynich et al., 2023). It involves integrating environmental, social, and economic considerations into mining practices to meet current needs without compromising the ability of future generations to meet their own needs (Malec et al., 2023; Pylypenko et al., 2023). Key aspects of sustainable mining management include:

- Minimising the environmental footprint of mining operations through practices like land reclamation, water conservation, reduced emissions, and proper waste management (Pylypenko et al., 2023; Wodołański et al., 2023). This involves using innovative technologies and best practices to minimise ecological impacts (Falshtynskyi et al., 2020).
- Engaging with local communities, indigenous groups, and stakeholders to ensure their concerns are heard and addressing social impacts, such as creating local job opportunities, respecting human rights, and fostering community development (Pylypenko et al., 2023; Wojtacha-Rychter et al., 2022).
- Emphasising efficient use of resources, reducing energy consumption, and promoting recycling and reuse to minimise waste and lessen the need for additional extraction (Falshtynskyi et al., 2020; Vladyko et al., 2022).
- Adherence to strict regulatory standards and ethical practices, ensuring that mining operations comply with environmental regulations, labour laws, and safety standards (Nikolsky et al., 2022). Embracing innovation and technological advancements to improve mining processes, reduce environmental impact, and enhance safety measures (Savchuk et al., 2022).

- Developing long-term strategies and comprehensive risk management plans to anticipate and mitigate potential environmental, social, and economic risks associated with mining activities (Siudyga et al., 2023).

Sustainable management in mining recognises the necessity of mining for economic development while ensuring that it is conducted in a manner that safeguards the environment, respects communities, and contributes positively to society in the long run (Dyczko, 2023; Dychkovskiy et al., 2013). So, it is necessary for mining companies often to employ various frameworks, certifications, and initiatives such as the International Council on Mining and Metals (ICMM) principles (Henstock, 1996), the Global Reporting Initiative (GRI) standards (E-Vahdati and Aripin, 2023), the EITI (2013), and certification programs like the Initiative for Responsible Mining Assurance (IRMA) (Syverson and Mahoney, 2020) to guide and demonstrate their commitment to sustainable mining practices.

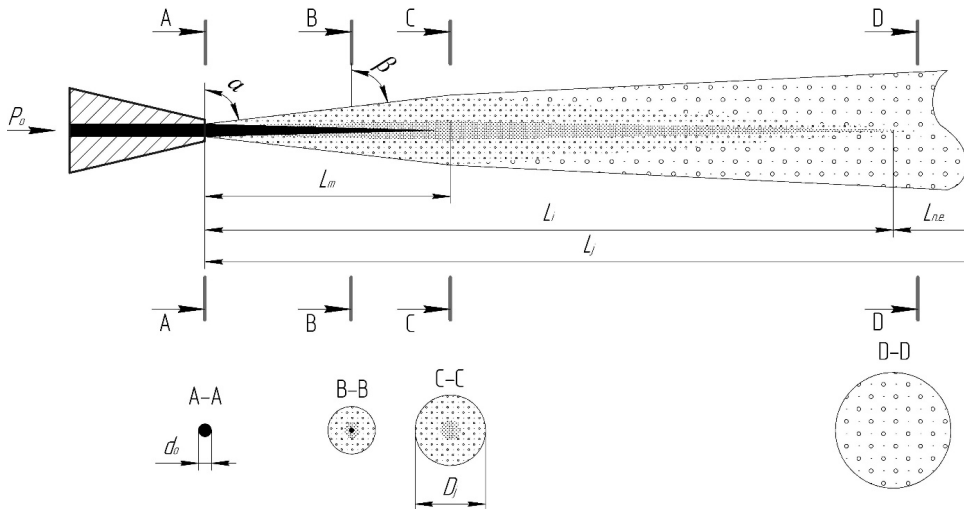
In the context of sustainable extraction, the importance of borehole hydrotechnology is growing (Felonenko and Trofymova, 2023). By using this method, the process of explosively preparing minerals for transportation is eliminated, thus achieving sustainable development effects (Sobolev et al., 2020; Yang et al., 2022). It reduces dust and gas emissions inside the mine and into the surrounding atmosphere, thus eliminating hazardous work that harms people's health (Sobolev et al., 2020; Vladko et al., 2022). A prerequisite for employing borehole hydro technology for rock disintegration (Miranda and Gorman, 2018) lies in the necessity to produce jets possessing favourable hydrodynamic characteristics at the nozzle exit (Cano-Salinas et al., 2023).

The efficiency of the hydro disintegration process depends on various factors, including the physical and hydro-technological properties of the rocks, hydrodynamic characteristics, and the methodology of water jet impact on the rock mass (Yang et al., 2022). Understanding these dependencies is crucial as it influences the design and optimisation of the water jet systems used in rock disintegration. The physical properties of rocks, such as hardness, porosity, and fracture toughness, determine the amount of energy required for effective disintegration (Kononenko et al., 2024). The hydro-technological properties, including the pressure and flow rate of the water jet, need to be carefully controlled to achieve the desired impact. Furthermore, the hydrodynamic traits, such as the velocity and direction of the water jet, play a significant role in maximising the efficiency of the disintegration process (Kononenko et al., 2023). Properly assessing and adjusting these parameters based can lead to significant improvements in the efficiency and effectiveness of hydro disintegration, making it a valuable tool in mining and geological applications.

A universally acknowledged criterion for assessing jet hydrodynamic properties and its structure is the concept of a compact jet (Liu et al., 2023). Under this concept is understood a jet's capacity to retain its kinetic energy at a specific distance from the nozzle (Momber, 1998). In the process of comparing pressurised water jets, the general concept of jet compactness turns out to be insufficient (Franco-Medrano, 2015). This arises from the investigation of various factors influencing jet hydrodynamic properties and its effectiveness in distracting the mountain mass when one of the hydraulic or geometric parameters is employed for a specific judgement about jet properties and its structure (Franco-Medrano and Fukumoto, 2015). These parameters, dependent on research conditions and available resources (Franco-Medrano et al., 2017; Bondarenko et al., 2007), are: the conicity of the jet's outer boundaries, determined by corresponding

angles (α, β) and depends on axial pressure (P_o) and nozzle exit diameter (d_o); the initial section length of the jet, wherein axial dynamic pressure (P_M) remains constant and equal to the initial value; jet impact force on outcrop of the hole at a specific distance from the nozzle (or the curve depicting the variation of jet impact force based on distance); the distribution diagram of axial (P_M) and average (P_c) dynamic pressures along the jet's length; cross-sectional profile of the jet at a certain distance from the nozzle. These enumerated jet parameters possess specific functional interdependencies and collectively characterise the jet compactness, either through simultaneous consideration or individual parameter assessment (Franco-Medrano et al., 2017). Figure 1 illustrates the water jet diagram exiting the nozzle, accompanied by key technological parameters.

Figure 1 Scheme of a water jet: P_o – axial pressure of the jet; d_o – initial nozzle diameter; D_j – the diameter of the jet moving along the outcrop of the hole; L_j – the length of the jet; L_m – the initial section of the jet; L_i – the main section of the jet; $L_{n.e.}$ – ineffective section of the jet; α, β – the angles of the outer boundaries of the jet



A structurally stationary water jet emerging from the hydro monitor nozzle into the air environment can be divided into three sections (Figure 1) (Franco-Medrano et al., 2017; Kwon et al., 2016): the initial section (L_m), characterised by a dense axial core where the velocity (v_c) and axial dynamic pressure (P_M) of the water remain constant and equal to the speed (v_o) and dynamic departure of the jet from the nozzle; the main section (L_j), in which the jet possesses a relatively dense central zone, but is already saturated with air bubbles near the surface boundaries that includes the working length of the jet (L_w), which is responsible for rock mass distraction; the ineffective area ($L_{n.e.}$) consisting of elementary jets and water droplets that move through the air at a progressively decreasing speed.

With help of summarising the experimental data, it was found that the most suitable hydrodynamic characteristic for describing jet compactness is the axial dynamic pressure (P_M), which has a close relationship with other characteristics. In general, the axial dynamic pressure of a jet (P_M) emerging from a nozzle of a given shape and size, under constant water flow conditions, depends on the average jet speed in the initial section

(v_o), the nozzle diameter (d_o), distance from the nozzle (L), water density (ρ), viscosity (μ), and surface water tension (δ) (Franco-Medrano et al., 2017).

Meanwhile, research on borehole hydro technology for the development of rich iron ore deposits has only been conducted under the conditions of the Veliko-Troitsky deposit within the Kursk magnetic anomaly (Miranda and Gorman, 2018). In this location, deposits are developed using pressurised water jets in challenging hydrogeological conditions (Miranda and Gorman, 2018). The primary challenges are linked to imperfect management processes and a lack of proper scientific substantiation for the rational parameters of borehole hydro technology (Miranda and Gorman, 2018). Hence, it is crucial to examine the qualities of compact jets generated by borehole hydro monitors and devise approaches for determining their properties in the context of hydro-dissolution of substantial quantities of martite ores. This research is aimed at conducting experimental investigations to determine the appropriate parameters for borehole hydrotechnology, in order to ensure the efficient extraction of iron ore from martite deposits located at significant depths.

2 Materials and methods

The general research method involved the phased implementation of mine experiments to destroy a mass of martite ores using a rotating stream of water through a hydro monitor nozzle. Fractal analysis of statistical data, which is based on performance metrics for evaluating the accuracy of predictive models, is often used to assess the variability of fluid parameters with changes in temperature (Yitayew and Melesse, 2011; Gonfa et al., 2022; Lemann et al., 2016). In our case, at each stage of the work, the following steps were undertaken: analysis of the engineering and geological context of ore deposits and the selection of test sections; development of technological schemes for ore hydro disintegration and creation of suitable experimental equipment; selection of means to ensure hydro-mining operations; identification of methods for controlling and measuring hydro disintegration process parameters; generalisation and analysis of experimental results, culminating in recommendations for technology and equipment creation based on the achieved outcomes.

To achieve the research goal, calculations were made for each stage of the study, particularly:

- 1 The experimental process of hydro monitor destruction of high-quality loosely-bound martite ores was determined in condition of the 950–1,240 m horizons of the Yuvileyna mine of Sukha Balka PrJSC and the Kryvorizka mine of Kryvorizk Iron Ore Combine JSC (Tarasyutin, 2015). A correlation has been established between the strength limit of ores under uniaxial compression and their porosity (Tarasyutin, 2015):

$$\sigma_c = \sigma_c^o \cdot (1 - \eta) \cdot e^{-\eta}, \text{ m} \quad (1)$$

where $\sigma_c^o = 180\text{--}230$ strength limit for uniaxial compression of oxidised quartzite samples similar in genesis, composition, and structure to porous martite ores, MPa;
 η – total porosity of ore samples, units.

- 2 Indicators of hydromonitor disintegration are characterised by several hydrodynamic indicators, including the integral parameter of jet compactness. That is, the length of its initial section (L_m), at which the axial dynamic pressure (P_M) is equal to the axial pressure (P_o) of the water at the exit from the jet-forming nozzle.
- 3 The parameters of water jets were set for six types of jet-forming nozzles with a diameter of 3.0–12 mm of conical-cylindrical shape (H1–H6). The ratio of the length of the cylindrical part to the initial diameter of the nozzle is 4. This type of nozzles (Nikonov-Shavlovsky) provides jets with the most optimal hydrodynamic characteristics.

In the process of studying the parameters of water jets, depending on the diameter and type of the jet-forming nozzle, the following were recorded: axial pressure of water at the exit of the nozzle (P_o); the length of the initial section of the jet (L_m), when the nozzle is located on a straight section of the pipe ($L_m(r)$), also on the side (at an angle of 90°) ($L_m(s)$); the diameter of the jet moving along the outcrop of the hole (D_j); the working length of the jet (L_w) (the distance from the nozzle at which the rock mass destruction is carried out). The water pressure P_o of each nozzle diameter was recorded with a manometer, and the average values of the geometric parameters were measured using a scale grid (Figure 4). At the same time, the experimentally established fact of a noticeable expansion of the diameter of the jet along the length of the initial section to the transition section, which separates the initial section from the main section, was used.

- 4 Based on the generalisation of experimental data, the authors obtained the dependence of the length of the initial section of jets on influencing factors:

$$L_m(A - B \operatorname{Re}) \cdot d_o, \text{ m} \quad (2)$$

where d_o – the diameter of the jet-forming exit nozzle, m ; A and B – respectively, empirical coefficients that depend on the type and quality of nozzle manufacturing, as well as the design of the hydro monitor; Re – the Reynolds number:

$$\operatorname{Re} = \frac{V_o \cdot d_o}{\nu} \quad (3)$$

where ν – the kinematic viscosity of the liquid, m^2/s ; V_o – the initial speed of jet departure from the nozzle, m/s :

$$V_o = 42\sqrt{P_o}, \quad (4)$$

where R_o – the axial pressure of the jet at the exit from the jet-forming nozzle, MPa .

For borehole hydro monitors, when $d_o = (5\text{--}15) \cdot 10^{-3} \text{ m}$ and $P_o = 1\text{--}8 \text{ MPa}$, the coefficients of A and B take the values of $80\text{--}100$ and $(45\text{--}50) \cdot 10^{-6}$, respectively.

The nature of the P_M parameter change outside the L_m section is generally determined from the ratio, MPa :

$$P_M = P_o \left(\frac{L_m}{L_w} \right)^k \quad (5)$$

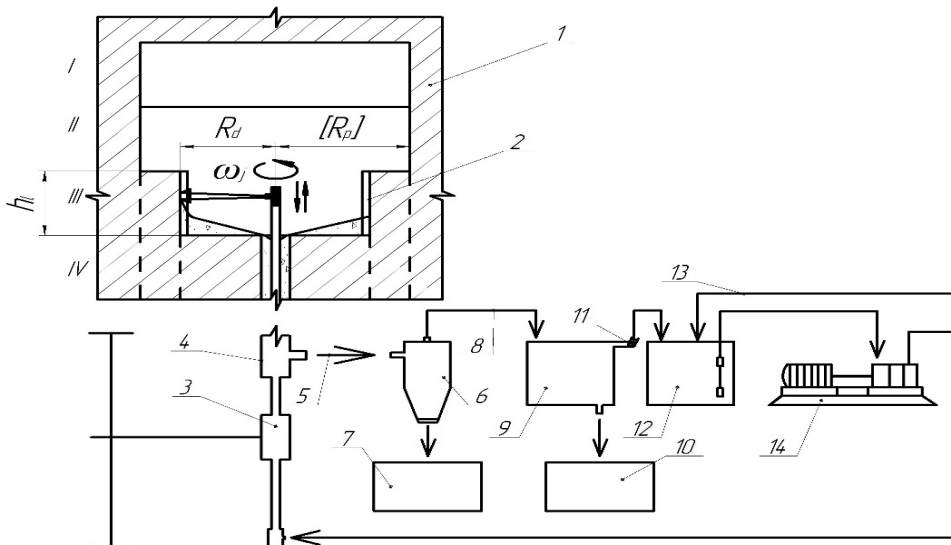
where k – an indicator that depends on the axial pressure, type and quality of nozzle manufacturing, $k = 1$ is taken; L_w – the length of the working section of the jet, m :

$$L_w \leq 6L_m, m \quad (6)$$

3 Results and discussion

Schematically, the hydro monitoring disintegration of an ore massif by rotating water jets through borehole (Figure 2) is a non-stationary process that depends on hydrodynamic parameters that constantly change along the length of the jet, the size of the formed cleaning spaces, the method of applying the jet to the outcrop of the hole, and the geological and technological characteristics of the ore massif.

Figure 2 Technological scheme of the chain and equipment of the modular complex of the borehole hydromonitoring disintegration of martite ores by a rotating water jet: R_d – radius of destruction of the massif; $[R_p]$ – the design radius of the cavity; h_1 – the height of the reflected ore layer; ω_j – the angular speed of jet movement along the exposure of the hole; I, II, III, IV – cavity formation intervals of 1 m; 1 – ore massif; 2 – outcrope of the hole; 3 – hydromonitoring aggregate; 4 – delivery borehole; 5 – pulp pipe; 6 – battery of hydrocyclones; 7 – superconcentrate container; 8 – sludge disposal; 9 – sludge remover; 10 – sediment concentrate container; 11 – pumping pump; 12 – capacity for process water; 13 – technical water pipeline; 14 – high-pressure pump with an electric motor



The tunnelling equipment complex of borehole hydrotechnology includes a borehole hydromonitor consisting of a control installation, drill rods, a head with a jet-forming nozzle and a preventer. The NKR-100MPA or KBU-1 drilling rig is used as a control hydromonitoring installation. It allows drilling boreholes and moving the hydromonitoring jet of water at a given speed along the borehole or with a given interval and rotation around its axis. The dimensions and weight of the aggregation allow the easy movement of the hydromonitor to any place. The length of boreholes can reach 40 m, and

the diameter – 105 mm–130 mm. A quasi-cylindrical cavity is formed from the hole to the head of the borehole with an interval of 1 m.

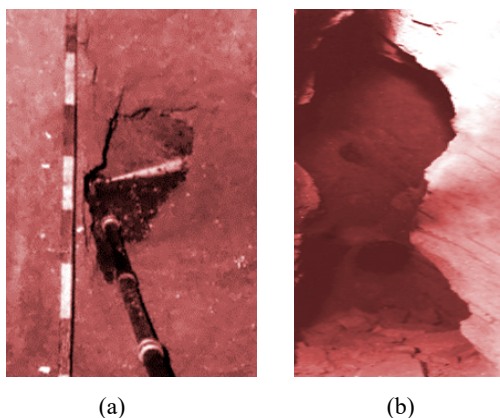
Delivery of the hydraulic mixture is carried out under the force of its own weight through the annular space of the technological borehole. Next, through the pulp pipe installed at the head of the borehole, along the pipes to the place of thickening in the delivery production. The hydraulic mixture delivery system consists of a preventer fixed at the wellhead, which is a metal pipe 2 m long and 100–150 mm in diameter with a flange seal and a lateral drainage of the hydraulic mixture, as well as a pulp pipe. The pulp pipe is a polyethylene pipe with a diameter of 150 mm, which ends with a flexible unloading device with a limiter that extinguishes the pulp flow rate.

The node for loading and dewatering the pulp consists of unified receiving and transport containers placed on the platforms of the VG-4 wagon, which are connected to each other by removable overflows.

The dewatering block consists of a battery of HYD-15 hydrocyclones, which process up to 70 m³/h of water mixture to a moisture level of 25%–30%, a system of pipelines, a reservoir-illuminator (chamber of the pumping station). The process water preparation block includes a pumping station with a set of pipelines, control, measuring and shut-off and regulating equipment as well as a centrifugal high-pressure pump ‘Sunflo’ P2000 with operating parameters: water supply – 41 m³/h, water pressure – 7–8 MPa, electric motor power –45 kW.

The borehole hydromonitoring aggregation can be located both in the lower and in the upper part of the future extraction. Photos of the process of formation of separate and united cavities in the martite ore massif during its disintegration by the borehole hydromonitor are presented in Figure 3.

Figure 3 Photographs of the process of formation of separated (a), united (b) cavities in the massif of martite ores during its borehole hydromonitor disintegration (see online version for colours)



During research, it was found that the lateral location of the nozzle significantly worsens the compactness of the jet, reduces the length of its initial section, increases the diameter, and accelerates the disintegration into separate parts.

The geometric characteristics of nozzles of various diameters and types that were tested (H1–H6) and the main parameters of the jets that were measured during experimental research are given in Table 1.

Analysis and processing of the obtained experimental data given in Table 1, made it possible to establish that for borehole hydro monitors with a lateral location of the nozzle, the empirical coefficient A, depending on the characteristics of the nozzle (shape, size, cleanliness of the internal surface), and not on the hydro monitor, changes in the range of 60–100. Meanwhile, the empirical coefficient B, depending on the hydraulic attributes of the hydro monitor – namely its type – varies within the range of $(45\text{--}50)10^{-6}$. The lowest values of A and the higher values of B are related to thin jets ($d_o = 3.0\text{--}3.5\text{ mm}$), whereas larger values of A and smaller B values are associated with medium jets ($d_o = 10\text{--}12\text{ mm}$).

Table 1 Test results of jet-forming nozzles of borehole hydro monitors

Nozzle type	$d_o, \text{ mm}$	$P_o, \text{ MPa}$	$L_{m(r)}, \text{ m}$	$L_{m(s)}, \text{ m}$	$L_w, \text{ m}$	$D_j, \text{ m}$
H1	3.0	8	0.27	0.05	–	0.03
H2	3.5	4.5	0.31	0.07	–	0.05
H3	4.0	2.5	0.37	0.1	–	0.05
H4	4.5	1.5	0.42	0.12	–	0.05
H5	10	1.0	–	0.3	3.0	0.1
H5	10	1.8	–	0.3	2.8	0.1
H5	10	2.2	–	0.3	2.6	0.08
H6	12	1.0	–	0.5	3.4	0.1
H6	12	1.5	–	0.5	3.2	0.1
H6	12	2.0	–	0.45	3.0	0.09
H6	12	2.5	–	0.45	3.2	0.1

Considering that in the process of disintegration of the hydro monitor (with an increase in the created space) the axial dynamic pressure ($[P_M]$) naturally decreases beyond the initial section of the jet (L_m), it is necessary to establish a critical value of $[P_M]$ for each type or grade of ore. This critical value guarantees the termination of the decay process under any conditions.

Based on the established experimental data, dependencies of the axial dynamic pressure of the jet ($[P_M]$) relative to the length of its section (L) were derived. These relationships are depicted in Figures 4 and 5.

Based on the conducted research, the dependence of the critical value of the axial dynamic pressure $[P_M]$, passing through which the process of destruction stops under any conditions, on the strength limit of the ore for uniaxial compression was obtained:

$$[P_M] \leq 0.15\sigma_c, \text{ MPa} \quad (7)$$

Based on expressions (5) and (6), the limit value $[P_M]$ at the distance $[L_w]$ will be determined by the formula:

$$P_M = \frac{P_o \cdot L_m}{[L_w]} = \frac{P_o \cdot L_m}{6L_m} = \frac{P_o}{6} \approx 0.15P_o, \text{ MPa} \quad (8)$$

Then, considering the expression (7), the expression (8) will have the form:

$$[P_M] = 0.15P_o = 0.15\sigma_c, \text{ MPa} \quad (9)$$

or

$$[P_o] \approx \sigma_c, \text{ MPa} \quad (10)$$

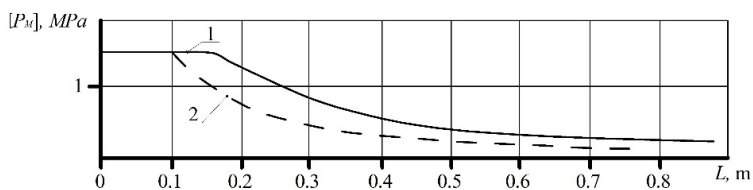
Thus, the jet pressure at the exit of the hydromonitor nozzle must be at least must not be less the limit of the compressive strength of martite ore, determined from dependence (1). Thus, when the strength limit for uniaxial compression is in the range from 0.1 to 7.0 MPa, it is necessary that the axial pressure is not less than 7.0 MPa.

The main design parameter is the length of the jet's working section ($[L_w]$), which is the limit for destructible rocks.

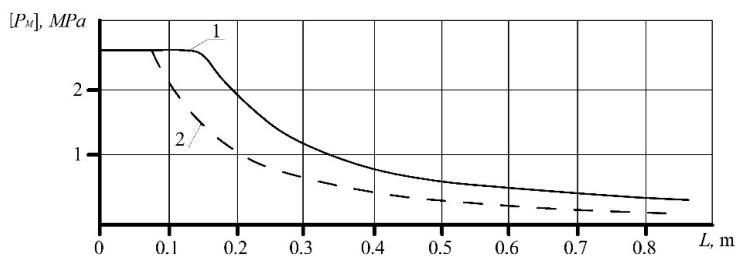
From expressions (8) and (9) we have:

$$[L_w] = \frac{P_o \cdot L_o}{0.15\sigma_c}, \text{ m} \quad (11)$$

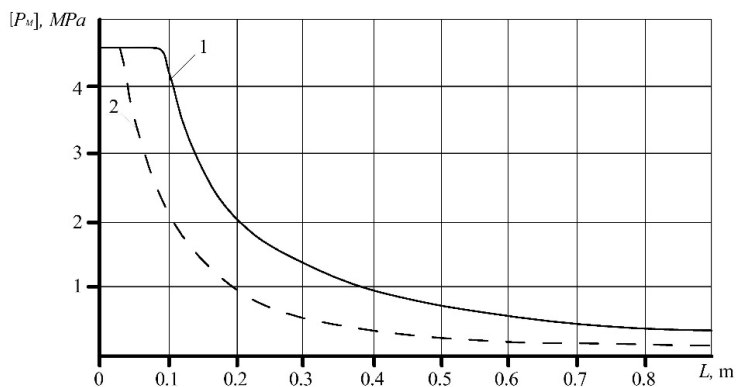
Figure 4 Graphs of the dependence of the axial dynamic pressure of thin water jets on their length: (a) $P_o = 1.5$ MPa, (b) $P_o = 2.5$ MPa, (c) $P_o = 4.5$ MPa; 1 – jet exit from the direct-flow nozzle; 2 – jet exit from the nozzle located on the side at an angle of 90°



(a)

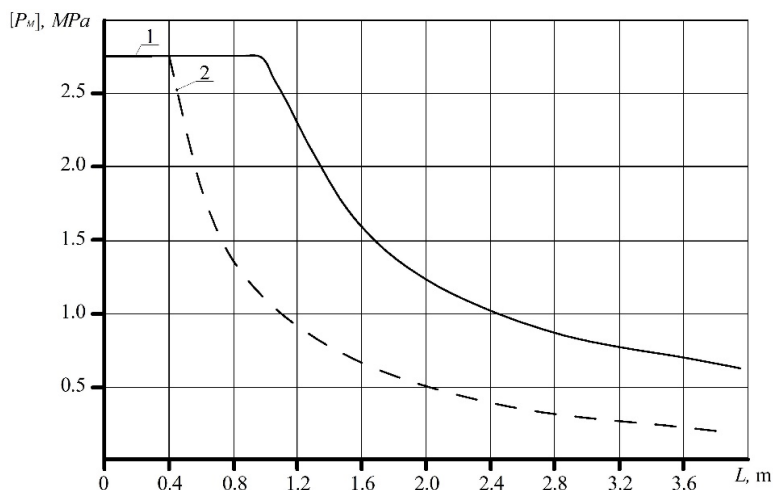


(b)



(c)

Figure 5 Graphs of the dependence of the axial dynamic pressure of the average diameter of the water jets on their length, when $P_o = 2.8$ MPa: 1 – jet exit from the direct-flow nozzle; 2 – jet exit from the nozzle located on the side at an angle of 90°



It has been established that for a given fractional composition of hydrodisintegration products, there is a corresponding limiting value of the specific impulse ($[I_M]$) of the axial dynamic pressure, which integrally reflects the structural-textural and mineralogical features of the ores, the geomechanical state of the ore massif, technologies, and parameters of the impact of the jet on the massif. The value of $[I_M]$, tailored to specific engineering and geological conditions, as well as a defined level of hydro disintegration, is determined experimentally.

- 1 The degree of disintegration (d_i) and the performance of ore destruction (Π) that are dependent on the velocity of water jet movement (v_j) along the outcrop of the hole that is, from the time of contact between the jet and the massif (t_k). For a water jet navigating a circular path within a borehole, situated at a certain distance from the nozzle (L), the velocity of water movement (v_j) within the dense axial core of the jet is as follows:

$$v_j = 2\pi \cdot L \cdot \omega_j, \text{ m/s} \quad (12)$$

where L – the distance from the nozzle to the outcrop of the hole, m ; ω_j – angular velocity of jet rotation around the axis of the pond of the borehole hydro monitor (revolutions/minute).

- 2 The contact time of the rotating jet with the massif (t_k) corresponds to the ratio (s):

$$t_k = \frac{D_a}{V_j} \quad (13)$$

where D_a – the average diameter of the destructive jet moving along the outcrop of the hole, m :

$$D_a = 10d_o, \quad (14)$$

- 3 The analysis showed that the process of disintegration of an ore mass by a rotating water jet is characterised by the specific impulse of its force dynamic pressure on the mass (I_M), which is determined by the formula:

$$I_M = P_M \cdot t_k, \text{ N/s} \quad (15)$$

or

$$I_M = \frac{P_M \cdot 5d_o}{L_M \cdot \pi \cdot \omega_c}, \text{ N/s} \quad (16)$$

where P_M – the axial dynamic pressure of the jet in contact with the outcrop of the hole, which must be greater than the critical value $[P_M]$, passing through which the destruction process stops under any conditions, MPa.

Considering expression (2), formula (16) will have the form (N/s):

$$I_M = \frac{K}{L_w^2 \omega_j} \quad (17)$$

where K – the coefficient characterising the standard size of the hydro monitor and is determined by the formula:

$$K = 1.59 P_o \cdot L_m \cdot d_o \quad (18)$$

It can be seen from expression (17) that the angular speed of rotation (ω_j) is the controlled parameter that ensures the specified mode of disintegration of the ore massif by borehole hydro monitors, under the conditions of the controlled initial section of the jet (L_m).

Considering the fact that for each standard size of the hydro monitor the parameters P_o , L_m , d_o have specific values and taking into account that the given fractional composition is controlled by a constant value $[I_M]$, expression (17) will be transformed into the form:

$$L_w^2 \cdot \omega_j = \frac{K}{[W]} = [W] \approx \text{const} \quad (19)$$

where $[W]$ – a value constant for specific conditions that integrally reflects the engineering and geological properties of the massif, the given degree of disintegration of the ore massif, the hydro monitor parameters, and the destruction technology:

$$[W] = \frac{P_o \cdot L_m \cdot d_o}{[I_M]} \quad (20)$$

In the general case, the performance (Π) of hydro monitor destruction of the ore layer for one revolution of the jet will be determined from the expression:

$$\Pi = 5,000 \frac{(P_o \cdot L_m)^{0.5} \cdot d_o \cdot \gamma}{L_w^{0.5} \cdot \omega_j}, \text{ t/rotation} \quad (21)$$

where γ – the volumetric weight of the ore, t/m³.

Achieving sustainable management of the iron mining process in Ukraine involves implementing various strategies and practices to minimise environmental impact and ensure the responsible use of resources. This article explores several technical solutions and considerations for achieving sustainability in iron mining.

4 Conclusions

Research and innovation are key instruments for uncovering new opportunities and identifying innovative technologies and methods to promote more sustainable iron mining processes. Specifically, the analysis of experimental studies on borehole hydro monitoring disintegration of martite ores demonstrates the potential and feasibility of its utilisation in the developing of new technologies for extracting ores with below-average strength. Borehole hydro technology can be employed for unmanned drilling of vertical isolated extractions and creating isolated quasi-cylindrical and combined chambers for diverse purposes.

As the research result of the technological process of hydro monitoring disintegration of high-quality low-strength iron ores through borehole, the following conclusions were drawn:

- Ore mass destruction by a rotating water jet occurs when the water pressure within the jet is 10–20% of strength limit on the uniaxial compression.
- Hydro monitor performance on ore, with a water jet pressure of 1.0–2.5 MPa, ranges from 9 to 25 t/h.
- Specific water consumption during hydro monitoring disintegration ranges from 0.7 to 2.5 m³/t or 2.7 to 9.6 m³/m³.
- Radii of cavities formed in massifs of martite ores with porosity of 20–35% and compressive strength limits of 5–10 MPa range from 1.6 m to 2.2 m.
- The hydraulic destruction of loose martite ores by 70%–90% is a process of selective hydro disintegration, occurring along the interphase boundaries of mineral grains and ore aggregates.
- Specific water consumption, effective radius of destruction, and fractional composition of the ore mass significantly depend on the orientation of the water jets relative to the ore mass stratification.
- Destruction along stratification reduces water consumption by nearly 2.5 times (to 0.7 m³/t), increases the destruction radius by 1.3–1.5 times, and enhances the outcomes of open ore classes by 5%–10%.
- An increase in the velocity of the jet along the outcrop of the hole (velocity of rotation of the jet around its axis) leads to an increase in the outcomes of small grain fractions and a decrease in the productivity of hydro distraction due to a decrease in the contact time of the jet with the massif and a decrease in the ability of the jet to penetrate the massif through structural disturbances (cracks, pores).

- Hydro disintegration efficiency increases more with larger nozzle diameters than with increased pressure, simplifying the system of process water preparation and supply to the hydro monitor.
- Effective hydro disintegration is achieved using a closed process water circulation system.
- Horizontal gravity delivery of ore pulp is 10 m–30 m.
- Parameters of the pressurised water jet (conicity, initial section length, dynamic pressure change) are determined by flow rate, water pressure, shape and dimensions of nozzle.
- The hydro monitoring head can be equipped with two nozzles to balance the reactive forces of the reactive reaction that rock the hydro monitor.
- Dewatering of the hydromix transfers the sludge part of the ore materials (hydro disintegration products) together with clay impurities, which significantly changes the properties of the ore mass on the alluvium map, bringing them closer to sands, sharply reducing agglomeration.
- Regulation of the impact of the hydro monitoring jet on the outcrop of the well allows for selective disintegration to obtain super concentrates with an iron content of 69.0%–69.5% for the homeless production of steels, leaving inter-ore schists and ferruginous quartzites in the subsoil, which form rock fragments.

Thus, the content of the hydraulic disintegration method in iron ore extraction is described in this article, the application of which offers advantages in achieving sustainable mining practices. Further research is aimed at investigating the effects of implementing the discussed method from the perspective of sustainable development.

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