Improvement of drilling efficiency in underground mines in Russia

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Abstract. Russian and foreign equipment and technologies of drilling are reviewed. The integrated assessment of blasthole drilling energy efficiency is carried out in terms of air-powered hammer P-160-5,5 SHV operation with drilling rig BP100P in a mine. Mechanical, run and volume velocities of drilling are determined using the data of video and acoustic processing of drilling process records. The cost of drilling is evaluated by the integral energy criterion of volumetric destruction of rocks. The analytical estimation of production rate is presented alongside with the methods of improvement. The reasons for the decline in the productivity of drilling operations in domestic mines have been established, and methods for improving it have been proposed. It is shown that energy efficiency and energy source cost should be use as the criteria when selecting drilling machines together with drilling productivity.

1. Introduction

In hard mineral mining, the bulk amount of drilling falls at blastholes which can reach tens and hundreds thousand meters of length annually in mines. In drilling in high-strength rocks, both surface and underground mines widely use rotary-percussive method and down-the-hole air hammers designed in Russia [1].

Methods of drilling in hard rocks with strength higher than 100 MPa feature flexibility in operation, which allows drilling of blast, production, drain, geological, degassing, construction and rescue holes. In drilling-and-blasting, diameters of full well bottom drilling may reach 100–254 mm to a length of 50 m in surface mines and 76–216 mm to a length of 150 m in underground mines. The drilling depth of geological and production wells has grown to 2000 m [2]. The leading role of pneumatic drilling over the other techniques was proved in San Jose mine in rescue of Chilean miners from the depth greater than 700 m [3].

Equipment and technology of rotary percussive drilling are steadily and rapidly developed all over the world. Such companies as Atlas Copco, Sandvic and other design new-generation drilling systems with three automation levels focused at determination of physical-mechanical properties and mineral composition of rocks, as well as air-powered hammers and rock-breaking tools adaptable to physical and mechanical properties of rocks. From 5 to 9 types of drill bits are available for the same size air hammer, etc. Of specific concern is sound power consumption of drilling and training of drilling rig operators to better understand mechanism of rock failure [4–8].

The situation is different in Russia. Series-produced air-powered drilling machines and tools for underground mines fall behind their foreign analogs by 30 years and more. In the meanwhile, the cost of
Blasthole drilling has risen 2.5 times for the recent 10 years, and productivity of drilling has dropped 1.5–2 times. Parameters set in the specifications of DTH air hammers differ from the factual performance by 30–50% in terms of capacity and 2–4 times in terms of life, and the cost of drill bit approaches the cost of air hammers due to the use of foreign-manufacture alloys. In drilling in rocks with strength of 140 MPa, domestic hammers powered by low-pressure compressed air (0.5–0.7 MPa), as compared with the foreign high-pressure air hammers (1.6–3 MPa), have 5–10 lower penetration rate, 15–30 shorter life and 10–50 shorter life of drill bits. For these reasons, the drilling rigs of domestic manufacture are gradually pushed by the import models [9, 10]. In connection with this, Russia calls for the integrated R&D projects targeted at improvement of energy efficiency of the pneumatic drilling in underground mining [11].

The problems of drilling productivity effective realization in Russian mines start with the absence of exact data on physical and mechanical properties of rock mass in current drill sites. The many years long experience gained by the members of the Institute of Mining, SB RAS in field works shows that geological exploration data used in open pit and underground mines date back from 20 to 45 years and often fall short of the actual data.

A detail geological characteristic of drilling layouts with mapped data on physical and mechanical properties of rocks in horizontal and vertical cross sections will bring drilling and blasting operations to the next quality level, will enable reasoned adaptation of machines and tools to specific rocks, as well as will assist in organization and evaluation of measures aimed at improvement of drilling efficiency.

Currently, an ample knowledge has been accumulated both on geological structure and physical–mechanical properties of rocks. At the same time, in view of a dim connection between innovations in geomechanics and management of optimization and risks in drilling, it is required to develop a strategy for implementing advanced methods and approaches in planning, design and upgrading of underground mines [12, 13]. Undoubtedly, such a strategy needs decision-making based on the knowledge geology and geomechanics. Model representation of a mineral deposit is a must [14, 15]. Furthermore, the level of safety should be sufficient to minimize all process and financial risks.

To date there are many efficient software packages (mostly, foreign design) on geological modeling and frame representation of mines. On the other hand, the interaction between a geological model and planning and optimization of drilling and blasting is scarcely studied thought there are certain approaches to its determination [16, 17]. The next stage of advancement in software should embrace geological and structural aspects based on analysis of mining geodesy information and drawing. These should be complete intelligence, including geographic location, topographical relief, morphology and lithology of rock mass, tectonics (tectonotype, faults, folds, etc.), jointing, fracturing (main systems of joints, dominant angles and azimuths of dip, jointing density, spacing and lengths).

Yet, availability of data on physical and mechanical properties of rocks is not always a guarantee of optimum drilling mode selected when there no specific recommendations in case of variable geological and geotechnical conditions. Figure 1 illustrates some of the typical problems in operation of foreign machines (Figure 1a) in Sheregesh mine, Gorno-Shorsky division of Evrazruda: oversizes (Figure 1b), excessive wear of expensive rock-breaking tools and deliverables (Figures 1c–1e). Operation of such equipment results in longer working shifts up to 10 hours, out of which 2–3 hours are taken to troubleshooting in drilling. An often cause of downtime is breaks of energy source feed lines when drilling rigs and load–haul–dumpers travel, which calls for extra measures to ensure occupational safety. Thus, selection of mining systems and equipment should be timely and duly preceded by sound feasibility study.

The energy efficiency of DTH air hammers should be evaluated starting with the hardest-to-drill rocks. A unique local reference of strength and abrasivity is often selected to be ore under mining. For geological composition of enclosing rocks is diverse, they should be divided into groups with quasi-uniform physical and mechanical properties. For example, the Irba iron ore field is composed of 17 types of ores and rocks (Figure 2) [18].
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When ore and enclosing rocks is grouped according to physical and mechanical properties and correlated with geological maps, it is possible to reasonably selects sites for rate setting and make recommendations on drilling and blasting equipment and technology. In case of additional exploration, the updated information on strength and jointing should duly be introduced on geological maps of drilling areas. Identification of the increased jointing zones along the horizontal and vertical of drilling areas allows anti-accident recommendations on reduction of air hammer power on bottomhole.

2. Evaluation of energy efficiency in blastholes drilling

The technical reasons of drop in the drilling efficiency in mines in Russia are similar in many ways. Below in this paper, the authors perform an integrated evaluation of energy efficiency in drilling
blastholes with a diameter of 160 mm and 56 m long by air hammer P-160-5.5 ShV using drilling rig BP100 in an underground mine. The scope of the evaluation embraced the cost of energy source consumption per 1 m of drilling (without regard to water and air consumption by rotation and feed rive system of the rig) and the integral volumetric rock destruction energy criterion \( k \), which totally correlates with the cost of energy source in drilling on the bottom. The criterion is calculated from the formulas:

\[
k = k_c \eta,
\]

where \( k_c \) is the criterion factor [19, 20]; \( \eta \) is the air-driven hammer efficiency;

\[
k_c = \frac{E_c(t)\alpha}{V_\rho(t)\rho v_\rho^2},
\]

where \( E_c(t) \) is the air energy fed to the drilling rig, J; \( \alpha \) is the estimated coefficient of seismic effect of underground blasts [19]; \( V_\rho(t) \) is the volume of broken rock in the control section of drill hole, \( m^3 \); \( \rho \) is the rock mass density in the drilling site, \( kg/m^3 \); \( v_\rho \) is the P-wave velocity, \( m/s \).

The air energy fed to the drilling string is given by:

\[
E_c = W_c \tau,
\]

where \( W_c \) is the energy source capacity, \( W \); \( \tau \) is the duration of rotary–percussion drilling in the control section of hole, s.

The value of \( W_c \) is found from the formula:

\[
W_c = \frac{RT}{\mu}Q_m \ln \frac{p}{p_{atm}},
\]

where \( R = 8.31 \) is the universal gas constant, J/mole·K; \( T \) is the absolute air temperature, K; \( \mu \) is the molecular weight of air, \( \mu = 0.02896 \) kg/mole; \( Q_m \) is the mass air flow, kg/s; \( p \) is the rated pressure of the air hammer, MPa; \( p_{atm} \) is the atmospheric pressure, MPa.

The mass air flow per second is obtained from the relation:

\[
Q_m = \frac{Q_{rate} \rho_{air}}{60},
\]

where \( Q_{rate} \) is the air flow rate, \( m^3/min \); \( \rho_{air} \) is the air density at the normal atmospheric pressure, \( kg/m^3 \).

The calculation data on magnetite ore are compiled in Table 1; P-wave velocity is assumed as 3100 m/s. the geology of block No. 32 was uncorrelated with the drilling site, and drill cuttings were therefore take for the analysis for additional exploration.

**Table 1.** Geological characteristic of rocks in block No. 32.

| Ore and rock types                  | Strength, MPa | Mass, kg/m³ | Jointing category | Joint set spacing, m |
|-------------------------------------|---------------|-------------|-------------------|---------------------|
| Grey magnetite ore                  | 150           | 3950        | III/II*           | 0.8 / 0.3           |
| Pecky banded chlorite–magnetite–granate–epidotic skarn | 130           | 2950        | III/I             | 0.65 / 0.1<         |
| Banded chlorite and sheet–plate shale | 110           | 2720        | III/I             | 0.75 / 0.1<         |
| Pinky–grey syenite                  | 100           | 2730        | III/I             | 0.7 / 0.1<          |
| Light-green feldsparic porphyre dyke | 100           | 2830        | II                | 0.25                |
| Dioritic porphyre dyke              | 90            | 2830        | II                | 0.25                |

*After the slash there is the jointing category for rocks nearby Vostochny tectonic fault.
Inasmuch as the common integral criterion of drilling is the cost of 1 m drilled, we calculated the cost of air spent by the air-driven hammer. The air cost was assumed 1 Rub/m$^3$. At the air hammer consumption of 14.9 m$^3$/min, the cost of the machine operation made 894 Rub/h, or 0.248 Rub/s. The cost of water consumption and air taken by rotation and feed drives was disregarded. Efficiency of the discussed-type air hammers within the pressure limits of 0.5–0.6 MPa totaled $\eta \approx 0.11–0.12$. In view of the fact that efficiency of the hammer model P-160-5.5 SHV was not determined in bench-test and drilling was carried out within the mine mains pressure limits of 0.48–0.58 MPa [21]; thus, the boundary was 0.58–0.6 MPa always, except for one shift when drilling pressure reduced to 0.48 MPa, which assumed to be $\eta = 0.12$. At $W_c = 45.7$ kW ($T = 295$ K, $\rho_a = 1.2466$ kg/m$^3$, $p = 0.58$ MPa), capacity of the air hammer model P-160-5.5 SHV is $W = 5.5$ kW. According to the specifications, this air-driven hammer has the capacity $W = 5.5$ kW at the pressure of 0.5–0.7 MPa [21]; thus, the boundary conditions at $\eta = 0.12$ are set correctly. When $p = 0.48$ MPa, it is assumed that air flow rate is 14 m$^3$/min, accordingly, $W_c = 38.3$ kW and $W = 4.6$ kW. The minimum energy input of rock drilling is reached at $k = 1 \cdot 4 \cdot 10^{-8}$.

The first meter drilling results were excluded from the calculation, for auxiliary operation connected with collaring were performed. Drilling involved reused drill bit. The mine air feed pressure was 0.58–0.6 MPa always, except for one shift when drilling pressure reduced to 0.48 MPa, which ended with an emergency situation.

Table 2 presents calculated data for a hole 55 m long with the determination internal of 5 m; for the shift with emergency situation in the hole section from 35 to 40 m with the determination interval of 0.75 m; and for the rod section of 0.3 m during drilling of which the emergency took place with the determination interval of 0.3 m. The air consumption cost was calculated for the specified check intervals $L_c$ (index $C_{check}$) and per 1 m in each interval ($C_{air}$). The penetration rates $V_p$ were determined based on video and acoustic processing of the drilling process records [20].

Table 2. Calculated energy efficiency of drilling with air hammer P-160-5.5 SHV and drilling rig BP100 for the hole with diameter 160 mm and 56 m long.

| $L_c$, m | 5  | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 |
|----------|----|----|----|----|----|----|----|----|----|----|----|
| $p$, MPa | 0.58 | 0.58 | 0.58 | 0.58 | 0.58 | 0.58 | 0.58 | 0.58 | 0.58 | 0.58 | 0.58 |
| $V_p$, m/min | 0.057 | 0.05 | 0.047 | 0.042 | 0.038 | 0.035 | 0.023 | 0.03 | 0.029 | 0.025 | 0.023 |
| $k_c$, 10$^{-7}$ | 1.28 | 1.47 | 1.55 | 1.74 | 1.93 | 2.09 | 2.58 | 2.37 | 2.52 | 2.93 | 3.09 |
| $k$, 10$^{-8}$ | 1.54 | 1.76 | 1.87 | 2.09 | 2.31 | 2.51 | 3.1 | 2.84 | 3.03 | 3.52 | 3.71 |
| $C_{check}$, Rub | 1296 | 1484 | 1573 | 1761 | 1949 | 2117.5 | 3116.5 | 2395 | 2550 | 2968.5 | 3125 |
| $C_{air}$, Rub/m | 259.2 | 296.8 | 314.6 | 352.2 | 389.8 | 423.5 | 623.3 | 479 | 510 | 593.7 | 625 |

Check interval length $L_c = 0.75$ m (35–40 m)

| $L_c$, m | 0.58 | 0.58 | 0.58 | 0.48 | 0.48 | 0.48 | 0.48 | — | — | — | — |
| $p$, MPa | 0.75 | 1.5 | 2.25 | 3 | 3.75 | 4.5 | 5.25 | — | — | — | — |
| $V_p$, m/min | 0.04 | 0.038 | 0.037 | 0.016 | 0.018 | 0.02 | 0.021 | — | — | — | — |
| $k_c$, 10$^{-7}$ | 1.54 | 1.62 | 1.66 | 3.84 | 3.41 | 3.07 | 2.92 | — | — | — | — |
| $k$, 10$^{-8}$ | 1.84 | 1.94 | 1.99 | 4.61 | 4.09 | 3.69 | 3.51 | — | — | — | — |
| $C_{check}$, Rub | 278.3 | 293 | 300 | 696 | 618.4 | 557 | 530 | — | — | — | — |
| $C_{air}$, Rub/m | 371 | 390.5 | 401.1 | 927.6 | 824.6 | 742.1 | 706.7 | — | — | — | — |

Check interval length $L_c = 0.03$ m

| $L_c$, m | 0.03 | 0.06 | 0.09 | 0.12 | 0.15 | 0.18 | 0.21 | 0.24 | 0.27 | 0.3 | — |
| $p$, MPa | 0.02 | 0.021 | 0.019 | 0.019 | 0.019 | 0.014 | 0.017 | 0.0125 | 0.013 | 0.01 | — |
| $V_p$, m/min | 2.97 | 2.9 | 3.11 | 3.28 | 3.17 | 4.2 | 3.58 | 4.91 | 4.47 | 5.8 | — |
| $k_c$, 10$^{-7}$ | 3.56 | 3.48 | 3.73 | 3.93 | 3.81 | 5.04 | 4.3 | 5.9 | 5.36 | 6.96 | — |
| $k$, 10$^{-8}$ | 21.6 | 21.08 | 22.568 | 23.808 | 23.064 | 30.504 | 26.04 | 35.712 | 32.488 | 42.16 | — |
| $C_{check}$, Rub | 712 | 695.6 | 744.7 | 785.6 | 761.1 | 1006.6 | 859.3 | 1178.4 | 1072.1 | 1391.2 | — |
Figure 3 illustrates energy efficiency of drilling with air hammer P-160-5.5 SHV beyond the range of $k \in (1/4) \cdot 10^{-9}$. This is typical of low-pressure and high-rate air hammers with low energy performance [21, 22].

![Figure 3](image3.png)

**Figure 3.** Drilling energy efficiency of air hammer P-160-5.5 SHV by $k$: 1—hole 55 m long; 2—hole section of 35–40 m; 3—emergency section 0.3 m long.

The volumetric rock destruction criterion $k$ and the criterion energy factor $k_c$ are identical in terms of rock–machine feedback and correlated with the energy source consumption cost $C_C$. For this reason, it is simple to evaluate cost of compressed air of drilling on the bottom by deviation $\Delta$ of $k$ or $k_c$. Figure 4 depicts energy efficiency evaluation by $k$.

![Figure 4](image4.png)

**Figure 4.** Evaluation of drilling energy efficiency with air hammer P-160-5.5 SHV.

Considering the data of earlier studies focused on evaluation of energy efficiency in air-powered hammer drilling by the direct cost $C$, as well as based on the international experience gained in operation of drilling machines and rock-breaking tools, the energy efficiency range of pneumatic drilling by $k(k_c)$ is $\Delta = 15–30\%$ [23–25]. The dash line in Figure 4 marks the point where it is required to eliminate the causes of decline in energy efficiency of drilling with air hammer P-160-5.5 SHV. With regard to the specific character of long blasthole drilling efficiency in mines, the range of 30–50% is tolerated in holes having reached 2/3 of their length as multi-trip drilling results in a drop of drilling productivity and in the drilling cost escalation.

The research finds that the major case of lower productivity of long blasthole drilling with the air hammer model P-160-5.5 SHV with a diameter of of 160 mm and drilling rig BP-100 is the loss of percussive capacity of the hammer due to:

- increased water consumption in composition of air-and-water mixture (by a factor of 1.5);
- lack of sealing rings in drill rods;
- use of small-size drill rods ($L = 0.75$ m);
- unavailability of sharpening for tungsten carbide insets of drill bits;
- long operation f drill bits with worn inserts (one drill bit per 3–4 holes).

During the experiments, standard capacity was 7 meters of drilling. Using the data on actual time of drilling the check sections in the hole, the other standard machine capacity is calculated as:
\[ H_{sl} = \left( \frac{T_{act} \cdot i}{t_{act1} + t_{act2} + \cdots + t_{actn}} \right) \cdot k_{cor}, \]  

(6)

where \( T_{act} \) is the actual time of drilling during a shift, min; \( i \) is the number of check sections; \( t_{act1}, \cdots, t_{actn} \) is the actual time of hole drilling (in open pit mines) or check sections of holes (in underground mines) with the known linear dimensions, min/m; \( k_{cor} \) is a correction factor of standardization (occupational safety, geotechnical conditions);

\[ T_{act} = T_{shift} - (T_{rt} + T_{serv} + T_{pn}), \]  

(7)

where \( T_{shift} \) is the overall shift duration, min; \( T_{rt} \) is the rigging up and tail-in time, min; \( T_{serv} \) is the time of servicing of the drill operator’s workplace, min; \( T_{pn} \) is the private need time, min.

The time of rigging up, tail in and workplace servicing totals 9.5% of the overall shift duration \( T_{shift} \) (420 min), checkup and safing of workplace—10 min; lubrication, fore-actuation and minor repair of drill rig—21 min; rigging up—4 min; cleanup of drill operator workplace—5 min; time for private needs and rest—10 min, \( k_{cor} = 1 \).

From (6) the standard machine capacity \( H_{sl} = 9.73 \) m, which means that prompt replacement of drill bits after drilling of two holes (100–112 m) with air hammer P-160-5.5 SHV, the minimum increment in the productivity of drilling (other failure causes unremoved) will make 39%. After all revealed trouble causes have been eliminated, the anticipated increase in the drilling productivity will be 12–14 meters at the monthly saving of money in amount of up to 2 million Rubles (at values of 2016). In the period of introduction of drill rigs BP100 and DTH air hammers P-160-5.5 SHV, such productivity per shift was assumed as average [26]. In order to improve energy efficiency of drilling in magnetite ore, it is required to replace this hammer model by a smaller size analog having lower air flow rate and the same capacity as P-160-5.5 SHV. An alternative may be DTH air hammer model P-150S (\( Q_{air} = 10 \) m³/min, \( W = 6.3 \) kW) [27].

The implemented research shows that potentiality of improving pneumatic drilling productivity should be analyzed from the viewpoint of energy efficiency of this process. The express-estimation can use the volumetric rock destruction criterion \( k \) and the energy criterion \( k_e \). As against the energy efficiency evaluation by the drilling cost \( C \), computation of \( k_e \) and \( k \) takes much less time and needs no economic figures though correlates with them (in terms of energy source consumption). Furthermore, the criteria \( k_e \) and \( k \) enclose physical and mechanical properties of rocks and, unlike \( C \)-index, allow exact and reliable determination of drilling energy efficiency over any time interval. The index \( C \) lacks that stability, for the cost of energy sources and the other indexes are fluid. It is very difficult to analyze decline or growth of pneumatic drilling energy efficiency in different years without conversion factors for all indexes involved in the calculation of drilling cost.

3. Conclusions

The review of the drilling technologies and equipment shows that introduction of heavy drill rigs of foreign manufacture in Russian mines is often economically inexpedient as the cost of energy sources (electricity, water, diesel fuel) rises essentially in this case.

The integrated assessment of energy efficiency in blasthole drilling in mines in terms of DTH air hammer model P-160-5.5 SHV and drill rig model BP 100 has discovered that the major cause of low productivity is the loss of the impact capacity of the hammer to to increased water flow rate in the air-and-water mixture, lack of sealing rings in drill rods, unavailability of sharpening for tungsten carbide inserts of drill bits, use of short drill rods and long operation of drill bits with worn inserts. From the evidence f the analyzed drilling costs and machine standard capacity calculations, it follows that elimination of the revealed causes will result in the anticipated improvement of drilling productivity not less than by 40%.

The undertaken studies show that the energy efficiency and the energy source cost should be the criteria for selecting drilling equipment alongside with the criterion of drilling productivity. The
express-assessment of energy efficiency in drilling with DTH air hammer is advisable to perform using the volumetric rock destruction criterion and the energy criterion.

Development of detailed flow charts, including geological characterization of drilling sites with indicated physical and mechanical properties of rocks along the vertical and horizontal will enable the next level performance of drilling and blasting. Moreover, it will become possible to use the same drilling machines and tools in the drilling site with analogous characteristics and distribute the equipment between scheduled drilling sites with regard to the wanted number of drilling machines and rock-breaking tools.

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