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# RESULTS OF STUDIES OF SHAFT BORING MACHINE OPERATION IN VERTICAL SHAFT CONSTRUCTION AT UPPER KAMA POTASH DEPOSIT

*Under evaluation is applicability of mechanized rock breakage in shaft sinking in aqueous strata of the Upper Kama Potash Deposit using shaft boring machine ASP-8.0.*

*The article describes the function and operating principle of shaft boring machine ASP-8.0, its structural scheme and flow chart of mechanized breakage by milling cutter in vertical shaft sinking in Palashersky mine site. A feature of the milling cutter with the vertical axis of rotation is down-the-hole operation.*

*Aiming to find and refine the laws of work load and capacity, as well as to evaluate parameters of the milling cutter of ASP-8.0, the full-scale field research into the operation of the machine in shaft boring has been performed. It is shown that the experimental data and the results of calculations using available procedures are in good correspondence. The article gives the calculation formulas for coefficients to account for contact area between the milling cutter and rock, as well as for torque and feed force of the milling cutter. The mathematical expressions are derived for the milling cutter rotary drive power, as well as for the technical and operating capacity of the milling cutter within the mechanized shaft boring machine set.*

*Proved promising of the use of mechanized destruction method in sinking shafts in aquifers of Verkhnekamskoe potash ores on the basis of the unit ASP-8.0. The purpose and principle of operation of shaft deepening aggregate ASP-8.0 is represented as well as its design map and the scheme for mechanized destruction of slaughter by screw-milling executive device during shaft advance at Palachersk plot of potash ores. Peculiarities of work of the executive device in the exploitation of the slaughter are identified. Experimental studies of executive device work in the natural environment during the construction of the shaft are performed to establish and clarify the patterns of load and performance, as well as justification of its parameters. The comparison of experimental results with those ones obtained on the basis of existing calculation methods is shown. Represented the formulas for determining the coefficients, taking into account the influence of the arc of contact of the executive device with the massif; they specify the calculation of the torque on the cutter and the efforts of the filing of the executive device. The dependences of the required power of the drive rotation of the cutter, as well as technical and operational performance of the unit that is a part of the mechanized shaft deepening complex.*

***Key words:*** *mine shaft, mechanized rock breakage, shaft boring machine set, milling cutter, down-the-hole mode, breakage energy intensity, milling cutter and rock contact arc, vertical transport of loose rock, technical capacity, operating capacity.*

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## Introduction

At the present time, mine shaft construction increasingly uses drilling-and-blasting which is a series of production processes aimed at separation of rock fragments by blasting. As applied to aquifers, this method is disadvantageous as it induces fracturing in rock mass, which results in failure of shaft sealing as reservoir water flows into the annular space between the tubbing and rock wall reinforced with freezing and grouting mortars [1].

Raise boring offers a promising way-out [2, 3, 4–6] as it ensures uniform, smooth, circular cross-section of a shaft, integrity of adjacent rock mass and competence of ice-and-rock shielding after freezing, as well as seismic stability under blast wave induced by drilling-and-blasting. Shaft boring uses drag bits [7, 8] or roller cone bits [9–11]. This approach allows sufficient safety as no explosives are used and people are evacuated from the face area [3, 12].

## Main part

For the construction of shafts by OGSK company in Usolsky Mine at the Upper Kama Potash Deposit, in the zone of aqueous rocks, the Tula State University and SOEZ company have developed a project of shaft drivage using a shaft boring machine set including loading machine 2KS-2U/40. Both the shaft boring machine to be a module of the machine set and its operating tool have been designed in the framework of the mentioned project.

The designed machine ASP-8.0 is intended for sinking long vertical shafts 8 m in diameter either with blasting (in rocks having compression strength over 38 MPa) or with boring (weak rocks, including aqueous strata) [13, 14]. The structural layout of shaft sinking machine ASP-8.0 and the circuit of mechanized rock breakage are given in **Fig. 1**.

The operation of the machine is divided into cycles. In the shaft, the machine is expanded to thrust against the shaft walls by bridging cylinders 13 (**Fig. 1**) and is anchored to tubbing 12. The worm milling cutter breaks rock over the cross section area of the shaft to a preset depth by means of horizontal rocking and lifting/putting down of the operating mechanism and rotation of internal ring 1. Then, the machine is detached from the shaft tubbing and moved down by vertical displacement cylinder 10 by a value of cut rock; here, new tubbing is installed and the machine is spread there again. This is the end of a cycle, and a new cycle is begun after that, etc.

Concurrently, broken rock is loaded by grab bucket machine 2KS-2U/40 in buckets to be transported in the shaft by a bucket cable hoist.

Considering influences on the process of potassium ore and enclosing rock destruction, the operating mechanism has been designed for machine ASP-8.0. The operating mechanism is equipped with one or two worm milling cutters depending on operating conditions. The milling cutters with a

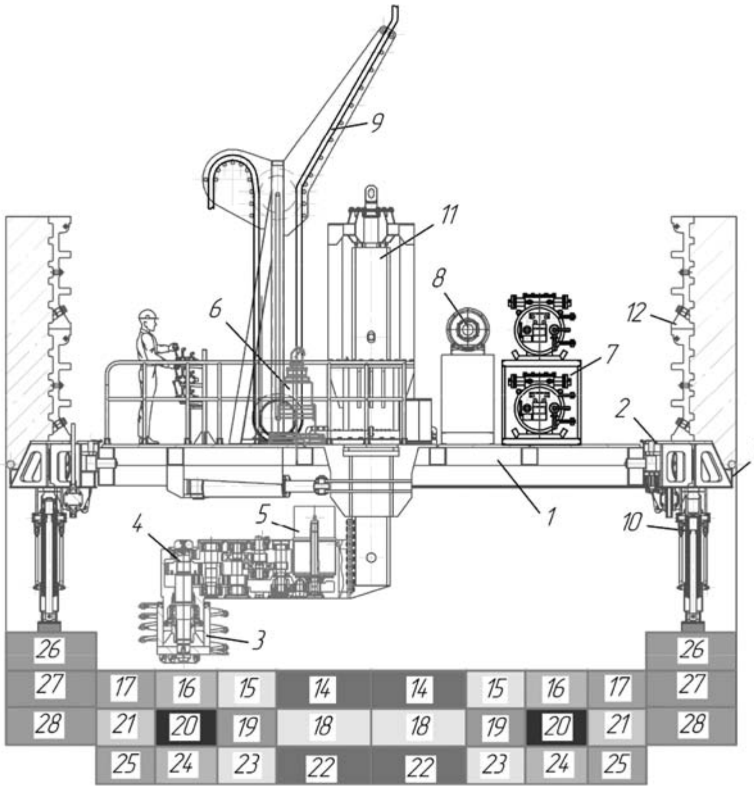


**Fig. 1. The structural layout of shaft sinking machine ASP-8.0 and the circuit of mechanized rock breakage:**
*1* — internal ring; *2* — installer ring; *3* — worm milling cutter; *4* — reduction gearbox of the operating mechanism; *5* — electric motor of the worm milling cutter; *6* — drive to rotate the internal ring;
*7* — electrical facilities; *8* — hydraulic equipment; *9* — cable layer; *10* — vertical displacement cylinders; *11* — rotary and feed gear of the operating mechanism; *12* — tubbing; *12* — bridging cylinders; *14–28* — set of ring-shaped segments

diameter of 1.2 m have vertical axis of rotation. The milling cutters are equipped with 30 and 50 cutting bits model PS-2, respectively [15].

The milling cutters have been manufactured and trialed by COEZ company. The commercial trials have shown that, given rational depth and pitch of cutting, destruction covers entire borehole bottom. On that ground, it has been decided on applicability of the milling cutters in shaft construction.

Design of the operating mechanism implies application of various schemes of mechanized breakage of rock. The schemes are the sets of ring-shaped segments arranged layer-by-layer, depending on operating conditions. **Fig. 1** depicts the scheme of borehole bottom cutting for rocks with the ultimate compression of 25–38 MPa: figures 14–25 and 26–28 indicate the internal and marginal ring-shaped segments.

It is worthy of mentioning that the marginal ring-shaped segments are always cut after the internal segments have been broken (see **Fig. 2**). This is required in order to create a bench to be a support for the vertical displacement cylinders of the shaft boring machine.

Accordingly, broken rock freely falls from the marginal sections down the created bench, while the milling cutter is in permanent contact with broken rock in the internal ring-shaped segments. Thus, this is a down-the-hole operating mode featuring unremoved broken rock in the internal ring-shaped segments, which continuously enter the work zone of the milling cutter. This results in over-crushing and mixing of rock and in additional friction between rock and the milling cutter. Considering vertical orientation of the axis of the milling cutter, broken rock is removed along a vertical worm, which creates extra resistance to rotation of the operating mechanism.

Aiming to determine work load and capacity of the worm milling mechanism in the down-the-hole operating mode and to evaluate operational parameters of the mechanism attached to the shaft boring machine, in situ tests were carried out during construction of a cage shaft in Palashersky site of the Upper Kama Potash Deposit. The test depth interval was chosen between marks 398 and 405 where the rock compression was $\sigma_{com} = 28$ MPa. The relevant recording and measuring equipment was involved. The borehole bottom was broken by the scheme illustrated in **Fig. 1**, by the milling cutter equipped with 50 bits.

The key indexes to characterize potassium ore breakage capacity of the worm milling cutter and the shaft sinking efficiency were: rock breakage power of the milling cutter $N_{mil}$ (kW), milling cutter feed force $P_{feed}$ (kN), shaft sinking capacity (m$^3$/min), including ore breakage capacity $Q_{break}$, technical capacity $Q_{tech}$ and operating capacity $Q_{oper}$, and breakage energy intensity $H_w$ (MJ/m$^3$).

From the analysis of the test results, the lowest rock breakage capacity (0.36–0.38 m$^3$/min) was achieved in central ring-shaped segments 18 and 22, and the highest breakage capacity (0.63–0.72 m$^3$/min) was in marginal ring-shaped segments 26–28 where the operating mode of the milling cutter was not down-the-hole (refer to **Fig. 1**). The average breakage capacity was 0.52 m$^3$/min.

The resultant data on the breakage energy intensity $H_w$ and the milling cutter feed force $P_{feed}$ were compared with the calculations performed using the known methods, at the preset capacity $Q_{break}$, considering bit patterns and ground conditions of operation of the worm milling cutter [16, 17]. To this effect, the curves of the dimensionless energy intensity, feed force and factors taking into account a contact angle $\varphi$ between the worm milling cutter and rock were plotted (**Fig. 3**). The analysis of the curves yields that the experimental curves of the energy intensity and feed force depend to a lesser degree on the contact angle between the milling cutter and rock than the theoretical curve, which is conditioned by additional contact of the milling cutter and rock when operating in down-the-hole mode. Thus, based on the disagreement of the curves, peculiarities of operation of milling cutters with the vertical axis of rotation have been revealed, which should be taken into account in calculation of torque and feed force using appropriate factors (constants).

For instance, the specified calculation of torque should include factor $K_{tr.down}$ of the trajectory of bits that contact rock in the down-the-hole mode of the milling cutter, given by

$$K_{tr.down} = 0.618 K_{tr.bit}^{0.318},$$

where $K_{tr.bit} = \varphi / 2\pi$, while the specified calculation of feed force should use factor $K_{fa}$ accounting for angles of the feed force at bits that are in contact with rocks and for a number of bits that are in contact with rock, given by:

$$K_{fa} = 0.614 K_{tr/feed}^{0.506},$$

where $K_{tr.feed} = 0.25(\varphi/2 + \sin 2\varphi)$.

Calculation of the overall power of the milling mechanism $N_{mill}$ (kW) should take account of extra power for vertical displacement of rock and the related power of crushing and mixing of rock by the milling cutter in the down-the-hole operation mode. In this case:

$$N_{mill} = N_c + N_r,$$

where $N_c$ is the power of rock cutting, conditioned by torque and rotation speed of the mechanism; $N_{vr}$ is the power of vertical removal of rock by the milling cutter.

The analysis of operation of the milling cutter yields that the behavior of rock particles transported by the worm of the milling cutter is similar to the behavior of rock particles transported by a screw conveyor. **Fig. 4** gives an analytical model of forces and velocities during rock displacement by the milling mechanism in the down-the-hole mode.

It has been found that the capacity in terms of mass, $Q_{mass}$, and the power $N_{mill}$ obey a linear relationship, where $N_{mill}$ grows with $Q_{mass}$ governed by the factor of transport resistance due to rock mixing and overcrushing and due to friction between transported and fixed rock, $f_{res}$. Based on the research findings:

$$f_{res} = 1.75 + 0.00267 Q_{mass}.$$

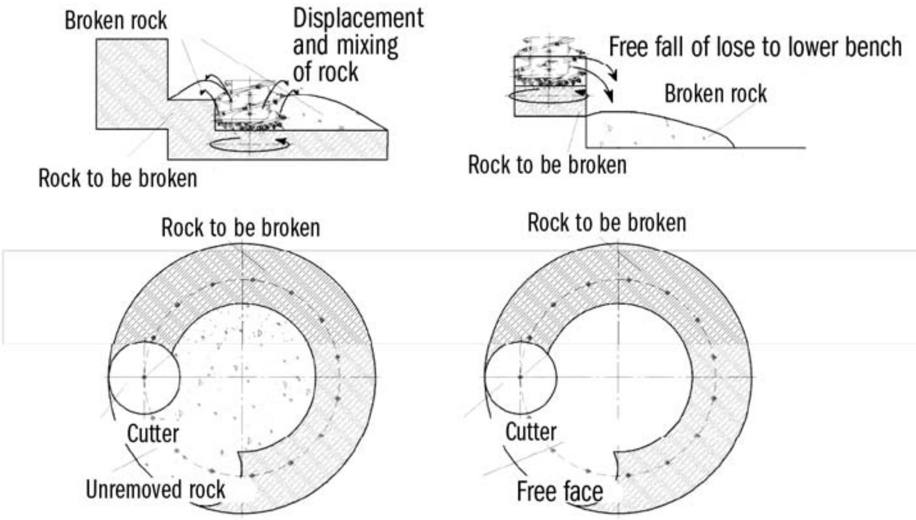


**Fig. 2. Operating modes of the worm milling cutter: (*a*) down-the-hole operation (internal ring-shaped segment); (*b*) non-down-the-hole operating mode (marginal ring-shaped segments**

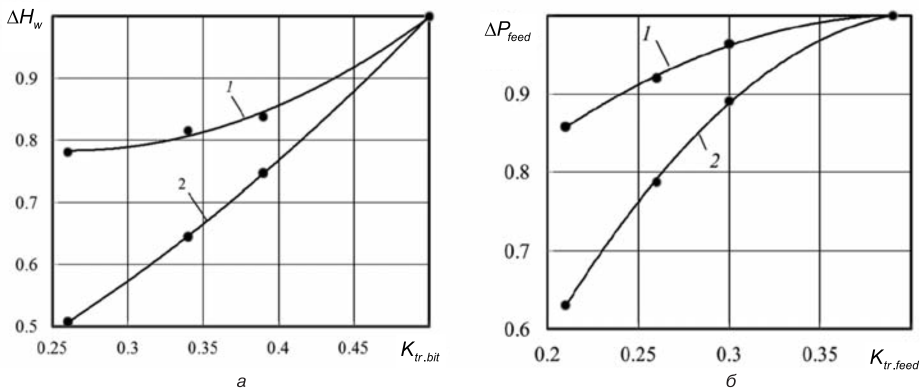


**Fig. 3. Dimensionless energy intensity and feed force versus factors of contact angle $\varphi$ between milling cutter and rock:**
(*a*) energy intensity factor $\Delta H_w$ versus $K_{tr.bit}$; (*b*) feed force factor $\Delta P_{feed}$ versus $K_{tr.feed}$;
*1* and *2* — experiemtnal and theoretical curves, respectively

Judging by the analytical model in **Fig. 4** and considering $f_{res}$, the power of vertical removal of rock is found from the formula:

$$N_{vr} = 10^{-3} v_r \rho g V_{rw} (1 + \cot \alpha_{worm}) f_{res},$$

where $\rho$ is the density of rock, kg/m$^3$; $V_{rw}$ is the volume of rock between the worm blades, m$^3$.

The vertical removal velocity of rock is given by:

$$v_{vr} = \frac{S_{wp} n_{rpm}}{60},$$

where $S_{wp}$ is the pitch of the worm, m; $n_{rpm}$ is the rotation speed of the milling cutter, rpm.

The volume of rock between the worm blades:

$$V_{rw} = \pi / 4(D_w^2 - d_w^2) B_{cut} - V_h,$$

where $D_w$ and $d_w$ are the outer and inner diameters of the worm, m; $B_{cut}$ is the cutting depth of the milling cutter, m; $V_h$ is the volume of the helix, m$^3$, given by:

$$V_h = \pi D_w B_w X_t (D_w / 2 - d_w / 2),$$

where $B_w$ is the worm width, m; $X_t$ is the number of spiral turns of the worm.

The technical capacity $Q_{tech}$ and operating capacity $Q_{oper}$ were determined from chronometric studies.

The technical capacity $Q_{tech}$, m$^3$/m, is given by the formula:

$$Q_{tech} = \frac{V_{cycle}}{1/K_{mode} T_{tech}},$$

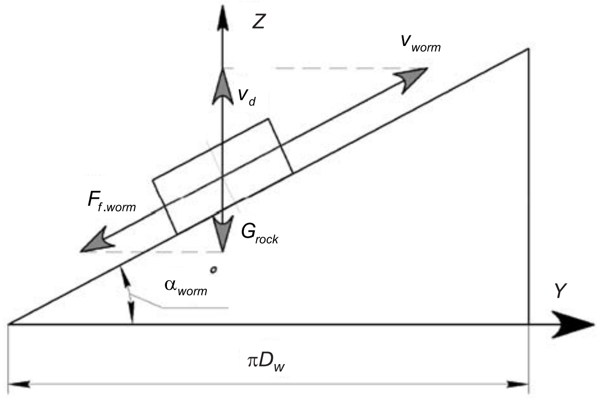


**Fig. 4. Analytical model of forces and velocities applied to rock in the course of the down-the-hole operation of the milling cutter:** $v_d$ — velocity of vertical displacement of rock; $v_{worm}$ — velocity of rock removal by worm; $G_{rock}$ — force of gravity of rock; $F_{f.worm}$ — force of friction between rock and worm under $G_{rock}$; $\alpha_{worm}$ — angle of worm

where $K_{\mathrm{mode}}$ is the factor of operating mode of the milling mechanism (0.82 for manual mode and 1 for automated control).

The time $T_{tech}$, min, includes time spent for operations conditioned by the design features of the milling mechanism and is calculated from the expression:

$$T_{tech} = t_{ring} + t_{vcut} + t_{hcut} + t_c + t_t + t_{ex} + t_{ser},$$

where $t_{ring}$ is the time spent to break ring segments; $t_{vecut}$ is the time of vertical cutting; $t_{hecut}$ is the time of horizontal cutting; $t_c$ is the time spent by cylinders for vertical displacement and spreading of the milling cutter in the hole; $t_e$ is the time of tubbing installation; $t_{ex}$ is the time of extra operations for realignment of components of the machine; $t_{ser}$ is the machine maintenance and repair time.

The operating capacity, apart from the above listed factors, includes downtime for reasons beyond the design features of the machine:

$$Q_{oper} = \frac{V_{cycle}}{1/K_{\mathrm{mode}} T_{tech} + T_{ex}},$$

where $T_{ex}$ is the downtime for reasons beyond the design features of the machine and is given by:

$$T_{ex} = t_r + t_{eq} + t_{con},$$

where $t_r$ is the time for removal of broken rock after the milling cutter has completed the current operating cycle; $t_{eq}$ is the time of delivery of auxiliary equipment for tubbing installation; $t_{con}$ is the time of concreting of one tubbing ring.

## Conclusion

The technical capacity has made 0.2 $m^3$/min, and the operating capacity equals 0.13 $m^3$/min. The research findings have been included in the procedure for calculation of the parameters and performance of the power-driven shaft boring machine set based on the shaft boring machine ASP-8.0 with the milling mechanism.

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