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MINERAL MINING TECHNOLOGY

Selection of High-Strength Dimension Stone Cutting Method, Considering Natural Jointing

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Abstract—The authors prove feasibility and efficiency of high-strength stone wire saw cutting in rock mass with subvertical and low-angle joints as well as drilling-and-wedge cutting of stone into marketable size blocks on the working site. The article presents and substantiates the procedure for rational selection of technology for high-strength stone preparation for cutting, considering geological conditions (shape of mineral body, orientation and spacing of joints), local temperature, as well as physico-mechanical properties and mineralogical composition of rocks.

Keywords: High-strength stone, preparation technology, rock mass jointing, combination method.

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INTRODUCTION

The analysis of the high-strength dimension stone market in Russia and in the world testifies the increased consumption of products made of stone for facing, and building and road construction. The market economy dictates that the determinants of stone products are their quality and cost conditioned by stone cutting technology, including preparation for cutting that makes 80% of overall stone production cost [1–3]. Inefficient use of dimension stone in Russia is due to inconsistency of stone block cutting technique and structural features of a developed deposit [4–6].

There are currently many approaches to prepare strong rocks for cutting using various equipment. Stone blocks can be separated using drill holes and wedging (mechanical, hydraulic wedges, sleeve explosives, non-explosive destruction mixtures, pressure gassifiers), which is widely applied at sheet deposits. This method is inefficient at mineral deposits with complicated ground conditions, with subvertical ($\delta > 45°$) and flat ($\delta < 45°$) joints as preparation takes long time and costs much while output of dimension stone appears to be unprofitable [7, 8].

The practical experience gained by the world's top producers of high-strength dimension stone exhibits tendency of wire sawing. Flexible diamond sawing [9–12] enables stone cutting with high benches, which considerably adds to dimension stone production. High-bench cutting technology is two-stage where the first stage is wire sawing of a solid stone block and its throwing on a work site, and the second stage is cutting of marketable dimension stone. Combination of sawing and stone separation using drill holes as the first and second stages of dimension stone production, respectively, in many cases improves the high-strength dimension stone production efficiency. Using wire saw as a key cutting tool in winter is complicated as water is required to cool the saw. Besides, it is inefficient to use the high-bench cutting technology in rocks without developed families of joints, or in rock mass composed of boulders and ridges.

This article describes a procedure and an algorithm for selecting efficient preparation technique for high-strength dimension stone, considering an integrated package of geological conditions (shape of a mineral body, spatial characteristics and spacing of systems of joints), regional temperature, physico-mechanical properties and mineralogical composition of rocks.

1. STATE-OF-THE ART OF DIMENSION STONE PRODUCTION IN THE WORLD

Though continuously competing with various man-made substitutes on the market, consumption of natural stone annually grows in the world by 7–9% and has by now reached 30 Mm^3 [8]. This speaks of the high competitive ability of natural dimension stone, which is first of all due to its natural ornamentality and durability. Based on the experience, the durability and appropriate use of dimension stone allows reduction in operational cost of buildings and near-by territories 5–8 times as compared with the natural stone substitutes.

In 2008–2009 production and processing of dimension stone declined but the market almost recovered in 2013 (see Fig. 1) [3, 6, 8]. Russia holds the largest and most diverse reserves of natural stone in the world. Overall in-place reserves of natural stone categories $A + B + C_1$ make some 1.5 Bm^3 in Russia [8]. These reserves occur in about 500 explored deposits, out of which 40% are abyssal rocks (granite, diorite, gabbro, basalt, etc.); nearly the same amount are medium strength rocks (marble, marmorized limestone, marble breccias, etc.); the remaining deposits are weak rocks (mainly sedimentary): limestone, banded marble, plaster stone, etc. However, the State Balance does not list all stone reserves in Russia: there are a few thousand deposits of natural stone at different stages of exploration (mostly, prospecting and preliminary survey stages). For instance, many geologists think that Russia has over 100 recorded occurrences of natural stone with possible reserves of 4 Bm^3 [8].

With such resources at hand, Russia is world's 25th producer of natural stone (0.3 Mm^3/yr) and 7th place consumer (0.4 Mm^3/yr). The weight of Russia in the world trade of granite is negligible. Overall world trade (export and import) of granite blocks was 4230 thou m^3 in 2013. Russia is the 35th place exporter of granite blocks in the world, which makes 0.085% or 3.3 thou m^3 on a global scale. More than fourth (26%) of the total granite stone production in Russia falls at the Ural Federal District [8, 13]. Deficient production of dimension stone is first of all associated with a trace amount and low efficiency of operating quarries and with low output of marketable stone (output range is 0.05–0.8, mostly 0.1–0.4) [8].

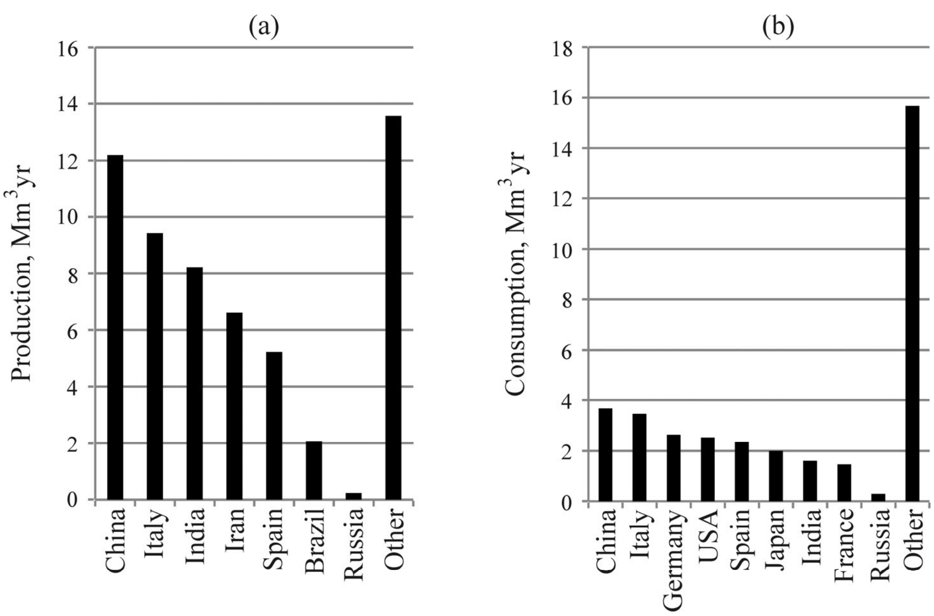


Fig. 1. (a) Production and (b) consumption of natural dimension stone in the world in 2013.

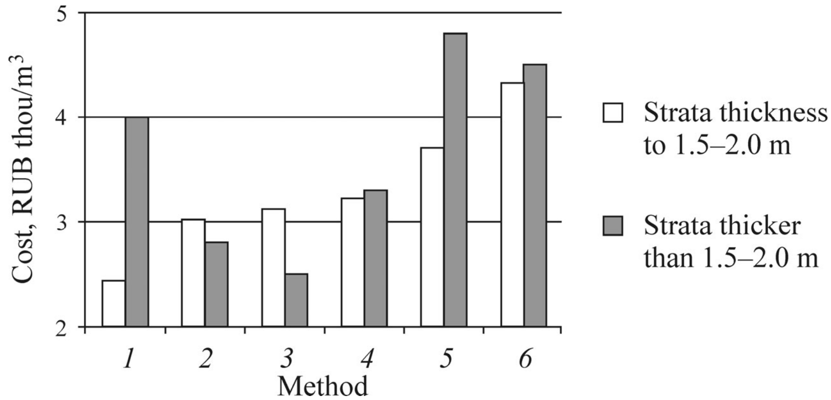


Fig. 2. Estimated cost of stone production in terms of Mansur granite deposit, with different methods of stone cutting (annual capacity 24 thou m^3 of rock mass): *1*—drill holes with mechanical wedges; *2*—drill holes and non-explosive destructive tools; *3*—combination of hole drilling and wire sawing; *4*—hole drilling and K-tubes; *5*—wire sawing at stages 1 and 2; *6*—drill holes and gassifiers.

Granite blocks are prepared for cutting by drill holes and wedging (mechanical and hydraulic wedges, non-explosive destruction, sleeve explosives, gassifiers) and wire sawing [6, 8]. Stone preparation for cutting by hole drilling and wedging is justified at sheet deposits with developed vertically and horizontally oriented jointing. In this case, stone preparation takes a single stage, considering layout of joints, which ensures sufficient output of marketable product. In deep quarries, strata are thick and wedges become inapplicable since they cause cleavage of large stone blocks. In beds thicker than 1.5–2.0 m, wedging uses sleeve explosives, non-explosive destructive tools and gassifiers (Fig. 2).

Dynamic-action wedges (sleeve explosives, gassifiers and others) have a common drawback—they induce jointing around the hole, which reduces output of marketable granite blocks of medium and high strength. Based on sawing data (courtesy of Tekhnogranit company, Chelyabinsk), the application of gassifiers reduces 1.5–2 times price and output of natural stone blocks.

Static wedging with non-explosive destructive tools exerts pressure of ~ 1 MPa on hole walls but induces no jointing in the near zone. However, water use in preparing non-explosive destructive mixture results in failure of the tool at a temperature below – 10°C, which prevents from using this method in winter.

Researches (see Fig. 2) showed that for sheet deposits with benches higher than 1.5–2 m, minimization of cost of natural stone cutting is achieved with the combination two-stage scheme, with the first stage of wire sawing to separate a stone block from the rock mass and the second stage of cutting the separated block into marketable blocks using drill rigs to drill lines of holes. This results in higher output of better quality stone blocks as compared with the single-stage hole drilling method.

Thus, in the sheet deposits with bed fractures spaced at 1.5–2.0 m, it is advised to separate stone blocks by holes and mechanical wedges, for greater spaced fractures—the combination of methods is recommended .

No every magmatic deposit is a sheet of beds with horizontal or nearly horizontal extensile fracturing. Sheet deposits have flat dip with vertical longitudinal and transversal steep-grade fractures. For such deposits with complex ground conditions, the basic criterion of economical efficiency of mining is the yield of stone blocks of a preset volume and minimized cost (see Fig. 3).

Survey of the leading mines in Russia and abroad shows that in mining under complex ground conditions, the minimized cost of stone cutting and the maximum possible yield of marketable stone blocks is achieved with the high-bench two-stage mining scheme, when a solid block is separated with a wire saw at the first stage and then this solid block is cut into marketable stone blocks using drill rigs and mechanical wedges.

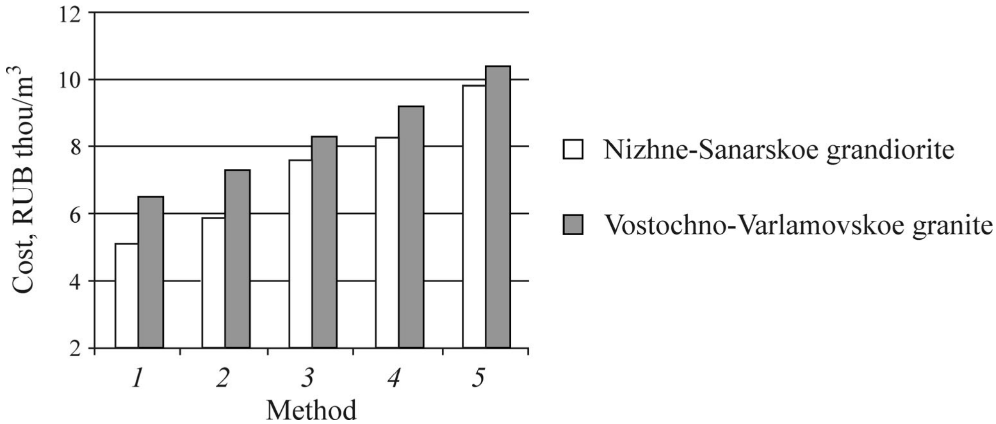


Fig. 3. Estimated cost of dimension stone quarrying with steep and flat systems of fractures using different cutting methods: *1*—combination (wire saw + hole drilling); *2*—wire saw (at 1st and 2nd stages); *3*—holes, mechanical wedges and nonexplosive destruction mixtures; *4*—holes and gassifiers; *5*—drilling-and-blasting.

Since nonorthogonality of steep longitudinal and transversal fractures is less than 15°, shaping of stone blocks is eliminated. Then, overall drilling in cutting-and-shaping (stage 2) makes:

$$L_{\text{drill}} = 2n_k l_k B / l_{\text{drill}},$$

where n_k—number of blocks divided by steep fractures within the linear dimension of a solid block; l_k—spacing of planes of steep fractures; *B*—width of the solid block, m; l_{drill}—spacing of drill holes.

Comparison of stone cutting costs (Figs. 2 and 3) shows that the cost of stone cutting at sheet deposits is 2–3 times less than at the deposits with complex natural fracturing (see Table 1), which is due to the higher yield of marketable stone blocks. Table 1 exemplifies natural stone quarrying in the Ural.

Table 1. Performance of stone cutting under different ground conditions (combination cutting method, conditional annual output 24 thou m^3)

Index	Sheet deposits: bed fractures are nearly horizontal (0–5°), longitudinal and transversal fractures are vertical		Deposits with flat (< 45°) and steep (≥ 45°) systems of fractures		
Deposit	Mansurovskoe	Malyginskoe	Nizhne-Sanarskoe	Sukhovyazskoe	Vostochno-Varlamovskoe
Average loose/hard overburden thickness, m	(1–2)/6	4.2/2.7	(4–12)/(6–10)	(2–3)/(6–9)	(0.5–1.5)/6
Capital expenditures, MRUB.	128.6	127.3	132.8	124.0	137.3
Operational expenditures, MRUB	75.3	73.1	73.8	72.4	78.0
Construction period, years	2.5	1.9	2.3	1.0	2.0
Stone block yield, %	80	75	40	44	30
Cost, thou RUB/m^3	2.4	2.3	5.0	4.7	6.5
Realization value, MRUB	230.8	228.2	126.6	135.6	113.2
General profitableness, %	80.5	79.7	17.8	35.8	13.8
NPV, MRUB	682.1	675.4	160.0	258.4	115.0
GNI, %	35	33	23	28	20
PI	1.3	1.3	1.1	1.2	1.1
Payback period, years	1.1	1.1	3.5	2.1	4.1

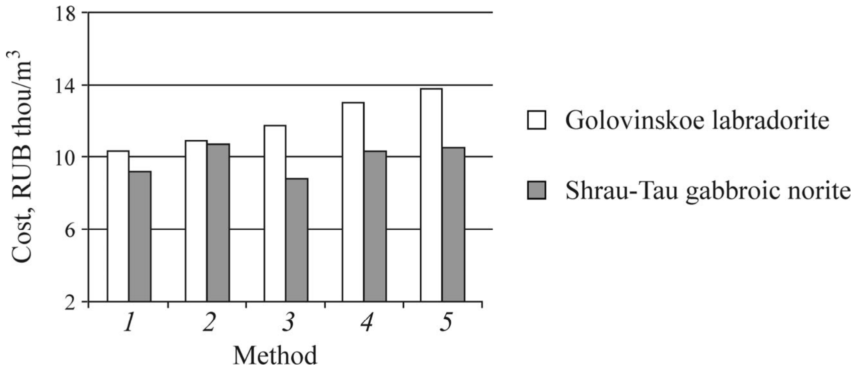
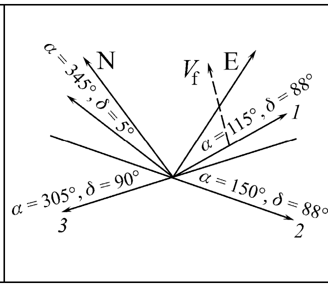
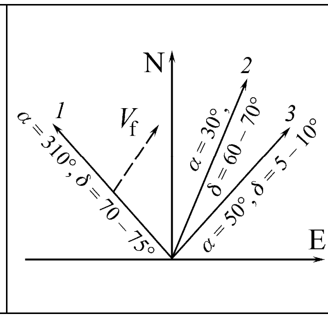
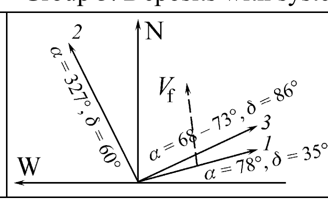
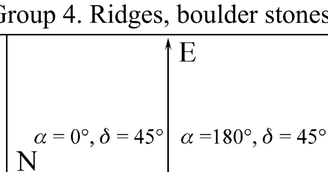


Fig. 4. Estimate cost of dimension stone cutting at heavily jointed deposits (Golovinskoe, labradorite) and block structure deposits (Shrau-Tau, gabbroic norite) using different methods (annual output 24 thou m^3): *1*—combination (wire saw + hole); *2*—wire saw (at 1st and 2nd stages); *3*—holes, mechanical wedges and nonexplosive destruction mixtures; *4*—holes and gassifiers; *5*—drilling-and-blasting.

Table 2. Classification of very strong stone deposits

Quarry, characteristics	Jointing pattern (1, 2, 3—rating of weight of jointing system)	Cutting flowsheet
Group 1: Deposits with system of horizontal fractures (sheet)		
Mansurovsky quarry (granite, Bashkiria). Bed fractures are slightly inclined, nearly horizontal (slope to 5°), longitudinal and transversal fractures are mainly vertical		Spacing of bed fractures is < limit: 1. Generation of initial cut with wire sawing or drilling. 2. Drilling of vertical holes and separation of solid block by wedges or nonexplosive destructive mixtures. 3. Splitting and shaping. Spacing of bed fractures is ≥ limit: 1, 2. Drilling and coupling of pilot holes, vertical cuts with wire saw. 3. Separation of solid block and its splitting. 4. Removal of blocks and waste
Group 2. Deposits with system of bed, step and flat fractures		
Nizhne-Sanarskoe deposit (grandiorites, Chelyabinsk Region). Slightly inclined (10–15°) bed fractures and steep (70–75°) longitudinal and transversal fractures		1. Treatment of a high bench (wire saw, hydraulic hammer). 2. Surface cleaning for visual detection of fractures (crow-bar, shovel, water, compressed air), drilling and coupling of pilot holes, generation of two vertical planes (and one horizontal if necessary) using wire saw, separation of solid block from the mass by a loading machine, pneumo- or hydro-cushions on a damping bedding. 3. Splitting of the solid block into marketable blocks by wedges perpendicular to the fracture planes, shaping. 4. Removal of blocks and waste
Group 3. Deposits with system of steep and flat fractures		
Vostochno-Varlamovskoe deposit (granite, Chelyabinsk Region). No bed fractures, steep and flat longitudinal and transversal fractures (30–75°)		Cutting flowsheet is the same as for deposits of Group 2. A distinction is generation of horizontal separation plane by wire sawing or hole drilling with sleeve explosives (though consistency of the solid block is broken) in any case
Group 4. Ridges, boulder stones and lumps with steep fractures		
Shrau-Tau (gabbroic norite, Bashkiria). No bed fractures, steep longitudinal and transversal fractures (45°)		The work is seasonal. Ridges are cut with wire saw, drill holes, nonexplosive destructive mixtures and mechanical wedges. Tires of loading machines have chains to protect from sharp edges and for operation on wet clay surface

For dimensional stone quarries with developed system of fractures (labradorite), it is efficient to use wire sawing, for block structure stone deposits (dolerite, gabbroic norite)—hole drilling with mechanical wedges and nonexplosive destructive mixtures. Profitability of cutting such stones is explained by their high ornamentality (refer to Fig. 4).

There exist many types of dimension stone deposits. In terms of representative stone quarries in the Ural, a classification has been developed based on a mineral body occurrence, spatial characteristics of fracturing (spacing, strike azimuth α, dip angle δ), which includes four groups (Table 1). In Groups 1–3, stone occurs in the form of subjacent intrusive, dykes; in Group 4—as jointing (boulders, ridges). The classification is adopted as the basis for the procedure of stone cutting method justification.

Group 1 deposits are characterized by a relative high yield of stone blocks. Orthogonality of fracture systems allows stone cutting over vertical planes. Furthermore, it is seldom required to shape blocks as their natural shape is regular. Representative deposits of this group are Mansurovskoe, Tashmurunskoe, Malyginskoe, Yuzhno-Sultaevskoe in Russia, Curu Grey in Finland, Prugnola 1 and Prugnola 2 in Italy. In Prugnola quarries, due to relative young age of granite, layers are from 7 m thick on the initial mining horizons already. Group 2 deposits are Nizhne-Saranskoe (grandiorite), Sibirskoe (granite), Sukhovyazskoe (granite) in Russia; Rosa Porrino in Spain. Group 4 deposits are Vostochno-Varlamovskoe granite deposit in Russia, Luboiu in Italy. Representatives of Group 4 are Severo-Buskunskoe deposit (the only deposit of perfectly black dolerite and gabbroic dolerite in Russia), Shrau-Tau (gabbroic norite), Bulatovskoe deposit (gabbroic dolerite) in Russia.

The procedure developed for justification of a chosen stone cutting method involves:

—optimized labor conditions in accordance with the effective sanitary and safety standards [14];

—use of wheel machines and exclusion of blasting for better consistency of stone [14–16];

—minimized manpower;

—effective utilization of production waste, including weathering zones (hard rock overburden), as a raw material for manufacture of crushed stone; loose overburden—construction of temporary motor roads and urban development;

—closer location of mining and production to a customer (plates, slabs, monuments, border stones, paving stone, crushed stone, etc.);

—feasibility of the variants chosen and decisions made;

—selection of the most efficient technology and quarrying in accordance with the technology from the very start of operation with ensuring high quality and maximum yield of stone blocks;

—orientation of work front in line with the facilitated splitting (cutting) considering anisotropic properties and natural fracturing: the front V_f is oriented orthogonally to the strike azimuth of the main (with the smallest spacing) system of vertical and steep fractures; creation of an access cutting and mining advance in opposite direction relative to the deposit dip;

—use of heavy-duty machines(bucket capacity not less than 8 m^3) for cutting, loading, auxiliary operations, transport of stone blocks and waste; no cranes are employed; no need to clear access ways to faces from waste;

—organization of two or more work fronts for contemporaneous and continuous employment of machines and generation of a temporary storage for marketable stone blocks in mined-out area of a quarry. The storage capacity is not less than 3 months output of a quarry. This allows rock pressure relief in a stone block, elimination of microflaws in finished blocks meant for construction and meeting all requirements: permissible error of 5 cm per side indication of cutting direction on a block. A purchaser selects blocks specifically for its own equipment.

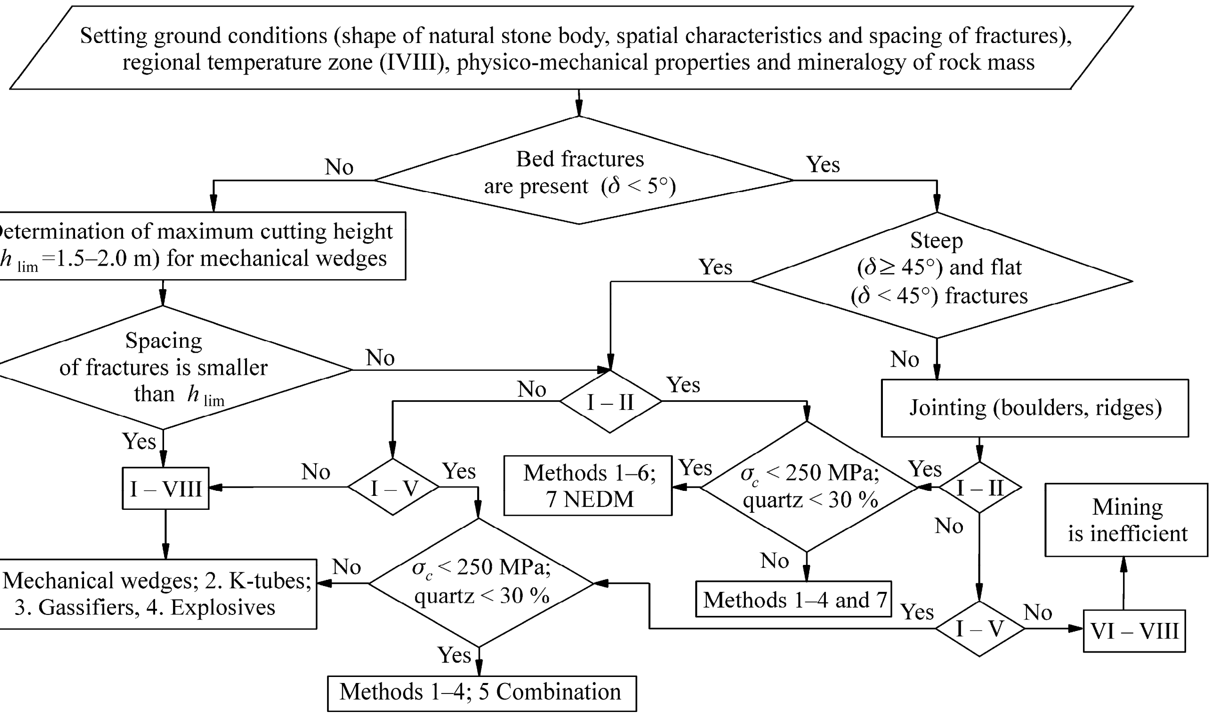


Fig. 5. Chart for choosing high-strength dimension stone cutting methods at preset conditions (NEDM—nonexplosive destructive mixture; σ_c—compression strength).

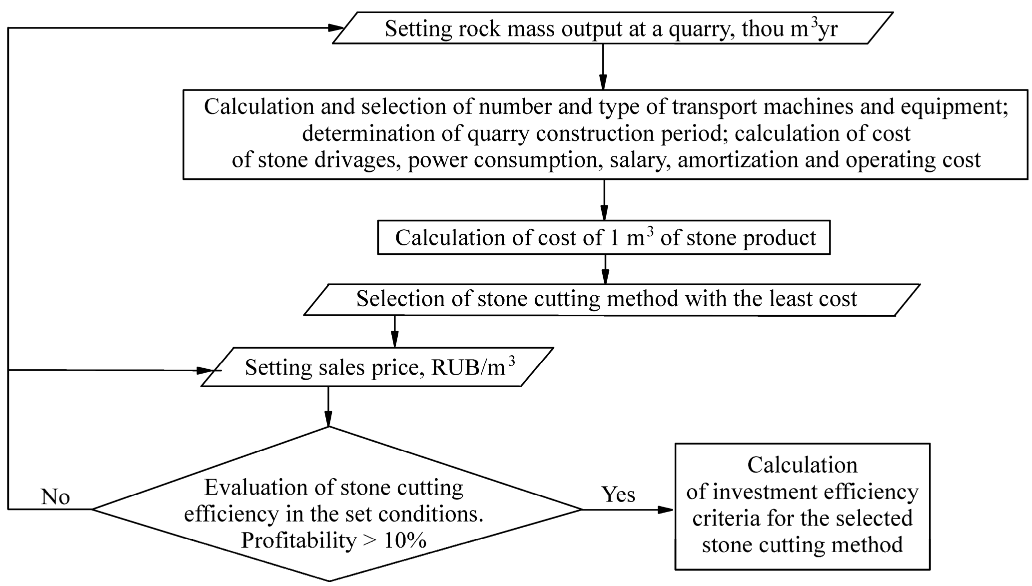


Fig. 6. Chart for choosing efficient high-strength dimension stone cutting method.

Permissible height for block splitting using mechanical and manual drill-and-wedge technique, $h_{\lim}$, so that no diagonal cleavage is possible in large-, mid- and fine-grain abyssal rocks is, respectively, 1.4–1.8, 1.6–2.0 and 1.8–2.4 m [17, 18].

Based on the classification of high-strength dimensions stone deposits (Table 2), the procedure has been developed for choosing a proper cutting method (see Figs. 5 and 6). In accordance with the algorithms in Figs. 5 and 6, the equipment is suggested for areas with different ground conditions (Table 3).

Table 3. Equipment

<table>
<tr><th rowspan="2">Method of high-strength stone cutting</th><th colspan="4">Ground conditions</th></tr>
<tr><th>Group 1, fracture spacing is under h_{lim}</th><th>Group 1, fracture spacing is above h_{lim}</th><th>Groups 2 and 3</th><th>Group 4</th></tr>
<tr><td>Hole drilling and mechanical wedges</td><td>DS, C, HD, MW, AH, WDP, S, LDR, SHH, L, DT/PT</td><td>—</td><td>—</td><td>DS, C, HD, MW, AH, WDP, S, SBR, L, DT/PT</td></tr>
<tr><td>Hole drilling and K-tubes</td><td colspan="2">DS, C, HD, F, WDP, S, LDR, SHH, L, DT/PT</td><td>—</td><td>DS, C, HD, F, WDP, S, SBR, L, DT/PT</td></tr>
<tr><td>Combination (wires sawing and hole drilling)</td><td>—</td><td colspan="2">DS, C, HD, WS, PDR, HCT, MW, AH, WDP, S, LDR, SHH, L, DT/PT</td><td>DS, C, HD, WS, PDR, MW, AH, WDP, S, SBR, L, DT/PT</td></tr>
<tr><td>Hole drilling with nonexplosive destruction mixtures</td><td>—</td><td>DS, C, HD, MW, AH, WDP, S, LDR, SHH, L, DT/PT</td><td>—</td><td>—</td></tr>
</table>

Comment: DS—diesel set (ore power line); C—compressor; HD—hammer drill; WS—wire saw; MW—mechanical wedges and feathers; AH—air hammer; F—Forsit's K-tubes; PDR—pilot drilling rig; HCT—hole coupling tool; WDP—water drainage plant; S—Sandvik drill rig Sandvik (DC, DQ, DX, DP); LDR—line-by-line drilling rig; SHH—shovel and hydraulic hammer; SBR—shovel and bucket-ripper; L—loader (bucket, fork, tipper); DT/PT—dump truck or platform truck.

CONCLUSIONS

Sheet deposits of natural stone with systems of fractures spaced at 1.5–2.0 m are efficient to develop with one-stage cutting with hole drilling and wedges. In thick beds it is better to use two-stage cutting, when the first stage is wire sawing to separate stone and the second state is splitting of the separated stone block into marketable blocks by drill-and-wedge.

It is possible to enhance cutting efficiency in stone quarries with steep and flat systems of fractures using a combination two-stage high-bench scheme when the first stage is wire sawing separation of a large stone block and throwing it on a work site and the second stage is splitting of the block with line-by-line hole drilling.

The developed procedure for choosing an efficient method for high-strength dimensional stone cutting in a specific area of a quarry takes into account geology of stone occurrence, local temperature conditions, physico-mechanical properties and mineralogical composition of a deposit.

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