Determining of rock fracture parameters in directional percussion drilling with drillhole path adjustability

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Abstract: The paper reviews the existing technologies and equipment for drilling in rocks and soil with adjustable path of drillholes. The author describes a new method of percussion drilling and its application prospects. A lab-scale testing installation for physical simulation of rock fracture in drilling by the new method is presented. The force and impact characteristics required for the method implementation are updated.

1. Introduction

Drilling is an integral process of mineral mining. Development and improvement of drilling technologies and equipment will contribute to safer, easier and more efficient production of minerals [1, 2]. One of the promising and lively evolving trends in the drilling technology is controllable path drilling in very strong and medium-strong rocks.

This trend is initiated in the mining science to enhance efficiency of increasingly deeper level mining for higher quality delineation of ore bodies, better heading and shaft sinking using efficient drill and blast pattern designs at lower oversize yield [3, 4].

In the coal mining industry, controllable path drilling is applicable in top coal caving as adjustment of drilling paths can allow considerable reduction in work content of initiation slot drilling. Other than that, directional drilling technique simplifies drilling of service and drainage holes.

Potentially, adjustable path drilling is applicable in oil and gas reservoir engineering, when vertical drilling is complicated due to terrain conditions or can cause major environmental damage. Furthermore, the method can be effective in drilling with by-pass of undrillable zones or different facilities arranged on ground surface [5].

Thus, we need a technology for any-purpose production or shot long hole drilling in mineral mining at the ensured accuracy of path and with capacity to come to a preset point in underground space. Considering the above listed limitations, development of the controllable path drilling technology and equipment for very strong and medium-strength rocks is a relevant and challenging problem.

2. Controllable path drilling technologies and equipment

Hole-making with adjustable path in construction in very strong rocks uses the horizontal direction drilling technology (HDD) [6]. A HDD plant is equipped with special blades (figure 1). Drilling involves rotation of a drilling column and feed of an energy source, which is also a mud fluid. Intended deviation of the drilling path trajectory at a wanted angle is achieved by means of stoppage of rotation, which results in asymmetrical breakage of the hole bottom. As the required offset is gained, rotation is resumed...
with uniform cutting of the bottom hole and with straight-line drilling. The features of this method are difficult navigation of the drilling tool in underground space, as well as complex working environment, i.e. soil and rocks up to medium strength [7].

(a)  

(b)  

**Figure 1.** Horizontal directional drilling: (a) process flow chart; (b) customized drill blade.

In the known method of carving [8], a HDD plant is equipped with a DTH air hammer and a drill bit having an asymmetrical canted front. The bottomhole is cut uniformly at constant rotation of the drilling tool, and rerouting of the path is achieved via nonuniform cutting of the bottomhole in alternate rotation of the drilling column at a certain angle. As against HDD with special blades, carving is applicable in a wider range rocks in terms of their strength though it also has a constraint which is associated with the need to prevent detorsion of the drilling column in reverse rotation, which greatly complicates the structural design and adds to the price of the equipment.

The oil and gas industries perform adjustable path drilling using rotary steerable systems and screw downhole motors with angle adjusters (figure 2).

(a)  

(b)  

(c)  

**Figure 2.** Rotary steerable systems and screw downhole motors with angle adjusters: (a) push-the-bit system; (b) point-the-bit system; (c) screw downhole motor with angle adjuster.

The rotary steerable systems bend drilling paths in three ways: Push-the-Bit—the assembly is pushed off the hole wall [9]; Point-the-Bit—the hole is bent through re-direction of the bit by bending the main shaft relative to the tool; Push-and-Point is a hybrid system combining the two methods above [10, 11].

Directional drilling with RSS most often uses structural configurations with the angle adjuster set between the drive and spindle assemblies with drive shaft running through. The wanted angle is set from the ground surface, by certain orientation of the lower adapter relative to the upper adapter. The range of the angle is from 0 to 2.5 deg.

Controllable path drilling in soil is performed using controllable air drills (figure 3). The drilling path is most commonly changed using differently shaped bits or by diversion of steering force [12-14].
Steering force is generated on air drills by pressure feed in the expanding cell. The cell expands and deflects the positioning elements which push the hole walls. The created steering effort changes the path of drilling. Shaft 2 can rotate in this case, and the process of rotary percussion drilling never stops.

Figure 3. Flow chart of re-direction of air drill.

From the review of the known methods and means for controllable path drilling, we arrive at the conclusion that HDD, carving or RSS need a drill rig to transfer both commands and forces to the tool at the bottomhole via the drilling column. The use of large-size drilling installations is not always possible in the confined space of underground mines. For another thing, with drilling column in a drill hole, a lot of energy is lost in friction between the column and the hole walls and the column can break down. Accordingly, a promising trend in improvement of drilling equipment is engineering of autonomous rod-less drilling assemblies for controllable path drilling in medium and high strength rocks.

3. Controllable path percussion drilling

The Institute of Mining, Siberian Branch of the Russian Academy of Sciences has proposed a new approach to controllable path drilling [15]. Figure 4 illustrates schematically this method. Here, the main implementers are a special rock-breaking tool, air/fluid/or other source-driven percussion facilities, a spacer and a control system to actuate and switch over the percussion facilities.

During drilling, impactors 1 make alternate blows on the sides of rock-breaking tool 2. The percussion facilities may be DTH air drills and mechanism described in [16–18]. Under the action of alternate impacts, the rock-breaking tool rotates in the fore-and-aft plane and breaks the bottomhole. At a certain angle of rotation, switch 4 actuates an opposite impactor to strike the opposite the side of the rock-breaking tool. Holding down, fixturing and pressing of the tool is carried out by aids 5 and 8. Hoses 6 and 7 enable operation and control of the assembly. A special algorithm of operation of impactors allows the change in the drilling path.

Figure 4. A new controllable path percussion drilling method: 1 - impactors; 2 - rock-breaking tool; 3 - sides of the rock-breaking tool; 4 - switch; 5 - slide bars; 6 and 7 - hoses; 8 - spacer.

This method differs from the known technologies by the oblique direction of blows which the impactors deliver to the rock-breaking tool, which reduces the energy intake of the process [19]. By varying the shape of the rock-breaking tool, it is possible to obtain holes of various cross-section: circular, square, rectangular, or slot-like. The other undeniable advantage of the new approach is unnecessity to rotate the rock-breaking tool around the drill hole axis, which eliminates drilling column
from the equipment package. The tool is pressed to the bottom hole and is advanced by the spacer. Moreover, no large-size drill rig is required, which greatly saves the cost of the equipment.

Efficient operating mode of the drilling assembly to implement the least energy-consuming process of breaking in rocks of medium and high strength in case of straightline and directional drilling was determined after applied and basic research findings on rock fracture by the rock-breaking tool of the proposed shape and geometry under the joint effect of static and dynamic loads.

The tool–rock interaction was studied in physical simulation of the effect exerted on rock by the rock-breaking tool under static and dynamic loading on a specially designed testing installation.

4. Lab-scale testing installation for physical modeling of rock-breaking tool–rock interaction

The lab-scale testing installation in figure 5 allows physical simulation of rock fracture using the newly proposed method with simultaneous measurement of all parameters of interest (bend angle, rotation angle of rock-breaking tool, broken rock volume) and concurrent adjustment of parameters, which influence the process (hold-down of rock-breaking tool to bottom hole, unit blow energy, blow frequency, number of blows, etc.).

Figure 5. Testing installation for physical simulation of rock-breaking tool–rock interaction: (a) general view; (b) hold-down gear; (c) shape of drill hole; (d) rock-breaking tool in the drill hole.
The testing installation in figure 5 is composed of a metal shape frame 1 and a rock mass model block 2. The test blocks can be of different size. Gear 3 to anchor and hold-down rock-breaking tool 4 to bottomhole is arranged on the frame. It was pre-set that the hold-down force was changed in the range from 50 to 300 N. At the top of the installation, there is a drop hammering facility 5 intended to deliver calibrated blows to two sides of rock-breaking tool 4. The range of the blow energy was 5–15 J. Before the tests started, an indent of the tool shape was made in in the block to eliminate pre-drilling, which was beyond the scope of the study, and to simulate the process of drilling. Penetration of the tool in the indent was recorded by a high-speed camera at a rate of 480 frames per second. After a series of blows on one side of the tool, broken material was removed from the hole scaled. The average angle of turn of the rock-breaking tool was determined as a ratio of the total angle of turn in the blow series to the number of calibrated blows. The limiting angle of turn of the rock-breaking tool of this size in the hole is 15 deg.

The rock mass model material was sand-and-cement with cement grade CEM I42.5 having the physical and mechanical properties as follows: compression strength 40–45 MPa and density 1800 kg/m$^3$. The block size was $400 \times 400 \times 400$ mm. Such material simulates rocks of medium strength, is uniform, has no inclusions, can provide better repeatability of the experiment and makes it possible to adjust and approve the experimentation procedure initially.

First, a series of blows was made on one side of the rock-breaking tool at a certain blow energy and hold-down pressure. Then, the bottomhole was cleaned, chips were removed and scaled. The process was video recorded. After processing and interpretation of the test data, rock drilling efficiency in the new method will be assessed using the procedure from [20, 21] and compared with the conventional rotary percussion drilling technology [22].

After the first test series, it has been found that at the hold-down pressure of the rock-breaking tool to the bottomhole of 300 N, the tool jumps off the bottomhole and slips without damaging and cutting of the test material. Figure 6 presents the graph of the average tool turn angle versus its hold-down pressure. At the hold-down of 250–300 N and blow energy more than 5 J, the tool penetrates the block and drilling takes place. Thus, feasibility of the approach is proved, but it is required to modify the testing installation to implement higher axial hold-down pressure of the rock-breaking tool to the bottom hole and higher energy of unit blow. An increase in the hold-down results in a decrease in the average turn of the bit at fulfillment of penetration as the pressure neutralizes jump-off of the tool from the bottom hole.

![Figure 6. Average turn angle of rock-breaking tool versus its hold-down pressure to bottom hole: (a) blow energy 10 J; (b) blow energy 5 J.](image)

5. Conclusions
1. The review and discussion of the existing controllable path drilling technologies and equipment for rocks and soil has revealed shortcomings of them.
2. The new method proposed for the directional drilling features adjustability of the drilling path and the capacity of the method to drill holes of differently shaped cross-section.

3. Feasibility of the new rock drilling method is proved on a laboratory scale. The force and impact values required for implementation of the new drilling method are refined, and appropriate modification of the testing installation is planned.

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References
[1] Karpov V N, Timonin V V, Konurin A I and Chernienkov E M 2019 Improvement of drilling efficiency in underground mines in Russia, IOP Conference Series Earth and Environmental Science DOI: 10.1088/1755-1315/262/1/012024
[2] Kondratenko A S, Timonin V V, Karpov V N and Popelyukh A I 2018 Ways to improve rotary-percussive drilling efficiency Gorny Zhurnal 5, pp 63–68
[3] Mametiev L E, Ananiev A N, Lyubimov O V and Zhaldin D V 2000 Prospects for horizontal drilling in underground mines, Gorn Inform-Analit Byull, 2000 11
[4] Levinson L M, Akbulatov T O and Akchurin Kh I 2000 Borehole Bending Adjustment: Teaching Aid, Ufa: UGNTU
[5] Norman J. Hyne 2001 Nontechnical Guide to Petroleum Geology, Exploration, Drilling and Production. 2nd Edition Penwell Corp.
[6] Serebrennikov A A 2020 Laying Underground Engineering Communications with Horizontal Directional Drilling: A Training Manual Moscow: KNORUS
[7] Kondratenko A S, Timonin V V and Patutin A V 2016 Prospects for directional drilling in hard rocks Journal of Mining Science 52 1 pp 129–134
[8] Maksimov A S 2018 Improving the efficiency of a horizontal directional drilling rig in difficult soil conditions Proc. II International Scientific and Practical Conference of Students, Graduate Students and Young Scientists Omsk: SibADI pp 46–48
[9] Push-the-Bit RSS—Weatherford. Available at: https://www.weatherford.com/en/products-and-services/drilling/drilling-services/rotary-steerable-systems/push-the-bit-rss/
[10] Point the Bit Rotary Steerable Systems—Schlumberger. Available at: https://www.slb.ru/
[11] Point+Point—Halliburton. Available at: https://www.halliburton.com/
[12] Danilov B B, Smolyanitsky B N and Cheshchin D O 2019 Design parameters of the device for adjusting a trajectory of pneumatic puncher motion in soil IOP Conf. Ser.: Earth Environ. Sci. 262 012012
[13] Danilov B B, Smolyanitsky B N, Chansyhev A I and Cheshchin D O 2018. Determination of pneumatic puncher turn radius during change of its motion path in solid Journal of Mining Science 54 3 pp. 397–403
[14] Danilov B B, Smolyanitsky B N and Cheshchin D O 2015 Justification of basic diagrams of horizontal drilling deflectors Journal of Mining Science 51 3 pp 553–561
[15] Timonin V V, Alekseev S E, Chernienkov E M 2018 Patent US2675614A Method of shock drilling
[16] Timonin V V DTH air hammers for underground mines. Gorn. Oborud. Elektromek. 2(11) pp 13–17
[17] Timonin V V, Alekseev S E, Kokoulin D I, Kubanychbek and Chernienkov E M 2018 Air distribution analysis in DTH air hammer with valve–piston couple Interexpo Geo-Sibir Conf. Proc. 6 pp 207–217
[18] Timonin V V, Alekseev S E, Kokoulin D I, Kubanychbek B and Chernienkov E M 2018 Influence of part-to-part gaps in air distribution system on operation of DTH hammer IOP Conference Series Earth and Environmental Science DOI: 10.1088/1755-1315/262/1/012073
[19] Pokrovsky G N and Zakablkovsky N G 1976 Analysis of rock fracture process under oblique impact as applied to drilling *Transfer of Impact and Percussive Machines* pp 51–65 (in Russian)

[20] Timonin V V and Karpov V N 2016 Assessment of rock failure process under percussion–rotary drilling *Fundament. Prikl. Vopr. Gorn. Nauk* vol 3 2 pp 172–176

[21] Karpov V N, Timonin V V, Tkachuk A K, Konurin A I et al 2018 Patent RU2674350C1 Acoustic test of impact of percussion tools of mining and construction machines on geomedium

[22] Oparin V N, Timonin V V, Karpov V N, Smolyanitsky B N 2017 Energy-based volumetric rock destruction criterion in the rotary–percussion drilling technology improvement *Journal of Mining Science* vol 53 6 pp 1043–1064