Experimental investigation of double scroll cutting pattern by using button cutting tool of raise boring machines

H Copur¹, A Shaterpour-Mamaghani¹, A Gumus¹, D Tumac¹, C Balei¹, A Kocbay², T Erdogan³, E Avunduk¹

¹ Department of Mining Engineering, Istanbul Technical University, Istanbul, Turkey
² General Directorate of State Hydraulic Works, Ankara, Turkey
³ Sargin Construction and Machinery Industry Trade Inc., Ankara, Turkey

mamaghani@itu.edu.tr

Abstract. Full-scale linear cutting test is one of the most preferred and reliable methods for performance prediction of mechanical miners. Raise Boring Machines (RBMs) are one of these mechanical miners which are commonly used for drilling / excavation of shafts for different purposes in mining and tunneling projects. This study aims at investigating experimentally double spiral (scroll) cutting pattern in raise boring machine. Full-scale linear cutting tests are performed by using button (kerf) cutting tool. The tests are performed at line spacing of 25 mm and varying depths of cut per revolution by using two hard rocks (diabase and granodiorite) that were obtained from the Yusufeli Dam and HEPP project site. The average and maximum normal, rolling and side forces; specific energy; yield; and coarseness index are measured in each cut. The study indicates that optimum ratio of line spacing to depth of cut per revolution are obtained as 8.3 and 4.2 for diabase and granodiorite samples, respectively.

1. Introduction

Shafts have an important role as access, transportation, and ventilation in mining, tunneling, and underground construction. In recent years, the raise boring method is widely used for shaft excavation in different projects. Raise boring provides a safe means of excavating a circular hole between two levels of a mine without the use of explosives. A raise boring machine (RBM) is set on a platform on the upper level to drill a small hole (around 230-350 mm) compared to reaming diameter, known as the pilot hole, up to the cavity below. Once the drill has been completed, the pilot bit is removed and is replaced by a reamerhead, of the desired diameter of the shaft, which is rotated and raised back toward the upper level. The drill cuttings from the reamerhead fall to the bottom of the hole and the reaming process creates a cylindrical hole with smooth walls. Safety, cost reduction, and faster advance rate are the important advantages of this method. However, this method possibly encounters serious troubles in fractured or weathered rock masses, such as the collapse of shaft walls, stoppage of excavation, and breakage of tools. These troubles lead to an extension of construction period and an escalation of budget. Therefore, it is essential to understand the rock mass conditions around a shaft before or during excavation [1].

The first RBMs were developed in Germany and Japan in about 1950 [2]. In 1962, the first drill rod of RBM was designed in US by the Robins Company. Although some researchers have paid attention to performance prediction of RBMs, little is known about the selection of suitable RBM for different geological conditions to obtain optimum performance. Morris [3] developed a semi-empirical method
of predicting the boring rate and cutter life. In his method, button penetration index with the other factors were used to predict the machine performance. Wilson and Graham [4] summarized their experience during raise boring operation in gold mines of South Africa. They investigated the performance of RBM excavated in shale and conglomerate rocks and the relationship between rate of penetration and thrust. Bilgin [5], Dollinger et al. [6] and Bilgin et al. [7] stated that penetration index obtained from indentation tests could be used to estimate the RBM performance. A research group from the Mining Engineering Department of the Istanbul Technical University investigated RBM performance in different shaft projects in Turkey ([8], [9], [10], [11]). In these studies, based on the limited data, they used some currently existing empirical models and also suggested some additional empirical models based on bit trace on the rock surface to estimate performance and operational parameters of RBMs. In addition, Shaterpour-Mamaghani et al. [12] attempted to suggest a new empirical performance estimation model for an RBM used in different geological conditions. Laboratory rock cutting test, together with deterministic estimation and/or computer simulation, is also one of the most reliable methods for predicting performance of mechanical miners. There are also limited studies on performance prediction of RBMs based on rock cutting tests ([13], [14]). Those cutting experiments were performed in laboratory by rotary cutting machines in a load-controlled manner (constant load, variable penetration) and provided quite limited data. Consequently, the selection and design of RBMs based on the project and excavation environment, the accurate predicting of their performance and the optimization and improvement of performance become very important in terms of project economics in the feasibility and planning stages.

The fundamental purpose of this study is to experimentally investigate the cutting performance of a button cutter used on RBM by applying double spiral (scroll) cutting pattern, which is common for these machines; firstly, the operational and performance parameters of RBM recorded/calculated during field visit of Yusufeli Dam and HEPP project in Turkey. Then, two block rock samples (diabase and granodiorite) were taken from the project site. The full-scale linear cutting tests were performed at line spacing of 25 mm and varying depths of cut per revolution on these rock samples.

2. Field studies
The Yusufeli Dam is an arch dam under construction on the Coruh River near Yusufeli in Artvin Province within the eastern Black Sea region of Turkey. The rockfill dam has a height of 270 m from the foundation and the total capacity of reservoir is about 2.2 billion m$^3$. In this project, the final diameter of the power tunnel will be 10.80 m. Due to the problems in transportation of the excavated material (muck), the project management decided to use a RBM manufactured by Sandvik (Rhino 1088 DC) for excavation of a small diameter hole (2.44 m). Then, using the drill and blast method, the drilled hole will be enlarged to the final diameter. The length of the power tunnel is 130 m.

Table 1. Recorded / calculated operational and performance parameters during the reaming operation.

| Parameters                        | Granodiorite | Diabase |
|-----------------------------------|--------------|---------|
| Rotational speed (rev/min)        | 4.0          | 4.0     |
| Consumed reamerhead torque (kNm)  | 64.0         | 57.0    |
| Consumed reamerhead power (kW)    | 27.25        | 24.17   |
| Field specific energy (kWh/m$^3$) | 16.53        | 13.50   |
| Instantaneous penetration rate (m/h)| 0.44         | 0.49    |
| Unit penetration (mm/rev)         | 1.80         | 2.02    |
| Net reaming thrust force (kN)     | 1074         | 937     |

The RBM performance data, such as rotational speed, consumed reamerhead torque, net reaming thrust (pulling) force, unit penetration rate, and field specific energy were recorded/calculated during...
the reaming operation (table 1). The RBM excavated 130 m of diabase and granodiorite rocks between the depth of 637 m (surface level) and 507 m (underground level). The pilot hole drilling and reaming diameters of this vertical shaft were 0.31 and 2.44 m, respectively. The machine began drilling the pilot hole on January 31st 2016 and completed on February 13th 2016. The average advance rate was 8.69 m/day. In addition, the reaming operation started on February 15th and the enlargement of the 130 m length shaft ended on March 22nd 2016. The mean advance rate in reaming was 3.83 m/day. Figure 1 shows the daily and cumulative advance rate in pilot hole drilling and reaming operations. The daily work schedule included a 12-hour shift for drilling and reaming the pilot hole. Additionally, an operator worked on this raise bore operation.

![Figure 1. Daily and cumulative advance rate in pilot hole drilling (left) and reaming (right) operations.](image)

3. Full-scale linear cutting test

3.1. Equipment, procedures and parameters

The block samples obtained from Yusufeli Dam and HEPP project were used for performing full-scale linear cutting tests with a 304.8 mm (12” inch) in diameter button (kerf) cutter having a tip width of ~35 mm (figure 2). The cutter used in the tests is only a single slice of a real life multi-row button cutter that is the one taken from the middle row (with average diameter) and it looks like a single disc cutter with insert bits. The reason using only one slice is that it is considered that the forces acting on a real-life multi-row button cutter would exceed the capacity of the linear cutting machine and give damage to it. It is considered that it is possible to convert the force values acting on a single slice to the force values acting on a real-life multi-row button cutter; performing consecutive cutting tests in certain line spacing values would duplicate the multi-row cutting action of a real-life multi-row button cutter. The button cutter is calibrated with the dynamometer prior to linear cutting tests by applying certain loads with a hydraulic jack and measuring the load from the voltage output of the load cell. Loading of the cutter is performed in an angled direction in order to produce simultaneous signal outputs from all four channels of the load cell. This calibration procedure is repeated at least three times to ensure system repeatability. The block samples were prepared with sizes of up to 60×70×60 cm (length, width, height). The blocks were placed in the metal sample boxes, then fast-curing concrete (C20 concrete) was used to provide the necessary confinement during testing. In this study, the full-scale linear cutting test machine found in the Excavation Technology and Mining Machinery Laboratory of the Mining Engineering Department of Istanbul Technical University was used. A picture of the full-scale linear cutting test machine is presented in figure 2. Thanks to a computer-assisted data collection system and an aluminum dynamometer, cutter forces up to 500 kN perpendicular to the cutting direction, 300 kN parallel to the cutting direction and 100 kN in the lateral (side) direction can be measured. The forces acting to the cutters were measured by the strain gauge bridges on the 4 feet of the dynamometer. The tool, tool
holder and load cell can move up and down with a mechanical gear to adjust the cutting depth. The cutting velocity and line spacing of the tool can be adjusted by hydraulic cylinders as required.

![Image of cutting test rig](image.png)

**Figure 2.** The button (kerf) cutter (SBC) used and picture of the full-scale linear cutting test rig.

The parameters in the full-scale linear cutting experiment are divided into three main groups as independent variables, dependent (measured or calculated) variables and constant variables. Independent variables included rock type, cutter type, cutting depth and cutting mode (relieved or unrelieved). Dependent variables included average and maximum forces (normal, rolling and side), specific energy (debris weight and cutting length), bursting and breaking mechanisms (based on calculations and observations), and size distribution of debris formed as a result of cutting and Coarseness index (CI). The parameters kept constant in the cutting experiments included rock samples bedding direction, cutting sequence (single-start), cutting speed and data collection frequency. The bedding direction of the rock samples was selected as perpendicular to the cutting direction. In all the experiments, the cutting speed was chosen as 127 mm/s. In addition, the data sampling rate was chosen 1000 Hz. Each test was replicated at least four times.

Generally, single or double spiral cutting patterns are applied in mechanized excavation machines. Double spiral cutting pattern is used in raise boring machine. The single and double spiral cutting patterns are shown in figure 3 [15]. In the single-spiral cutting pattern, the tool in each pass (cutting levels as shown in figure 3), cuts in the same cutting trajectory as that of the previous pass, whereas in the double spiral cutting pattern, it cuts along the midline (as staggered) between the cutting trajectories of the previous pass. A tool in the double-spiral cutting pattern sweeps a symmetrical area, so the lengths of the right-hand and left-hand side cracks (broken lines) created by Tool A (empty triangle) are theoretically equal ([16], [17]). In this study, double spiral cutting pattern is applied in the cutting test, then based on the results of these tests, the optimum depth of cut has been found for the two tested rocks.

A schematic drawing of the orthogonal force components (normal, rolling and side forces) acting on button tool is presented in figure 4. The rolling force, acting parallel to the horizontal plane and tool travel (cutting) direction, is directly related to the torque requirement of a mechanical miner such as raise borer and is used for estimating the specific energy. The normal (thrust) force, acting perpendicular to the horizontal plane and tool travel direction, is used to estimate the required effective mass and thrust of the mechanical miner and keep the tool at a desired depth of cut (penetration). The side force, acting perpendicular to the tool travel direction and to the direction of the normal and rolling forces, is used along with the normal and rolling forces to balance the tool faking for minimizing the machine vibrations [15]. An example showing the variation of the forces acting on the button cutter with the cutting length (or cutting time) is presented in figure 4.

One of the most important parameters used to calculate the cutting system performance and determine the optimum cutting geometry is the specific energy [18].
It is defined as the energy (work) required to excavate a unit volume or mass of rock [19] and is estimated by equation 1:

\[
SE = \frac{FC}{Q}
\]  \hspace{1cm} (1)

where \(SE\) is the specific energy (MJ/m\(^3\)), \(FC\) is the cutting force acting on the tool (kN), and \(Q\) is yield or rock volume cut in the unit cutting length (m\(^3\)/km). Using the optimum specific energy value, the net cutting rate of an excavation / cutting machine can be estimated by equation 2 ([20], [21], [22], [7]):

\[
ICR = k \frac{P}{SE_{opt}}
\]  \hspace{1cm} (2)

where \(ICR\) is the instantaneous cutting rate (m\(^3\)/h), \(P\) is the cutterhead power (kW), \(SE_{opt}\) is the optimum specific energy usually obtained from full-scale linear cutting tests (MJ/m\(^3\), which should be converted to kWh/m\(^3\) to be used in equation 2), and \(k\) is the total system efficiency coefficient, that is related to the cutting tool type and geometry, rock type and its properties, cutting conditions (line spacing, depth of cut, cutting pattern, cutting speed, etc.) and the type of machine.

In order to determine the cutting depth and the distance between the two cut lines parameters, the applied values in the field and the capacity of the cutting rig in the laboratory, and the distance of the button tips in RBM reamerhead are taken into consideration, respectively. Cut spacing (\(S_C\)) parameter was taken as 5 cm (50 mm) in cutting tests (\(S_C = 2S_I\)). The applied depths of cut per revolution are summarized in table 2 for each rock sample and a double spiral cutting pattern.
Table 2. Depths of cut and spacing applied for double-spiral cutting pattern and rock samples tested.

| Rock sample | s_l (mm) | s_c (mm) | d_s (mm/spr.) |
|-------------|----------|----------|---------------|
| Granodiorite| 25       | 50       | 1  2  3       |
| Diabase     | 25       | 50       | 1  1.5  2     |

s_l: line spacing, s_c: cut spacing, d_s: depth of cut per spiral.

3.2. Results and discussion

Figure 5 shows some pictures of rock cutting tests in granodiorite and diabase samples. The trimmed surface and double spiral cutting patterns are shown in these pictures.

![Granodiorite Trimmed surface](image1)

![Diabase Trimmed surface](image2)

Figure 5. Different pictures of rock cutting test in the granodiorite and diabase samples.

The variation of average FN and FR with d_R are presented in figure 6. As seen, FN and FR increased with increasing d_R for the tested rocks, as expected on the basis of the rock-cutting science. The variations of the ratios of F’N/FN and F’R/FR with d_R are given in figure 7. The variations of SE with the ratio of s_l/d_R are given in figure 8. The optimum or minimum specific energy (SE_{opt}) is obtained as 33.74 and 29.04 kWh/m³ for granodiorite and diabase, respectively. In addition, the optimum ratio of s_l/d_R for these rocks are 4.2 and 8.3, respectively.

4. Conclusions

The experimental results indicated that the specific energy values obtained from double spiral cutting tests in granodiorite are higher than those obtained in diabase (at optimum depth of cut per revolution). Furthermore, the optimum ratios of line spacing to depth of cut per revolution are obtained as 8.3 and 4.2 for diabase and granodiorite samples, respectively.
Figure 6. Variation of average normal and rolling forces with depth of cut per revolution.

Figure 7. Variations in the ratios between maximum normal force and average normal force and maximum rolling force and average rolling force with depth of cut per revolution.

Figure 8. Variation of the specific energy with the ratio between line spacing and depth of cut per revolution.

Acknowledgments
This study summarizes some of the results of PhD research work carried out by Aydin Shaterpour-Mamaghani. Scientific and Technological Research Council of Turkey (TUBITAK) is thanked for its support in Project MAG-217M729. The authors are grateful to the support of DSI (State Hydraulic Works), Joint-venture Limak-Cengiz-Kolin, and Sargin Construction and Machinery Industry Trade Inc.; this work would be impossible without their support.

References
[1] Hashiba K, Fukui K, Kitahara M, Kiyama R and Okutsu K 2018 Estimation of Rock Mass Conditions during Shaft Excavation with the Raise Boring Method. In: 10th Asian Rock Mechanics Symposium. Singapore, 6 p.
[2] Bennett RD 1985 State-of-the-art construction technology for deep tunnels and shafts in rock.
Technical Report GL-85-1, US Army Corps of Engineers.

[3] Morris RI 1969 Rock drillability related to a roller cone bit. In: Proceedings of society of petroleum Engineers of AIME. Paper No. SPE 2389, pp 79-86.

[4] Wilson JW and Graham PC 1972 Raise-boring experiences in the gold mines of the Anglo-American corporation group. Journal of the South African Institute of Mining and Metallurgy, October, pp 103-115.

[5] Bilgin N 1989 Applied Rock Cutting Mechanics for Civil and Mining Engineers. 1st ed. Birsen, Istanbul (In Turkish).

[6] Dollinger GL, Handewith HJ and Breeds CD 1998 Use of the punch test for estimating TBM Performance. Tunnelling and Underground Space Technology, 13 (4), pp 403-408.

[7] Bilgin N, Copur H, Balci C 2014 Mechanical Excavation in Mining and Civil Industries. 1st ed. CRC Press, New York.

[8] Shaterpour-Mamaghani A, Bilgin N. 2016 Some contributions on the estimation of performance and operational parameters of raise borers – A case study in Kure Copper Mine, Turkey. Tunnelling and Underground Space Technology, 54, pp 37-48.

[9] Shaterpour-Mamaghani A, Bilgin N, Balci C, Avunduk E, Polat C 2016a Predicting Performance of Raise Boring Machines by Using Empirical Models. Rock Mechanics and Rock Engineering, 49 (8), pp 3377-3385.

[10] Shaterpour Mamaghani A, Erdogan T, Engin D, Bilgin N 2016b Evaluation of the Performance of a Raise Boring Machine in Pb-Zn Underground mine, Balya, Turkey. World Tunnel Congress, San Francisco, USA.

[11] Shaterpour-Mamaghani, A, Copur H, Bilgin N, Kochay A, Erdogan T 2017 Raise Boring Machine performance in the Yusufeli Dam and HEPP Project. World Tunnelling Congress (WTC2017), Bergen, Norway.

[12] Shaterpour-Mamaghani A, Copur H, Dogan E, Erdogan T 2018 Development of new empirical models for performance estimation of a raise boring machine. Tunnelling and Underground Space Technology, 82: pp 428-441.

[13] Takaoka S, Hayamizu H, Misawa S, Kuriyagawa M 1973 Studies on the cutting of rock by rotary cutters. Part II: Cutting using a spherical chip and a milled tooth cutter. Tunnels and Tunneling, 5 (3): pp. 276-277, 279, 281-283.

[14] Linqvist PA 1982 Energy consumption in disc cutting of hard rock. In: Tunnelling '82: papers presented at the third international symposium, organized by the Institution of Mining and Metallurgy, (ed) M.J. Jones, London: The Institution of Mining and Metallurgy, pp 189-196.

[15] Copur H, Bilgin N, Balci C, Tumac D, Avunduk E 2017 Effects of Different Cutting Patterns and Experimental Conditions on the Performance of a Conical Drag Tool. Rock Mech Rock Eng. 50: pp 1585–1609.

[16] Hurt KG and Laidlaw DD 1979 Laboratory comparison of three rock cutting tools. Tunnels &Tunneling, May, 13–16.

[17] Hurt KG and Evans I 1980 A laboratory study of rock cutting using point attack tools. Proc. the 21st Symposium on Rock Mechanics, Ed. D. Summers, pp 112–122.

[18] Roxborough FF 1973 Cutting rock with picks. The Mining Engineer, June, pp 445-452.

[19] Pomeroy CD 1963 Breakage of coal by wedge action: factors affecting breakage by any given shape of tool. Colliery Guardian, November 21: 642–648; November 28, pp 672–677.

[20] Rostami J, Ozdemir L, Neil DM 1994 Performance prediction: a key issue in mechanical hard rock mining. Mining Engineering 46, pp 1263–1267.

[21] Copur H, Tunedemir H, Bilgin N, Dincer T 2001 Specific energy as a criterion for the use of rapid excavation systems in Turkish Mines. IMM Trans a Mining Tech 110(A), pp 149-157.

[22] Rostami J 2011 Mechanical rock breaking. In: Darling P (ed) SME mining engineering handbook, 3rd edn. Chapter 7.1, Society for Mining, Metallurgy and Exploration Inc., pp 417–434.