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Evaluating RBM performance considering the geometric parameters of the raise borer machine and the geomechanical properties of the rock

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Abstract

In recent years, there has been a tendency towards mechanized drilling due to safety, high rate and efficiency, and environmental compatibility. Raise Boring Machines (RBM) are used for the mechanized drilling of shafts and other inclined structures in civil and mining projects. Choosing the type of RBM and accurately estimating the functions are the main parameters that affect the cost estimation and planning of mining and construction projects. This study aims to calculate the RBM performance considering the geometric parameters of drilling and based on the geomechanical properties of the rock. In this research, drilling the chief shaft in the Azad Dam in Iran has been evaluated using theoretical approaches and the cutting geometry of cutters. Shaft depth and diameter are 510 and 1.5 meters, respectively. The findings of this study showed that the rates of thrust force, machine power, and predicted torque are 4116KN, 125KW, and 199KNm, respectively, which are close to the actual value and proportional to the capacity of RBM. As a result, the device's operating parameters have been compatible with the characteristics of the rock mass. Results showed that the rock's uniaxial compressive strength and the roller cutter's characteristics could determine the thrust rate behind the spindle and the amount of torque required. However, the accuracy and reliability of the proposed models should be improved with different rock types and RBMs with different sizes and capacities.

Keywords: *Azad Dam, Drilling penetration rate, Raise borer machine, Roller cutter, Compressive strength.*

1. Introduction

Modern societies must dig the earth's crust for mining and construction activities. Human intervention in natural energy resources has expanded and encouraged societies to develop knowledge and technology with increasing energy needs. With advances in technology, drilling activities are also increasing. In addition to the traditional blast hole and blasting technique, mechanized drilling was invented. The drilling industry is becoming more competitive and demanding efforts to improve safety and reduce costs. There are many variations in underground drilling conditions; therefore, it is difficult to achieve the highest efficiency. Field experience usually determines the field for activity in a range; however, laboratory tests are costly and time-consuming. Therefore, optimal determination of drilling techniques and parameters with minimal engineering effort and drilling experience is essential (Bilgin et al. 2013).The RBM is used for drilling shafts and other vertical structures in mining and civil engineering for transportation, ventilation, hydropower, and other applications (Shaterpour-Mamaghani et al. 2016). The penetration rate is the most significant drilling parameter based on which other parameters are optimized. The bit penetration rate in the drilling depends on the drilling area in time, and many factors affect it. It is impossible to study the actual effect of one parameter on the penetration rate without considering the effect of other parameters (Lummus and Azar 1986).

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Some of these parameters operate linearly, and increasing or decreasing one parameter causes another to increase or decrease (Paiaman et al. 2009).
Several factors play a role in determining the actual drilling penetration rate, some of which are controllable and some dependent on nature and uncontrollable. The controllable factors are the collar diameter, the type and design of the drill bit, the weight on the bit, and the rotational speed. Also, uncontrollable factors include formation characteristics, rock strength, lateral limiting stresses, porosity, and rock permeability.
Maurer (1962) proposed a penetration rate equation based on the conical roller type considering the igneous rock type in which all rock fragments are removed between the bit teeth. Bingham (1965) presented the drilling penetration rate based on laboratory results. In the given equation, he considers the weight of the bit threshold to be insignificant. The researcher considers the penetration rate as a function of the rotational speed and the operating weight of the bit. Shaterpour-Mamaghani et al. (2018) obtained the drilling capability index using dividing the hydraulic pressure load of a tungsten carbide cone body into a smooth surface of the rock. Graham (1976) propounded the estimate of the penetration rate of the TBM machine for rocks with a compressive strength in the range of 140-200 MPa. Farmer and Glossop (1980) obtained the penetration rate based on data from six tunnel projects whose model was similar to Graham's.
Kirsten (1983)'s approach to the tunneling quality index of the Norwegian Institute of Geotechnics (Q system)

was proposed to determine Qr, modified for the RBM. Pigott (1985) suggested cheaper and better drilling using an RBM for medium and low-strength rocks. McCracken and Stacey (1989) used the rock quality index to assess the geotechnical risk for drilling shafts with an RBM. Zhiqiang (2004) provided experimental relationships to predict the RBM performance, and Liu and Meng (2015) provided relations for the cutter head's rotational speed amount and the RBM's torque. Visser (2009) stated that rock formation with different geological conditions has a risk assessment factor for RBM drilling activity. In such cases, a detailed geotechnical assessment is performed by estimating the quality of RBM's rock for shafts with greater depth and diameter. Bilgin et al. (2013) used the penetration index obtained from the penetration test to estimate the RBM performance. Shaterpour-Mamaghani et al. (2016) presented the performance estimation of an RBM using the mechanical properties of rock. In another research, Shaterpour-Mamaghani et al. (2018), in a study on the drilling of ventilation shafts in the lead and zinc mine of Ballia, Turkey, using the RBM, provided relationships for the RBM penetration rate.

Mechanized drilling for deep shafts is an essential alternative to traditional drilling. In traditional blasting drilling, only a small part of the explosion energy is used to break the rock. It has adverse effects such as recoil, ground and surface vibration, and wall stability (Mishra et al. 2018; Karimiazar et al. 2023; Dehghan and Yazdi 2023). As a result of the explosion, a sudden change of waves is created in the surrounding environment. These waves can cause severe damage to the environment around the rock mass. For this reason, blasting should be designed based on the geomechanical properties of the rock. Therefore, designing an optimal blast requires detailed information on rock properties.

Geological conditions and geomechanical properties of the rock mass are among the most significant parameters that have always overshadowed the implementation of mechanized drilling and can play a substantial role in choosing the right type of drilling machine (Singh et al. 2004). Peck and Lee (2008) consider drilling deep shafts to require a detailed geotechnical evaluation in the drilling of the RBM based on the McCracken and Stacey (1989) technique. Everell (1972) expressed the correlation between rock penetration rate and uniaxial compressive strength by examining the RBM's operating parameters. Therefore, RBM performance results are derived from a theoretical model developed from disc cutting penetration geometry and rock mechanics concepts. Many approaches are proposed to optimize drilling parameters and maximize the penetration rate, and most of them specify the point that determines the maximum penetration rate. Although these approaches increase drilling performance, they cannot accurately assess the penetration rate. Optimizing drilling parameters must have a particular drilling system and a unique formation. In most research, predicting the penetration rate of the RBM is based on theoretical and experimental research.

All studies have estimated the penetration rate and efficiency of the RBM and how the rock mass and the characteristics of the drilling machine interact. However, in a realistic model, the features of the machine and the rock mass must be highly accurate. In this research, the geometric properties of the drilling bit in the fracture structure are used and based on this, the penetration rate of the RBM is obtained theoretically. Earlier, existing methods based on optimum specific energy have been performed experimentally or based on a series of existing tables. Also, the theoretical penetration rates obtained in this research are compared to previous experimental methods.

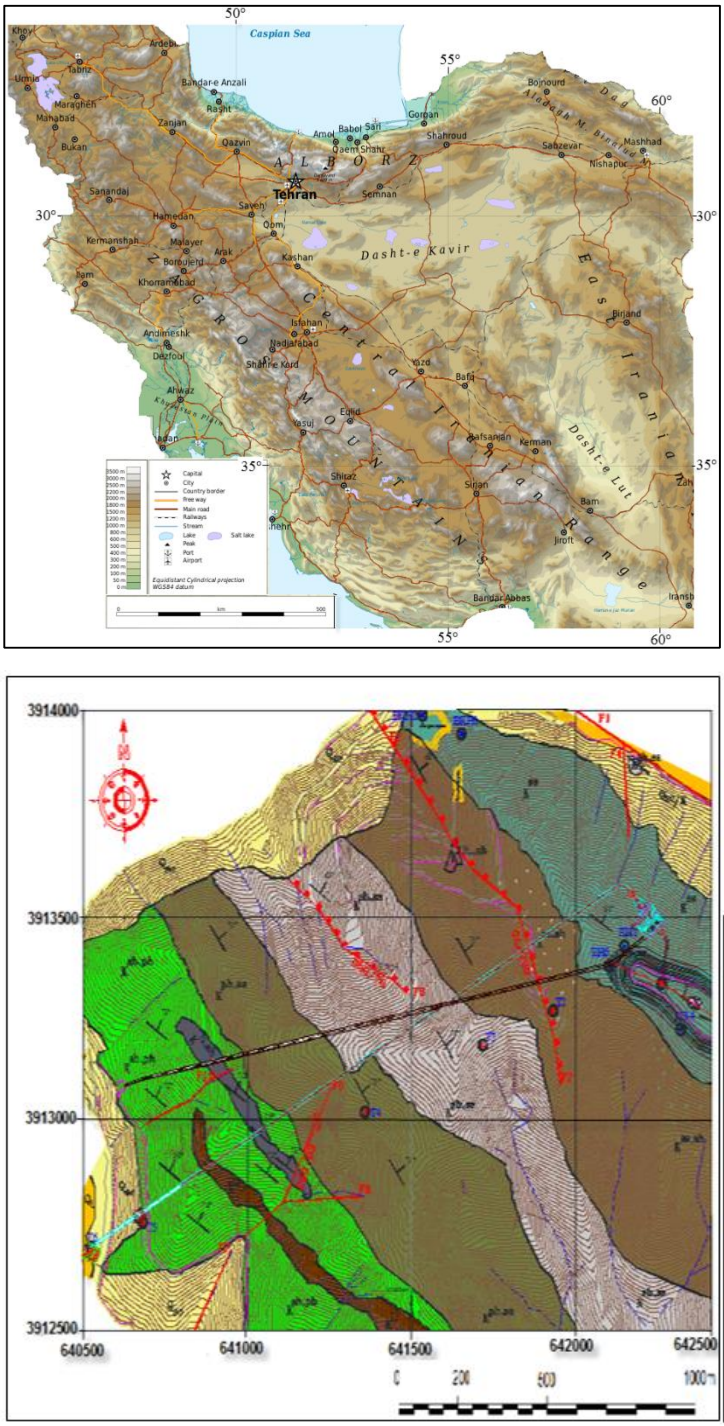
2. Materials and Methods

2.1. The study area

The design of the power plant of Kurdistan Azad Dam, Iran, is a storage pump, so the communication route between the upstream reservoir to the power plant is through the shaft. A pump-storage power plant is applied to save electricity more than consumption and reproduce it when demand is high. Although electricity storage is not directly feasible, the pump-storage power plant can increase the hydraulic capacity by pumping water from a lower tank to a higher tank when demand is low (overnight). This water can later be returned to the bottom tank when demand is high or electricity is needed to turn the turbines and eventually turn the generator around. For such a power plant to be cost-effective, the difference in height between the downstream and upstream tanks must be at least 300 meters. This level difference in the Azad Dam and power plant design equals 472.5 meters (1869-1351). Fig 1. shows the geographical location of the study area.

2.2. Geology of the area

The pump-storage power plant of Azad dam is located in the Sanandaj-Sirjan zone. Immediately after the high Zagros and in its northeast, there is a significant zone called Sanandaj-Sirjan. This part is similar to Central Iran in sedimentation and structural features. Its general direction and extension follow the Zagros trend (northwest-southeast). This zone is Iran's most active tectonic zone, and many metamorphic rocks can be seen there. This zone has undergone significant metamorphic and magmatism phases up to the Cenozoic. Therefore, it can also be considered a metamorphic belt formed in the Late Triassic. The intensity of metamorphic rocks, altered due to the occurrence of Laramide, is so low that not all schistosity is seen in them, and only slate and fracture facies have spread.The 73RHC in the Azad Dam is a lightweight shaft drilling machine and one of the most flexible and technically advanced machines. The specifications of this machine are provided in Table 1.



Abbreviations in the map legend are defined as follows:

K^{C}: Medium to thick-bedded gray to brown fine to very coarse grain meta conglomerate with carbonate cementation and some fine to coarse grain sandstone intercalations.
K^{SS}: Medium to thick-bedded gray to brown coarse grain meta sandstone with some part of the schist.
Qss: SLOPE WASH: Consist of gravel, sand, silt, and clay with some cobble and trace of boulder subangular to angular.
Qt: TERRACES: Contains gravel, sand, and clay with some silt and trace of the pebble.
$K^{ca.ss}$: Light calcareous thick bedded meta sandstone with calcite veins and veinlet.
$K^{ss.sh}$: Alternation of meta sandstone, schist, and phyllite with thin to moderate bedded meta sandstone.
$K^{Alt.sh}$: Highly altered green to brown foliated schist with minor thin interbedded meta sandstone.
$K^{sh,ss}$: Alternation of schist, calcite phyllite, and meta sandstone with gray to greenschist thin interbedded of meta sandstone.
$K^{Ph,ss}$: Green to brown foliated phyllite with thin interbedded of meta sandstone.
$K^{li,sh}$: Alternating dark gray phyllite and red to green meta limestone.
K^{li}: Gray to green meta limestone with some part of schistose limestone.
M. Li: Gray to dark gray meta limestone with calcite veins.
$K^{sh.Ph}$: Alternation of schist and calc-phyllite.

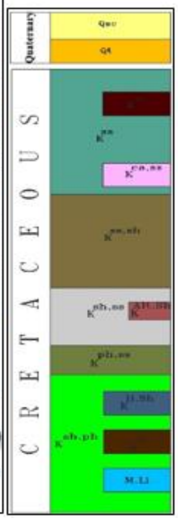


Fig 1. Geological map of the studied area.

1.2. Experimental equations to predict the operating parameters of an RBM

Shaterpour-Mamaghani et al. (2018) presented equations (1) and (2) for penetration rate using a field study on drilling the ventilation shafts by an RBM in a lead and zinc mine in Ballia, Turkey.

$$IPR = \frac{L_e}{t_e} * 60 \quad (1)$$

$$P = \frac{IPR}{RPM} * \frac{1000}{60} \quad (2)$$

IPR is instantaneous penetration velocity, L_e is drilling length, t_e is drilling time, P is drilling velocity in m/hour, and RPM is the spindle velocity in rounds per minute.

Zhiqiang (2004) presented the experimental equations (3) and (4) to predict the RBM performance.

Table 1. Main characteristics of 73RHC Raise Bore.

Parameter	Value
Average drilling diameter	1.2 m
Average drilling depth	550 m
Torque	210 kNm
Thrust force	4159 kN
Power	200-250 kW
Maximum drilling depth	700 m
The rotational speed of the pilot hole	0-52 rpm
The rotational speed of reaming	0-17 rpm
Maximum drilling rate	7.1 m/min
Pilot diameter	254 mm
Reaming diameter	1524 mm

$$TOR = \sigma_c \frac{P}{16n}\left({D_r}^2 - {D_h}^2\right)tan\varphi_f \quad (3)$$

$$n = \frac{\acute{C}D_c P sin\alpha}{6 D_r T_i} \quad (4)$$

Where σ_c is the compressive strength, p is the penetration per round of cutter head rotation, D_r is the reamed shaft diameter in meters, and D_h is the diameter of the pilot. Also, φ_f is the cutter breaking angle (20°-35°), $\acute{C}$ is the angle between rock and cutter, D_c is the pilot hole diameter, and T_i is the cutter contact time with rock in seconds. n is the spindle velocity in rounds per minute, and TOR is torque.

Snowdon et al. (1982) proposed equation (5) based on the vertical and rolling force of the disc cutter.

$$\frac{F_r}{F_n} = f = 21.71 * ROP - 0.656 \quad (5)$$

F_r is the rolling force, F_n is the vertical force, f is the ratio of rolling force to the compressive strength, and ROP is the rate of penetration.

Liu and Meng (2015) presented the rotational speed of the cutter head and torque. To achieve greater crushing efficiency in shaft reaming and minimum abrasion, the contact time of the bit cutter with the rock should be 0.02-0.03 seconds, and the linear velocity of lateral cutting, Vc, should be 0.7-1 m/s. In addition to drilling velocity, the maximum rock-breaking torque is related to the diameter of the cutter head, expressed in equations (6) and (7).

$$RPM = \frac{60V_c}{\pi D_r} \quad (6)$$

$$TOR = \frac{K_r \pi\left(D_r^2 - D_h^2\right)p}{4} \quad (7)$$

Vc is the linear velocity of lateral cutting, and K_r is the energy value required to break rock, equal to or less than the uniaxial compressive strength of rock.

Home (1978) expressed the power equation of a rotary drilling machine as equation (8).

$$power = 2\pi RPM . \frac{Torque}{\gamma} \quad (8)$$

γ is the constant value, equal to 0.7, and depends on the drilling tool.

The instantaneous penetration rate for a continuous drilling machine was presented by Rostami et al. (1995) as equation (9).

$$IPR(\mathrm{m}^3/\mathrm{h}) = \frac{HP(hp) * \eta}{SE\left(\frac{kwh}{\mathrm{m}^3}\right)} \quad (9)$$

η (0.75~0.8) is the mechanical coefficient of the drilling machine, SE is the specific energy, and HP is the power of the drilling machine in kilowatt-hours.

Specific energy is used to predict the shear penetration rate by a sequential shear test with a single groove (Rostami et al. 1995; Çopur et al. 2001).

$$NCR = \frac{\mathrm{K}P_{cutting}}{SE_{opt}} \quad (10)$$

NCR is the net shear rate, K (0.4~0.8) is the energy transfer ratio from the cutter head to the face, and SE_{opt} is the specific energy obtained in the laboratory.

3. Results and Discussions

3.1. Penetration theory of roller cutter in shaft drilling in RBM

Roxborough and Phillips (1975) proposed the most widely used model for determining the forces acting on a disc cutter in rock drilling. They presented a simple mathematical model to describe compressive and rolling forces based on cutter diameter, edge angle, and cutter disc penetration. Also, they assumed that the normal force is equal to the compressive strength of the rock in the disc contact area in the axial direction, expressed as the equation (11).

$$F_n = Q_c * A \quad (11)$$

Q_c is the compressive strength of the rock, and A is the area of disc contact in the axial direction.

Penetration is related to the cutter's depth entering the rock in a complete round of the cutter head, which is equal to the ratio of the penetration rate to the rotational speed of the cutter head (Yagiz 2008). As in Fig. 2, some cutter rollers are in the spindle with several rows of bits on the cutter edge alternately. Calculating the vertical force and the roller applied to a roller cutter is shown in Fig 2.

The maximum bit penetration in the rock is expressed as equation (12).

$$P_{max} \geq r - r\cos\delta \qquad (12)$$

P_{max} is the maximum bit penetration, r is the cutter radius of the RBM, and δ is the angle between two consecutive bits in the cutter.

Generally, there is always at least one bit in the rock under load. Before a bit leaves the rock, the last bit penetrates it; therefore, the maximum penetration rate and the relationship between the bit height, the most penetration, and the geometric properties of the cutter are expressed as equation (13).

$$P_{max} \geq r - r\cos 2\delta \qquad (13)$$

Considering the maximum cutting depth in equation 13 and this limitation that at least one bit should always be in contact with the rock, equation (14) is presented in operating conditions.

$$t > P_{max} \geq r - r\cos 2\delta \qquad (14)$$

t is the bit height. Generally, two points must always be in place, and the cutting depth must be less than the bit's height.

The main principles of the force acting on the roller cutter must first be examined according to the rock strength and the geometric conditions of the cutter to measure the maximum penetration rate. The roller cutter is the chief tool for cutting in the RBM. A roller cutter's bit is shown in Fig 3.

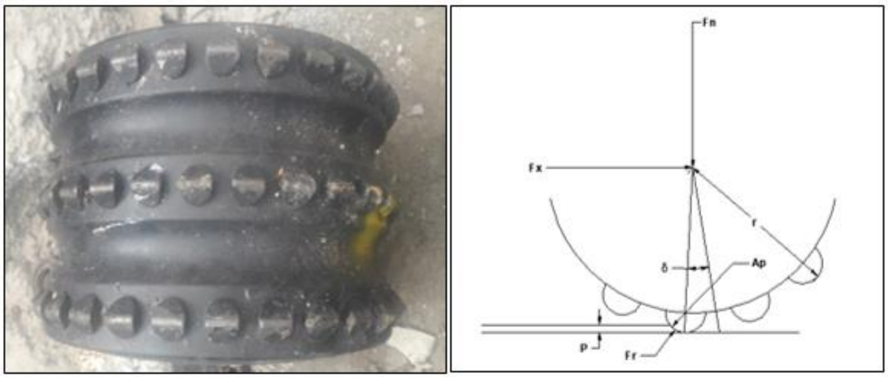


Fig 2. Reamer roller cutter.

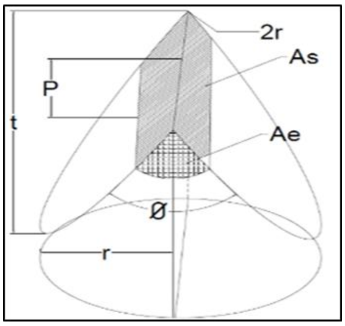


Fig 3. The geometry of the roller cutter bit. p is the vertical force acting on the rock to the penetration depth, φ is the edge angle for a bit, and r is the cutter diameter.

The penetration area of each bit is calculated via equation (15).

$$A_p = 2A_s + A_e \qquad (15)$$

According to the penetration rate of each bit in the rock (Figs. 2 and 3), each bit's contact surface is expressed as equation (16), considering the cycloid path.

$$A_s = ((t \sec\frac{\varphi}{2} r\pi) - \left(\sqrt{(r^2 - (p\tan\frac{\varphi}{2})^2)} \,.\, (t-p)\sec\frac{\varphi}{2}\,\pi\right) \qquad (16)$$

A_p is the penetrating bit area in the rock, A_s is the area of the penetrating bit edge in the rock, and A_e is the frontal area of the bit.

To obtain the area of A_e, the area of the two hoofs of bit penetrating must be calculated according to Archimedes' law and subtracted from the total area of the bit cylinder. Figure 4. shows the cylindrical hoof, presented to analyze the penetration rate of the drilling bit surface in the rock.

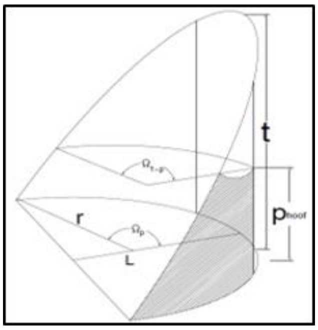


Fig 4. Cylindrical hoof.

According to Fig 4. related to each bit, the value of the obtained angle is calculated based on the value of the cutting depth variable as equation (17).

$$\Omega_p = 90\ ,\ \ \Omega_{t-p} = \sin^{-1}\left(\frac{\sqrt{(r^2-(p\ tan\frac{\varphi}{2})^2}}{r-x}\right)$$

$$\Omega_{t-p} > 90,\ \ \Omega_{t-p} = \cos^{-1}\left(\frac{\sqrt{(r^2-(p\ tan\frac{\varphi}{2})^2}}{r-x}\right)$$

$$x = r - p\ sin\frac{\varphi}{2} \quad (17)$$

The area of the bit edge in contact with the rock should be subtracted from the area of the cylinder hoof calculated in equation (17) and expressed as equation (18). The cylinder area is given as equation (19).

$$A_e = \frac{1}{2}(A_{cylinder} - 2A_{p\ hoof}) \quad (18)$$

$$A_{cylinder} = 2\pi rp \quad (19)$$

The contact area of the frontal edge of each bit with rock is calculated according to the penetration variable value.

$$A_{p\ hoof} = 2\left(\frac{rt[sin\Omega_p - \Omega_p cos\Omega_p]}{[1-cos\Omega_p]}\right) - \left(\frac{(t-p)r[sin\Omega_{t-p} - \Omega_{t-p}cos\Omega_{t-p}]}{[1-cos\Omega_{t-p}]}\right) \quad (20)$$

Ω_p is the angle between the bit radius and the bisector of the bit cylinder hoof in minimum bit penetration in the rock, and Ω_{t-p} is the angle between the bit radius and the bisector of the bit cylinder hoof in maximum bit penetration in the rock. Also, x is the distance of the bit penetration edge to the cylinder surface.

As the penetration increases, the contact area of each bit with the rock increases. Based on the geometric shape of the drilling bit, the frontal area and the two edges of the bit are obtained via equation (21).

$$(A_p = 2\left(\left(t\ sec\ \frac{\varphi}{2}\ r\pi\right) - \left(\sqrt{\left(r^2-(p\ tan\frac{\varphi}{2})^2\right)}\ .(t-p)sec\ \frac{\varphi}{2}\ \pi\right)\right) + \frac{1}{2}\left(2\pi rp - 2\left(\frac{rt[sin\Omega_p - \Omega_p cos\Omega_p]}{[1-cos\Omega_p]}\right) - \left(\frac{(t-p)r[sin\Omega_{t-p} - \Omega_{t-p}cos\Omega_{t-p}]}{[1-cos\Omega_{t-p}]}\right)\right) \quad (21)$$

Theoretically, a roller cutter can break rock with a constant force by ignoring the drill cuttings resulting from rock break. Therefore, the force acting on the rock in each bit must be checked separately in a roller cutter. On the other hand, another bit enters the cutting operation before reaching the maximum bit depth in the roller cutter (equation (14)). Thus, the penetration will never be higher than the bit height.

Consider the cutter shown in Fig 2. The position of each bit inserted into the stone is defined by the angle δ. As the cutter rotates, the maximum depth of each bit is driven into the rock along a cycloidal path. The maximum cutting depth of the bit is a function of the contact angle of the arc, expressed as equation (22).

$$dF_{radial} = \sigma_c * dA * dn \qquad dF_{radial} = \sigma_c * dA * n * d\delta \quad (22)$$

According to the bit penetration in Fig 2. and the bit geometry in Fig 3., the forces acting on the rock are applied as radial and tangential forces. The tangential force for crushing the rock in the roller cutter is ignored. The shear and normal forces of each bit acting on the rock are calculated from equation (23).

$$dF_x = dF_{radial} * sin\delta \qquad dF_y = dF_{radial} * cos\delta \quad (23)$$

The force value acting on each bit concerning the bit area and the angle between the two bits in the roller cutter is expressed as equation (24).

$$F_x = \int dF_x = A_p N\sigma \int sin\delta\ d\sigma \qquad F_y = \int dy = A_p N\sigma \int cos\delta\ d\sigma \quad (24)$$

N is the number of bits on the cutter.

The horizontal and rolling forces acting on each bit are expressed as equations (25) and (26).

$$F_r = F_x = A_p N\sigma(1 - cos\delta) \qquad F_n = F_y = A_p N\sigma sin\delta \quad (25)$$

$$F_r = F_x = A_p N\sigma_c 2\left(\frac{p}{d}\right) \qquad F_n = F_y = A_p N\sigma_c\sqrt{2rp - p^2} \quad (26)$$

The acting force on the cutting axis is given as equation (27).

$$F_{radial} = \sqrt{[F_r^{\ 2} + F_n^{\ 2}] =} A_p N\sigma_c\sqrt{(2 - 2cos\delta)} \quad (27)$$

In practice, the above equations are used to normalize the field shear, and the shear coefficient is expressed as equation (28).

$$f = \frac{F_r}{F_n} = \frac{1-cos\delta}{sin\delta} = \tan\frac{\delta}{2} \quad (28)$$

The total number of bits on the cutter related to the rock must be determined according to equation (29) to determine the penetration rate.

$$N = N^{\cdot} * 0.05 \quad (29)$$

$N^{\cdot}$ is the total number of tungsten bits and depends on the cutter shape (Bilgin et al. 2013).

Home (1978) proposed equation (30) to determine the torque value.

$$Torque = 0.66\ rnfF_n \quad (30)$$

According to Home (1978), the torque is expressed as equation (31).

$$Torque = 0.66\, rn\tan\frac{\delta}{2}F_n \quad (31)$$

As a result, the RBM reamer's driving force according to the bit's geometrical characteristics and the cutting depth, the rock's compressive strength, and the number of cutters is presented as equation (32).

$$F_n = N^{\cdot} * 0.05A_p\sigma\sqrt{2rp - p^2} \quad (32)$$

n is the number of cutters.
The compressive force value acting on the cutters is obtained as equation (33).

$$F_N = P_u + N * F_n \qquad F_N = P_u + N^{\cdot} * 0.05A_pN\sigma\sqrt{2rp - p^2} \quad (33)$$

The tensile force of the device for reaming upwards is calculated using equation (34).

$$P_u \geq k_1(W_h + W_t + W_s) \quad (34)$$

P_u is the total weight of the spindle with the drill rod of the RBM, W_h is the maximum pressure per bit, W_t is the weight of the bit rod and bit in drilling depth, and W_s is the weight of the water and hydraulic system.
By introducing the theory of cutter penetration rate and amount of torque in the RBM, the power value of the RBM is expressed as equation (35).

$$power = 2\pi RPM.\frac{0.66\, rn\tan\frac{\delta}{2}F_n}{\gamma} \quad (35)$$

Based on equations (30)-(35), the value of the instantaneous penetration rate is given as equation (36).

$$IPR\left(\frac{\mathrm{m}^3}{\mathrm{h}}\right) = \frac{HP(hp)*\eta}{SE\left(\frac{kwh}{\mathrm{m}^3}\right)} = \frac{(2\pi N.\frac{0.66\, rn\tan\frac{\delta}{2}F_n}{\gamma})*\eta}{SE\left(\frac{kwh}{\mathrm{m}^3}\right)} \quad (36)$$

3.2. Analysis of the results of predicting RBM performance

Table 2 shows the estimated value of the RBM's operating and performance parameters, including the RBM's power, thrust, and torque values. The obtained equations give other researchers a unique opportunity to control the drilling machine's operating parameters according to the results of the rock properties and the penetration rate value.
A limited number of scientific studies have used physical and mechanical properties to estimate the performance of RBMs. The rock samples tested in this research show various characteristics, from relatively hard to tough rocks. Due to insufficient data, Wilson and Graham (1972) stated that no reliable relationship exists between compressive strength and RBM riming. However, Everell (1972) studied some geological conditions, including fractures, earth layers, groundwater, and other parameters that affected RBM performance. The researcher also pointed out that by keeping all conditions constant, a good correlation between the penetration rate and the uniaxial compressive strength can be expected.
This research uses two basic concepts of rock cutting and cutter geometry to estimate the performance. The operating parameters are a function of rock strength and contact bit geometry with the rock. The results show that the minimum and maximum thrust force for the RBM to ream is 1000-4116 kN, and the torque is 41-205 kN, which is close to the actual value.
The most reliable technique for estimating the mechanical performance of mechanical drilling machines is linear cutting tests in the cutting tool (Bilgin et al. 2013). However, it is difficult and sometimes impossible to do this research due to the difficulties of performing this test in large samples and by experts. This study used it without any conversion to estimate the project's initial design.

Table 2. Measured/calculated operating and performance parameters in reaming.

Row	Rod number	σ_c (kgf/cm^2)	RPM (rev/min)	Depth of cut per revolution (Cm/rev)	Measured thrust (kN)	Estimated thrust (kN)	Measured torque (kNm)	Estimated torque (kNm)	Estimated Power (kW)	Estimated IPR(m^3/h)
1	70	950	2.5	0.2	3400	2838.8	121.5	137.52	51.43	1.39
2	65	1100	6	0.2	3500	2586.4	134.8	125.29	112.46	1.49
3	60	1050	3	0.3	3500	3889.1	141	188.39	84.55	1.56
4	55	1150	4	0.2	1200	2986.2	141	144.65	86.56	0.92
5	50	950	5.5	0.2	1500	2711.8	141	131.36	108.09	1.06
6	45	1110	3	0.2	3000	3783.1	124	183.26	82.25	1.49
7	40	1080	2.5	0.2	3800	2287.9	199.7	110.83	41.45	1.56
8	30	1120	3.5	0.2	3800	2908.3	193.5	140.88	73.76	1.35
9	35	990	6	0.2	2000	2826.0	83.6	136.90	122.88	0.58
10	20	950	4	0.3	3500	4116.8	184.5	199.42	119.34	0.78
11	25	650	2.5	0.3	2400	3734.9	180	180.92	67.66	0.69
12	20	1100	2	0.2	2300	3140.0	111.3	152.11	45.51	1.35
13	15	800	4.3	0.3	2200	4011.3	110.3	194.31	125.00	1.49
14	10	700	3.5	0.2	1500	1482.9	90	71.83	37.61	0.69
15	50	450	3.2	0.2	2300	1168.5	90	56.60	27.10	0.97
16	(reamer rod)	450	2	0.2	2800	1005.0	90	48.68	14.57	0.80

4. Conclusions

This study was conducted to show the basic concept of mechanical rock cutting to estimate the performance of the operating parameters of the RBM. Functional parameters of rock compressive strength, number of bits in contact with rock, and total area of contact with rock were formulated.

Choosing an appropriate machine for drilling according to the rock's characteristics and the RBM's operating specifications is significant. Drilling in sandstone was done at the level of 1873-1600. The bit's contact surface with the rock was calculated based on the characteristics of the geometric shape of the drilling bit related to the rock mass. Also, the thrust force acting on the rock at each bit in the roller cutter was calculated separately according to the number of bits in contact with the rock. According to the research conducted by other researchers and the equations obtained in this research, the torque, power, and thrust force required by the drilling machine were determined based on the geomechanical properties of the rock to investigate the physical-mechanical effects on the RBM's performance.

This research showed that shaft reaming operations' average daily progress rate is 1.8 m/h, about 1.8 mm/rev for reaming. Also, the torque value of the RBM for shaft reaming was 48-199 kNm, which is less than the machine's torque of 220 kN and closer to the actual value. The findings showed that the machine's thrust force value and power were 4116 kN and 125 kW, respectively, close to the actual value. As a result, the machine's operating parameters are consistent concerning the characteristics of the rock mass. The rock samples tested in this research show a wide range of characteristics. Therefore, the models proposed can be used for different geological environments and similar RBMs. Also, the results can be used to predict the performance of the RBM for other similar projects.

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