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Analysing the Feasibility of a Full-face Cutting Machine for the Robominers Project

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Abstract: Several methods of excavation have previously been studied to choose the most suitable approach to be applied in the Robominers project. Compared to drilling and blasting and partial-face cutting, the full-face cutting option is regarded as one of the methods which can offer, among others, high advance rates and a safer working environment for the machinery. Current technologies of these methods, however, suffer from several limitations, such as the inability to bore very hard rocks, significant lack of geometrical flexibility in mine working areas, and low mobility due to large and heavy components. In this study, two of the most commonly applied small diameter full-face machines including the pipe jacking and the Boxhole Boring Machine (BBM) are studied with regards to their performance parameters. The pipe jacking machine option with a cutterhead consisting of disc cutters exhibits higher efficiency in excavation with only slightly lower production rates compared to a BBM with strawberry cutters. They are also much lighter machines. Yet, using the jacking concept means a limited driving length and does not apply to the Robominers. Therefore, the introduction of small gripper or shielded Tunnel Boring Machines (TBMs) can significantly improve the mobility. Their application, however, requires considering the risks of jamming in difficult ground conditions and the possible requirements of a support installation. These rock mechanics issues need to be carefully considered in the design of such machines. In addition, further studies are required to employ assisted cutting methods in very hard rocks and to increase the geometrical flexibility of these machines by lowering their turning radius.

Keywords: Robominers, Full-face cutting, Drilling and blasting, Advance rate

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Zusammenfassung: Für das ROBOMINERS Projekt wurden bereits einige andere relevant erscheinende Abbaumethoden analysiert. Im Vergleich zum Bohren und Sprengen sowie zu Teilschnittmaschinen wird die Option der Vollschnittmaschinen als eine der Methoden angesehen, die unter anderem hohe Vorschubraten und ein sichereres Arbeitsumfeld für die Maschinen bieten können. Gegenwärtige Technologien dieser Verfahren leiden jedoch unter mehreren Einschränkungen, wie der Herausforderung sehr hartes Gestein zu schneiden, einem signifikanten Mangel an geometrischer Flexibilität in einer Bergbauumgebung und einer geringen Mobilität aufgrund großer und schwerer Komponenten. In diesem Beitrag werden zwei der am häufigsten verwendeten Vollschnittmaschinen mit kleinem Durchmesser hinsichtlich ihrer Leistungsparameter untersucht – Pipe Jacking Machines und Boxhole Boring Machines (BBM). Die Pipe Jacking Maschinen mit einem Schneidkopf, der aus Scheibendisketten besteht, weisen eine höhere Effizienz mit nur geringfügig niedrigeren Produktionsraten auf als ein BBM mit sogenannten „strawberry cutters“. Weiters sind diese Maschinen wesentlich leichter. Die Verwendung der Pipe Jacking Methode bedeutet jedoch eine begrenzte Vortriebslänge und gilt für das Projekt Robominers als nicht gut geeignet. Daher kann die Einführung von „small gripper“- oder Schildtunnelbohrmaschinen (TBMs) die Mobilität erheblich verbessern. Ihre Anwendung erfordert jedoch die Berücksichtigung der Risiken unter schwierigen Bedingungen und der möglichen Anforderungen an eine geeignete Infrastruktur sowie Maßnahmen zur Stabilisierung. Diese Probleme der Felsmechanik müssen bei der Konstruktion solcher Maschinen sorgfältig berücksichtigt werden. Darüber hinaus sind weitere Studien erforderlich, um kombinierte Schneidmethoden in sehr harten Gesteinen anzuwenden und die geometrische Flexibilität dieser Maschinen durch Verringern ihres Abzweigradius zu erhöhen.

Schlüsselwörter: Robominers, Vollschnittmaschinen, Bohren und Sprengen, Vortriebsrate

1. Introduction

The project Robominers is aiming to develop a bio-inspired and modular robot for selective mining in specific environments. The limitations in power and weight require an applicability assessment of various excavation methods for development and mineral extraction. The two most common methods of excavation in mining and tunneling are the conventional drilling and blasting and the mechanized excavation, each having their own merits and demerits. Higher advance rates in sound rock mass conditions, less damage to the excavation profile, lower ventilation requirements, and generally safer excavation conditions are some of the most prominent merits of mechanized excavation. Depending on how they attack the rock face, underground excavation machines can be categorized as full-face and partial-face machines. In full-face cutting machines, the whole cutting face takes part in the excavation process together and at the same time. Tunnel, shaft, and raise boring machines as well as microtunneling are the typical full-face machines applied in underground excavations. The

partial-face machines engage a part of the cutting tools in a single step of excavation, which brings about the unique capability of creating non-circular excavations. Continuous miners, roadheaders, shearers, and others are some of the main partial-face machines.

In this contribution, an overall comparison of full-face machines with partial-face machines and the conventional drilling and blasting method is conducted first. Subsequently, some technical parameters of the current technologies of full-face machines, which can be involved in a decision-making process for choosing the equipment for Robominers, are evaluated. In the last section, the main limitations of applying a full-face machine as an option for Robominers are discussed to open the path for future investigations in this regard.

2. Comparison of Different Mining Methods

Comparing a full-face cutting option with other methods can be done by considering various criteria. Table 1 con-

TABLE 1 Individual comparison of full-face excavation with drilling and blasting and the partial-face excavation method from different aspects		
Criterion	Compared to drilling and blasting	Compared to partial-face excavation
Safety	Higher safety	Generally safer ^a
Production rate	Higher production/excavation rates in favorable ground conditions (higher economic benefits/saving money, early mining of high-grade ore, earlier job completion)	
Selective excavation	<i>Not suitable (partial-face enjoys minimum ore dilution/minimum mixing with gang, increased ore recovery, separate excavation of rock layers in different strengths making excavation easier)</i>	
Muck or mineral fragmentation quality and haulage	Uniform muck size (easy muck/excavated material haulage, no secondary breakage of large rock chunks, lower crushing and mineral processing costs)	Equivalent ^b
Continuity of operation	Continuous operation (not periodic, conducive to automation, excavation-loading-ground supporting simultaneously)	Equivalent ^c
Cuttable ground types	<i>Not applicable in very hard and abrasive rocks</i>	Wider range of rock strength compared to partial-face
Ground disturbance	Less overbreak, less scaling-support requirement, minimized support maintenance, superior ground control in jointed/broken rocks ^d	Equivalent
Environment adaptability	More environment-friendly operation (no blast vibrations, no blasting ventilation required)	Equivalent
Flexibility	<i>Less flexibility on working conditions, very sensitive to ground conditions, Limited opening cross-section area and shapes and usually not able to cut low turnoff radii, especially compared to roadheaders, Difficult adaptability to a working mine design</i>	
Mobility	<i>Very large and heavy machines with low mobility from one face to another^e</i>	
Maintenance	<i>In hard and abrasive rocks, frequent maintenance of the machine might be necessary</i>	<i>Less accessibility to the cutterhead face and harder maintenance operation</i>
Capital cost	<i>Higher initial/capital cost</i>	Equivalent or higher depending on the conditions

^a In unstable ground conditions, shields make partial-face cutting machines as safe as full-face machines
^b Yet, the capability of slurry transportation is an advantage in some full-face cutting machines
^c The partial-face cutting machines can also be equipped with simultaneous support installation
^d It should be noted, however, that, in rather deep underground excavations (overstressed hard rocks), blasting is deemed as an effective method for releasing a part of the saved energy in the rock mass. Thus, the ground disturbance caused by blasting could be a positive fact in deep mining conditions
^e There are unique technologies, however, where the maneuverability of the full-face cutting machines is improved significantly. For instance, the BBMs can excavate short length and small diameter openings in highly strengthened rocks. A crawler transports the machine quickly from one cutting position to another

Fig. 1: A pipe jacking machine by Herrenknecht (AVN XC) [3]

tains some of the most important parameters for comparison of the full-face excavation method with the drilling and blasting and the partial-face excavation method [1, 2].

3. Current Technologies of Small Diameter Full-face Machines

Current technologies of full-face cutting machines which are small enough to be close to the scale in the Robominers project need to be compared individually. By neglecting the large diameter TBMs, two methods of pipe jacking and the BBMs with approximate diameter of 1 m are discussed accordingly. After an introduction, they are further discussed technically.

3.1 Pipe Jacking Machine

The machines implementing the pipe jacking technology can be divided into two main categories of methods with the possibility of working in man-entry mode of up to 4.8 m (AVN Machine—Herrenknecht) and the other category of non-man entry mode also called microtunneling of down to 0.4 m in diameter. With the slurry mode, almost all the ground conditions from soft ground, heterogenous ground, and hard rocks (up to UCS of 250 MPa depending on the disc cutter type) can be excavated using this method. Unlike

tunnel boring machines, the pipe jacking methods take advantage of concrete pads inside entry shafts to produce the reaction forces for excavation, pushing the whole machine forward and compensating against the ground and water pressure on the tunnel face in unstable grounds (Fig. 1; [3]).

3.2 Boxhole Boring Machine (BBM)

The BBM technology with the ability to drill from bottom to top is based on the existing microtunneling pipe jacking technology (Fig. 2). High mobility, quick relocation, high performance, and minimum space requirements are its main advantages. Above all, it offers a drilling operation independent from an upper level. It allows a wide range of applications in the mining field especially for drilling draw bell slot holes for block caving operations, ventilation shafts, ore passes, or service shafts. The BBM is applied in stable rocks of 180 MPa UCS (Uniaxial Compressive Strength) and more and up to 70 m long holes with an inclination from vertical of 30 degrees. This method provides the reaction forces for cutting and lifting the boring part by gripping to the roof and floor. Another variation of this method could use the side walls to grip and push the machine horizontally as well [3].

3.3 A Technical Comparison Based on Performance Parameters

In this section some of the main performance parameters of two typical pipe jacking and BBM are evaluated. Parameters, such as the reaction forces, the specific energy (SE), and the production rate, are estimated in a stable hard rock ground with a UCS = 150 MPa. The following two machines from Herrenknecht are assumed in this study (Table 2).

In order to estimate the cutting forces for the AVN800XC, a presumed cutterhead design is required. We assume the cutterhead for our example as a typical hard rock cutterhead with the following parameters and calculate the performance parameters by the formulations developed in the CSM (Colorado School of Mines) model:

Fig. 2: Herrenknecht Boxhole Boring Machine BBM1100 [3]

TABLE 2

The two full-face machines for comparison and their geometrical features

Model	Excavation diameter (mm)	Outer diameter of concrete pipe (mm)	Recommended drive length (m)
AVN800XC	975	961	150
BBM1100	1100	–	30

Number of disc cutters= 4 double discs (monoblock) + 4 single disc cutters

Disc cutter diameter= 11 inches

Disc cutter tip width= 12 mm

Disc cutter spacing= 40 mm

The load bearing capacity= 170 KN

As for the BBM1100, for drilling in hard rocks (e.g. up to 250 MPa UCS) in this diameter, a typical cutterhead contains 5 tungsten carbide cutters (two four-row and three five-row cutters with a bearing capacity of 27 t) to achieve a maximum row spacing of approx. 25 mm. Thus, 23 rows of bits are assumed on a cutterhead. The formulations by Bilgin et al. are applied for these estimations [1]. The main performance parameters are gathered in Table 3.

A high contrast can be easily distinguished in the calculated power values. Besides, the penetration per revolution is almost 3 times more for the pipe jacking excavation method. A slightly higher torque value and a relatively lower penetration of the BBM1100 compared to the Pipe Jacking machine results in a much larger optimum specific energy (SE_{opt}) (3 to 4 times more depending on the applied methodology for calculation of torque) (see Table 3).

Moreover, the BBM1100 weighs 41 tons. In comparison, the AVN 800 XC weighs 4.5 t. The other weight to be added to both is the piping material weight. The existence of piping material in both machines is mandatory.

The BBMs are also much larger machines:

- BBM1100 dimension (l/w/h): 7.6 m/2.5 m/3.3 m, the crawler dimension: 6.25 m/2.52 m/1.61 m
- AVN 800 XC: Outer diameter: 975 mm, Length articulation shield: 2.4 m, Length machine can: 2.2 m

4. Main Aspects for Adapting Full-face Cutting Machines to Counteract Their Drawbacks

The BBM and the pipe jacking machine apply the same mechanisms in two individual approaches. The pipe jacking technology is applied in shallow depths and with much less flexibility. It provides, however, much longer driving lengths. Both methods are clearly very limited in terms of driving length. As it was also shown in Table 1, the main limitations of full-face cutting machines include less adaptability to different working conditions (geometrical limitations and driving length), the low selectivity in excavation, the inapplicability in very hard and abrasive rocks, low mobility especially in larger diameters and maintenance demanding. Some of these limitations seem to be inevitable. For example, the low selectivity in full-face cutting machines is due to the fact that the shape and size of these machines are predetermined. Yet, these machines can be adapted to fit the required conditions.

4.1 Less Adaptability to Working Conditions (Geometrical Limitations) and Low Mobility

The microtunneling and the BBMs use a fixed jacking station for providing the reaction forces of excavation and pushing the excavation parts forward. The pipe installation in microtunneling not only serves its main role for the project (drainage, cable installation etc.), but is also used as the means for transferring the pressure from the jacking station to the tunnel face. This unique way of advance limits their application in sharp curving tunnel paths. The articulation cylinders can provide very low degrees of turning. As BBMs also utilize piping segments for transferring the pressure to the face, they are also limited in turning radius. In terms of mobility, BBMs can be transferred from one point to another underground. But they are limited in the tunneling length on the other hand. The mandatory existence of piping material significantly rises the weight of both machines and reduces their driving length. Therefore, in a future option for Robominers, this way of force transfer cannot be applied. The shielded Tunnel Boring Machines (TBMs) take advantage of segmental lining to push the whole machine forward and thus are not limited to a specific length. Yet, they are not currently a fully automated machinery, and interference of personnel to install the segmental lining is necessary. The introduction of a similar mechanism in the future requires automation of this process. Gripper TBMs with a less geological risk of

TABLE 3

Comparison of BBM and Pipe Jacking performance parameters for a rock with UCS=150 MPa

Machine Type	Thrust (kN)	Torque (kNm)	N (rpm)	P (kW)	Penetration per revolution (mm/rev)	NPR (m ³ /h)	SE_{opt} (kWh/m ³)
BBM1100	1200	31.68	29	96.2	0.9	1.12	68.8
Pipe jacking (1100 mm) ^a	1005	29.3	7.4	22.7	3	0.95	19.1

^a The results of calculation of a pipe jacking machine with 975 mm are converted to the equivalent diameter of 1100 mm

Fig. 3: Schematic presentation of the underground robot concept (BADGER) [4]

shield jamming, on the other hand, also require a support for the protection of mining equipment in difficult grounds.

Recent projects are running to eliminate important drawbacks of full-face machines. The main purpose is to devise autonomous drilling robots that can easily adapt themselves to special geometries and have a rather high flexibility in transferring from point to point. The idea behind such techniques are bio-inspired from earthworm locomotion. One of these interesting projects being supported by the European Union is called BADGER. The project is introduced to envision an underground robotic system that autonomously navigates underground by pulverizing the soil, removing it, and pushing through the environment. At the same time, advanced sensing modalities, perception techniques, and cognition are used to localize the robot, to map, and to understand the working environment and make decisions on how to better pursue its goals ([4]; Fig. 3).

The propulsion mechanism is done by peristaltic crawling motion (bio-inspired) by clamping to the soil. The joint modules apply the propulsion forward and also enable the steering in different directions by dint of special motors. This results in a maximization of robot maneuverability and in increasing the curvature of the curved path robots can take. The propulsion mechanism is applied by linear actuators.

The clamp mechanism provides a point of contact between the walls of the tunnel and the system. The clamp allows the corresponding module to remain stationary while other modules are moving. It is also used to react the torque from the drill head. This technology is being developed for soil. In case the same mechanism can be adopted for hard rock conditions, it can remarkably assist maneuverability of an automated mining machinery.

4.2 The Inapplicability in Very Hard and Abrasive Rocks

As mentioned before, the very important fact about micro-tunnelling technology or generally small size cutterheads is their limitation in boring very hard and abrasive rocks. Smaller disc cutter size means less load bearing capacity and less cutter wear volume. Therefore, modern methods, such as thermal energy (laser, electric), ultrasound or microwave energy, chemical energy, and water jet cutting, are being studied to be deployed in the future for harder rock conditions.

5. Conclusion

Among the advantages of a full-face cutting option, there are drawbacks which necessitate modifications in the current existing technologies to become a viable option for Robominers. The relatively high production rate of at least 1 to 1.1 m³/h for a 1.1 m diameter hole is exciting. But on the other hand, the current technologies are quite large and heavy. The central jacking station in Pipe Jacking and BBM requires high thrust forces. In addition, the necessity of applying a high length piping material endangers their application in a region with a possibility of high convergence, as the machine might be entrapped inside the ground eventually. This limitation can be partially controlled by introduction of a small diameter TBM with lower length shields. Gripper TBMs have a significantly lower risk of jamming, but automated supporting the unshielded part of the machine is another challenging operation. Shielded TBMs with segmental lining can fully support the excavation with a higher risk of jamming. In general, rock mechanics issues start to become critical when application of a full-face machine is planned in difficult ground conditions. These rock mechanics issues (squeezing, rockburst, fractured rocks, and more) can restrict the application of a full-face machine mainly in deep underground mines. Nevertheless, the continuity of excavation and their relatively high advance rates can keep these machines feasible to apply in more suitable mining conditions.

The lack of selectivity during excavation in mining can be partially addressed by providing the machine with a higher flexibility in turning by using the similar concepts of joint modules e.g., BADGER project. Enabling the machine to excavate very hard rocks is also another area of further work by modern facilitating methods.

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