Advancements in drillability prediction for conventional hard rock drill and blast tunnelling – implementing automation into the equation

Tanja Sattler
Technical University of Munich (Engineering Geology), Munich, Germany
Baugeologisches Büro Bauer GmbH, Munich, Germany

Kurosch Thuro
Technical University of Munich (Engineering Geology), Munich, Germany

ABSTRACT: With tunnelling projects being part of critical infrastructural development, it is of uppermost importance to schedule the construction for an on-time delivery. Specifically, a reliable drillability prediction is indispensable to forecast advancement rates adequately. With the drillability being a very complex entity, predicting advancement rates is challenging, potentially leading to extensive additional cost and operational delays. Based on a case study from an Austrian tunnelling project, various influencing factors were examined. Comparing predicted with actual drilling velocities, it was shown that the actual drilling rates remained behind the expectations by about 20 %. The analysis clearly shows that the geological conditions are not responsible for these shortcomings, but the working process and the machine parameters including the degree of automation being significant factors of influence.

Keywords: drillability, penetration prediction, drilling automation, collaring, drill and blast tunnelling.

1 DEFINITION OF DRILLABILITY

The term excavatability is not strictly defined. In general, it describes the mechanic operation of breaking loose or excavating soil or rock. Specifically for tunnelling operations the term excavatability can be narrowed down to the drillability and the blastability for conventional tunnelling and the cuttability for mechanized tunnelling methods with roadheaders and TBMs. For all these different methods, the excavatability manifests itself in two different criteria: the performance criterion and the material criterion. These two criteria can be quantified on a construction site by measuring the drilling velocity and the usage of steel parts, which is a simple task. However, associating the measured values with the underlying influencing parameters is more complicated and challenging, as a multitude of influencing factors exist and interact with one another. These influencing factors on the drillability can be subdivided into three main parameters according to Thuro (1997) as shown in Figure 1. Over the past decades the influence of geological parameters has been analyzed in depth and their role for performance prediction models has been progressively refined. For the other two groups of influencing factors – the working process and machine parameters – it is more challenging putting the different aspects into numbers for forecasting and planning. In particular, the ongoing improvement of the drilling tools has been overlooked in the past, leading to shortcomings in performance predictions.

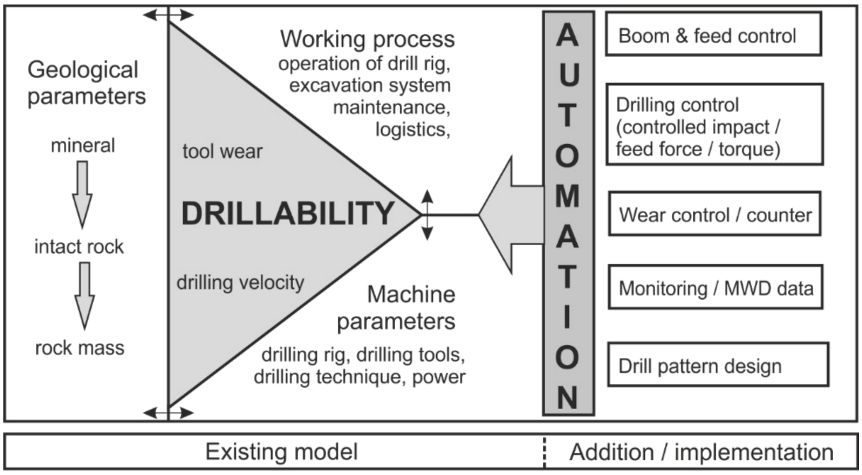

Figure 1. The existing model of the influences on the drillability after Thuro (1997) is displayed on the left side. The right side shows necessary modifications to incorporate the drilling automation.

1.1 Overview of automatic drilling

These advancements regarding the drilling equipment and available drilling modes need to be implemented into the conceptual model of the drillability. Most notably, the invention of a wide range of automatic drilling functions with the possibility of fully autonomous drilling operations are an important development. The equipment of the leading suppliers of underground mobile equipment is available with a wide range of automatic drilling functions. For example, drilling jumbos designed by Epiroc (former Atlas Copco) are equipped with the ABC (advanced boom control) system or Sandvik rigs with the iData software (Nord & Appelgren 2001, Sandvik Mining and Rock Technology 2020). Without going into detail, both systems allow for a fully automatic drilling process including boom and feed control and the actual drilling.

Taking up the conceptual model (Figure 1), with the higher degree of automation a linking element between the working process and the machine parameters needs to be considered when analyzing drillability. It is obvious that with increasing automation the significance of the impact factors is redistributed. For instance, with the growing level of drilling automation, action of the operator is required less. Hence, the impact of the "human factor" as part of the working process becomes decreasingly important. Therefore, with the shift from manual drilling to an automated or even autonomous drilling process, it is essential to analyze and quantify this significant change with regard to drillability and to reevaluate the existing penetration prediction models.

In addition to the automatic drilling process a significant advancement is the technology of collecting data from the drilling process. With the so-called MWD-technology (Measurement while drilling), relevant drilling parameters are recorded in the background. These include penetration rate, percussive/feed/rotation/damper pressure, rotation speed, flushing water pressure and flushing water flow (Epiroc 2023). The automatically recorded data allows for an evaluation of the rock mass and conclusions to be drawn regarding the drilling process and therefore gives an interesting insight into the drilling operation.

2 CASE STUDY: PROJECT SETTING AND GEOLOGY

The case study we present was conducted at a conventional hard rock drill and blast tunnelling project in Austria in 2021. Geologically the study site comprises crystalline basement of the Bohemian Massif at the depth of the tunnelling project (see Figure 2 and Figure 3). The so-called pearl-gneiss

(“Perlgneiss”) was formed by regional metamorphism, with high temperatures leading to metatexis of the source rock. This process is responsible for the rock on site showing a granite-like appearance and can therefore be described as a granitic diatexite (Finger et al. 2005). These basement rocks are overlain by sedimentary deposits which have no relevance for this study and are therefore not characterized.

Figure 2. Top heading drilling operation with parallel drilling of two booms.

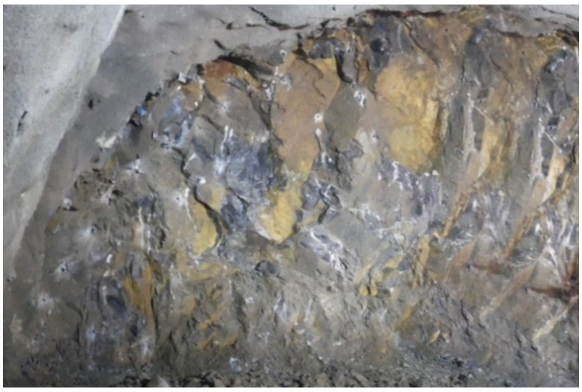

Figure 3. Face conditions in the top heading, comprising slightly to moderately granitic gneiss.

2.1 Methodology: Documentation of drilling process and parameters

To assess and quantify the influence of the drilling automation on the penetration rate a detailed documentation was produced for 21 tunnel blasting rounds for top headings and benches. The length of the drilling depth for the blasting rounds varied from 1 m to 4 m, as the maximum length is defined by the length of the drill rods with 4.2 m. The used drill rigs are electro-hydraulic jumbos, two DT922i (two booms) and a DT1130i (three booms) from Sandvik, both equipped with RD525 drifters. The rigs display a wide range of automatic drilling functions, as per the manufacturer’s specifications (Sandvik Mining and Rock Technology 2020). As part of this study, the following parameters were recorded:

- Net drilling time for blast holes and rock bolts
- Length of drill holes
- Drilling velocity (determined from the drilling time and length of each blast hole)
- General observations of the drilling process and the drilling equipment
- Geological documentation of the working face including rock mass properties
- Documentation of the extensive wear on the tools / tool changes

Laboratory testing was carried out focusing on the relevant intact rock properties for the drilling velocity. With the drilling velocity showing a good correlation with the uniaxial compressive strength, testing was carried out accordingly (Thuro 1996). Additionally, the CAI, LAC and equivalent quartz content were determined as a measurement for the abrasivity of the rock. With tool wear not being an integral part of this study, the results have informative value.

3 RESULTS

3.1 Intact rock properties

The results from the laboratory testing are shown in Table 1. The UCS ranges from 37 MPa to 167 MPa with a median value of 110 MPa. The results from the CERCHAR abrasivity tests, the LCPC abrasivity tests and the equivalent quartz content are displayed for completeness.

3.2 Drilling parameters

The observed drilling velocity varied between 0.9 m/min and 6.0 m/min with a median value of 2.7 m/min and a standard deviation of 0.4 m/min. A plot of the achieved drilling rates is shown in Figure 4. It shows an approximate Gaussian distribution, with the core range (defined as the average value +/- standard deviation) being between 2.3 m/min and 3.1 m/min.

Table 1. Results from the laboratory testing at the Technical University of Munich.

Rock properties		Median	Min	Max
UCS	[MPa]	110	37	167
CAI	[-]	3.1	2.4	4.6
LAC	[g/t]	1250	580	1380
EQu	[%]	52	33	59

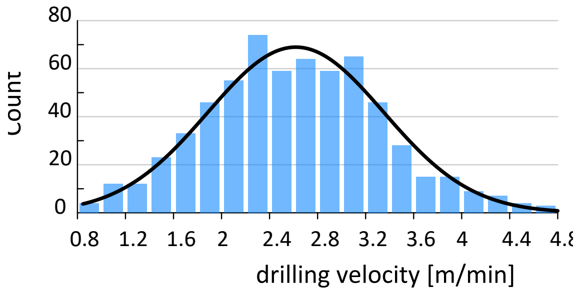

Figure 4. Distribution of recorded drilling velocities.

Through all recorded rounds the geology comprises granitic gneiss, mainly showing slight to moderate weathering characteristics. In 30 % of the drilling rounds fresh to slightly weathered conditions prevailed, with joints and fractures playing an inferior role. Based on the gained data from 21 blasting rounds the analysis of the drilling velocities in correlation to the rock mass characteristics shows that with an increasing degree of weathering the median drilling velocity declines (see Figure 5). In fresh to slightly weathered parts, the average drilling velocity equals 2.8 m/s in comparison to 2.5 m/s in the slightly/moderately weathered areas.

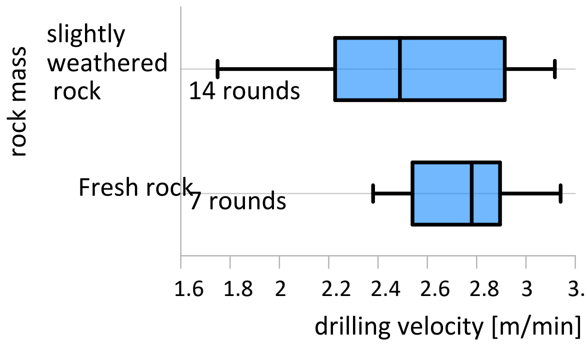

Figure 5. Dependency of the drilling velocity on the rock mass properties.

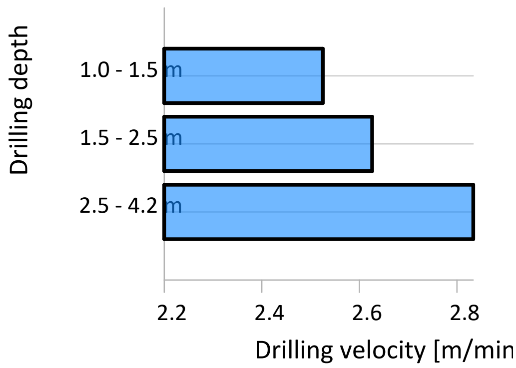

Figure 6. Correlation of drilling depth and the achieved drilling velocity.

During the monitoring on site, it became apparent, that the drilling was not conducted at full drilling feed force frequently. Most prominently, during the collaring process, the drilling velocity was significantly reduced and with increasing depth of the hole, the velocity was continuously increased. As the recording of the net drilling time for each hole was carried out manually, a plot showing the correlation between the depth and the velocity cannot be provided. Based on the gained data and observations, a significant throttling down to around 50 to 70 % of the maximum advance rate for approximately the first meter of the drill hole was observed. This finding becomes obvious when analyzing the data in regard to the dependency of the drilling velocity on the length of the blast holes. The trend towards higher average drilling velocities in longer drill holes is shown in Figure 6. Blasting rounds with a depth of less than 1.5 m show an average drilling velocity of around 2.5 m/s, with the velocity increasing around 0.3 m/s when the length of the drill hole is 2.5 to 4.2 m.

4 DISCUSSION

To evaluate the achieved drilling velocities, the graph from Fig. 7 was used for comparison. For a 25-kW hammer and a median UCS value of 110 MPa, a drilling rate of roughly 3.1 m/min is a realistic estimation. In comparison, the actual drilling velocity averaged 2.7 m/min, meaning a deficit of around 15 %. In short rounds with a drilling depth of less than 1.5 m the average drilling velocity was significantly lower, resulting in an average performance deficit of around 20 %.

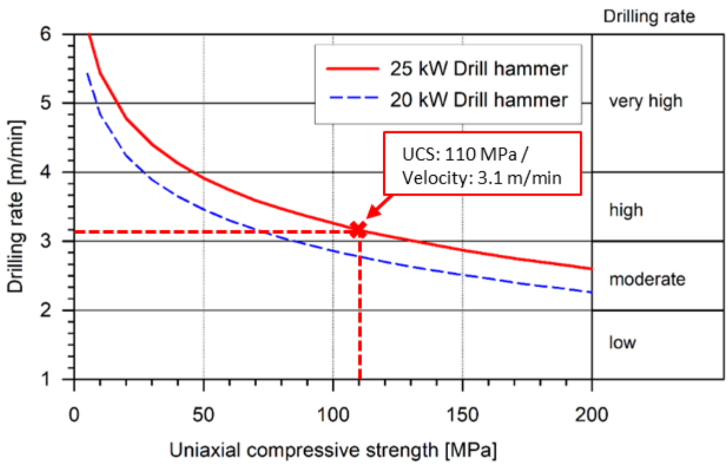

Figure 7. Correlation of the uniaxial compressive strength with the drilling rate for widely used drill hammers (20 + 25 kW impact power). The graph is based on Thuro (1996) and modified with additional research data.

When looking at the reasons for the deficit in the drilling velocity, the process needs to be looked at in its entirety, considering all different influencing factors. First of all, the monitoring of the drilling process showed that the geological conditions did not deviate from the anticipated ground conditions. As shown in Figure 7, in general it can be expected that with an increase of rock strength the penetration rate decreases. The case study shows that this basic and commonly applicable principle is to some extent overridden by automatic drilling control. The mean drilling velocity in competent and fresh rock was measurably higher than in weathered rock. With drilling performance being a trade-off between penetration rate and tool wear, the data suggests that the drilling velocity is automatically reduced in disturbed and fractured zones to avoid jamming and material damage.

The outlined principle of the drilling automation restricting the drilling velocity in fractured ground was most noticeable in the collaring process. Based on the visual assessment in combination with the gained data, it is one of the most prominent factors in the context of underachieved drilling rates. Depending on the ground conditions the first half meter to a meter of each drillhole was drilled with a significantly reduced velocity. One of the main reasons for this are the high levels of blasting induced fracturing, leading to the drilling automation downregulating the velocity. In addition, the collaring process is already carried out at reduced speed to avoid drill hole deviations. With both these causes being applicable to basically all blasting rounds, the impact on the overall drilling performance cannot be neglected. For example, for round lengths of only 1 m the reduced velocity is used for at least half the length of the hole, leading to a considerably lower penetration rate. With increasing hole length, the impact of the collaring process on the overall performance is minimised. Therefore, for an adequate drilling prediction, it is important to consider the round length in early project stages. An in-depth-analysis of the collaring process based on MWD data was carried out by Eldert (2020), confirming the significantly reduced percussive pressure and penetration rate in the first half meter to a meter of the drill hole. The two processes pointed out are the most obvious contributing factors to the mean drilling velocity remaining behind the expectations. It needs to be emphasized though, that the drilling velocity of the prognosis is achievable, when there are no obstructions in the drilling process and the automation can run smoothly. This cannot be shown by analysing median values of a drill hole or even a whole round.

5 CONCLUSION AND OUTLOOK

Drilling automation is a helpful tool for a technically efficient drilling process, but comes with limitations, which shall not be overlooked. The case study shows that with drilling automation, the focus for the prediction of drilling velocities needs to shift to include additional factors. It was shown that the commonly used principle in forecasting - a decreasing drilling velocity with increasing rock strength - has only limited applicability. In the presented study weathered areas, with fractures and lower intact rock strength led to a lower drilling velocity in comparison to areas of solid rock mass. Similar geomechanical responses were observed in zones with blasting induced fracturing, as it can lead to the drilling automation downregulating the drilling velocity and preventing the drill rig from utilizing its full capacity. The gained data suggests that the drilling velocity is lowered by about 15 to 20 % compared to predicted values, with the range of applicable reduction factors highly depending on the borehole length. The most prominent reduction in comparison to the predicted velocity appears in the collaring process, which roughly covers the first meter of each drillhole.

This demonstrates that the principles of drilling prediction, focusing on the geological conditions, the machine parameters and the working process must be updated to account for the parameter of the drilling automation. The drilling automation is a complex and essential impact factor on the performance of the drill and blast operation. Drilling rate predictions on the base of the geological parameters are still effective and up-to-date but must be used with caution in the planning process as they only provide information regarding achievable drilling velocities in a certain geological and geomechanical setting. This does not necessarily mean, that the predicted drilling rate is achieved, as drilling automation settings can prevent this. These predicted values are usually met in certain sections of a borehole, but average values do not display this adequately.

In conclusion the drilling automation is a very effective way of adjusting the drilling process to the geological conditions and the requirements of the construction process, but it is essential to keep in mind that the achieved values, especially average values, do not necessarily have to match the prognosis. For a better understanding of the interaction of the ground with the drilling automation MWD-data shall be analysed to study the characteristics more precisely. Nevertheless, MWD data alone is not sufficient for an adequate analysis but needs to be complemented with the knowledge of a qualified engineering geologist monitoring the drilling process for the identification of causes and a back analysis. In addition, skilled operators overseeing the automatic drilling process are needed to assess the changes, the hindrance and the enhancements in the drilling process. When these different approaches and perspectives are combined, an optimization of the drilling process and the drilling automation can be achieved.

REFERENCES

Nord, G. &Appelgren, J. 2001. The Next Atlas Copco Generation of Tunnel-Rigs and Some Experience. In: Proceedings of the 17th International Mining Congress and Exhibition of Turkey (IMCET 2001), Ankara, Turkey, June 19 – June 22, 2001, pp. 289-295.

Eldert, J. 2020. Drill Monitoring for Rock Mass Assessment in Tunnelling. Doctoral Thesis. Luleå University of Technology, Luleå, Sweden. Retrieved December 14, 2022, from http://ltu.diva-portal.org.

Epiroc 2023. Measurement While Drilling. Epiroc. Retrieved January 13, 2023, from: https://www.epiroc.com/en-au/innovation-and-technology/automation-and-information-management.

Finger F., Doblmayr, P. & Reiter, E. 2005. Bericht 2004 über petrographische und geochemische Untersuchungen an den „Perlgneisen“ im Kristallin der Böhmischen Masse auf Blatt 32 Linz. In: Jb. Geol. B.-A. 145 (3+4), pp. 365-383.

Sandvik Mining and Rock Technology. 2020. Drilling Automation Packages Development / Tunneling Rigs. Retrieved January 09, 2023, from https://www.rocktechnology.sandvik.

Schunnesson H. 1997. Drill process monitoring in percussive drilling for location of structural features, lithological boundaries and rock properties, and for drill productivity evaluation. Doctoral Thesis. Luleå University of Technology, Luleå, Sweden. Retrieved December 15, 2022, from http://ltu.diva-portal.org

Thuro, K. 1996. Bohrbarkeit beim konventionellen Sprengvortrieb. *Münchner Geol. Hefte* Reihe B: Heft 1, pp. 1-149. Prof. Dr. G. Spaun Prof. Dr. H. Miller, Prof. Dr. S. Wohnlich (eds.), Munich, Germany, 1998.

Thuro, K. 1997: Drillability prediction: geological influences in hard rock drill and blast tunnelling. *Geol. Rundsch* 86, pp. 426-438. DOI: 10.1007/s005310050151.