The influence of extremely abrasive rock on the drilling velocity and tool wear in bored piles

T Sattler\textsuperscript{1,2}, A Loibl\textsuperscript{1}, J Festl\textsuperscript{1}, T Zweininger\textsuperscript{1}, W Eckl\textsuperscript{3} and K Thuro\textsuperscript{2}

\textsuperscript{1} Baugeologisches Büro Bauer GmbH, Germany
\textsuperscript{2} Chair of Engineering Geology, Technical University of Munich, Germany
\textsuperscript{3} Bickhardt Bau AG, Germany

tanja.sattler@tum.de

Abstract. The significance of the excavatability for the successful completion of constructional projects has been recognized in recent years, but little attention has been paid specifically to rotary pile boring. Given the quantity of geological parameters alone which need to be taken into account, it is apparent that the estimation of the drilling rate is difficult. Based on a case study in extremely abrasive tertiary silcretes (quartzite), the engineering geological influences on the drillability are examined. A minutely detailed documentation of the drilling process was produced, and laboratory testing was conducted to gain a better understanding of the correlation between significant rock properties and wear on drilling tools. The examined silcretes (quartzite) show CERCHAR abrasivity indices (CAI) up to a value of more than 6. It comes as no surprise that this highly abrasive rock causes extensive wear on piling equipment and an extremely high consumption of wear parts. In combination with the drilling velocity of both the drill tools and the casing shoe remaining well below 10 cm/min, it is obvious that the drilling performance is significantly impacted in more than one way. A correlation between the lifespan of the wear parts and the net drilling velocity is developed, allowing for a more reliable performance prediction for bored piles.

1. Introduction
In recent years, the number of pile foundations for bridges and pile walls has been ever-increasing, due to economical, constructional, and structural reasons. Unavoidably, this increasing demand of pile boring has led to an increase in difficulties during the construction process, often caused by problems regarding the drillability of the ground. Challenging ground conditions are often ascribed to high strength and highly abrasive rocks. As a result, tool wear often exceeds the forecasted amount by far and the drilling velocity remains well beyond the expectations. With these two performance criteria not being met, extensive additional cost is the outcome. This shows the need for the drillability to be considered at early stages in a project to allow for adequate performance predictions instead of encountering problems during the construction stages of a project and solving them along the way.

2. Definition of excavatability
There is no strict definition for the term excavatability. In general, it describes the mechanic operation of breaking loose or excavating soil or rock material. In case of bored piles, this term describes the drilling process and is therefore referred to as the drillability. It manifests itself in two different criteria, the performance criterion, and the material/wear criterion. These can be quantified by the drilling velocity and the usage of steel parts. The drillability is a very complex entity with many influencing
factors which interact with one another. The influence factors on the excavatability can be subdivided into three different groups according to [1] as shown in Figure 1.

These fundamental principles can be applied to all excavation processes. Regarding underground excavations, the excavatability can be translated into drillability and blastability for drill and blast tunnelling and cuttability for mechanized tunnelling methods. The influence of the geological factors has been thoroughly researched and their role for performance prediction has been progressively refined for tunnelling methods. In comparison to the tunnelling sector, little research has been conducted regarding the drillability for large diameter bored piles. At this point it is hard to tell, whether the findings from tunnelling are applicable to bored piles. This presented research project is aiming at narrowing the gap between the well-known interactions between the ground and tools for different tunnelling methods and the not very well-established knowledge base regarding bored piles.

Figure 1. Overview of influencing factors on the drillability (modified from [1]).

Figure 2. Schematic rock cutting mechanism of a round shank chisel with illustration of the applied force components/moments (modified from [2]).

3. Fundamentals of pile boring

3.1. Selection of suitable drilling tools for bored piles in rock
The selection of drilling tools for large diameter bored piles (up to 3,000 mm) depends on various factors, as shown in Figure 1. Regarding the ground conditions, different drilling tools can be chosen from, depending on their range of application from soils to hard rock. As for rock formations, according to manufacturer’s recommendations [3], conventional rotational drilling tools are suitable for rock strengths of up to around 100 MPa. For the upper end of this range, core barrels and drilling augers fitted with round shank chisels (also known as bullet shape drill teeth) are mostly used. For harder rock formations conventional tools are only suitable to a limited extent or uneconomical, also depending on rock mass properties and weaknesses. Alternative drilling tools, such as air roller bit core barrels or cluster drills are specifically designed for very strong rocks exceeding a uniaxial compressive strength of 100 MPa.

3.2. Principles of drilling performance
To be able to comprehend the wear on tools, the understanding of the working principles of rock cutting with round shank chisels (RSC) is essential. Rock cutting mainly depends on three force components applied to the rock surface (see Figure 2): the vertical thrust force (V), a cutting force parallel to the cutting direction (C) and a lateral force (M*) (normal to the plane going through V and C). A rotary torque (M) is applied, which is equal to the product of cutting force and lever arm length.
Efficient cutting is achieved by applying sufficient rotary torque (M) and vertical thrust force (V). An adequate ratio of these two components manifests itself by the round shank chisels biting and breaking the rock into cuttings and chips. When drilling extremely high strength rock, the induced forces are insufficient to produce a fracturing stress field in the contact area of the tungsten carbide tip and the rock surface. As a result, the cutting motion and removal of large chips does not occur, but instead the rock is ground into fine particles. This grinding motion results in tool wear, especially blunting of the tools. Adding extra thrust and torque, the wear pattern shifts from blunting to breaking off the tungsten carbide bits [2].

The theory behind the cutting and drilling performance is well-known but translating this into actual drilling rates and quantifying tool wear is very complex and difficult. Even though these parameters are decisive for the fine line between the successful completion of a project or extensive additional costs, performance prediction models based on geotechnical parameters for pile boring are still lacking or only exist at a basic and rudimental stage.

3.3. Working principles for casing shoe
Simultaneously, while progressing with the drilling tool, a steel casing is inserted in the ground to ensure borehole stability. The casing shoe is fitted with replaceable teeth (RT) to allow for a cutting motion while rotating and pushing down the casing. At this point it is already obvious that the insertion of the casing into the ground by a rotating and grinding motion is not comparable to any methods from the tunnelling sector. With the lack of comparability, it is apparent that specific research for pile boring is long overdue.

4. Significance of geological factors for the drillability
The significance of the drillability for pile construction has been recognized over the past few years and the abrasivity, as a measurement of the capability of a rock to cause wear on drilling equipment, has been implemented into national standards in Germany. Even though this being a step in the right direction to allow for better prediction of drilling advance rates, it is not sufficient. One reason being that the abrasivity itself is not sufficient for an adequate estimation of the drilling velocity and tool wear in bored piles. From a geological perspective, the rock mass properties, including jointing, weathering, and anisotropy are further contributing factors which need to be taken into account. Secondly, the abrasivity can be tested in the laboratory and depending on the result the abrasivity is classified from “not abrasive” to “extremely abrasive” [4]. When looking at this scale and the categories, the question which needs to be asked is what tool wear and drilling advance rate have to be expected in “not abrasive” compared to “extremely abrasive” rock material?

Little research has been conducted regarding the impact of the geological factors, especially the abrasivity as one of the major contributing factors, on the drilling process for bored piles. With the following case study shedding light on the impact of selected rock properties on drilling performance and progress, it aims at contributing to a more reliable prediction of the drilling velocity and tool wear for large diameter bored piles. This is done by exploring the limits of pile boring in extremely hard and abrasive rock.

5. Case study: Project setting and geology
The study we would like to report on was conducted from 2018 till 2019 at a bridge project in Central Germany. The bridge foundation is planned with 1.2 m diameter piles (DN1200). The length of the piles in the abutment is around 20 m and the buttress piles exhibit a length of about 12 m.

According to the preliminary site investigation, the site comprises made ground and silty/sandy quaternary deposits. Underneath these units, deposits of weathered and at the top completely disintegrated Bunter Sandstone follow. The Triassic Bunter Sandstone mainly comprises sandstone with interbeds of clay-/siltstones.

Unexpectedly during pile boring, tertiary sands containing quartzite (silcrete) were encountered underneath the quaternary deposits. The presence of the silcretes was unforeseen and their existence at
the site was not known. The tertiary quartzite within the tertiary deposits are secondary siliceous concretions, internationally known as silcretes. These were formed through the cementation of tertiary sands by dissolved silica. In Germany local names exist for these silcretes, but are commonly known as “Einkieselungsquarzit”, “Tertiärquarzit”, “Süßwasserquarzit” or “Kieselkonkretionen”. Owing to their genesis, the silcretes present themselves as nodular deposits or an irregular horizon with greater lateral extent. Exemplary silcrete outcrops in the vicinity of the site are shown in Figure 3 and Figure 4.

![Figure 3](image1.png)  ![Figure 4](image2.png)

**Figure 3.** Silcretes in a matrix of tertiary sands at a quarry in Gambach (Central Germany/Hessen), showing the typical irregular, nodular shape of these silica concretions.

**Figure 4.** Exposed silcrete concretion in Gambach (Central Germany/Hessen).

The grade of cementation of the tertiary sands/silcretes varies at the investigated site. Hence, the tertiary horizon either comprises silcretes with a spatially great lateral extent (greater than the pile diameter) or loose sands with varying amounts of silcretes, ranging from gravel-sized up to cobble- and boulder-sized (Ø < 63 cm) concretions. Due to their formation conditions, the transition between these forms is fluent. The different forms are schematically shown in Figure 8. The silcretes are fresh and unweathered and joints are not visible.

6. **Impact of the silcretes on the drilling progress and tool wear**

Where silcretes were encountered during the pile boring process the drilling rate dropped significantly and advancement was often unnoticeable with the naked eye. Extremely high tool wear was evident in the silcretes. The round shank chisels on the boring equipment were worn out after a short period of time and needed to be changed frequently. The round shank chisels displayed thermal wear by exhibiting tempering colors. The wear pattern indicates extreme abrasive wear, with the tungsten carbide bit not visible anymore and often asymmetrically deformed steel (see Figure 5).
Since the silcretes occur in a sandy matrix, the casing needed to be worked through the silcrete concretions to ensure borehole stability in the underlying sands. The tungsten carbide inserts on the replaceable teeth of the casing shoe are worn out after little penetration and do not allow for any further drilling progress. Similar to the round shank chisels, extreme abrasive and thermal wear were evident, with a complete abrasion of the tungsten carbide inserts and deformation of the steel carrier material (see Figure 6). With only little penetration achieved with a full set of replaceable teeth, they needed to be changed several times for each drillhole. To change the replaceable teeth, the borehole needed to be backfilled and the casing retracted.

After changing the worn teeth, the boring process started again in the predrilled hole (see visualization in Figure 7). For a single borehole, this sequence for replacement boreholes needed to be repeated several times (up to nine times) to penetrate through the silcretes with the casing shoe. Backfilling and redrilling are no standard procedure for pile boring and the drilling process required up to around ten times longer than a normal pile boring procedure.
Figure 7. Necessary work steps for the penetration of the silcretes with the drill tool and the casing including the required measures for replacement boreholes.

Figure 8. Simplified geological model showing the geological units on site. From top to bottom: Made ground (MG), quaternary deposits (Q), tertiary sands with silcretes, weathered/disintegrated Bunter Sandstone (BS). Typical gross drilling times are indicated, for a pile length of approx. 20 m and a thickness of the tertiary horizon of around 4 m.

6.1. Drilling parameters
To assess and quantify the influence of the silcretes and their geotechnical properties on the drillability, a minutely detailed documentation was produced for 23 piles. The following steps in the drilling process and the time required were individually documented:

- (1) Drilling with tool and casing
- (2) Tool changes due to extensive wear
- (3) Backfilling the drillhole for replacement drillholes
- (4) Re-drilling the backfilled borehole

Additionally, a borehole log was produced to ensure the geological data can be matched with the observed tool wear and drilling time log. The main task being the assessment of the influence of the silcretes on the pile boring process, the following analyses focus on the drilling process in this unit. By using the documented drilling time and the thickness of the silcretes, the gross and net drilling velocity is calculated. The gross drilling velocity being the thickness of the silcretes divided by the gross drilling time, including the above stated work steps (1) – (4). The net drilling velocity is determined from the drilling time with tools and casings (1) for penetrating through the silcretes.

In order to assess the influence of the silcretes on the tool wear, the lifespan of the wear parts was measured in units of centimeters per wear part. It shows the amount of advance, which can be achieved before the tools are too blunt to allow for any further penetration and need to be replaced.

6.2. Rock mechanical parameters
In addition, rock samples were taken from the cuttings and testing was conducted in the rock mechanics laboratory of the Technical University of Munich. Geotechnical parameters were determined, with the main foci being the uniaxial compressive strength and the abrasivity of the silcretes. In total
19 uniaxial compressive strength tests were carried out according to the code of practise No. 1 of the German Geotechnical Society (DGGT) [5]. To determine the abrasivity, 5 LCPC tests and 12 CERCHAR tests were conducted. The LCPC tests were conducted according to [4] following the standard AFNOR NF P18 579:2013-02 [6] and the CERCHAR tests were carried out according to [7].

7. Results

7.1. Intact rock properties

The determined uniaxial compressive strength of the silcretes is to be described as very to extremely high, ranging from 150 MPa to about 290 MPa with an average value of 220 MPa. According to the abrasivity tests, the silcretes are extremely abrasive due to their high quartz content. With a LCPC Abrasivity Coefficient (LA) between 1,400 g/t and 1,700 g/t, the abrasivity can be described as extremely high. The CERCHAR Abrasivity Index (CAI) ranges from around 3.8 to 7.4 with an average value of 5.8. Normally, the upper limit on the scale for the CAI is 6. With the test results exceeding the scale, it is obvious, that this material displays an extraordinary or even abnormally high abrasivity.

7.2. Analysis of drilling parameters

The total time needed for the penetration of 1 m of silcretes at the investigated site is shown in Figure 9. The actual drilling time of the tools and the casing only accounts for 33% of the total time. The other 67% of the required time are made up by tool change due to wear (20%) and backfilling including re-drilling to the depth of the previous drillhole (47%). This equals a reduction of performance by 67% due to the additionally necessary work steps.

As can be seen, especially the wear on replaceable teeth is linked to significant delays in the drilling process as backfilling is needed to change these wear parts. It needs to be stated that the backfilling process is independent of the thickness of the quartzite and cannot be normalized. At the site, the silcretes were encountered at a depth of around 15 m, therefore the time needed for backfilling this stretch up to multiple times is shown here. This may vary and the applicability to other projects is limited.

The advance rates while drilling in made ground and quaternary deposits was high as to be expected in soil (around 1 m/min). Within the tertiary sands, the drilling velocity remained high, when no silcretes were encountered or the size of the silcretes was small in relation to the diameter of the borehole. With increasing size of the quartzite concretions, the drilling process was hindered. As soon as the size of the concretions equals large boulders or comprises a continuous horizon, the drilling rate dropped significantly. In these extremely hard sections, the drilling velocity of the tools dropped from around 100 cm/min in the tertiary sands to around 3 cm/min on average in the silcretes. The achieved drilling rate shows a narrow margin, ranging from 7 cm/min to less than 1 cm/min. As for the boring tool, the
net velocity of the casing was also determined and ranged from 1 cm/min to 10 cm/min, with an arithmetic mean of 4 cm/min.

With the sharp drop in drilling velocity, a prompt increase in wear on the tools and a significantly shortened lifespan of the wear parts was evident. During penetration of the silcretes, the lifespan of the round shank chisels varied between 1 cm and 36 cm, with an average value of 7 cm. The replaceable teeth showed an average lifespan of 3 cm, with a range from 1 cm to 7 cm. The relation between the drilling rate and the lifespan (as the factors defining the drillability) is illustrated in Figure 11.

The correlation shows that the pile boring performance is significantly impaired by the presence of the silcretes. The analysis demonstrates that the drilling velocity and the lifespan of the wear parts for both the drilling tool and the casing are in an exceptionally low range due to the extremely strong and highly abrasive silcretes. The achieved drilling rate with the casing is slightly higher than with the drilling tools, whereas the lifespan of the replaceable teeth is significantly shorter than the lifespan of the round shank chisels.

8. Impact of this study for future pile boring operations

With rock being an overly complex material, it is difficult to put the cause and the consequence for drilling performance into perspective. The presented project allows for the analysis of the influence of different geotechnical factors on the drillability. Owing to their genesis the silcretes do not contain any joints and no weathering signs are visible. Therefore, the silcretes can be viewed as homogeneous on a rock mass scale, meaning that the drilling process is governed predominantly by the intact rock properties. This enables a good correlation between the conducted laboratory tests and the performance criteria (drilling rate/tool wear).

Not only does the study show the impact of intact rock properties on the drillability. It also emphasizes the importance of discontinuities for an economical excavation in hard rock, allowing for deeper penetration by promoting chipping of the rock.

This complexity of the geological influencing factors in combination with a lack of literature values is the downfall of the prediction of drilling rates and leads to performance assumptions based on experience from previous projects. To overcome this issue detailed data from different project settings is needed to evaluate the effect of the individual influence parameters on the drillability. This project sets a guideline for performance prediction and tool wear for large diameter rotary pile drilling. In Figure 12 the absolute time needed for the penetration of 1 m of silcretes is displayed and can be used for the estimation of required time for drilling in similar geological conditions.
Figure 12. Required time for the penetration of 1 m of silcretes derived from the collected data in the case study (pile diameter DN1200, average pile length: 20 m) providing a basis for the prediction of drilling rates in highly abrasive and extremely strong rock. The time for backfilling is based on the depth where silcretes were encountered (roughly 15 m bgl). As it is normalized to the thickness, the timespan includes up to three backfilling operations per meter silcretes.

9. Summary
With this piece of research, we wish to contribute to a better understanding of the drilling performance and prediction in hard rock. The drillability needs to be brought into focus during the design phase to not run into problems during the construction phase. A rethinking must take place based on the knowledge that high strength and highly abrasive rock cannot be drilled economically with conventional drilling tools as shown in this case study. Therefore, if this type of rock is expected, additional measures need to be described in the tender offer allowing for a transparent calculation. If no additional measures are described in the tender documents, the bidder needs to expect that these units can be drilled with conventional tools. The described backfilling and re-drilling are no acceptable approach and cannot be expected from the bidder unless specifically outlined. The same applies to rock properties, if no information regarding the abrasivity is given in reports, the bidders have to assume a normal abrasivity with a CAI < 1. With the drillability bearing a high financial risk due to additional cost and construction-time-delays, further advancement in this field is necessary for a better understanding of the complex relations and consequences.

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