# Roadheader excavation performance - geological and geotechnical influences

## Le progrès des machines de percement - influences geologiques et geotechniques

## Vortriebsleistung von Teilschnittmaschinen - geologische und geotechnische Einflußgrößen

K. THURO & R.J. PLINNINGER, Department for General, Applied and Engineering Geology,
Technical University of Munich, Germany

ABSTRACT: The prediction of tunnel stability usually is the main subject in geotechnical site investigations prior to tunnelling projects. During the last few years in mechanical excavation, problems have occured also connected with the accurate prediction of excavation performance and tool wear in soft and hard rock. Every now and again problems have been encountered leading to high bit consumption and low cutting performance of roadheaders. In this paper the connection between some geological features, cutting performance and bit wear is presented. Further, some major correlations of specific rock properties as well as geological factors with measured bit wear and excavation rates are shown.

RÉSUMÉ: D´ordinaire lors d´études préliminaires aux grands projets de percement de tunnel, les pronostics sur la stabilité de l´excavation se trouvent au premier plein d´intérêt. Ce pendant ces dernières années les difficultés de prévoir correctement la résistence des roches lors de percement méchaniques. Encore des problèms revenaient en connexion avec la consommation des ciseaux et avec le progrès de couper de bas avec des machines de percement. Dans cet bulletin, sont exposées les corrélations fondamentales entre quelques propriétés géologiques, le progrès de couper et l´usage des ciseaux, utiliser l´assistance des études allemandes en différentes entourages géologiques.

ZUSAMMENFASSUNG: Bei den geotechnischen Voruntersuchungen zu großen Tunnelprojekten steht üblicherweise die Vorhersage der Stabilität des auszubrechenden Hohlraums im Vordergrund. In den letzten Jahren haben sich beim Vortrieb mit Teilschnittmaschinen in Fels allerdings auch vermehrt Probleme bei der Prognose der Fräs- bzw. Schneidleistungen in den verschiedenen Gesteinen ergeben. Hierbei sind vor allem niedrige Vortriebsleistungen und hoher Werkzeugverschleiß zu nennen. In den folgenden Ausführungen soll auf die geologischen Verhältnisse und die Zusammenhänge zwischen geomechanischen Gesteins- und Gebirgseigenschaften und den vortriebsrelevanten Parametern eingegangen werden.

## 1 INTRODUCTION

Excavation performance is a term used in underground construction to describe the influence of a number of parameters on the cutting rate and the tool wear of a roadheader. The interaction of the main factors is illustrated in Figure 1.

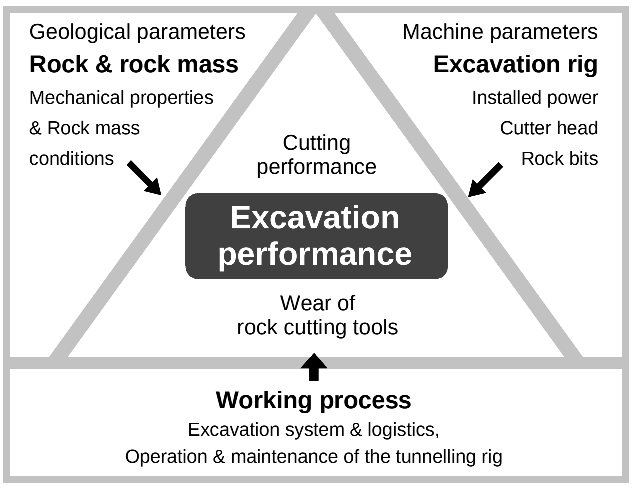


Figure 1: Main influencing parameters of "excavation performance" in roadheader operation.

First of all, the excavation performance is influenced by the machine parameters of the chosen tunnelling rig - the installed power, the type of cutter head and the rock cutting tools mounted.

Apart from technical parameters, especially the geological parameters will basically influence the cutting performance and the tool wear (Figure 2). The specific characteristics of rock material and rock m/ass may be at least partly put into figures with the help of mechanical rock properties. But rock mass conditions also highly depend on the geological history, weathering conditions, hydrothermal decomposition and the structure of discontinuities. Therefore, one has to go through three levels of investigation: mineral - rock type - and rock mass - meaning also three levels of dimension!

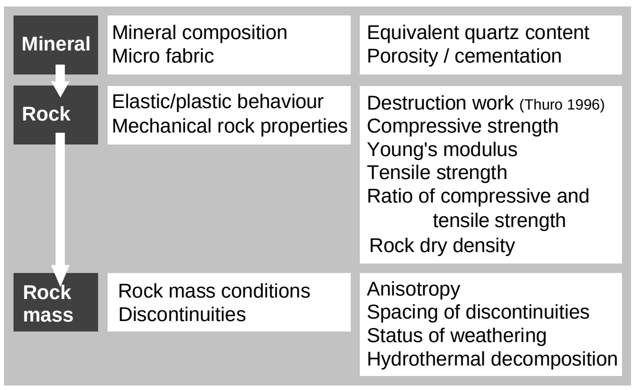


Figure 2: Geological parameters: General view of the characteristics of mineral, rock and rock mass

The last important factor influencing rock excavation performance is the working process itself. Firstly, smooth operation and permanent maintenance of the tunnelling rig contributes to a successful cutting performance. Secondly, a high penetration rate at the tunnel face does not automatically lead to a high performance of the tunnel heading (Thuro & Spaun 1996a). Therefore, it is a matter of understanding the entire excavation system before applying expertise to the investigation of excavation performance.

## 2 SCOPE

The prediction of tunnel stability is usually the main subject in preliminary site investigations prior to tunnelling projects. While the choice of an economic tunnelling method is normally admitted a certain priority, special investigations for rock fragmentation - e.g. the cutting performance or the wear of the cutters - are carried out quite rarely. For this reason arising problems often have to be solved during tunnel excavation rather than in the design period. Table 1 and Figure 3 give an idea of the kind of main problems in the different processes of roadheader excavation.

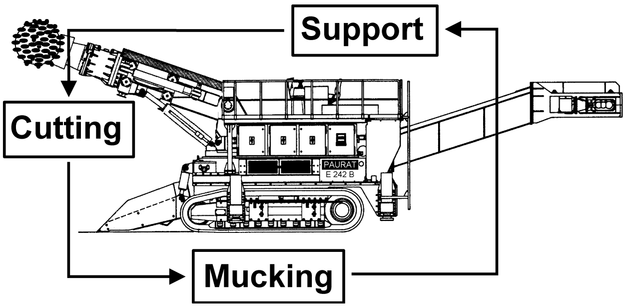


Figure 3: Working cycle and main problems in roadheader excavation.

Table 1: Main Problems in roadheader excavation.

| Process | Problem |
|---|---|
| Cutting | poor cutting performance |
| | high bit consumption ⇨ high tool wear |
| | no cutter head penetration, smudging of the cutter head |
| Mucking | soft soil behaviour & water (⇨ water-saturated mud) |
| | excavated blocks too big for haulage / conveyor belt |
| Support | according to stability problems (not discussed here |

Cutting and drilling performance as well as the wear of tools and equipment are decisive for the progress of excavation works. The estimation of these parameters in predicted rock conditions might bear an extensive risk of costs. Therefore an improved prediction of cutting performance and bit consumption would be desireable. For some years now basic rock drilling processes and bit wear have been studied in drill and blast tunnelling (Thuro 1996, Thuro 1997a, 1997b).

While performance is mainly influenced by macroscopic qualities such as rock strength, toughness (deformability), anisotropy, jointing or the weathering stage of rock mass (Gehring 1997, Thuro & Spaun 1996a, 1996b, Verhoef 1997) tool wear is predominantly affected by microscopic rock properties such as equivalent quartz content and the degree of mineral interlocking (Deketh 1995). Apart from conventional rock properties some special effects may hit the excavation process quite badly. For example in apparently good rock conditions with easy cutting of soft sandstones and clay-siltstones, even a low water inflow can lead to a total disaster: In one case, the cutter head has been smudged by clay and in another the mucking of the excavated material was nearly impossible due to the behaviour of the mud.

Extensive field studies and laboratory work has been carried out to record the correlation between some geological features and geotechnical parameters on the one side and technical parameters such as cutting performance and bit consumption on the other. This short paper can only give some insigths in these connections.

## 3 EXCAVATION PERFORMANCE

### 3.1 *Cutting performance*

#### 3.1.1 *Mechanical rock properties*

The most frequently used rock property for predicting cutting performance is the unconfined compressive strength. To be able to predict the cutting performance from compressive strength, a diagramm of the machine manufacturer like Figure 3 is usually used. In the diagram the expected and actual cutting performance in the Zeulenroda sewage tunnel (Thuringia, Germany) are plotted versus the unconfined compressive strength. There is a great variation of the UCS-values which is connected with the specific behaviour of the different rock types (argillaceous slates and quarzites of the Thuringian Slate Mountains). For project details see Thuro & Plinninger (1998).

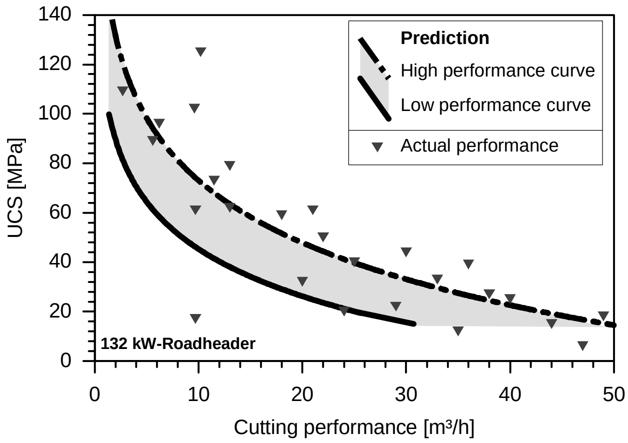


Figure 4: Cutting performance of a Atlas Copco Eickhoff ET 120 (132 kW) roadheader versus compressive strength. Expected and actual performance in the Zeulenroda sewage tunnel.

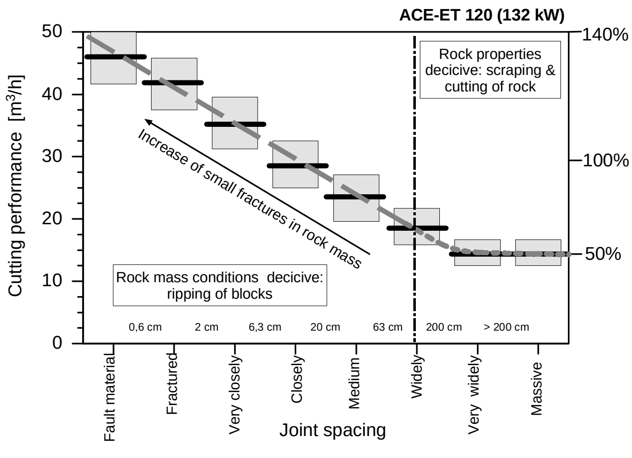


Figure 5: Cutting performance of the AC-ET 120 versus joint spacing in argillaceous slates and quartzites of the Zeulenroda sewage tunnel.

The two prediction curves are stated for two cases: The low performance curve is used for prediction, if the spacing of discontinuities is (very) widely or if the orientation of the discontinuities is unfavourable. The high performance curve is used, if the spacing of discontinuities is closely or if the orientation is favourable.

However net cutting rates increase with decreasing spacing of discontinuities - joints and cleavage. Figure 5 indicates that at least two processes are taking place during cutting: As long as the rock is massive, scraping and cutting of material is dominant.

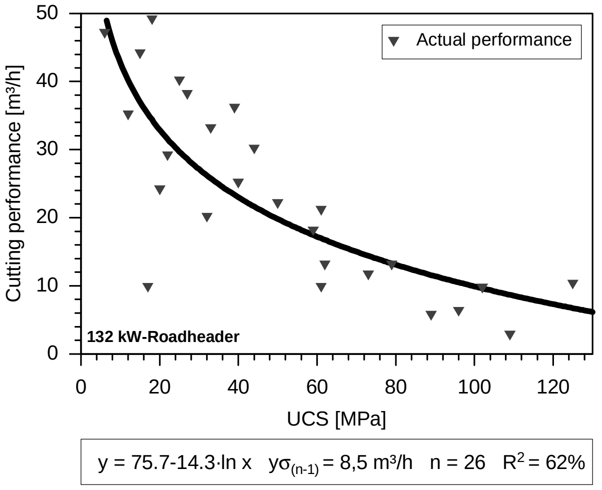


Figure 6: Cutting performance, correlated with compressive strength of 26 rock samples. Statistic parameters: $y\sigma_{(n-1)}$ - standard deviation, n - number of values, $R^2$ - square of correlation coefficient.

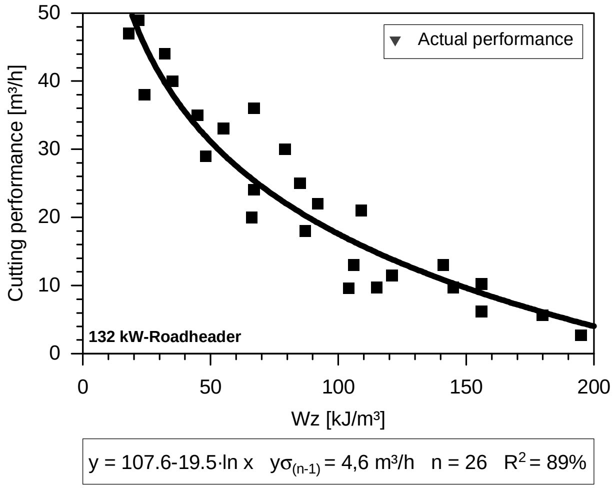


Figure 7: Cutting performance, correlated with destruction work of 26 rock samples (argillaceous slates and quarzites, Zeulenroda sewage tunnel). The correlation of the curve is very good.

There is much energy needed to carve the rock - resulting in a relatively low cutting performance. With closer joints the cutter head is able to rip out blocks or at least larger pieces of rock which are already precracked by small attending fissures. This process consumes less energy and the cutting performance is much higher. Similar observations in trench cutting were recently published by Deketh et al. (1998).

Looking at the diagram in Figure 6, the quality of the correlation between unconfined compressive strength and cutting performance is not sufficent. It seems, that the UCS is not able to describe the energy used for rock fragmentation during the excavation process.

Therefor the so-called specific destruction work $W_z$ has been introduced (Thuro 1996, Thuro & Spaun 1996a, 1996b), as a measurement for the quantity of energy, required for destruction of a rock sample or - in other words - the work, necessary to build new surfaces (or cracks) in rock. The specific destruction work seems to be the best fitting parameter for drillability prediction in drill- and blast tunnelling (Thuro 1997). Figure 7 shows the cutting performance for the same rock material with their values of the specific destruction work. The correlation is much better than that of Figure 6.

### 3.1.2 *Mucking problems*

During the excavation works of the underground of Nuremberg (Bavaria, Germany) in sandstones and clay-siltstones of the upper triassic (Keuper), in one lot the performance of the roadheader proved to be far behind from what had been expected. Field studies soon discovered that this was not effected by poor cutting performance, but was indeed a problem of the roadheader´s mucking system. Due to the soft soil behaviour the muck haulage could not transport as much material as excavated by the cutter head. From time to time the cutting process had to be interrupted, so that the workers had time to shovel the forming mud into the haulage device.

It was revealed that the mucking problem was clearly related to the amount of clay and silt in the excavated series. As shown in Figure 8, the roadheader performance generally decreases with an increasing percentage of clay and silt. During the excavation process the clay- and siltstone-layers were cut to small debris by the roadheader. They were mixed together with sand from the sandstone-layers, that - unfortunately - are highly water permeable. In combination with the encountered water inflow of 2 - 5 l/sec this seemed to be the right mixture to form a water-saturated mud. This material could no longer be mucked by the roadheader´s muck haulage.

This model can also explain the flattening of the curve at higher amounts of clay and silt, which can be seen in Figure 8: With an increasing percentage of clay and silt the amount of sand in the excavated material decreases and for this reason the material becomes less permeable for inflowing water.

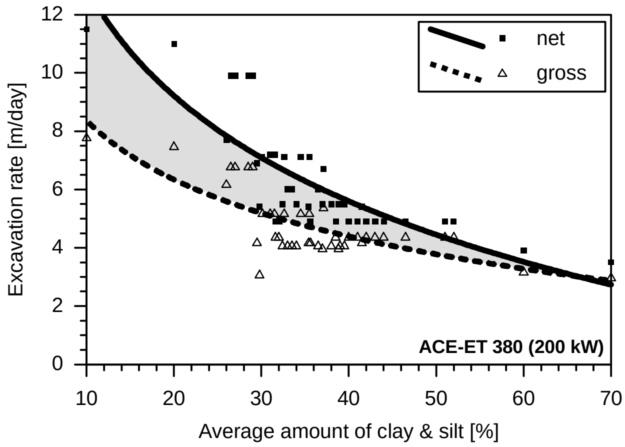


Figure 8: Net and gross excavation rates versus average amount of clay and silt in the Keuper formation ("sandstones") of the Underground Nuremberg. For project details see Thuro & Plinninger (1998).

## 3.2 *Tool wear - bit consumption*

### 3.2.1 *Abrasivity and mineral content of rock*

While cutting performance is mainly influenced by macroscopic qualities, tool wear is predominantly affected by microscopic rock properties such as equivalent quartz content (Thuro 1997) and the degree of mineral interlocking.

Only few authors worked on the correlation between abrasivity and the mineral content of rock and the connection is not fully understood by now. Although the correlation between the CERCHAR abrasivity index and bit consumption has been proved by Verhoef (1997), there is only little data for printing a representative diagram. By now, the quartz content in connection with the unconfined compressive strength seems to be the only reliable database. Figure 9 shows a simple diagram for the prediction of bit consumption.

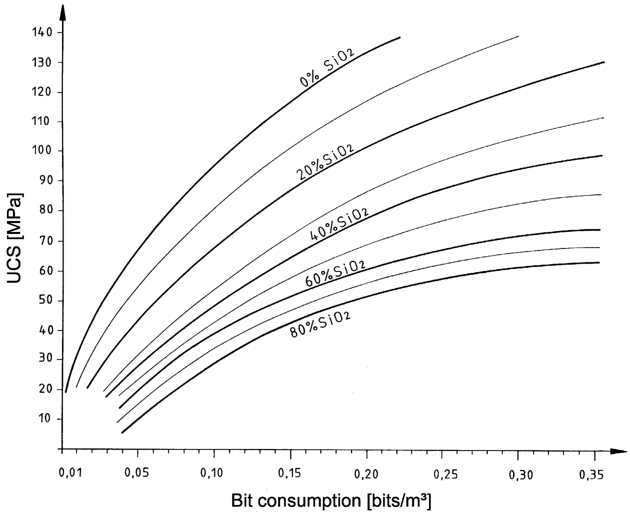


Figure 9: Connection between bit consumption, unconfined compressive strength and quartz content (according to Atlas Copco Eickhoff company informations and own studies).

Although the diagram seems to work in most usual rock conditions, the correlation is only valid for scraping and cutting of rock material. If the cutter head is ripping blocks out of the tunnel face or moves jerkily at the face (e.g. because of extreme hard layers in the rock strata), the tool wear may be much higher.

An example may illustrate that: During the excavation works in one lot of the underground of Nuremberg in sandstones and clay-siltstones, the roadheader suffered from an immense bit consumption that reached amounts of up to 508 bits per day. Related to the excavated mass quantity, the specific bit consumption reached values up to 4 bits per m³ instead of less then 0.1 bits per m³ in “normal” sandstone.

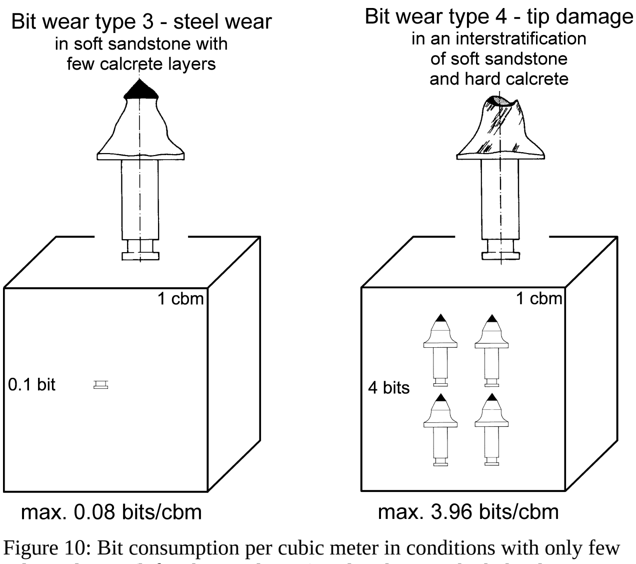


Figure 10: Bit consumption per cubic meter in conditions with only few calcrete layers (left cube, steel wear) and with some thick, hard “quacken”-layers (right cube, tip damage & tip removal).

The assessment of about 100 used bits showed, that in most cases the hard metal bit was broken or even broken out of the bit´s steel body. This pointed at highly abrasive rock with a high compressive strength. Indeed there was a clear connection between enormous bit consumption and appearance of thick and very hard dolomitic and calcitic calcrete layers (so called “Quacken”). The highest wear of bits was achieved in an area, where two unjointed layers of calcrete were encountered with a thickness of 0.9 m and 0.5 m.

Although the investigations gave evidence of a high quartz content (up to 60 %) and a compressive strength of up to 180 MPa in these concretions, the immense bit consumption was not effected by the abrading properties of the calcretes alone. The interchanging series of relatively soft sandstones and calcretes with a compressive strength of up to 100 MPa led to an increased breaking of the bit´s hard metal inserts: While the inserts - made of tungsten carbide - are relatively resistant to grinding, their brittle behaviour makes them susceptible to hits, as obtained when the cutting head leaves a more soft sandstone layer and moves into a hard layer of calcrete. Since the broken or even broken out inserts can no longer protect the bit´s steel body from abrasion, the wear of such bits increases rapidly. Figure 10 shows the clear differences between two neighbouring lots in bit comsumption and bit wear type - one with only few calcretes, the other with thick “Quacken”-layers.

## 4 CONCLUSION

Even if there are a lot of rock properties controlling the excavation performance of a roadheader, a geological phenomenon may cause much more trouble in excavation than “just” higher rock strength values. Therefore, preliminary site investigations should also especially focus on geological conditions and problems. Both geological-mineralogical and geotechnical aspects should be taken into consideration to raise the level of geotechnical contribution to underground construction. Nevertheless the description of some geological and geotechnical influences on the effectiveness of cutting works given in this paper may help to improve the estimation of rock excavation rates and bit consumption in planning future tunnel projects.

## REFERENCES

Deketh, H.J.R. 1995. *Wear of rock cutting tools. Laboratory experiments on the abrasivity of rock.* Rotterdam: Balkema, 160 pp.

Deketh, H.J.R., Alvarez Grima, M., Hergarden, I.M., Giezen, M., & Verhoef, P.N.W. 1998. Towards the prediction of rock excavation performance. *Bull. Eng. Geol. Env.* 57: 3-15.

Gehring, K. 1997 Classification of drillability, cuttability, borability and abrasivity in tunnelling. *Felsbau* 15: 183-191.

Thuro, K. & Plinninger, R.J. 1998. Geological limits in roadheader excavation - four case studies. In Moore & Hungr (eds.), *Engineering geology. A global view from the pacific rim; Proc. 8th Int. IAEG Congr., Vancouver, 21-25 Sept. 1998:* 3545-3552. Rotterdam, Brookfield: Balkema.

Thuro, K. & Spaun, G. 1996a. Drillability in hard rock drill and blast tunnelling. *Felsbau* 14: 103-109.

Thuro, K. & Spaun, G. 1996b. Introducing `destruction work´ as a new rock property of toughness refering to drillability in conventional drill- and blast tunnelling. In G. Barla (ed.) *Eurock ´96. Prediction and performance in rock mechanics and rock engineering* 2: 707-713. Rotterdam, Brookfield: Balkema.

Thuro, K. 1996. Bohrbarkeit beim konventionellen Sprengvortrieb. Geologisch-felsmechanische Untersuchungen anhand sieben ausgewählter Tunnelprojekte. Drillability in conventional drill and blast tunnelling. Geological and rock mechanical investigations on seven tunnel projects. *Münchner Geologische Hefte, Reihe B, Angewandte Geologie,* B1: 1-145.

Thuro, K. 1997a. Drillability prediction - geological influences in hard rock drill and blast tunnelling. *Geol. Rundsch*. 86: 426 - 437.

Thuro, K. 1997b. Prediction of drillability in hard rock tunnelling by drilling and blasting. In Golser, Hinkel, Schubert, (eds), *Tunnels for People. Tunnel für Menschen; Proc. World Tunnel Congr., Vienna, 12-17 Apr. 1997*: 103-108. Rotterdam, Brookfield: Balkema.

Verhoef, P.N.W. 1997. *Wear of Rock Cutting Tools. Implication for the site investigation of rock dredging projects*. Rotterdam, Brookfield: Balkema, 340 pp.