Experimental Study of Forces Induced in Mechanical Excavation of Rock

John Pultorak,[1] Dmitry Drozdov,[2]
Jia-Liang Le, P.E., M. ASCE,[3] and Emmanuel Detournay, A.M. ASCE[4]

[1]Department of Civil, Environmental, & Geo- Engineering, University of Minnesota, Minneapolis, MN, 55455; e-mail: pulto001@umn.edu
[2]Department of Civil, Environmental, & Geo- Engineering, University of Minnesota, Minneapolis, MN, 55455; e-mail: drozd018@umn.edu
[3]Department of Civil, Environmental, & Geo- Engineering, University of Minnesota, Minneapolis, MN, 55455; e-mail: jle@umn.edu
[4]Department of Civil, Environmental, & Geo- Engineering, University of Minnesota, Minneapolis, MN, 55455; e-mail: detou001@umn.edu

ABSTRACT

This paper presents preliminary results of an experimental campaign aimed at mapping the dependence of the cutting force on the depth of cut in scratch tests performed with a sharp cutter. Tests conducted in Berea sandstone and Indiana limestone confirm that the scaling of the force with the depth of cut depends on the cutting regime. They also show a dependence of the nature of the frequency distribution of the cutting force on the modes of failure.

INTRODUCTION

The drive to mechanize the excavation of hard rocks has brought to the forefront the need to quantify the mechanics of tool-rock interaction. Indeed, machine design relies on our ability to predict the average cutting force as well as the expected force fluctuations corresponding to given operating parameters and rock properties (Nishimatsu 1993, Fowell 1993, Nelson 1993). In this regard, the following fundamental question arises: what is the dependence of the cutting force (i) on the depth of cut and the cutter geometry, and (ii) on the strength and fracture properties of the rock. Rephrased in terms of the energy spent per volume of rock removed, how does the specific energy (Teale 1965) scale with depth of cut and rock properties. Incidentally, a possible dependence of the specific energy on the depth of cut is usually ignored in the literature on mechanical excavation, where attempts to correlate the specific energy to rock properties are presented (Tiryaki et al 2009).

A related issue is the interpretation of the scratch test, which involves tracing a groove on the surface of a specimen with a cutting tool. The scratch test is typically conducted under kinematic control: the depth of the cut d (or depth of the groove) and the cutter velocity v (tangential to the sample surface) are imposed and maintained constant along the entire cut, while the magnitude and orientation of the force acting on the cutter are measured. This experimental technique has garnered interest lately, because it appears to offer a simple means to measure strength properties of quasi-brittle materials (Richard *et al* 1998, Akono *et al* 2011, Richard *et al* 2012, Zhou and Lin 2014). However, there is strong disagreement between researchers on how to interpret the results (Lin and Zhou 2013, Akono *et al* 2014, Lin and Zhou 2015, Le and Detournay 2016). At stake is which parameters can be determined in these experiments and how to interpret them from the test data.

To address these fundamental questions, a research program has been initiated that is exclusively concerned by the force on the cutting face of the tool, noting that in a controlled scratch test, a sufficiently sharp tool can always be used so that the frictional contact force is negligible compared to the cutting force, or that the frictional force can be assessed from the force measurements under certain conditions (Detournay and Defourny 1992, Richard *et al* 2012). Finally, a possible dependence of the cutting force on the velocity will not be investigated, as cutting experiments on dry rocks do not show any significant rate effects over the range of cutter velocity typically achieved in laboratory testing (Nishimatsu 1993, Fowell 1993). It is also convenient to introduce the specific energy ϵ, defined as the energy expended per unit volume of fragmented rock; ϵ corresponds to the ratio of the average cutting force over the cross-sectional area of the groove created by the motion of the cutter. Reformulated in terms of ϵ, the fundamental question is the scaling of the specific energy ϵ with respect to depth of cut d and the strength properties of the rock, namely unconfined compressive strength q and toughness K_{Ic}.

The paper is organized as follows. First we review the dependence of the rock failure mode on the depth of cut. We then provide a short description of the scratch apparatus and of the testing procedure. Finally, we give preliminary results of the transition from the ductile to the fragmentation regime for tests conducted in Berea sandstone and Indiana limestone and discuss change in the nature of the frequency distribution of the cutting force between the two regimes.

CUTTING REGIMES

Rock cutting experiments suggest the existence of three distinct modes of failure for depth of cut larger than the average grain size (Chaput 1992, Richard *et al* 1998, Richard *et al* 2012). Each mode is characterized by a different dependence of the cutting force on the depth of cut and on the rock strength parameters.

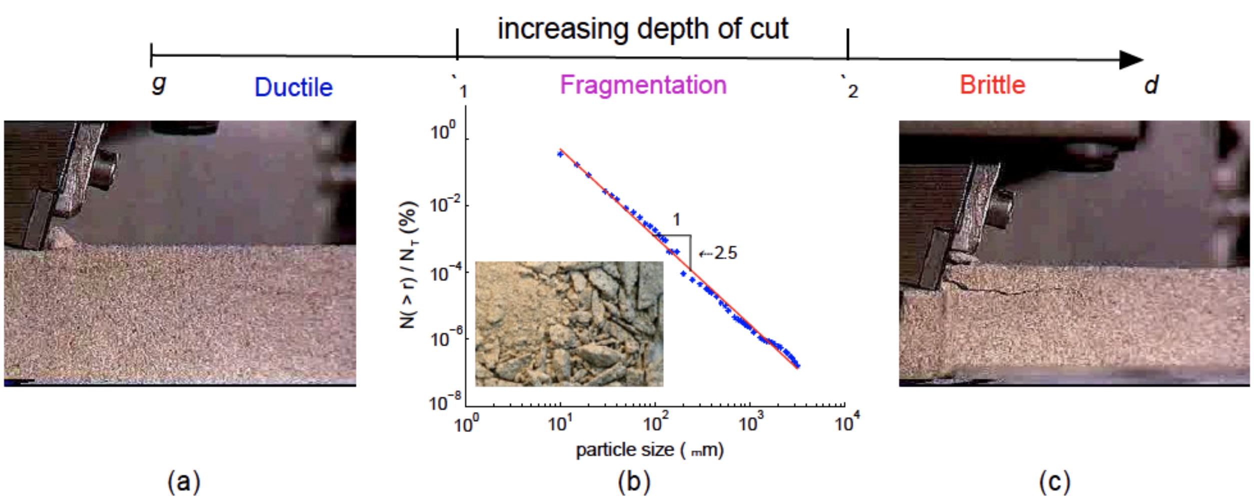

Figure 1: Different regimes of cutter/rock interaction with increasing depth of cut

- *Ductile regime*: shallow depth of cut (typically less than 1 mm for a medium strength sandstone), the rock is intensively sheared ahead of the cutter; this cutting regime is mainly characterized by a de-cohesion of the constitutive matrix and grains, with grains and powder accumulating progressively in front of the cutter, see Fig. 1(a). A comprehensive laboratory experimental program has shown convincingly that the specific energy ϵ; does not depend on the depth of cut d at shallow depths of cut (or in other words that the cutting force is proportional to d) and that ϵ is well correlated to the UCS unconfined compressive strength (Richard *et al* 2012).

- *Fragmentation regime*: With increasing depth of cut, the rock breaks into fragments that are distributed according to a power law over a significant range of sizes. The photograph in Fig. 1(b) shows the particle size distribution curve for the fragments collected from a scratch test on a slab of Tuffeau limestone with $\mathrm{d} = 1.3$ mm (Pena 2010). The fractal dimension D_f of the fragment-size distribution curve is about 2.5, a value broadly consistent with D_f determined for a variety of fragmentation processes (Turcotte 1986). A limited set of experiments and numerical simulations suggests that a progressive transition between the ductile and the fragmentation regime takes place around a depth of cut $d = \ell_1 \sim (K_{Ic}/q)^2$ (Richard *et al* 1998, Huang and Detournay 2008, Zhou and Lin 2014). This transition length scale is of order $O(1 \text{ mm})$ for medium strength sedimentary rocks, and could presumably be of order $O(0.1 \text{ mm})$ or less for hard rocks.

- *Brittle regime*: At larger depth of cut, brittle failure occurs with macroscopic cracks initiating from the tool tip and propagating unstably ahead of the cutter, see Fig. 1(c). Large chips are created by the propagation of sub-horizontal tensile cracks (i.e., sub-parallel to the free surface). An asymptotic fracture mechanics analysis based on treating the chips as beam-like structures indicates that the specific energy scales according to $\epsilon \sim K_{Ic}^2/Ed$ (Le and Detournay 2016). (The energy scales by d^{-1} under these assumptions and not by $d^{-1/2}$ as claimed by some researchers (Akono and Ulm 2011, Akono *et al* 2011). The erroneous scaling stems from not recognizing the cyclic nature of the chipping process in rock cutting.) Presumably the transition depth of cut from the fragmentation to the brittle regime, ℓ_2, is proportional to K_{Ic}^2/E^2, but the (large) magnitude of the proportionality factor is currently unknown. There are hints, however, that transition depth of cut ℓ_2, is of order $O(\,1 \sim 10\,)$ mm in hard rocks.

SCRATCH APPARATUS

The scratch apparatus used for the experiments is a commercial version of the Rock Strength Device that was developed at the University of Minnesota in the late 1990's (Detournay *et al* 1997), see Fig. 2. The RSD scratches the surface of rock samples under precise kinematic control, while enabling the accurate measurements of the force acting on the cutter. The main components of the frame are: a traverse with a sample holder, a moving cart housing the vertical positioning system, the load cell, and the cutting element. The horizontal movement of the cart is operated by a computer controlled stepper-motor driving a horizontal ball screw via a gearbox. The depth of cut is adjusted manually with the vertical positioning system and a micrometer. A locking system secures the vertical traveling mechanism against the frame, in order to maintain a constant depth of cut while cutting.

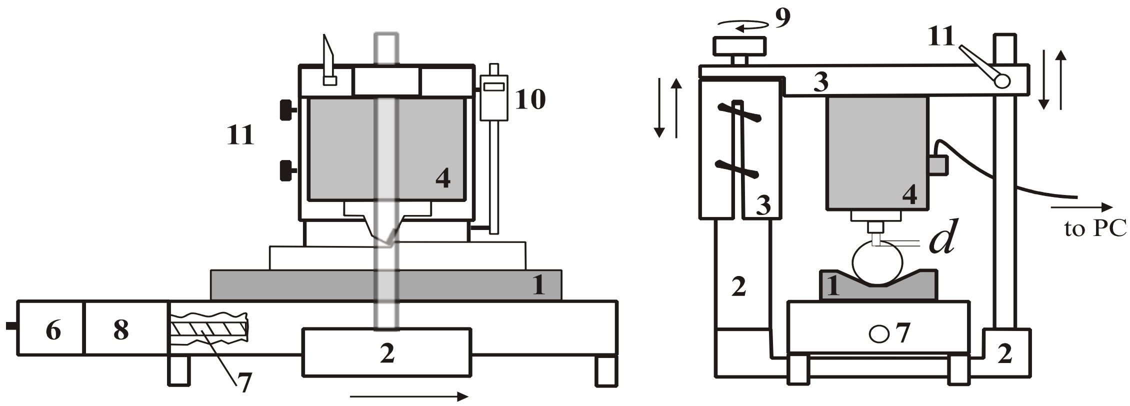

Figure 2: Sketch of the Rock Strength Device (Richard *et al* 2012)

A load sensor measures the components (F_s, F_n) of the cutting force $\boldsymbol{F}$, which are respectively parallel and normal to the cutter velocity. The complete system (sensor, data, acquisition) achieves about 1 N of precision and resolution over the entire measurement range [0-4000 N]. The scanning rate is typically set at 25 samples per millimeter travelled by the cutter. The cutter velocity is set to $v = 20$ mm/s. The force components are measured at a sampling rate of 200 Hz, meaning 10 measurements of force per mm of cut. The sharp cutters used for the tests reported in this paper are characterized by a width $w = 10$ mm and a back rake angle $\theta = 15°$. The cutting face of the cutters are made of a thin layer of polycrystalline diamond compact (PDC) laid down on a carbide tungsten base.

VARIATION OF AVERAGE CUTTING FORCE WITH DEPTH OF CUT

A series of scratch experiments were conducted on 2” diameter cores of Indiana Limestone (UCS $q \simeq 28$ MPa, toughness $K_{Ic} \simeq 1.1$ MPa$\cdot\sqrt{\text{m}}$) and Berea Sandstone ($q \simeq 40$ MPa, $K_{Ic} \simeq 0.5$ MPa$\cdot\sqrt{\text{m}}$). The depth of cut d ranged between 0.1 and 3.5 mm. The testing procedure consisted

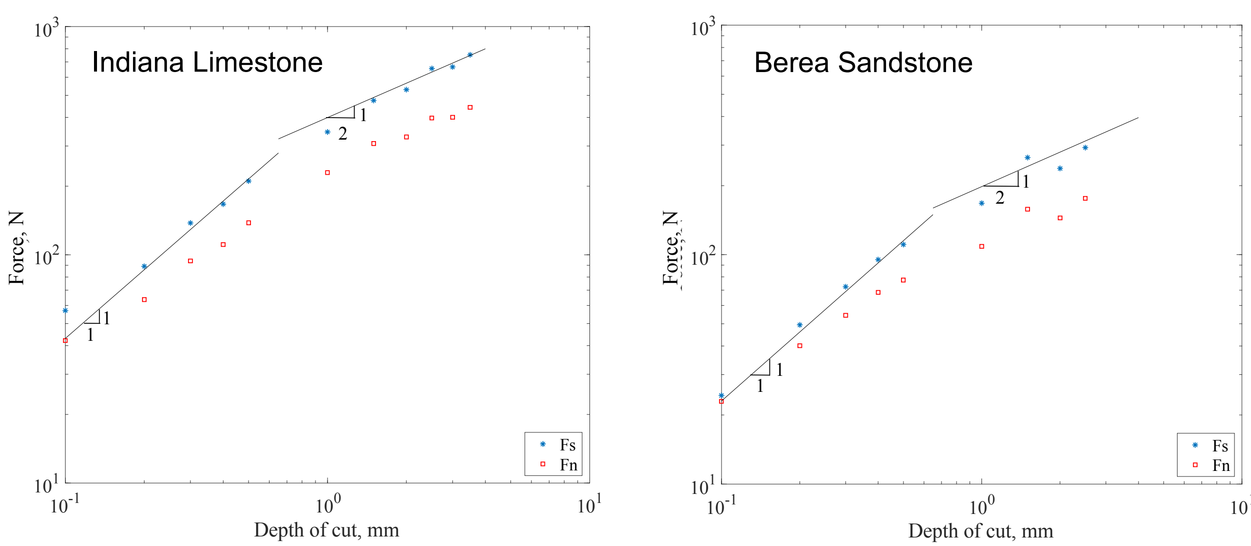

Figure 3: Average force components F_s and F_n versus depth of cut d for scratch tests in Indiana limestone and Berea sandstone

of cutting grooves on the surface of the rock core, while measuring the force components F_s and F_n. (Some of the tests involved deepening the groove.)

The variation of the average force components F_s and F_n with the depth of cut d is shown in Fig. 3 for tests conducted in the two rocks. These plots clearly show the existence of two regimes of cutting, one with $F_s \sim d$ and the other with $F_s \sim \sqrt{d}$. Furthermore, parameters ϵ_0 (dimension FL^{-2}) and κ (dimension $FL^{-3/2}$), respectively expected to be related to UCS q and toughness K_{Ic}, can be extracted from these two data sets. These two parameters are defined by the following expressions for the mean force component F_s:

- In the ductile regime

$$F_s = F_{sc} + \epsilon_0 w d$$

  where F_{sc} is a (small) force arising from frictional contact at the tip of the cutter and ϵ_0 is a constant specific energy.
- In the fragmentation regime

$$F_s = \kappa w \sqrt{d}$$

  where the frictional contact force has been ignored.

For the Indiana limestone, $\epsilon_0 \simeq 38$ MPa and $\kappa \simeq 1.2$ MPa$\cdot\sqrt{\text{m}}$ and for the Berea sandstone $\epsilon_0 \simeq 22$ MPa and $\kappa \simeq 0.6$ MPa$\cdot\sqrt{\text{m}}$. The transition depth of cut ℓ_1 between the ductile and the fragmentation regime takes places at about 0.7 mm for the Berea sandstone and at about 0.9 mm for the Indiana limestone.

STATISTICS OF THE CUTTING FORCE

The continuous force measurement in the scratch test directly provides the statistics of the cutting force. Recent studies have shown that, for quasibrittle materials, the failure mode has a profound influence on the stochastic structural response (Bazant and Le 2017). Therefore, it is

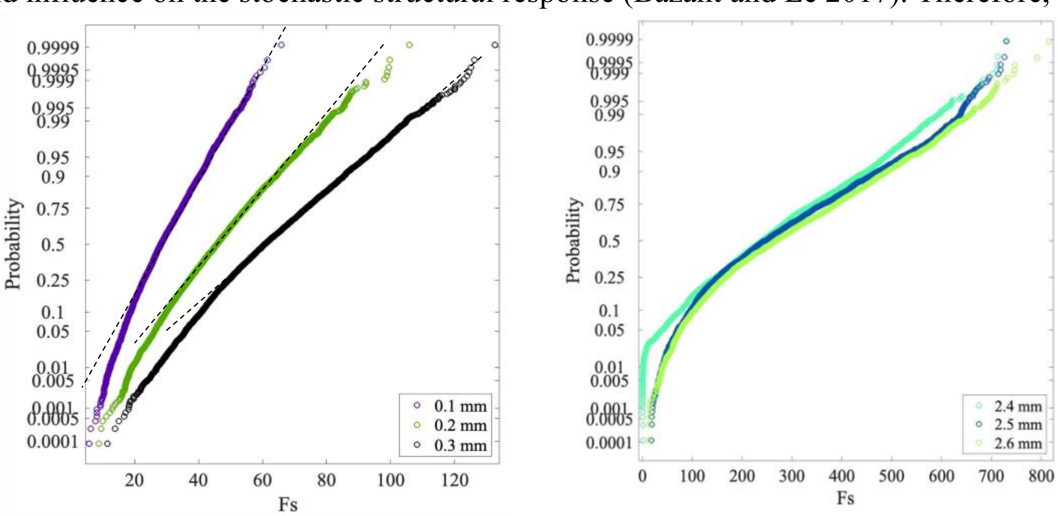

Figure 4: Probability distributions of cutting force plotted in Gaussian paper for small (left) and large (right) depth of cut *d*

interesting to examine the statistics of cutting force at different cutting depths as shown in Fig. 4. These data pertain to cutting tests conducted on slabs of Mountain Gold Sandstone (Pena, 2010).

It is observed that, at small cutting depths ($d < 0.3$ mm), the randomness of the cutting force can reasonably be described by a Gaussian distribution except for the left tail. This is consistent with the observed ductile failure mode. In ductile failure, the failure load can be regarded as a weighted sum of random strengths of material elements along the failure surface. As a consequence of the Central Limit Theorem, the resulting failure load would follow a Gaussian distribution. Meanwhile, it should be noted that the Gaussian distribution cannot be applied to the tail distribution since the failure load is non-negative. It has recently been suggested that the far-left tail would exhibit a power-law behavior (Bazant and Le 2017, Le and Xu 2019).

When the cutting depth increases, the probability distribution of the cutting force clearly shows a non-Gaussian nature (Fig. 4). It has been speculated that, at this range of cutting depths, the dominant failure mode is material fragmentation. A simple analysis of energy balance indicates that the cutting force could directly be related to the total area of fragments. Meanwhile, the individual fragment size is expected to follow some probability distribution. For example, the well-known model by Kolmogorov (1941) predicts a lognormal distribution of fragment size. One essential point is that the random sizes of individual fragments are not statistically independent, and thus one cannot directly apply the Central Limit Theorem to determine the distribution of the total area of fragments. This is probably why we did not observe a Gaussian distribution. To properly capture the statistical dependence of the fragment sizes, one would need a stochastic model for the fragmentation process (e.g. Fowler and Scheu 2016).

CONCLUSION

Scratch tests conducted on different sedimentary rocks confirm the existence of at least two asymptotic regimes of cutting: ductile for $d < \ell_1$ and fragmentation $d > \ell_1$. The available equipment does not permit to assess whether a brittle regime indeed exists for $d > \ell_2$. A preliminary analysis of the force statistics indicates that the functional form of the probability distribution of cutting force varies with the cutting depth. This dependence is fundamentally related to the prevalent failure mode. In view of the richness of the data measured in the scratch test, it will be desirable to develop a probabilistic model, which would naturally yield the effect of cutting depth on the mean specific energy.

Acknowledgements

The authors gratefully acknowledge support from the National Science Foundation under Grant No. 1742823. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

REFERENCES

Akono, A.-T., P. M. Reis, and F.-J. Ulm (2011). Scratching as a fracture process: From butter to steel. *Physical Review Letters* 106(20), 204302.

Akono, A.-T. and F.-J. Ulm (2011). Scratch test model for the determination of fracture toughness. *Engineering Fracture Mechanics* 78(2), 334–342.

Akono, A.-T., F.-J. Ulm, and Z. Bažant (2014). Discussion: Strength-to-fracture scaling in scratching. *Engineering Fracture Mechanics* 119, 21–28.

Bazant, Z. P. and J.-L. Le (2017) *Probabilistic Mechanics of Quasibrittle Fracture: Strength, Lifetime, and Size Effect*, Cambridge University Press. Cambridge, U.K.

Chaput, E. J. (1992). Observations and analysis of hard rocks cutting failure mechanisms using PDC cutters. Technical report, Imperial College, London, United Kingdom.

Detournay, E. and P. Defourny (1992). A phenomenological model of the drilling action of drag bits. *Int. J. Rock Mech. Min. Sci.* 29(1), 13–23.

Detournay, E., A. Drescher, and D. Hultman (1997), Portable Rock Strength Evaluation Device, U.S. Patent 5,670,711.

Fowler, A. C. and B. Scheu (2016) "A theoretical explanation of grain size distributions in explosive rock fragmentation", *Proc. Royal Soc., A*, 472, 2015843.

Huang, H. and E. Detournay (2008). Intrinsic length scales in tool-rock interaction. *Int. J. Geomechanics* 8(1), 39–44.

Fowell, R. J. (1993). The mechanics of rock cutting. In J. A. Hudson (Ed.), Comprehensive rock engineering; principles, practice and projects, Chapter 7, pp. 155–176. Pergamon Press.

Kolmogorov, A.N. (1941). The logarithmically normal law of distribution of dimensions of particles when broken into small parts. Proceedings of Academy of Sciences of URSS, 31(2), 99-101. (NASA Technical Translation, NASA TT F-12, 287, June 1969)

Le, J.-L. and E. Detournay (2016). Discussion on the "fracture mechanics interpretation of the scratch test" by Akono et al. *Engineering Fracture Mechanics* 168, 46–50.

Le, J.-L. and Z. Xu (2019). A simplified probabilistic model for nanocrack propagation and its implications for tail distribution of structural strength, *Physical Mesomechanics*, Special Issue in Memory of Professor G. I. Barenblatt, 22(2), 85–95.

Lin, J.-S. and Y. Zhou (2013). Can scratch tests give fracture toughness? *Engineering Fracture Mechanics* 109, 161–168.

Lin, J.-S. and Y. Zhou (2015). Rebuttal: Shallow wide groove scratch tests do not give fracture toughness. *Engineering Fracture Mechanics* 133, 211–222.

Nelson, P. P. (1993). TBM performance analysis with reference to rock properties. In J. A. Hudson (Ed.), *Comprehensive rock engineering; principles, practice and projects*, Chapter 10, pp. 261–291. Pergamon Press.

Nishimatsu, Y. (1993). Theories of rock cutting. In J. A. Hudson (Ed.), *Comprehensive Rock Engineering*, Oxford, pp. 647–662. Vol. 1. Pergamon Press Ltd.

Peña, C. (2010). An experimental study of the fragmentation process in rock cutting. Master of Science Thesis, Faculty of the Graduate School of the University of Minnesota, U.S.A.

Richard, T., E. Detournay, A. Drescher, P. Nicodeme, and D. Fourmaintraux (1998, July). The scratch test as a means to measure strength of sedimentary rocks. In SPE/ISRM Eurock 98, SPE 47196, Trondheim, Norway, pp. 1–8. Society of Petroleum Engineers.

Richard, T., F. Dagrain, E. Poyol, and E. Detournay (2012). Rock strength determination from scratch tests. *Engineering Geology* 147–148(12), 91–100.

Teale, R. (1965). The concept of specific energy in rock drilling, *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 2, 57–73.

Tiryaki, B., I. D. Gipps, and X. S. Li (2009). Rapid estimation of rock cuttability using fracture toughness and rock strength. *Advanced Materials Research* 76-78, 591–596.

Turcotte, D. (1986). Fractals and fragmentation. *Journal of Geophysical Research* 91(B2), 1921–1926.

Zhou, Y. and J.-S. Lin (2014). Modeling the ductile–brittle failure mode transition in rock cutting. *Engineering Fracture Mechanics* 127, 135–147.