Cutter/Rock Interface Friction: Worth Measuring Accurately?

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Abstract: *Although most microtunnelling machines (MTBMs) use slurry to support the face and transport the muck, they may also be used open faced when boring through soft to medium strength dry rock, such as the Ashfield Shale in Sydney. BRTS has recently developed the capability to predict the behaviour (thrust and torque requirements, and advance rates) for cutting rock tunnels with MTBMs using drag picks or mini-discs, from the measured rock mechanical properties. The machine torque has to overcome the frictional resistances of cutters, scraping across the rock face, as well as the cutting forces in the rock. Previous authors have guessed at the appropriate friction coefficients, but we have now developed a technique to accurately measure the friction coefficient of any cutter material scraping across any rock. Some recent results measured for different cutters on several rock types are presented. Numerical examples demonstrate the results of modelling MTBM performance, using measured friction coefficients versus the range of previously-guessed friction coefficients.*

Keywords: *Direct Shear Test, Microtunnelling, Cutter/Rock Friction, Torque.*

1. INTRODUCTION

The optimum design and operating control parameters of micro-tunnelling machines (MTBMs) utilizing drag bit cutters should most efficiently proceed from an understanding of the geotechnical properties of the rocks to be cut. Nishimatsu (1972) [1] and Roxborough (1995) [2] presented analyses of rock cutting forces utilizing strength characteristics of the rock substance and also the coefficients of friction between the cutting tools and the rock materials. Several authors have attempted to measure coefficients of friction between cutting tools and rocks [1; 2; 3; 4; 5; 6; 7; 8; 9]. The coefficients of friction that they reported ranged from 0.063 to 0.72, i.e. friction angles ranging from 4^o to 36^o. The mean of the reported lower bound values was 0.32 (18^o), and the mean of the reported upper bound values was 0.46 (25^o).

Using Nishimatsu's equations, for Drag Bits with a depth of cut = 5mm, a width of cut = 3mm, and a rake angle of 5^o, a rock having Shear Strength = 9.72 MPa and ϕ = 28.7^o would be predicted to have the cutting forces presented in Table 1.

Table 1- Predicted cutting forces using Nishimatsu's equations [1]

Friction angle between tool and material (degrees)	**Calculated Cutting Force (N)**
4	39.4
18	61.9
25	79.0
36	132.0

Using Roxborough's equations, for Conical Picks with a depth of cut = 5mm and a tip angle of 5^o, a rock having Compressive Strength = 47.4 MPa and Tensile Strength = 6.68 MPa would be predicted to have the cutting forces presented in Table 2.

Table 2- Predicted cutting forces using Roxborough's equations [2]

Friction angle between tool and material (degrees)	Calculated Cutting Force (N)
4	1.7
18	26.3
25	40.4
36	62.0

It seems evident that if the actual tool/rock friction coefficients differ from those explicitly or implicitly assumed, then the actual cutting forces and productivity may also greatly depart from those assumed by a contractor or designer. Several recent authors [10; 11; 12] have conducted numerical simulations of the rock cutting processes, and assumed rock cutting friction coefficients ranging from 0.0 to 1.0. It would seem that any conclusions derived from sophisticated analysis techniques including faulty assumptions regarding rock properties would be suspect.

When invited to give advice on a microtunnelling project where a MTBM appeared to be having trouble overcoming rock resistance, the authors decided to investigate not only the mechanical properties of the "difficult" rock, but also the friction coefficients between the rock and the several different cutters being tried. This study was later expanded to investigate the main rock types likely to be encountered in MTBM projects in Melbourne and its environs: Ordovician sandstones, Silurian siltstones, and Tertiary basalts.

2. MATERIALS AND METHODS

In this research, three types of rocks, namely sandstone (S), mudstone (M) and basalt (B) were used. Table 3 presents depths and properties of these rock cores.

Table 3- Properties of the rock samples used in this research

Lithology:	Sandstone	Mudstone	Basalt
Approx. Depth (m)	<1	15.7	10.4
Location	Melbourne Suburbs	Melbourne Suburbs	Melbourne Suburbs
Sklerograf Hardness	5	6	50
Shore Hardness	16	16	49
Dry Density (kg/m^3)	2622	2381	2788
Wet Density (kg/m^3)	2602	2180	2820
Uniaxial Compressive Strength (MPa) (standardised for 54mm diameter & 1:1	57.82	4.16	82.87
Uniaxial Compressive Strength (MPa) (standardised for 54mm diameter & 2.5:1)	45.82	3.87	64.06

Three types of cutters were used: PENGO cutter (PEN), polycrystalline diamond compact (PDC) button cutter, and EM 405-22 drag bit (DB). The cutters and rock samples are illustrated in Figure 1. Table 4 presents the test identifications (ID) and describes the rock/cutter combinations that were investigated in this research.

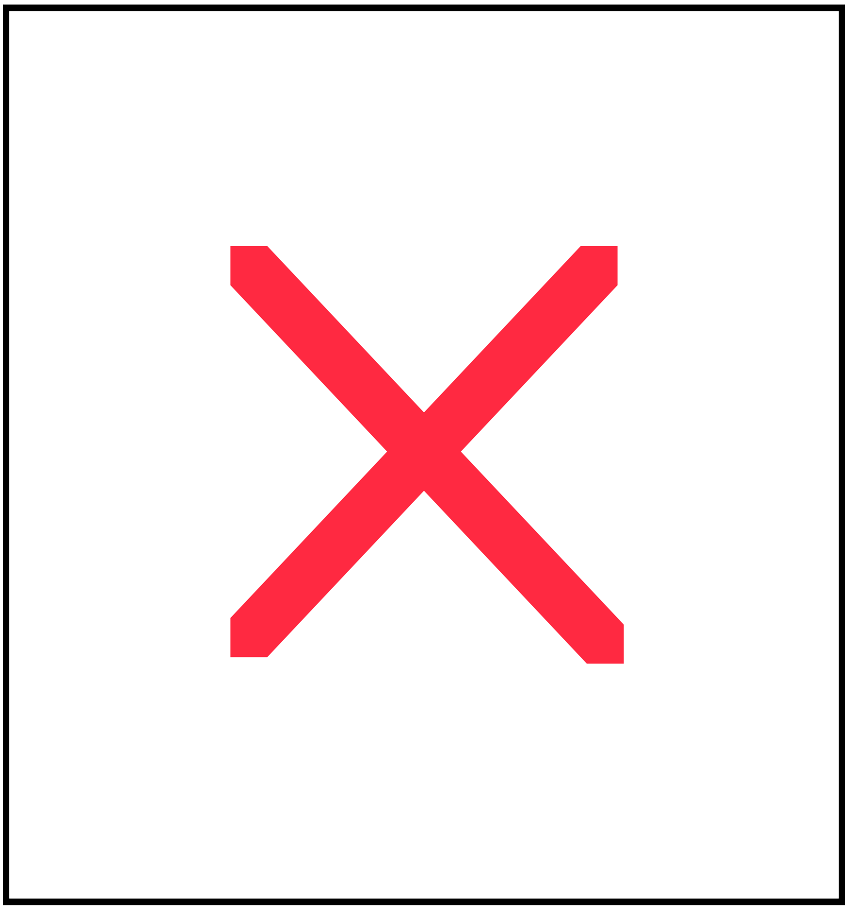

Figure 1 – cutters and rock samples used in this research.

Table 4 – Test IDs based on cutter/rock combinations used in this research

Test ID	Description
PEN-S	PENGO Cutter on Sandstone
PDC-S	PDC Button Cutter on Sandstone
DB-S	Drag Bit on Sandstone
PEN-M	PENGO Cutter on Mudstone
PDC-M	PDC Cutter on Mudstone
DB-M	Drag Bit on Mudstone
PEN-B	PENGO Cutter on Basalt
PDC-B	PDC Cutter on Basalt
DB-B	Drag Bit on Basalt

Direct shear testing of rocks was carried out following ASTM D5606-16 [13]. The encapsulating material used was ultra-hard gypsum gaining 75 MPa compressive strength after 24 hours. Direct shear testing was done by applying normal loads of 1 to 8 kN in four stages. Figure 2 illustrates an example of load-displacement plots of this research with four stages of normal loads.

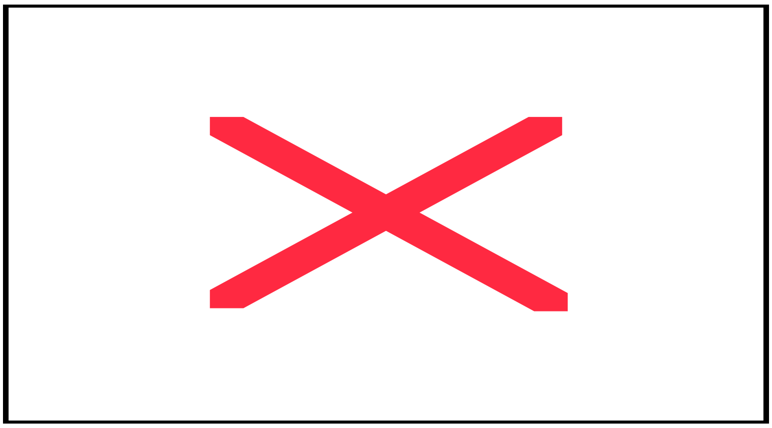

Figure 2 – An example of shear/normal load-displacement plots.

Figure 3 shows the after the test PEN-M sample cast in the steel rings of the direct shear apparatus using the ultra-hard gypsum.

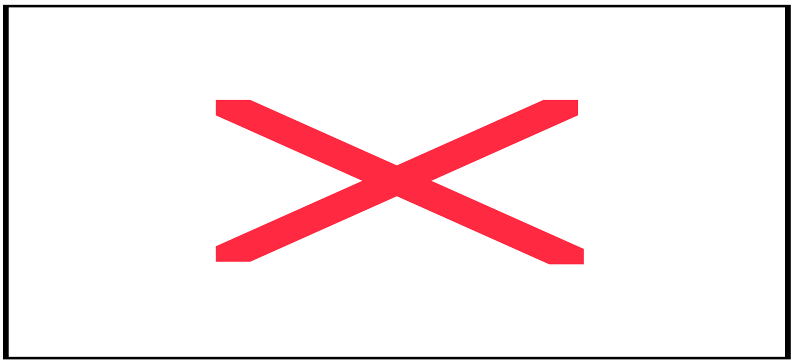

Figure 3 – After the test PEN-M sample encapsulated in the ultra-hard gypsum

3. RESULTS AND ANALYSIS

Figures 4 and 5 compares different cutter/rock friction angles (φ) obtained respectively using different cutters for a specific sample, and a specific cutter for different rocks.

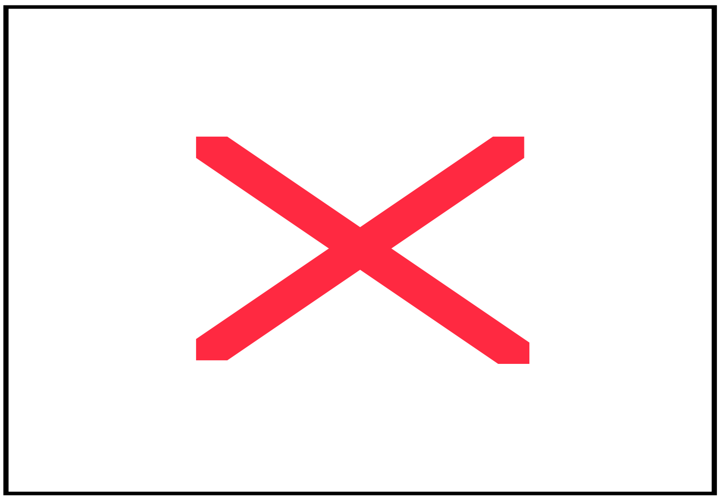

Figure 4 – Comparison of the friction angles of the three cutters on a specific rock type.

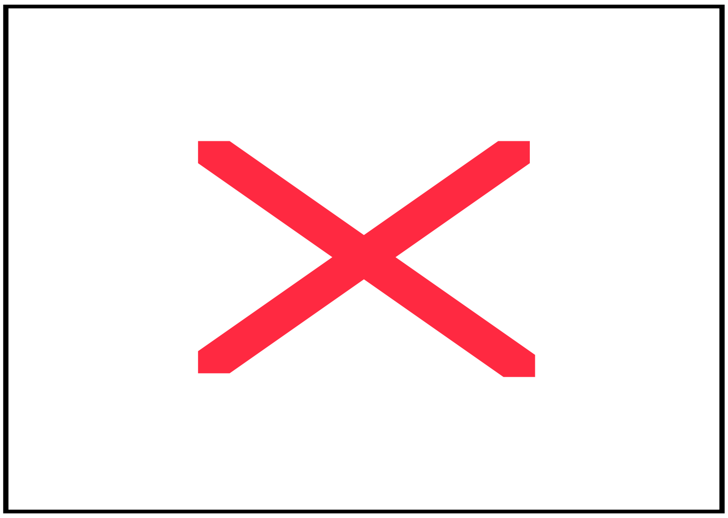

Figure 5 – Comparison of the friction angles of a specific cutter on the three rock types.

Figures 4 and 5 show that under the same normal load both cutter type and rock type can result in different ϕ values. Figure 6 shows peak and residual friction angles obtained for all cutter/rock combinations used in this research. Using 9 different cutter/rock combinations, the ϕ value ranges approximately between 10 and 24.

Figure 6 – Peak and residual friction angles for all cutter/rock combinations.

The friction angles presented in Figure 6 were obtained by developing a linear trend line using the shear stress (τ) – normal stress (σ) data points. However, τ - σ plots show that assuming a constant friction angle for all normal stresses can lead to erroneous interpretations. A power trend line, on the other hand, not only presents a greater R^2 value, thus a better correlation, but could also reduce the possibility of the mis-prediction of the friction angles under different normal loads. Figure 7, as an example, compares the correlation of data points and the achieved friction angles using a linear or a power trend line. Figure 7 (a) shows a great improvement in the R^2 value by using a power trend line, and Figure 7 (b) indicates that the ϕ value can differ as high as 9° by increasing the normal force from 1 to 6 kN.

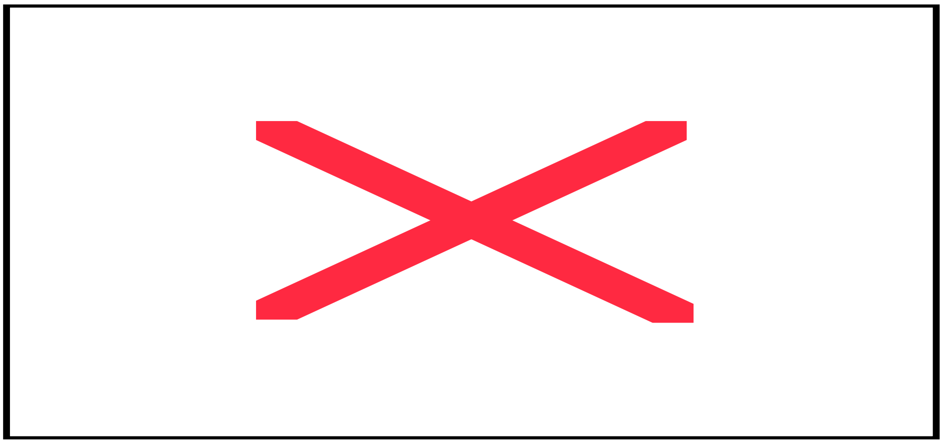

Figure 7 – Comparison of (a) linear and power trend lines, (b) ϕ values obtained from a linear and power τ-σ relationship for PEN-M test.

Figure 8 compares the ϕ values obtained by taking a linear or power relationship between τ and σ for all cutter rock combinations. Evidently, each cutter/rock combination showed a different behaviour both in the magnitude and range of friction ϕ values under different normal forces.

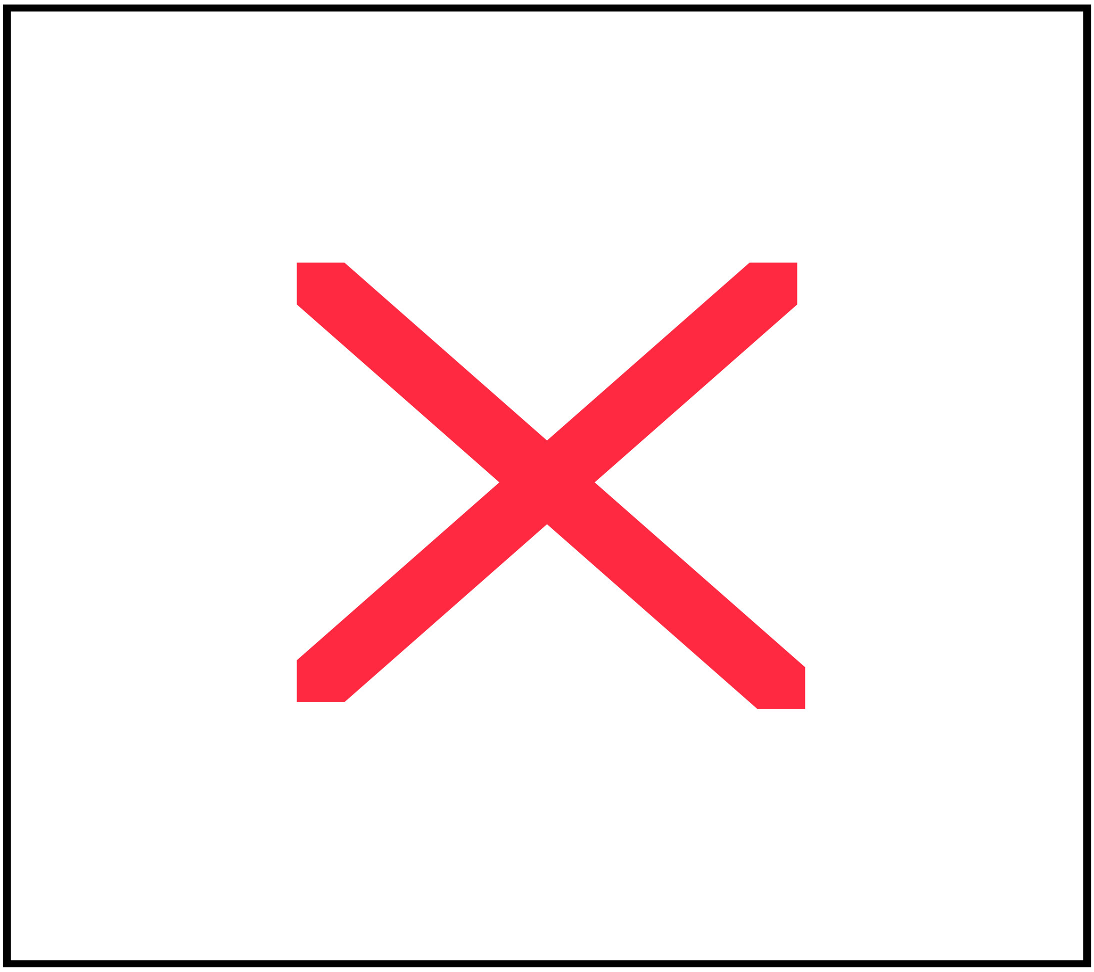

Figure 8 – Values of ϕ obtained from a linear versus power τ-σ relationship for all cutter rock combinations.

4. DISCUSSION & CONCLUSION

The lab tests demonstrated a practical and reproducible technique for accurately measuring rock/cutter friction coefficients. They also demonstrated that it is not feasible to assume or specify a single friction coefficient, valid for all rock types, cutter materials, and cutter geometries. Every combination gave different results. An intriguing indication was that the PENGO cutter and EM 405-22 drag bit gave higher friction coefficients on the 2 sedimentary rocks than on the Basalt, whereas this was reversed for the PDC button cutters.

This information is offered to the micro-tunnelling industry, as an aid to their being able to more accurately simulate and model machine performance during the investigation and tendering phases, rather than waiting to trouble-shoot and improvise after a MTBM seems to have approached the limits of its capacity.

5. ACKNOWLEDGMENT

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6. REFERENCES

1. Nishimatsu, Y. *The mechanics of rock cutting*. Int. J. Rock Mech. Min. Sci., 1972; 9: 261-272

2. Roxborough, F F, and Liu, C Z. Theoretical considerations on pick shape in rock and coal cutting. Proc. 6th Underground Operators' Conference, Kalgoorlie, 1995; 189-193

3. Bilgin, N. Investigations into the Mechanical Cutting Characteristics of Some Medium and High Strength Rocks. Ph.D. Thesis, University of Newcastle upon Tyne, 1977.

4. Bilgin, N., Demircin, M. A., Copur, H., Balci, C., Tuncdemir, H., & Akcin, N. *Dominant rock properties affecting the performance of conical picks and the comparison of some experimental and theoretical results*. Int. J. Rock Mech. Min. Sci., 2006; 43(1):139-156

5. Bilgin, N. *Mechanical Excavation in Mining and Civil Industries*. CRC Press Boca Raton, FL, 2014.

6. Kuru, E. *Effects of Rock/Cutter Friction on PDC Bit Drilling Performance: An Experimental and Theoretical Study*. Ph.D Thesis, Louisiana State University, 1990.

7. Zhao, J. *Construction and utilization of rock caverns in Singapore*. Tunnelling and Underground Space Technology, 1996; 11(1): 65-72.

8. Lislerud, A. Principles of Mechanical Excavation. Posiva OY, Helsinki Finland, 1997. 247p.

9. Goktan, R M, and Gunes, N. *A semi-empirical approach to cutting force prediction for point-attack picks*. J South African Inst of Mining and Metallurgy, 2005; 105: 257-264

10. Moon T, and Oh, J. *A Study of Optimal Rock-Cutting Conditions for Hard Rock TBM Using the Discrete Element Method*. Rock Mech Rock Eng, 2012; 45: 837-849

11. Huang, H., Lecampion, B., & Detournay, E. *Discrete element modelling of tool-rock interaction I: rock cutting*. Int Jour Numerical and Analytical Methods in Geomechanics, 2013; 37:1913-1929

12. Menezes, P L. *Influence of cutter velocity, friction coefficient and rake angle on the formation of discontinuous rock fragments during rock cutting process*. Int J Adv Manuf Technol, 2017; 90: 3811-3827

13. ASTM-D5607-16. Standard Test Method for Performing Laboratory Direct Shear Strength Tests of Rock Specimens Under Constant Normal Force. ASTM International, West Conshocken, PA, 2016.