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TOOL FORCES AND SPECIFIC ENERGY PREDICTION MODELS IN THE PROCESS OF SANDSTONES CUTTING BY USING CONICAL PICKS

KALEM UÇLU KESKİLERLE KUMTAŞI KAZISINDA KESKİ KUVVETLERİ VE SPESİFİK ENERJİ TAHMİN MODELLERİ

Xiang Wang[a,b,*] , Qing-Feng Wang[a,b,**], Okan Su[c,***]

[a] Chongqing Key Laboratory of Manufacturing Equipment Mechanism Design and Control, Chongqing Technology and Business University, Chongqing, China
[b] China Coal Technology Engineering Group Chongqing Research Institute, Chongqing, China
[c] Department of Mining and Mineral Extraction, Bulent Ecevit University, Zonguldak, Turkey

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Specific energy,
Regression analysis.

ABSTRACT

In this study, unrelieved rock cutting experiments were conducted at the linear rock cutting machine and the characteristics of tool forces were discussed. The correlations among tool forces, specific energy, cutting depth, and rock strength were analyzed using single factor regression analysis method. Based on multiple non-linear regression method, the models of tool forces and specific energy were developed considering the rock strength and cutting depth. The results indicate that models of tool forces have the superior performance. When the model of specific energy is analyzed using the compressive strength of the rock, it was seen that the correlations are weak compared to the model related to tensile strength of rock. In conclusion, it is emphasized that the proposed models presented in this study are particularly recommended for performance prediction of soft and medium-hard strength sandstones in case conical picks are employed.

Anahtar Sözcükler:
Konik keski,
Kayaç kazısı,
Keski kuvvetleri,
Spesifik enerji,
Regresyon analizi.

ÖZ

Bu çalışmada, doğrusal kesme setinde bağımsız kesme deneyleri yapılmış ve buna göre keski kuvvetlerinin karakteristiği tartışılmıştır. Tek faktörlü regresyon analiz yöntemi kullanılarak keski kuvvetleri, spesifik enerji, kesme derinliği ve kayacın dayanımı arasındaki ilişkiler analiz edilmiştir. Ayrıca, kayacın dayanımı ve kesme derinliği göz önüne alınarak doğrusal olmayan çoklu regresyon yöntemiyle keski kuvvetleri ve spesifik enerji modelleri geliştirilmiştir. Sonuçlar, kesme ve normal kuvvetleriyle ilgili tüm modellerin oldukça üstün olduğunu göstermiştir. Spesifik enerji ile basınç dayanımına bağlı olarak model kurulduğunda ilişki katsayılarının çekme dayanımına göre zayıf olduğu belirlenmiştir. Sonuç olarak, bu çalışmada sunulan modellerin yumuşak ve orta-sert dayanımdaki kumtaşının kalem uçlu keski kullanılarak kazılması durumunda kullanımının önerilebileceği vurgulanmıştır.

* mywayok@163.com • https://orcid.org/0000-0002-6179-6888
** Corresponding author : wqf518@aliyun.com • https://orcid.org/0000-0002-9561-9206
*** okansu@beun.edu.tr • https://orcid.org/0000-0003-1846-6020

INTRODUCTION

Tool forces and specific energy are two main topmost concerns of rock cutting. Tool forces, mainly including cutting and normal forces, are basic parameters used for calculating the torque of cutterhead, motor power, and rock cutting efficiency (Bilgin et al. 2012). On the other hand, the specific energy is usually used for assessing rock cuttability and it is one of the most significant parameters used for both the performance assessment and efficiency evaluation of excavation systems (Rostami et al. 1994; Balci et al. 2004; Bilgin et al. 2006; Balci and Bilgin 2007). Cutting experiments not only are performed to study the effects of cutting parameters on the performance of cutting picks, but also they are direct methods to obtain the accurate values of tool forces and specific energy. However, the basic disadvantages are that the costs are very expensive and also experiments take a long time. Thus, theoretical and semi-empirical models (Evans, 1984; Roxborugh and Liu, 1995; Goktan, 1997; Goktan and Gunes, 2005; Bao et al., 2011), empirical models (Balci et al., 2004; Bilgin et al., 2006; Tiryaki et al., 2010; Wang et al., 2017) and numerical models (Su and Akcin, 2011; Rojek et al., 2011) are commonly used to predict the tool forces and specific energy values by engineers in this field.

A large and growing body of literature has investigated that both the physical and mechanical properties of the rock and relevant cutting parameters have significant influences on cutting and normal forces (Copur et al., 2003; Balci et al., 2004; Balci and Bilgin, 2007; Tiryaki et al., 2010; Shao et al., 2017).

Evans (1984) theoretically demonstrated that the compressive and tensile strength were dominant properties of the rock influencing the cutting force acting on the conical picks. His cutting model also showed that the cutting forces linearly increase with the square of cutting depth and decrease with the brittleness of the rock. Considering the friction between the pick and rock, Roxborugh and Liu (1995) and Goktan (1997) improved Evans' cutting force model. Based on Evans' rock cutting mode, Bilgin et al. (2006) found that the cutting force in unrelieved cutting mode had a strong and statistically linear relationship with the cutting depth. Shao et al. (2017) also reported the similar test results using one type of rock.

On the other hand, specific energy, defined as the work required to break a unit volume of rock, is usually studied based on experimental tests. A considerable amount of literature indicate that the physical and mechanical properties of the rock are the main factors affecting the specific energy of rock cutting. In this context, some prediction models of specific energy have been developed by using single factor regression analysis (Copur et al. 2003; Balci et al. 2004; Bilgin et al. 2006; Tumac et al. 2007, Gunes et al. 2015), regression trees and artificial neural networks (Tiryaki 2009), and adaptive hybrid intelligence techniques (Yurdakul et al. 2014).

The main objective of this study is to investigate the effect of cutting depth on the performance of rock cutting using the conical pick and also develop further empirical models considering the rock strength and cutting depth. To achieve this goal, five different sandstones, which have the uniaxial compressive strength ranging from 17.91 to 85.98 MPa, were subjected to cutting tests at the linear rock cutting rig under different levels of cutting depths in unrelieved cutting modes. As a result of the tests, empirical models of cutting and normal forces and specific energy were developed using the multiple non-linear regression method. The performance of proposed models was also statistically analyzed.

1. EXPERIMENTAL STUDIES

1.1. Linear Rock Cutting Test

In the scope of the experimental studies, a small scale linear cutting machine (LCM), which can accommodate block samples up to150 mm x 150 mm x 200 mm, was used (Figure 1).

Figure 1. General view of linear rock cutting machine.

A conical pick is employed in all tests. The main cutting and geometrical parameters on the conical pick are illustrated in Figure 2. The main body of the pick is made of steel while the tip is made of tungsten carbide. The conical pick was mounted on the tool holder, which is fixed directly to the 3-D dynamometer to measure the tool forces acting on the pick. The data acquisition system records the forces and they are processed in MATLAB software. After each cutting, rock pieces were carefully collected from the rock surface and weighed on the scale. Based on the measured forces and collected chip masses, the specific energy of rock cutting was also determined.

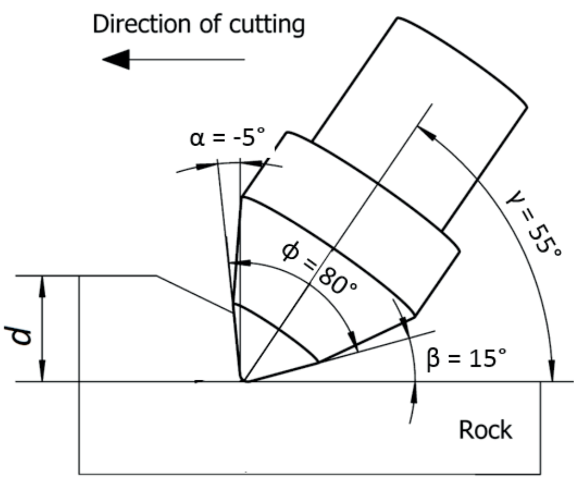


Figure 2. Cutting parameters of conical bit.

In the course of cutting experiments, the attack angle (γ) was set to be 55°, while the skew and tilt angles were assumed to be 0°. Accordingly, the rake angle (α) and the clearance angle (β) were calculated to be -5° and 15°, respectively. The cutting depth (d) varied from 3 to 18 mm.

1.2 Physical and Mechanical Properties of Rocks

Sandstones are widely encountered in underground excavations and they present a wide distribution in terms of strength. Five different sandstones were collected from commercial quarries in Sichuan province and Chongqing city for the cutting tests. (Figure 3).

The physical and mechanical properties of the rocks, including density, the uniaxial compressive strength and the Brazilian tensile strength were determined and the results are listed in Table 1. The uniaxial compressive strength values of the rock samples varied between 17.91 and 85.98 MPa. The Brazilian tensile strength values changed from 1.64 to 4.97 MPa. The friction angle between the rock and hardened steel was also tested using a special cutter in the LCM.

Figure 3. Sampling locations of sandstones.

Table 1. Physical and mechanical properties of rocks.

Rock name	ρ	σ_c	σ_t	φ
Sandstone 1	2.22	17.91	1.64	36
Sandstone 2	2.43	79.20	4.97	30
Sandstone 3	2.36	52.99	3.67	42
Sandstone 4	2.35	59.80	3.93	47
Sandstone 5	2.59	85.98	3.69	15

where ρ is the rock density (g/cm^3); σ_c is the uniaxial compressive strength (MPa); σ_t is the tensile strength of the rock (MPa); φ is the friction angle between the rock and pick.

2. CONSIDERATIONS ABOUT THE TOOL FORCES AND SPECIFIC ENERGY

A number of researchers discussed the effect of cutting speed before and it was reported that cutting speed has not a considerable effect during rock cutting, especially in low speeds (Nishimatsu 1972; Bilgin et al. 2006, 2012; Copur et al. 2017). He and Xu (2015) also analyzed it within the ranges of 4-20 mm/s and found that it is insignificant neither on tool forces nor on specific energy. Therefore, we ignored the effect of cutting speed in our tests and assumed to be 13 mm/s for the entire cutting experiments in unrelieved cutting mode. It has also no influence between adjacent cuts as shown in Figure 4. Each cutting test was replicated at least three times.

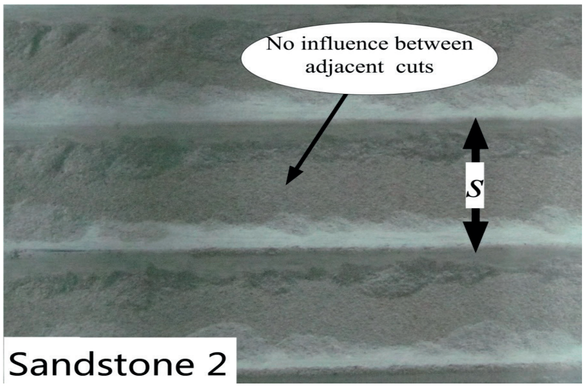
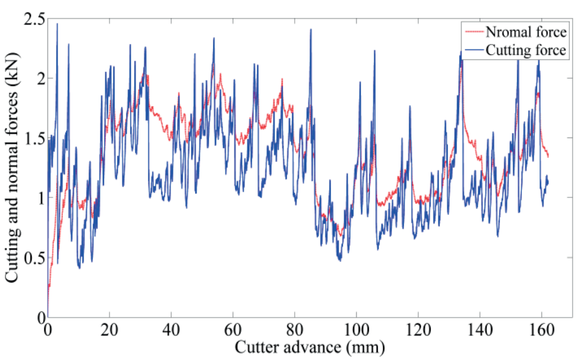


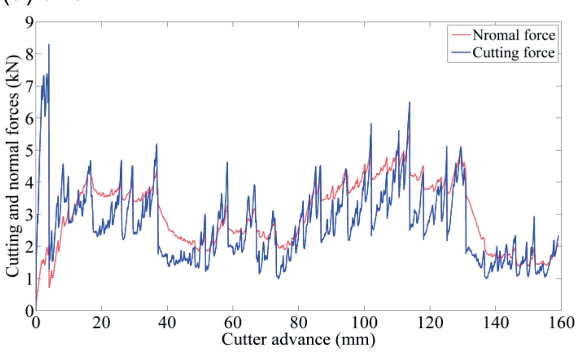
Figure 4. Characteristic of cuts in unrelieved mode.

2.1. Effect of Cutting Depth on Tool Forces and Specific Energy

The cutting and normal forces in the cutting depths of 3 and 9 mm are shown in Figure 5. It can be observed in Figure 5a that the cutting and normal forces exhibit some repetitive patterns in that the force increase to a peak value and then drops and increase again. The peak forces are approximately close to each other which means that the biggest chips have more or less the same size.



(a) d=3 mm

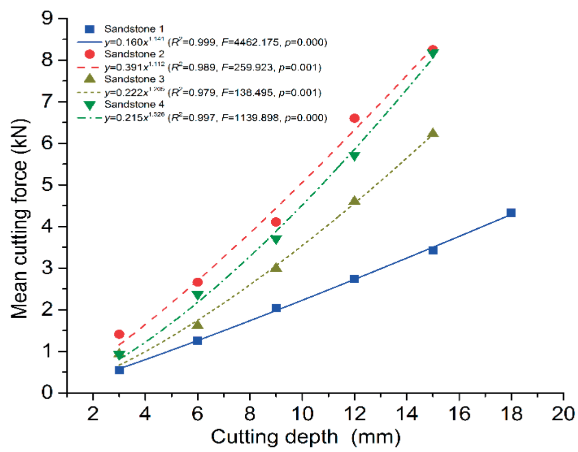


(b) d=9 mm

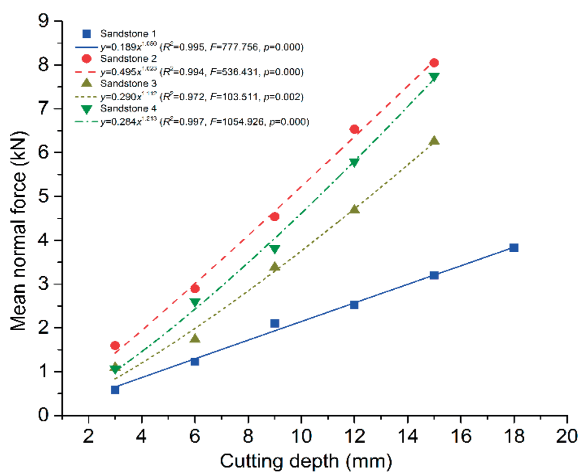
Figure 5. Tool forces at the 3 and 9 mm of cutting depths in unrelieved cutting mode of sandstone 3.

It should be noticed that the distances between the peaks of cutting forces for deep cuts are longer than those for shallow cuts. This indicates that the bigger chips are formed in the process of deeper cutting. On the other hand, it can be seen that the fluctuation intensity of cutting force is much greater than the normal force.

The relationships between mean cutting and normal forces and depths of cut are shown in Figure 6 for sandstones 1~4. It can be seen that there are meaningful relationships as exponential functions between mean tool forces and cutting depth (R^2>0.97), and the correlations are all statistically valid at the confidence level of 99 percent due to having the *F*-values higher than 103 and also *t*-values lower than 0.01. The power values of cutting depth in regression equations change between 1.112 and 1.326 for mean cutting force, 1.023-1.213 for mean normal force.



(a)



(b)

Figure 6. Correlations between mean tool forces and cutting depth.

The relationship between the specific energy and cutting depth is shown in Figure 7. It can be seen that the specific energy decreases exponentially with increasing cutting depth. The correlations are also meaningful (R^2=0.907-0.972) and are all statistically significant at the confidence level of 99% since *F*-values are higher than 38.028 and *p*-values are lower than 0.05. The power values of regression equations change between 0.620 and 0.850.

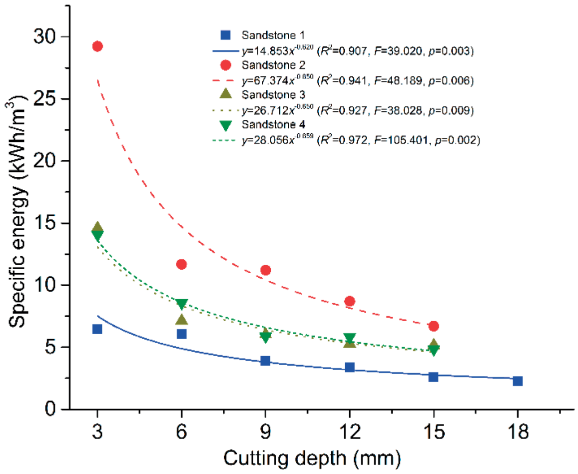


Figure 7. Relationship between specific energy and cutting depth.

2.2. Effect of Rock Strength on Tool Forces and Specific Energy

A number of studies have examined that the uniaxial compressive and tensile strengths had significant influence on cutting and normal force and specific energy (Balci et al. 2004; Bilgin et al. 2006, Wang et al. 2017).

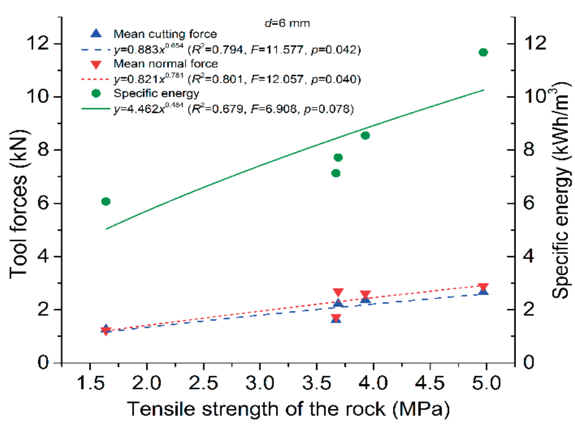


Figure 8. Relationship between tool forces, specific energy and uniaxial compressive strength.

Figures 8-9 designate that there are weak exponential correlations between mean cutting / normal forces and uniaxial compressive / tensile strengths at the cutting depth of 6 mm.

As can be seen from Figures 8-9, the uniaxial compressive and tensile strengths of the rock increased exponentially with increasing the specific energy.

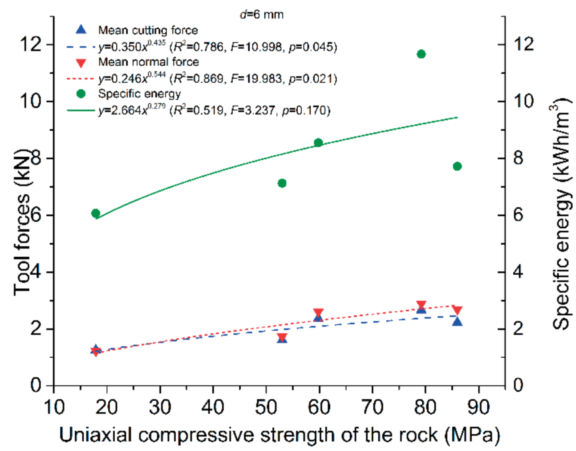


Figure 9. Relationship between tool forces, specific energy and tensile strength of the rock.

3. EMPIRICAL PREDICTION MODELS BASED ON MULTIPLE NON-LINEAR REGRESSION METHOD

3.1 Development of Models

Previous and present studies indicate that tool (cutting and normal) forces and specific energy are mainly influenced by the rock strength and cutting depth. Therefore, the cutting and normal forces and the specific energy can be expressed in Equation 3.1.

$$\begin{cases} FC(FN) = R_f \sigma_c^{ncf} \sigma_t^{ntf} d^{nf} \\ SE = R_s \sigma_c^{ncs} \sigma_t^{nts} d^{-ns} \end{cases} \quad (3.1)$$

where R_f and R_s are the constants *ncf*, *ntf*, *ncs*, *nts*, *nf* and *ns* are the undetermined coefficients

Based on test data, the undetermined coefficients in Equation 3.1 can be obtained using multiple non-linear regression method. In this context, the Levenberg-Marquardt method was used for solving the models and all regression models were analyzed in SPSS software. The empirical models of cutting force are developed as in

Equations 3.2-3.4. It can be seen that the uniaxial compressive strength of the rock and cutting depth are involved in Equation 3.2, the tensile strength of the rock and cutting depth are involved in Equation 3.3, and the uniaxial compressive and tensile strengths of the rock and cutting depth are included in Equation 3.4. It should also be noted that the statistical relationships are very strong for all regression equations due to having dramatically high determination coefficients values (R^2=0.959-0.974).

$$FC_m = 0.019\,\sigma_c^{0.551}\,d^{1.355} \quad (R^2=0.959) \qquad (3.2)$$

$$FC_m = 0.075\,\sigma_t^{0.797}\,d^{1.277} \quad (R^2=0.972) \qquad (3.3)$$

$$FC_m = 0.049\,\sigma_c^{0.164}\,\sigma_t^{0.582}\,d^{1.299} \quad (R^2=0.974) \qquad (3.4)$$

Furthermore, empirical models of normal force can be developed as given in Equations 3.5-3.7 and it is clear that all regression equations have very strong statistical relationships (R^2=0.956-0.978).

$$FN_m = 0.027\,\sigma_c^{0.573}\,d^{1.179} \quad (R^2=0.956) \qquad (3.5)$$

$$FN_m = 0.107\,\sigma_t^{0.843}\,d^{1.113} \quad (R^2=0.976) \qquad (3.6)$$

$$FN_m = 0.072\,\sigma_c^{0.152}\,\sigma_t^{0.646}\,d^{1.229} \quad (R^2=0.978) \qquad (3.7)$$

Moreover, the models of specific energy can be purposed as presented in Equations 3.8-3.10. The uniaxial compressive strength, the tensile strength of rock, and the cutting depth are taken as independent variables for the non-linear regression analysis. The results specify that the regression equation predicts a decrease in specific energy as the uniaxial compressive strength of the rock increases. This is inconsistent with previous studies although it has a relatively high determination coefficient (R^2=0.904). On the other hand, if the ratio of σ_c/σ_t is assumed to be the empirical brittleness index, the specific energy models can be rewritten as in Equation 3.10.

$$SE = 4.274\,\sigma_c^{0.521}\,d^{-0.769} \quad (R^2=0.660) \qquad (3.8)$$

$$SE = 3.284\,\sigma_t^{1.832}\,d^{-0.821} \quad (R^2=0.870) \qquad (3.9)$$

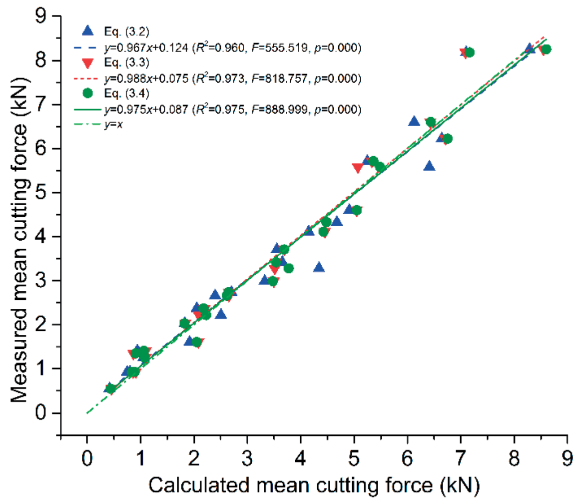
$$SE = 33.332(\sigma_c/\sigma_t)^{-0.764}\sigma_t^{1.705}d^{-0.823} \qquad (3.10)$$

According to the equations given above, it is clear that both the tool forces and specific energy have a good agreement with the cutting depth, rock strength and value of empirical brittleness index. However, more data is necessary so as to verify these relationships.

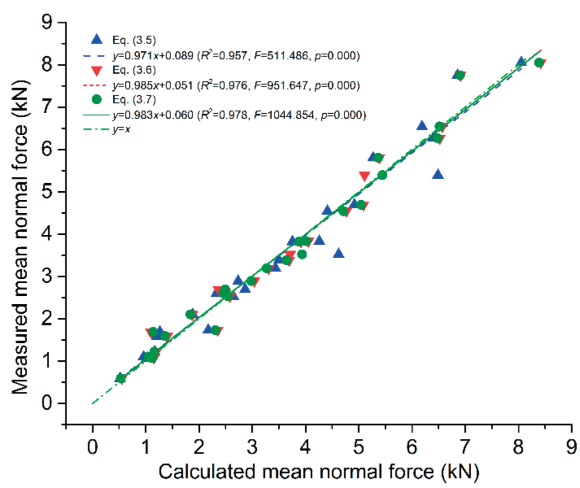
3.2. Testing the Empirical Performance of Models

3.2.1. Models of Cutting and Normal Forces

Statistical analysis of *t*-test at the confidence level of 95% was performed to check whether the measured forces are significantly different from predicted values. To expand the performance prediction of the cutting and normal forces, relevant regression curves are plotted. From the data and trend lines in Figure 10, it is apparent that the Equations 3.2-3.7 are statistically valid.



(a)



(b)

Figure 10. Relationship between measured and calculated mean cutting and force.

As can be seen in Figure 10, on the one hand, data points calculated by Equations 3.2-3.7 are consistently distributed over, above and below the line of *y*=*x* without any outlying data points.

On the other hand, the determination coefficients R^2 are all greater than 0.90, statistically indicating that the models as fitted explains more than 90% of the variability in calculated cutting and normal forces. The correlation coefficients *r,* yielded by the cutting and normal forces models, are all also greater than 0.90, which lead to strong relationships between variables. The relationships between calculated and measured cutting and normal forces are all statistically significant at the confidence level of 99% since *p*-values are lower than 0.01.

Additionally, the variance account for (VAF) and the root mean square error (RMSE) were calculated by Equation 3.11 and Equation 3.12, respectively. The results of VAF and RMSE of each model are summarized in Table 2.

$$VAF = \left(1 - \frac{\operatorname{var}\left(y_i - \hat{y}_i\right)}{\operatorname{var}\left(y_i\right)}\right) \times 100\% \quad (3.11)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i}^{N}\left(y_i - \hat{y}_i\right)^2} \quad (3.12)$$

where y_i is the measured value, y_i is the calculated value, and N is the number of samples.

Table 2. The *VAF* and *RMSE* values and *t*-test results of different prediction models

Model	*VAF*(%)	*RMSE*	*t*-value	*p*-value
Eq. (3.2)	96.02	0.4414	0.017	0.986
Eq. (3.3)	97.32	0.3634	0.055	0.957
Eq. (3.4)	97.48	0.3509	0.003	0.998
Eq. (3.5)	95.68	0.4344	-0.024	0.981
Eq. (3.6)	97.65	0.3200	-0.005	0.996
Eq. (3.7)	97.85	0.3063	0.002	0.999
Eq. (3.8)	50.88	3.1697	0.045	0.965
Eq. (3.9)	82.20	1.9579	0.274	0.785
Eq. (3.10)	86.57	1.6816	0.181	0.857

The interpretation of *VAF* and *RMSE* are: the higher *VAF*, the better model performs. VAF of 100% means that the measured output has been predicted perfectly. *VAF* of 0 means that the model performs as poorly as a predictor using simply the mean value of the data (Gunes et al. 2007). The lower RMSE, the better model performs. From the data in Table 2, it is apparent that the *VAF* values are generally greater than 95.68% while the RMSE values are lower than 0.4414 for cutting and normal forces models. The overall response of these models verify that the empirical models of cutting and normal forces exhibit a good performance.

3.2.2 Models of Specific Energy

We also conducted t-test to statistically analyze the validity of specific energy models. The results of *t*-test reveal that there is no significant difference between predicted specific energy given in Equations 3.8-3.10 and the measured ones at the confidence level of 95%. However, the determination coefficient of 0.66 derived from Equation 3.8 resulted in relatively poor performance compared with the Equations 3.9-3.10. The relationships between calculated and measured specific energy are presented in Figure 11.

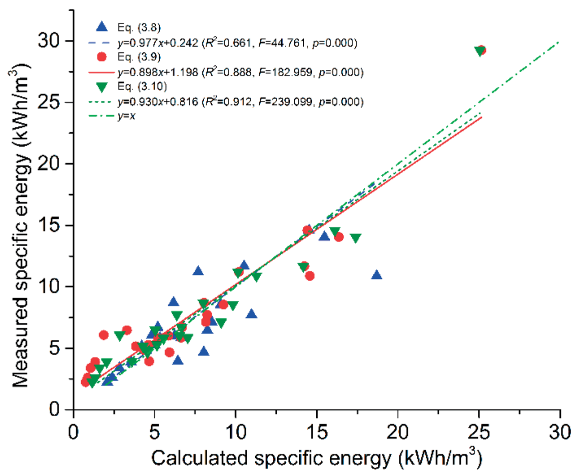


Figure 11. Relationship between measured and calculated specific energy.

It can be seen in Figure 11 that the calculated values by Equations 3.8-3.10 are all evenly distributed around the trend line. However, the determination coefficient of regression equation between measured and calculated specific energy by Equation 3.8 is 0.661, and *VAF* and *RMSE* values are 50.88% and 3.1697 respectively, which corresponds to Equation 3.8 has a weak prediction compared to Equations 3.9-3.10. The VAF and RMSE values of Equations 3.9-3.10 are found to be 82.20%, 1.9579; 86.57%, 1.6816, respectively, indicating that Equations 10-11 have good prediction performance. However, the effect of rock brittleness (σ_c/σ_t) on specific energy is uncertain since the ratio of σ_c/σ_t used in regression analysis change from 10.93 to 23.30. Therefore, Equation 3.10 should be carefully used for examining the specific energy when the σ_c/σ_t is not in the range.

3.3 Comparison of Empirical Models and Theoretical Models of Cutting Forces

Evans (1984) developed a cutting force model for conical picks based on tensile failure as presented in Equation 3.13. Afterwards, Goktan (1997), Roxborough and Liu (1995) modified Evans' (1984) model of conical picks considering the friction between rock and the pick as indicated in Equations 3.14-3.15.

$$FC_E = \frac{16\pi d^2 \sigma_t^2}{\sigma_c \cos^2(\phi/2)} \quad (3.13)$$

$$FC_G = \frac{4\pi d^2 \sigma_t \sin^2(\phi/2+\varphi)}{\cos(\phi/2+\varphi)} \quad (3.14)$$

$$FC_{RL} = \frac{16\pi d^2 \sigma_c \sigma_t^2}{\left[2\sigma_t + \left(\sigma_c \cos(\phi/2)\right)\left(1+\tan(\varphi)/\tan(\phi/2)\right)\right]^2} \quad (3.15)$$

where FC_E, FC_G, FC_{RL} are the peak cutting forces (N), σ_c is the compressive strength of the rock (MPa), σ_t is the tensile strength of the rock (MPa), ϕ is the cone angle of the conical pick; φ is the friction angle between the rock and pick; *d* is the cutting depth (mm).

Goktan and Gunes (2005) proposed a semi-empirical cutting force model considering the rake angle as shown in Eq. (3.16).

$$FC_{Gm} = \frac{4\pi\sigma_t d^2 \sin^2\left[(\pi/2-\beta)/2+\varphi\right]}{\cos\left[(\pi/2-\beta)/2+\varphi\right]} \quad (3.16)$$

where, β is the rake angle

$\beta = \pi/2 - (\gamma + \phi/2)$; γ; is the attack angle.

Based on rock cutting test data, Bilgin et al. (2006) found that there was a strong linear relationship between the ratio of cutting force to cutting depth and the compressive strength of the rock. The regression equation is shown as follows.

$$FC_{Bm} = (8.0948\sigma_c + 213.248)d \quad (3.17)$$

where, FC_{Bm} is the mean cutting force.

Based on the rock properties given in the Table 1, the cutting force were calculated by Equations 3.13-3.17. The correlations between measured and calculated cutting forces by different models are shown in Figure 12.

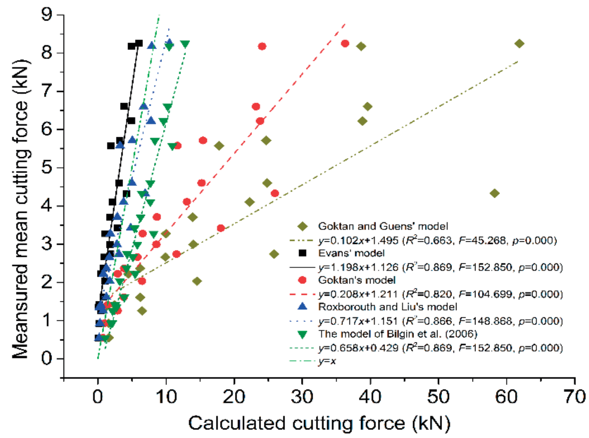


Figure 12. Relationship between measured and calculated mean cutting forces of different models.

It can be seen that there are significantly statistical linear relationships between measured and calculated cutting forces (p=0.000). The linear relationships between measured and calculated cutting forces by the models of Evans (1984), Roxborough and Liu (1995), Goktan (1997) and Bilgin et al. (2006) are very strong in terms of their determination coefficients (R^2>0.8). However, the linear relationship between measured and calculated cutting force by the model of Goktan and Gunes (2005) is relatively weaker compared to others (R^2=0.663). The reason is that the friction angle between the rock and the pick was set to be 10°, which was significantly lower than the measured ones of this study. It can be concluded from the fitting lines and the line of $y=x$ that the cutting forces calculated using these models are obviously greater than the measured ones.

In order to further investigate whether the measured force values are significantly different from predicted values, *t*-test was carried out at the confidence level of 95% as listed in Table 3. What is interesting in this data is that the cutting forces calculated by Roxborough and Liu (1995) model has not a significant difference with the measured forces.

Table 3. *t*-test results of different prediction models.

Model	*t*-value	*p*-value
Eq. (3.13)	-2.684	0.010
Eq. (3.14)	3.734	0.001
Eq. (3.15)	-0.317	0.753
Eq. (3.16)	4.462	0.000
Eq. (3.17)	3.131	0.003

It should also be noted that the cutting forces calculated by theoretical models and semi-empirical models are all lower than that of measured ones when the cutting depth is 3 mm. Therefore, the model of Bilgin et al. (2006) is also reliable based on safe considerations.

CONCLUSIONS

Rock cutting experiments were carried out on five different sandstones under different levels of cutting depths in unrelieved cutting modes. The effects of cutting depth on cutting and normal forces and specific energy were discussed in detail. Some empirical models were developed based on non-linear regression method. The main conclusions can be drawn as follows:

1. Exponential function was found for expressing the relationships between cutting, normal forces, and cutting depth from a statistical perspective.

2. Empirical models of cutting and normal forces were developed considering the uniaxial compressive strength, tensile strength and cutting depth using non-linear regression method. Statistical analysis indicates that all models have good prediction performance. Therefore, engineers can choose the appropriate model to preliminary estimate of the forces according to known parameters.

3. Regression analyses reveal that the empirical model of specific energy with respect to uniaxial compressive strength and cutting depth has a relatively weak performance prediction. However, if the tensile strength of the rock is taken into consideration in the model, the performance of the model represents more reliable results. However, the most surprising correlation is obtained with the ratio of uniaxial compressive to tensile strengths since the model has the best performance compared to the other models. Additionally, it is reported that the specific energy has a good relationship with the brittleness index (σ_c/σ_t).

4. The *t*-test was carried out to check whether the experimental cutting force are significantly different from the theoretical models. In this context, it was seen that Roxborough and Liu's model provides the best results based on the test data of this study.

It should be noted that the uniaxial compressive strengths of the rock samples used for cutting experiments vary from 17.91 to 85.98 MPa. Therefore, it is emphasized that the models of this study are especially suitable to predict the tool forces and specific energy of the conical picks while cutting from soft to medium-hard strength sandstones.

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