



Effect of cutting depth and line spacing on the cuttability behavior of sandstones by conical picks

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Abstract

Various types of conical picks in different shapes are produced and widely employed on mechanical excavators. Depending on the mechanical and abrasivity properties of rocks, appropriate shape of pick is selected. In order to obtain maximum efficiency from the pick during excavation, the interaction between the pick and rock and the cutting mechanism play very important role. In this context, linear cutting tests were conducted by using a conical pick at the cutting depths between 3 and 18 mm and also at the various line spacings on sandstones exhibiting different mechanical properties. The results indicated that cutting depth and line spacing have significant influences on the tool forces acting on the pick, the ratio of normal to cutting force, and the specific energy. Accordingly, strong correlations and empirical models were developed. In conclusion, the empirical models proposed for estimating the forces and specific energy would be used for producing the conical bits and also designing the cutter heads of mechanical excavators on soft and medium-hard strength sandstones.

Keywords Conical pick · Rock cutting · Cutting depth · Line spacing · Tool forces · Specific energy

Introduction

Rock cutting is one of the most commonly used processing methods for excavating and removing materials. Various types of cutting systems are employed in this process for mining and tunneling activities. The behavior of cutting tools used in these systems were investigated from different aspects (Zhou et al. 2009, Karakurt et al. 2014, Haeri and Marji 2016, Zichella et al. 2017, Menezes 2017). As one of the most popular rock cutting

tools, conical picks are usually mounted on roadheaders, shearers, and continuous miners in underground excavations.

The conical picks are designed relying on their tip radius and shapes. They are generally manufactured in rounded, standard, and sharp shapes. Depending on the mechanical and abrasivity properties of rocks, appropriate tip type is selected and hence a maximum penetration rate and performance can be obtained from the conical picks. The cone angle is dominant on the shape of the bits. Larger tips, having higher degree of cone angles, are assumed to be rounded and usually applied in abrasive and hard rocks. As the angle is reduced, the pick is more suitable to cut the medium-hard rocks. However, radial bits are generally preferred in soft rock environment. In this respect, it could be claimed that the mechanical excavators (e.g., shearers, continuous miners) driven in low strength rock such as coal and trona employ the picks having low degree of cone angle whereas the conical picks having high degree of cone angles are used on the roadheaders since they are usually driven in sandstone formation in tunneling activities.

Although the rock properties and geometry of the pick are relatively important during rock cutting, the cutting mechanism also plays an important role on the efficiency of the conical pick. It has been studied in recent decades by a number of researchers from different aspects, for example, wear rate of materials (Yang et al. 2015), rock failure mechanism (Evans 1984, Bao et al. 2011), tool forces, and specific energy (Balci

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et al. 2004, Bilgin et al. 2006, Sengun and Altindag 2013, Kang et al. 2016, Hasanpour et al. 2016). In this context, tool forces and specific energy are two main topics to evaluate the cutting performance of the picks.

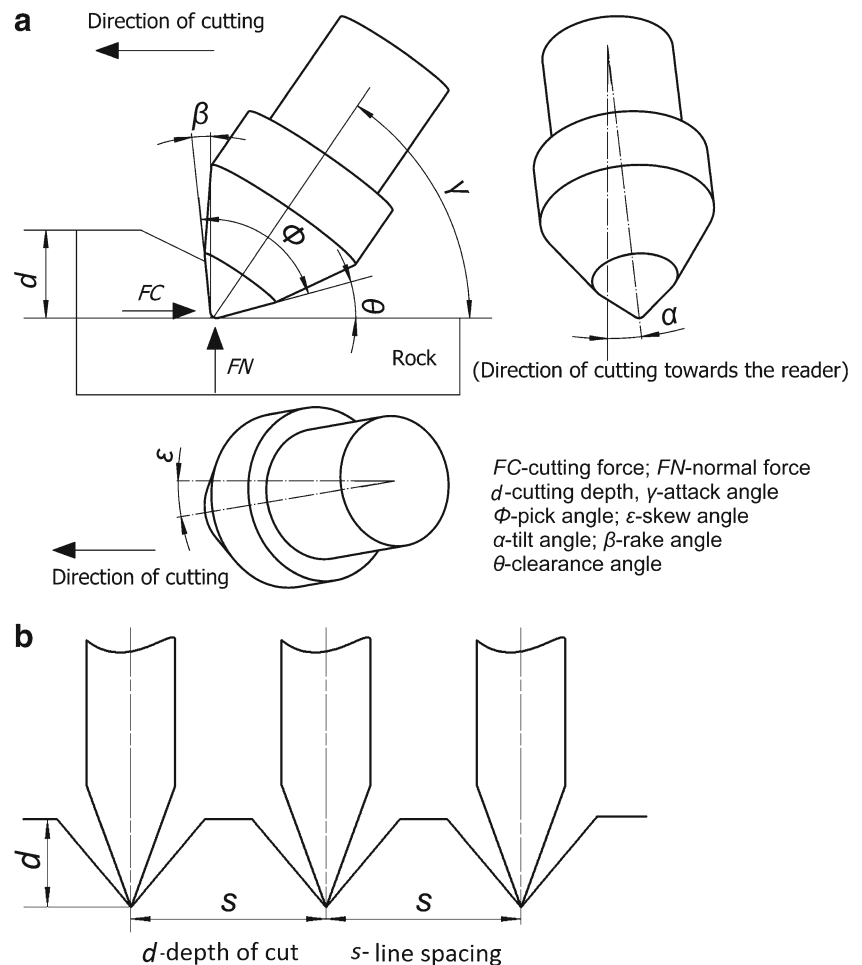
Tool forces, mainly including cutting and normal forces, are basic parameters used for calculating the loads of working units of excavators (Jang et al. 2016). Specific energy, which could be defined as the work required to break a unit volume of rock, is usually used for the evaluation of rock cuttability and performance assessment of conical picks as well as excavation machines (Balci et al. 2004). Both the tool forces acting on a pick and the specific energy are closely related with the rock strength, the characteristics of picks (i.e., the cone, the attack, the clearance, and the rake angles of the picks) and the characteristics of the cut (i.e., the cutting depth and the line spacing). A general view of a conical pick is depicted in Fig. 1 in which all the cutting parameters are demonstrated.

According to the cutting theory of Evans (1985), dominant mechanical properties such as uniaxial compressive strength and tensile strength of the rock influence the cutting forces of conical picks. Bilgin et al. (2006) proposed that cutting force, normal force, and the specific energy could be well predicted by

the uniaxial compressive strength, tensile strength, and rebound hardness of the rock. Copur et al. (2017) carried out rock cutting experiments in order to investigate the effects of cutting patterns and cutting speed on the performance of the conical pick using two cutting speeds on five different rock samples. Hekimoglu (2017) proposed that tool forces of drag-typed picks can be predicted using “effective area”, which is encompassed by a triangle with an apex angle twice the breakout angle of unrelieved groove. Shao et al. (2017) indicated that the cutting depth, attack angle, line spacing, and cutting speed had a considerable influence on mean cutting and normal forces based on linear rock cutting tests using SMART*CUT picks.

To date, the effects of rock strength and relevant cutting parameters on tool forces and specific energy have been studied based on theoretical analysis and experimental tests. However, there are still several confusing issues. The first one is the relationship between tool forces, specific energy, and cutting depth. The cutting force acting on a conical pick is proportional to the square of the cutting depth in the model of Evans (1985). Bao et al. (2011) theoretically determined the power of cutting depth to be 4/3 based on fracture mechanics using Evans’ (1985) rock cutting mode. Therefore, it is

Fig. 1 The cutting parameters of conical picks



necessary to study the relation between tool forces and cutting depth. Secondly, it should be noted that the normal force models have never referred in the theoretical models. In this context, recent researches have shown that the rock strength has a considerable impact on the ratio of normal to cutting force which is a key parameter used for determining the normal force in practical applications. However, the effects of cutting depth and line spacing on this ratio were not referred due to limited number of data. Bilgin (1977) found that the ratio of normal to cutting force acting on radial picks decreases as the cutting depth is increased. Thus, it is clear that cutting depth influence the ratio for conical picks. For this reason, it is necessary to further investigate this finding.

Moreover, it is known that there are significant influences of cutting depth and line spacing on specific energy in the process of rock cutting (Bilgin et al. 2006). Experimental tests indicated that there is an optimum ratio of line spacing to cutting depth, at which the cutting operation result in the minimum specific energy values. However, quantitative correlations between cutting depth, spacing, and the specific energy are still need to be investigated more. For these reasons, it is necessary to carry out rock cutting tests at different levels of cutting depth and line spacing in order to determine the abovementioned doubtful issues.

In this study, rock cutting tests using one type of conical pick were carried out utilizing a linear rock cutting machine. The tests were conducted on five sandstones exhibiting different mechanical properties. The aim of this paper is to determine the characteristic parameters of cuts affecting the performance of conical picks and also establish reliable empirical models of tool forces and specific energy considering the characteristic parameters of cuts.

Experimental setup

Test equipment

Cutting tests were carried out at the linear rock cutting machine (LRCM) displayed in Fig. 2. The maximum cutting and normal load capacities of the LRCM are 100 and 50 kN, respectively. The maximum thrust of the hydraulic cylinder is 89 kN. During the cutting tests, a rock is placed in a heavy steel box and clamped by bolts around the box after setting the cutting depth. The cutting force and normal force are monitored using a 3D load cell mounted between the cutter holder and the stiff base. The cutter advance is measured using a magnetostrictive displacement transducer. The data acquisition system consists of an acquisition card, computer, and acquisition software. The data sampling rate was set to be 1 kHz for each cutting test and can be adjustable up to 125 kHz.

Conical pick

A conical pick illustrated in Fig. 2 was employed for all cutting experiments. It has the cone angle of 80° , and the tip diameter of 22 mm. The tip radius of the pick is also about 1 mm. The shank geometry of the conical pick is designed according to the LRCM. It is well-known that the rock breaking process is mainly completed by the hard alloy head and therefore the experimental results also have universal significance.

Rock samples

Five different sandstones were collected from commercial quarries in Sichuan province and Chongqing city. Each

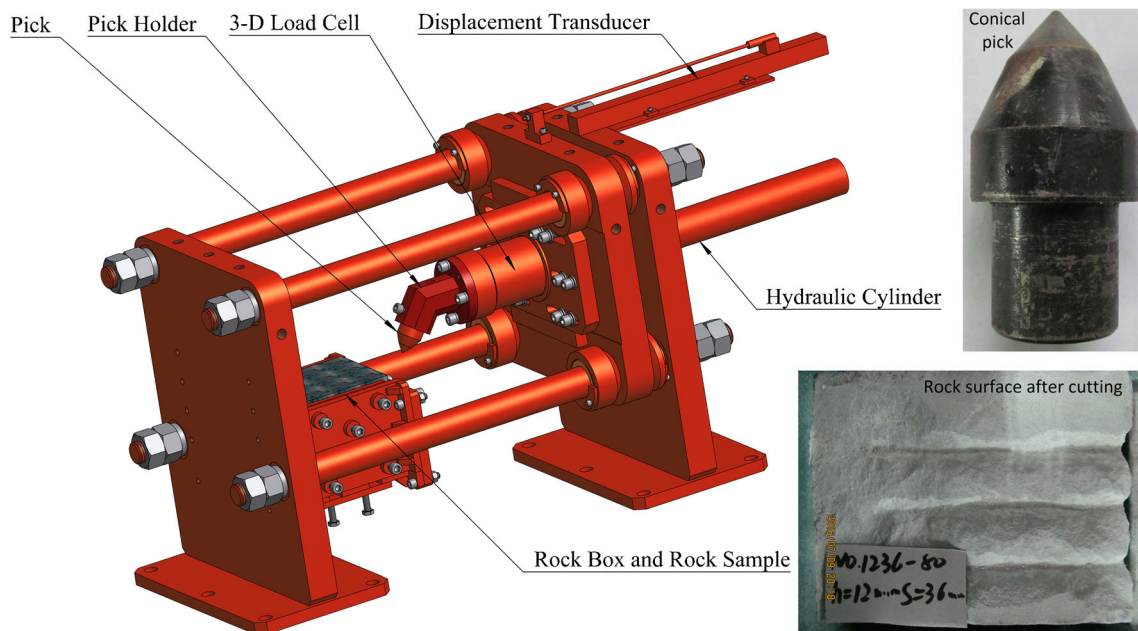


Fig. 2 Schematic view of linear rock cutting machine (LRCM) and a conical pick

rock sample was approximately in the dimensions of 150 mm × 150 mm × 200 mm and was trimmed to the required size depending on the test. The physical and mechanical properties of the rocks including density, uniaxial compressive strength, Brazilian tensile strength, and elasticity modulus were determined based on ISRM (1981) standards, and the results are listed in Table 1. Uniaxial compression tests were performed on trimmed core samples, which have a diameter of 50 mm and a length of 100 mm. The stress rate was applied within the limits of 0.5–1.0 MPa/s. Brazilian tensile strength tests were performed on core samples having a diameter of 50 mm. The ratio of thickness to diameter of the disc samples varied between 0.5 and 0.7. All the tests were repeated 5–6 times and the mean values were taken to be the final results.

Cutting parameters

In all experiments, the attack angle was set to be 55°, while the skew and tilt angles were set to be 0°. Accordingly, the rake angle and the clearance angle were calculated to be -5° and 15°, respectively. The cutting depth was changed from 3 to 18 mm in unrelieved cutting mode and from 3 to 12 mm in relieved cutting mode. Bilgin et al. (2006) suggested that the optimum ratio of line spacing to cutting depth changes between 2 and 5 for conical picks. Based on this finding, line spacing was set from 6 to 48 mm depending on the cutting depth. Therefore, the ratio of spacing to cutting depth changed to be between 1.33 and 6. There was no evidence to suggest that the cutting speed had considerable effects on the tool forces and specific energy.

Moreover, He and Xu (2015) showed that the effect of cutting speed on tool forces was in the range of 4–20 mm/s and specific energy were insignificant compared with other parameters such as cutting depth. The test results indicated that cutting speed was less than 13 mm/s for all rock cutting experiments in this study. On the other hand, rock cutting simulations carried out by Menezes et al. (2014) demonstrated that there is only a minimal effect of cutting speed on cutting forces. Therefore, the effect of cutting speed on rock cutting performance was ignored in this study.

Data processing

The raw data of cutting forces, normal forces, and cutting distance (S_p) were processed using MATLAB software. Firstly, the wavelet filter was used for noise removal. Next, mean cutting and normal forces and mean peak cutting and normal forces were calculated. After each cut, rock chips with the same cutting parameters were carefully collected in a box with a unique tag and weighted later. Based on the measured forces and collected chip

Table 1 Physical and mechanical properties of the rocks

Rock name	ρ	σ_c	σ_t	E
Sandstone 1	2.22	17.91 ± 4.18	1.64 ± 0.10	3.00
Sandstone 2	2.43	79.20 ± 5.43	4.97 ± 0.48	15.94
Sandstone 3	2.36	52.99 ± 2.08	3.67 ± 0.25	5.07
Sandstone 4	2.35	59.80 ± 6.14	3.93 ± 0.44	5.50
Sandstone 5(black)	2.59	85.98 ± 9.33	3.69 ± 0.42	6.31

where ρ is the density of the rock (g/cm³), σ_c is the uniaxial compressive strength (MPa), σ_t is the Brazilian tensile strength, E is the elasticity modulus (GPa)

masses, the specific energy of rock cutting was calculated using Eq. (1). Each cutting test was repeated at least three times and the mean values were taken as the final results which are summarized in Table 2, 3, and 4.

$$SE = \frac{FC_m S_p \rho}{3.6 M} 10^{-6} \quad (1)$$

where SE is the specific energy (kWh/m³), FC_m is the mean cutting force (N), S_p is the cutting distance (m), ρ is the density (kg/m³), and M is the masses of rock chips (g).

Experimental tests and discussions

In order to examine the effects of relevant cutting parameters of the conical tool on the tool forces and specific energy, a number of linear cutting tests were conducted at the various cutting depths and line spacings using five sandstone samples. Then, statistical analyses were carried out based on the test data and some empirical models were proposed.

However, a proper cone angle was initially selected from the bits where the angle varies from 60° to 90° in unrelieved cutting mode. In this context, the variation of the cutting force on the bits was examined at the cutting depth of 6 mm and at the clearance angle higher than 5°. It was seen that the mean cutting forces increase as the cone angle of the bit increases (Fig. 3). Since the rocks used in the cutting tests were medium-hard sandstones which include a high percentage of quartz, the cone angle of 80° was selected for the entire tests. Because such a high degree of angle would have a good resistance to be worn in course of rock cutting.

It should be noted that rock cutting tests in unrelieved cutting mode were carried out on sandstone 1–5 and the results have been listed in Table 2. Rock cutting tests in relieved cutting mode were conducted on sandstone 1 and sandstone 2 and the results have been listed in Tables 3 and 4, respectively. On the other hand, the boundary cuts which were close to the edge of the rock have been eliminated from the analyses since these tests would cause unreliable results.

Table 2 Rock cutting results in unrelieved cutting mode

Rock name	d	FC _p	FC _m	FN _p	FN _m	FC _p /FC _m	FN _p /FN _m	FN _p /FC _p	FN _m /FC _m	SE _u
Sandstone 1	3	0.886	0.551	0.815	0.586	1.61	1.39	0.92	1.06	6.47
	6	2.009	1.256	1.759	1.221	1.60	1.44	0.88	0.97	6.07
	9	3.397	2.034	2.939	2.103	1.67	1.40	0.87	1.03	3.88
	12	4.774	2.740	4.062	2.525	1.74	1.61	0.85	0.92	3.40
	15	6.767	3.421	4.640	3.194	1.98	1.45	0.69	0.93	2.61
	18	8.602	4.329	5.494	3.828	1.99	1.44	0.64	0.88	2.25
Sandstone 2	3	2.708	1.410	2.295	1.592	1.92	1.44	0.85	1.13	29.24
	6	5.660	2.661	4.434	2.891	2.13	1.53	0.78	1.09	11.67
	9	8.862	4.108	6.753	4.538	2.16	1.49	0.76	1.10	11.21
	12	13.545	6.601	9.932	6.535	2.05	1.52	0.73	0.99	8.70
	15	17.986	8.252	11.935	8.050	2.18	1.48	0.66	0.98	6.70
Sandstone 3	3	1.520	0.928	1.544	1.096	1.64	1.41	1.02	1.18	14.60
	6	3.260	1.613	2.589	1.732	2.02	1.49	0.79	1.07	7.13
	9	5.464	2.991	4.782	3.380	1.83	1.41	0.88	1.13	6.02
	12	8.815	4.601	7.384	4.685	1.92	1.58	0.84	1.02	5.28
	15	11.656	6.224	9.611	6.256	1.87	1.54	0.82	1.01	5.16
Sandstone 4	3	1.836	0.932	1.570	1.070	1.97	1.47	0.86	1.15	14.05
	6	4.670	2.369	3.825	2.604	1.97	1.47	0.82	1.10	8.55
	9	8.849	3.709	5.929	3.818	2.39	1.55	0.67	1.03	5.86
	12	12.944	5.713	8.867	5.795	2.27	1.53	0.69	1.01	5.82
	15	18.180	8.178	13.789	7.752	2.22	1.78	0.76	0.95	4.84
Sandstone 5	3	2.676	1.348	2.572	1.687	1.99	1.52	0.96	1.25	10.89
	6	4.895	2.223	4.047	2.690	2.20	1.50	0.83	1.21	7.72
	9	8.401	3.275	5.926	3.519	2.57	1.68	0.71	1.07	4.67
	12	13.849	5.577	7.790	5.385	2.48	1.45	0.56	0.97	3.94
Mean	–	–	–	–	–	2.02 ± 0.26	1.50 ± 0.90	0.79 ± 0.11	1.05 ± 0.09	–

where *d* is the cutting depth (mm), FC_m, and FN_m are the mean cutting and normal forces (kN), respectively. FC_p and FN_p are the mean peak cutting and mean peak normal forces (kN), respectively. SE_u is the specific energy in unrelieved cutting mode (kWh/m³)

Effect of cutting depth and line spacing on tool forces

Analysis of cutting depth

During the process of rock cutting, the cutting depth leads to increase the amount of production. When the picks are advanced in deeper cutting depths, the tool forces shows an increasing trend although the capacity increases gradually. However, this condition might result in early wear of the bit and shorten the cutting life of picks. For this reason, an optimum cutting condition should be determined in the laboratory.

In this sense, the variation of tool forces versus the cutter distance conducted on sandstone 2 in unrelieved cutting mode were examined and the results of shallow (3 mm) and deeper (12 mm) cutting depths are shown in Fig. 4a, b, respectively. It can be observed in Fig. 4a that the cutting and normal forces exhibit some repetitive patterns in that the force builds up to a peak then drops and builds up again, while the values of peak forces are approximately very close. For deeper depths as in

Fig. 4b, the cutting and normal forces curves also show the same fluctuation pattern as that of the shallow cut. However, it should be noticed that the distances between the peaks of cutting forces in deeper cuts are longer than those for shallow cuts. This indicates that the bigger chips are formed in the process of deeper cutting. Moreover, tool forces in Fig. 4 illustrate that the fluctuation intensity of cutting force is much greater than that of normal force.

The results of laboratory tests described in the paper confirmed that there exist linear correlations between the ratios of mean cutting and normal forces to uniaxial compressive strength, which is an important performance assessment parameter, and cutting depth in unrelieved cutting mode ($R^2 = 0.755\text{--}0.776$) based on the test results given in Tables 1 and 2. The *F* values are all greater than 70 and the *p* values are all equal to 0.000 which indicates that the correlations are all statistically significant at the confidence level of 99% (Fig. 5). Furthermore, there is a strong linear relationship between the ratios of mean cutting and normal forces to tensile

Table 3 Rock cutting test results in relieved cutting for sandstone 1

No.	<i>d</i>	<i>s</i>	<i>s/d</i>	FC _{<i>m</i>}		FN _{<i>m</i>}		FC _{<i>p</i>} /FC _{<i>m</i>}	FN _{<i>p</i>} /FN _{<i>m</i>}	FN _{<i>m</i>} /FC _{<i>m</i>}	FN _{<i>p</i>} /FC _{<i>p</i>}	SE _{<i>r</i>}
				FC _{<i>m</i>}	FN _{<i>m</i>}	FC _{<i>p</i>}	FN _{<i>p</i>}					
0306-80	3	6	2	0.181	0.221	0.333	0.336	1.84	1.52	1.22	1.01	3.38
0309-80	3	9	3	0.270	0.307	0.563	0.576	2.09	1.88	1.14	1.02	2.99
0312-80	3	12	4	0.461	0.479	0.809	0.763	1.75	1.59	1.04	0.94	3.90
0318-80	3	18	6	0.520	0.561	0.956	0.882	1.84	1.57	1.08	0.92	4.20
0609-80	6	9	1.5	0.210	0.252	0.456	0.475	2.17	1.88	1.20	1.04	2.05
0612-80	6	12	2	0.277	0.298	0.664	0.599	2.40	2.01	1.08	0.90	1.50
0618-80	6	18	3	0.525	0.553	1.157	1.053	2.20	1.90	1.05	0.91	1.65
0624-80	6	24	4	0.701	0.695	1.416	1.093	2.02	1.57	0.99	0.77	2.26
0636-80	6	36	6	1.116	1.083	1.818	1.407	1.63	1.30	0.97	0.77	3.69
0912-80	9	12	1.33	0.409	0.424	0.881	0.845	2.15	1.99	1.04	0.96	2.20
0918-80	9	18	2	1.006	0.983	1.960	1.818	1.95	1.85	0.98	0.93	1.35
0924-80	9	24	2.67	1.184	1.151	2.428	1.812	2.05	1.57	0.97	0.75	1.71
0936-80	9	36	4	1.803	1.753	3.466	2.789	1.92	1.59	0.97	0.80	2.52
0948-80	9	48	5.33	1.927	1.812	3.407	2.737	1.77	1.51	0.94	0.80	3.81
1218-80	12	18	1.5	0.764	0.733	1.616	1.301	2.12	1.77	0.96	0.81	2.22
1224-80	12	24	2	1.225	1.189	2.270	1.888	1.85	1.59	0.97	0.83	1.92
1236-80	12	36	3	1.376	1.256	2.940	2.229	2.14	1.77	0.91	0.76	1.15
1248-80	12	48	4	2.020	1.898	3.870	3.200	1.92	1.69	0.94	0.83	1.57
Mean	–	–	–	–	–	–	–	1.99 ± 0.19	1.70 ± 0.19	1.03 ± 0.09	0.88 ± 0.10	–

where *s* is the line spacing (mm), SE_{*r*} is the specific energy in relieved cutting mode (kWh/m³), other notations are same as given in Table 2

Table 4 Rock cutting test results in relieved cutting mode for sandstone 2

No.	<i>d</i>	<i>s</i>	<i>s/d</i>	FC _{<i>m</i>}		FN _{<i>m</i>}		FC _{<i>p</i>} /FC _{<i>m</i>}	FN _{<i>p</i>} /FN _{<i>m</i>}	FN _{<i>m</i>} /FC _{<i>m</i>}	FN _{<i>p</i>} /FC _{<i>p</i>}	SE _{<i>r</i>}
				FC _{<i>m</i>}	FN _{<i>m</i>}	FC _{<i>p</i>}	FN _{<i>p</i>}					
0306-80	3	6	2	0.802	0.879	1.549	1.603	1.93	1.82	1.10	1.03	16.24
0309-80	3	9	3	1.127	1.250	2.210	1.991	1.96	1.59	1.11	0.90	14.8
0312-80	3	12	4	1.214	1.374	2.218	1.934	1.83	1.41	1.13	0.87	22.89
0318-80	3	18	6	1.378	1.572	3.039	2.341	2.21	1.49	1.14	0.77	22.36
0609-80	6	9	1.5	0.980	1.088	2.179	1.936	2.22	1.78	1.11	0.89	8.67
0612-80	6	12	2	1.411	1.524	3.249	2.652	2.30	1.74	1.08	0.82	7.43
0618-80	6	18	3	2.208	2.532	4.923	4.289	2.23	1.69	1.22	0.87	7.66
0624-80	6	24	4	2.490	2.690	6.274	4.951	2.52	1.84	1.08	0.79	7.67
0636-80	6	36	6	2.580	2.737	6.246	4.390	2.42	1.60	1.06	0.70	10.03
0912-80	9	12	1.33	1.440	1.600	3.351	2.866	2.34	1.79	1.11	0.86	6.72
0918-80	9	18	2	2.226	2.494	5.861	4.199	2.60	1.68	1.12	0.72	5.39
0924-80	9	24	2.67	2.901	3.097	7.053	5.298	2.43	1.71	1.07	0.75	6.19
0936-80	9	36	4	3.403	3.550	8.381	6.132	2.46	1.73	1.04	0.73	5.94
0948-80	9	48	5.33	3.750	3.792	9.400	6.488	2.51	1.71	1.01	0.69	7.14
1218-80	12	18	1.5	2.465	2.711	6.796	4.943	2.76	1.82	1.10	0.73	4.99
1224-80	12	24	2	3.140	3.279	8.470	6.071	2.70	1.85	1.04	0.72	4.58
1236-80	12	36	3	4.548	4.290	11.236	7.140	2.47	1.66	0.94	0.64	4.31
1248-80	12	48	4	5.398	5.494	12.000	9.249	2.22	1.68	1.02	0.77	4.59
Mean	–	–	–	–	–	–	–	2.34 ± 0.26	1.70 ± 0.12	1.08 ± 0.06	0.79 ± 0.10	–

The notations are as given in Tables 2 and 3

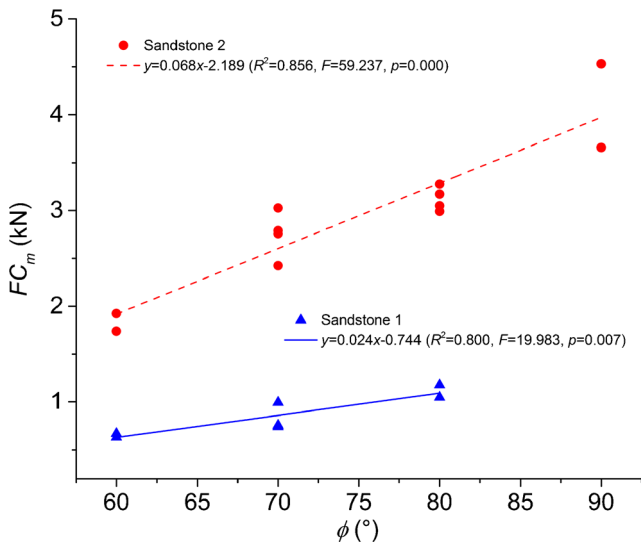


Fig. 3 Variation in mean cutting force with cone angle (ϕ) at cutting depth of 6 mm in unrelieved cutting mode

strength and cutting depth in unrelieved cutting mode ($R^2 = 0.936-0.957$, $F = 334.989-507.845$, $p = 0.000$) as shown in Fig. 6. The power values are very close to 1. It is apparent that these results are also statistically significant. Bilgin et al. (2006) also pointed out that there are strong and statistical

Fig. 4 Tool forces in unrelieved cutting mode for sandstone 2

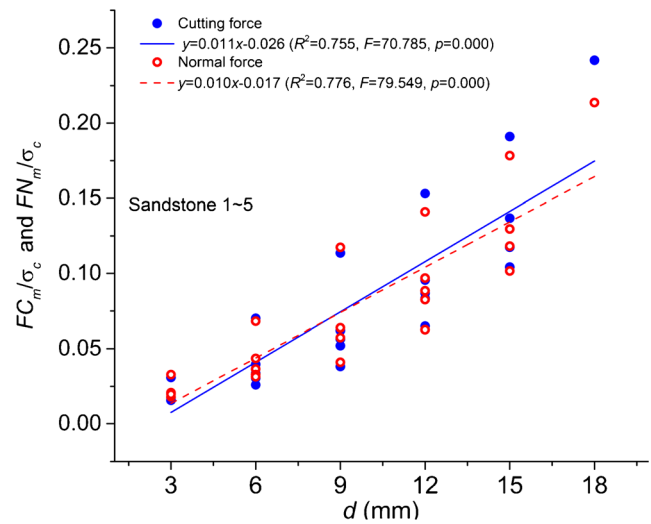
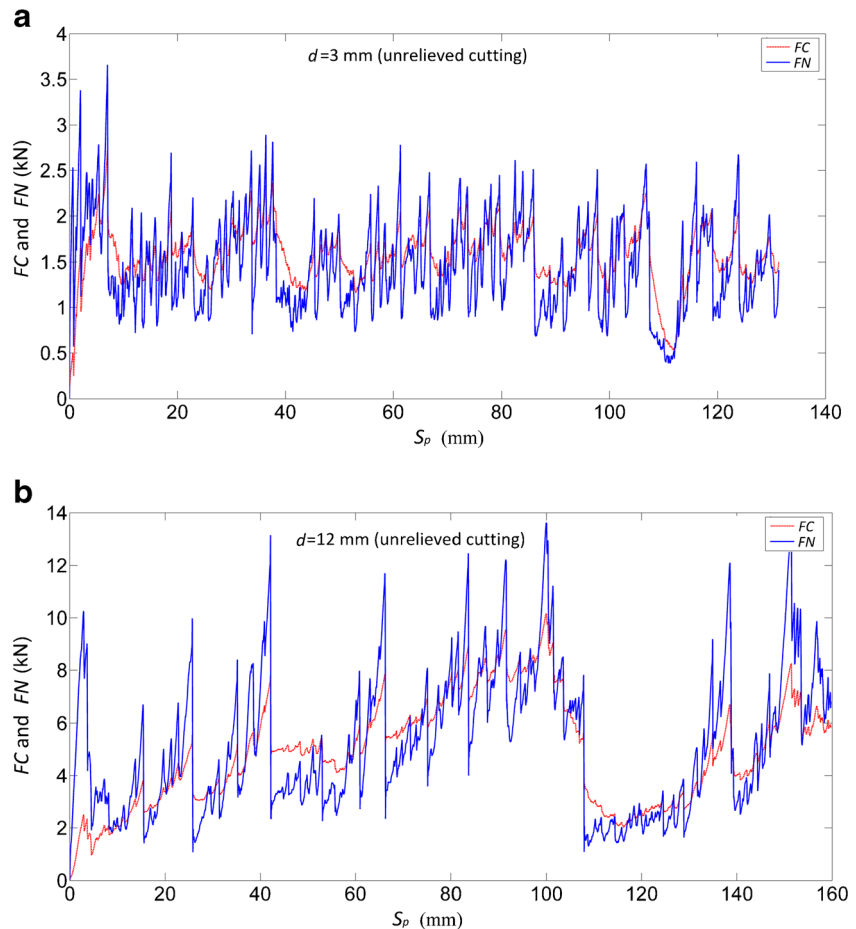


Fig. 5 Variation in the ratio of tool forces to compressive strength with cutting depth in unrelieved mode

relationships between tool forces and rock strength based on linear rock cutting tests performed on 22 different rocks.

Meanwhile, it should be noted that the correlations based on tensile strength of the rock are higher than those based on uniaxial compressive strength of the rock in terms of correlation coefficients. The predicted equations of tool forces

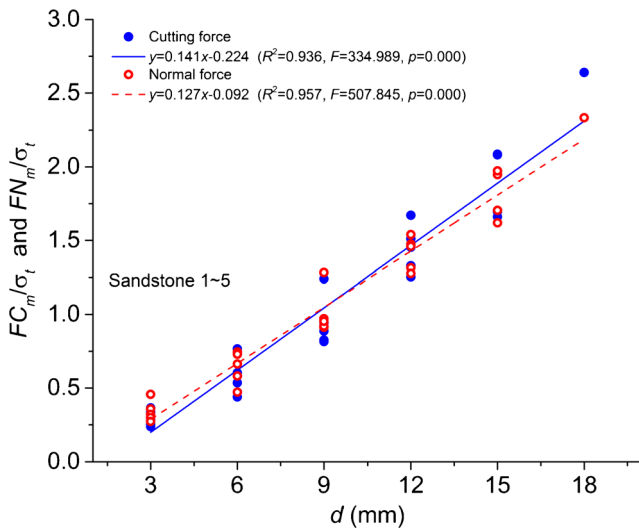


Fig. 6 Variation in the ratio of tool forces to tensile strength with cutting depth in unrelieved mode

depending on the rock strength and cutting depth in unrelieved cutting modes are summarized in Table 5.

On the other hand, in relieved cutting modes, the relationships between tool forces and cutting depth are presented in Fig. 7 for sandstone 1 and sandstone 2. It can be seen that all linear regression equations are statistically significant at the confidence level of 99% since the *F* values are all greater than 13 and the *p* values are all lower than 0.05. However, the determination coefficients, which vary between 0.448 and 0.608, are found to be low for the tested rocks. Thus, it can be claimed that line spacing in relieved cutting has a considerable influence on cutting and normal forces.

It can also be observed from Tables 2, 3, and 4 that the cutting forces in relieved cutting mode are occasionally higher than those in unrelieved cutting mode at the same cutting depth, especially for peak cutting force. This is because larger rock chips are easier to form in relieved cutting.

Furthermore, the ratio of peak to mean tool forces is also of concern, since it is an important factor affecting the vibration of a cutting head or a shearer drum. Bilgin et al. (2006) showed that the ratio was not affected by the rock properties. The experimental results of the present study verify that there is no effect of cutting depth and line spacing on this ratio in unrelieved cutting mode. The ratio of peak to mean cutting force and the ratio of peak to mean normal force are found to be 2.02 ± 0.26 and 1.50 ± 0.09 based on test data in unrelieved cutting modes. It is worth noting that the ratio of peak to mean cutting force is always greater than the ratio of peak to mean normal force, indicating that the fluctuation intensity of cutting force is much greater than that of normal force. This is also reflected in Fig. 4.

Table 5 Regression equations of mean cutting force, mean normal force, and depth of cut in unrelieved cutting mode

Regression equation	<i>R</i> ²	<i>F</i> value	<i>p</i> value
$FC_m = 0.004 \sigma_c d^{1.243}$	0.839	119.760	0.000
$FC_m = 0.075 \sigma_t d^{1.177}$	0.950	438.343	0.000
$FN_m = 0.006 \sigma_c d^{1.125}$	0.854	125.152	0.000
$FN_m = 0.100 \sigma_t d^{1.059}$	0.952	451.647	0.000
$SE = 0.454 \sigma_c d^{-0.586}$	0.402	15.478	0.000
$SE = 7.822 \sigma_t d^{-0.652}$	0.896	71.740	0.000

Analysis of line spacing

When the line spacing is too large, the fact is that mean tool forces and specific energy would be high due to providing unrelieved cutting condition. However, if it is considered to be too close, tool forces may be very low, but the specific energy will actually be high due to the over-crushed rock. On the contrary, relieved cutting may make up the greater peak forces since bigger chips are easily formed.

During the cutting tests in relieved mode, the line spacing was varied from 6 to 48 mm while the cutting depth was changed between 3 and 12 mm. Accordingly, the ratio of spacing to cutting depth was calculated to be between 1.33 and 6 (Tables 3 and 4). Cutting tests indicated that the neighboring grooves would not affect each other (becoming unrelieved cutting) for sandstone 1 and sandstone 2 when the ratio of line spacing to cutting depth is great than 6. The relationship between tool forces and line spacing at the cutting depth of 9 mm was plotted in Fig. 8. It can be seen that the forces gradually increase in a non-linear fashion versus spacing and then asymptotic to the values in unrelieved cutting mode. For

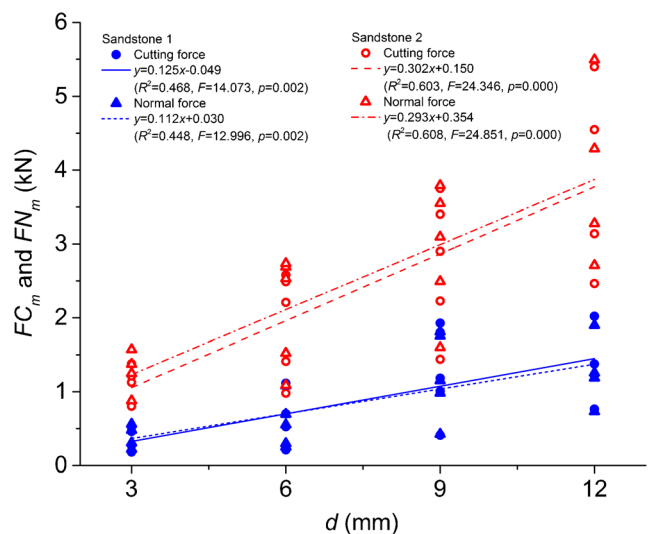


Fig. 7 Relationships between mean tool forces and cutting depth in relieved cutting mode

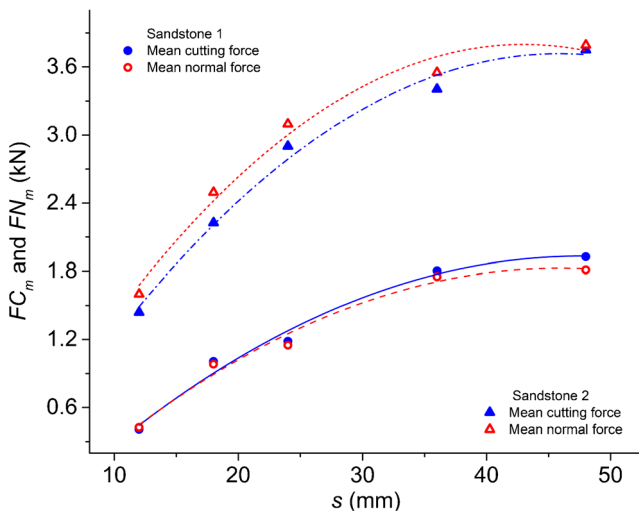


Fig. 8 Variation in cutting and normal forces with line spacing at cutting depth of 9 mm

all tests data at the cutting depths of 3, 6, 9, and 12 mm by excluding those in unrelieved cutting mode, the correlations between tool forces and line spacings are presented in Fig. 9 for sandstone 1 and sandstone 2. It can be seen that mean cutting and normal forces increase linearly with increased line spacing ($R^2 = 0.828-0.896$). Furthermore, the linear relations are all statistically significant at the confidence level of 99% based on the statistical parameters ($F = 77.277-138.384$ and $p = 0.000$). These findings reveal that line spacing has a significant impact on tool forces.

Effect of cutting depth and line spacing on the ratio of normal to cutting force

The ratio of normal to cutting force (FN/FC) is an essential parameter in determining the efficiency of a mechanical

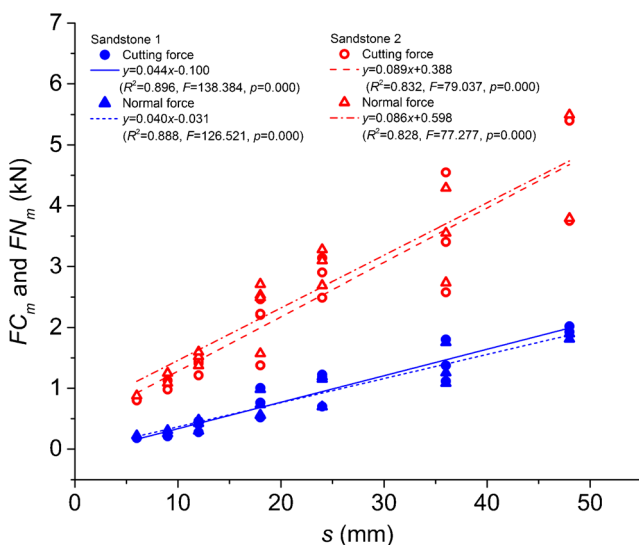


Fig. 9 Relationships between tool forces and line spacing in relieved cutting mode

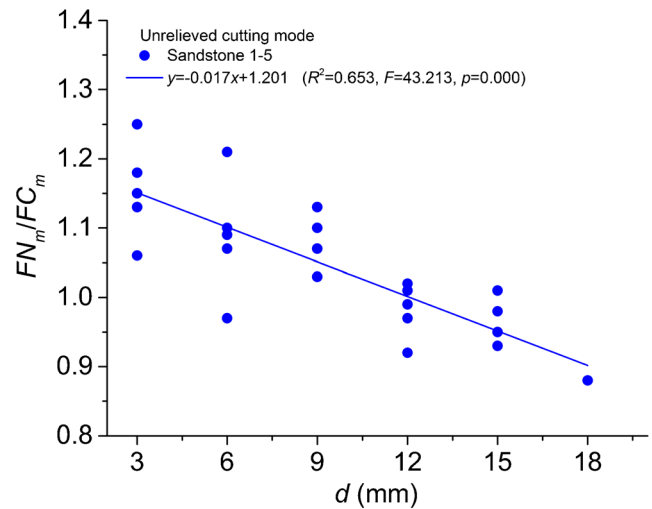


Fig. 10 Relationship between the ratio of normal to cutting force and cutting depth in unrelieved cutting mode

excavator. The ratio increases as the wear on the pick increases (Bilgin et al. 2014). As can be seen from Fig. 10, the ratio of normal to cutting force decreases linearly as the cutting depth increases in unrelieved cutting mode. Although the correlation coefficient (R^2) equals to 0.653 and the F value and the p value are found to be 43.213 and 0.00, respectively, these findings suggest that the linear correlation is statistically significant at the confidence level of 99%.

On the contrast, in relieved cutting mode, where the spacing is taken to be between 6 and 48 mm, lower determination coefficients were obtained at the same cutting conditions as shown in Fig. 11. Therefore, it is clear that the ratio of mean normal to mean cutting force is also related to line spacing. In this context, Fig. 12 shows that the ratio of normal to cutting force decreases exponentially with increasing line spacing for both sandstone 1 and sandstone 2 ($R^2 = 0.382$ and $R^2 = 0.795$).

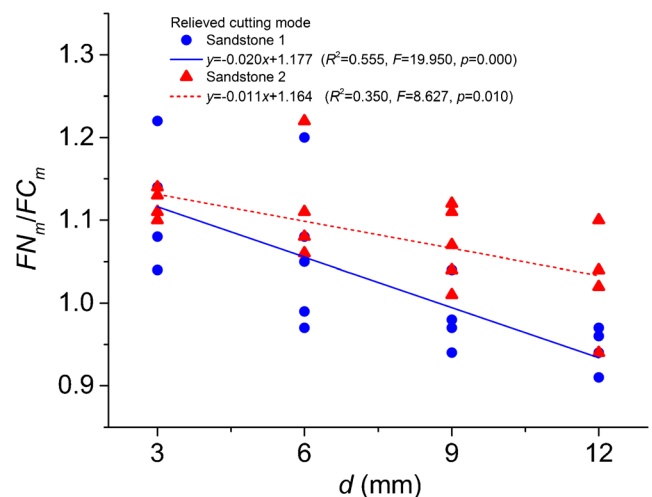


Fig. 11 Relationships between the ratio of normal to cutting force and cutting depth in relieved cutting mode

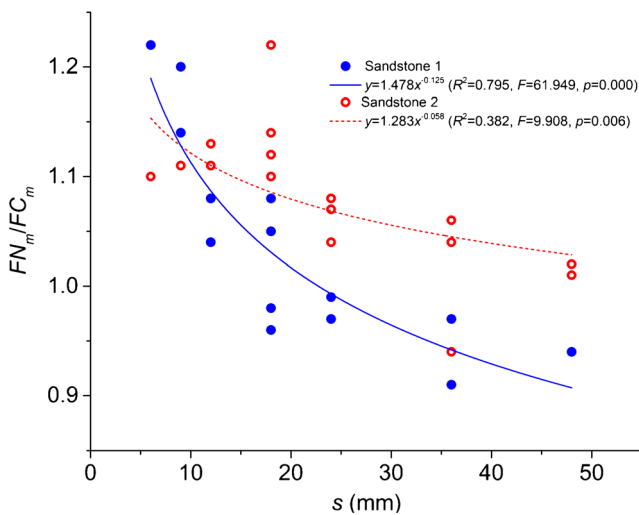


Fig. 12 Relationships between the ratio of normal to cutting force and line spacing

However, statistical analyses revealed that the correlations are valid and reliable.

Empirical models based on multiple linear regression analysis

Univariate analysis indicated that the tool forces and the ratio of normal to cutting force are both influenced by cutting depth and line spacing in relieved cutting mode. Moreover, regression correlations are not very strong due to low correlation coefficients of tested data in relieved cutting mode. To better understand the dependence of tool forces and the ratio of normal to cutting force on different cutting depths and line spacings, multiple linear regression analysis was adopted in this study.

It is well-known that there is usually a certain degree of multicollinearity in the multiple regression models due to the nature of observational data. Multicollinearity occurs in regression models when independent variables are highly correlated and it can lead to unstable prediction models and unrealistic regression coefficients. The variances inflation factor (VIF) for the cutting depth and line spacing are 1.502 and 1.502, respectively, which implies that multicollinearity is not a serious problem in the multiple linear regression models of this study. Finally, relevant models and statistical parameters using multiple linear regressions were obtained and the results are listed in Table 6.

The results show that tool forces in relieved cutting mode have a strong and statistically significant linear relationships with the cutting depth and line spacing due to high determination coefficients ($R^2 = 0.894-0.950$, $F = 63.381-143.440$, $p = 0.000$). However, cutting depth in the models of the ratio of peak normal to cutting force for sandstone 1 and the ratio of mean normal to cutting force for sandstone 2 are not statistical at the confidence level of 90% due to their t values lower than the tabulated t value (1.741) ($\alpha = 0.1$, $df = 17$) and p values greater than 0.1. Therefore, it can be deduced from these multiple linear regression equations that both the cutting depth and line spacing significantly affect the tool forces although line spacing is more dominant on the ratio of normal force to cutting force comparing with the cutting depth.

Effect of cutting depth and line spacing on specific energy

The lowest cutting force does not correspond to the lowest specific energy at the same level of cutting

Table 6 Regression equations and statistical parameters of tool forces in relieved cutting mode

Rock	Multiple regression model	Coefficients in the model								
		Regression equation			<i>d</i>		<i>s</i>		Constant	
		R^2	<i>F</i> value	<i>p</i> value	<i>t</i>	<i>p</i> value	<i>t</i>	<i>p</i> value	<i>t</i>	<i>p</i> value
Sandstone 1	$FC_p = 0.101 d + 0.065 s - 0.506$	0.919	84.676	0.000	3.292	0.005	8.370	0.000	-2.424	0.028
	$FC_m = 0.037 d + 0.038 s - 0.258$	0.924	91.781	0.000	2.362	0.032	9.521	0.000	-2.387	0.031
	$FN_p = 0.080 d + 0.049 s - 0.270$	0.894	63.381	0.000	2.944	0.010	7.166	0.000	-1.471	0.162
	$FN_m = 0.031 d + 0.035 s - 0.162$	0.911	76.895	0.000	1.987	0.065	8.840	0.000	-1.515	0.151
	$FN_p/FC_p = -0.007 d - 0.004 s + 1.030$	0.608	11.652	0.001	-1.219	0.242	-3.107	0.007	26.375	0.000
	$FN_m/FC_m = -0.012 d - 0.004 s + 1.196$	0.737	20.982	0.000	-2.728	0.016	-3.217	0.006	39.899	0.000
Sandstone 2	$FC_p = 0.457 d + 0.154 s - 1.115$	0.950	143.440	0.000	6.646	0.000	8.870	0.000	-2.385	0.031
	$FC_m = 0.146 d + 0.068 s - 0.223$	0.925	92.808	0.000	4.333	0.001	8.035	0.000	-0.976	0.345
	$FN_p = 0.297 d + 0.102 s - 0.186$	0.927	95.136	0.000	5.338	0.000	7.293	0.000	-0.492	0.630
	$FN_m = 0.143 d + 0.065 s - 0.004$	0.925	92.763	0.000	4.404	0.001	7.971	0.000	-0.016	0.988
	$FN_p/FC_p = -0.011 d - 0.004 s + 0.962$	0.633	12.950	0.001	-2.022	0.061	-2.642	0.018	25.211	0.000
	$FN_m/FC_m = -0.005 d - 0.002 s + 1.177$	0.528	8.404	0.004	-1.348	0.198	-2.380	0.031	43.305	0.000

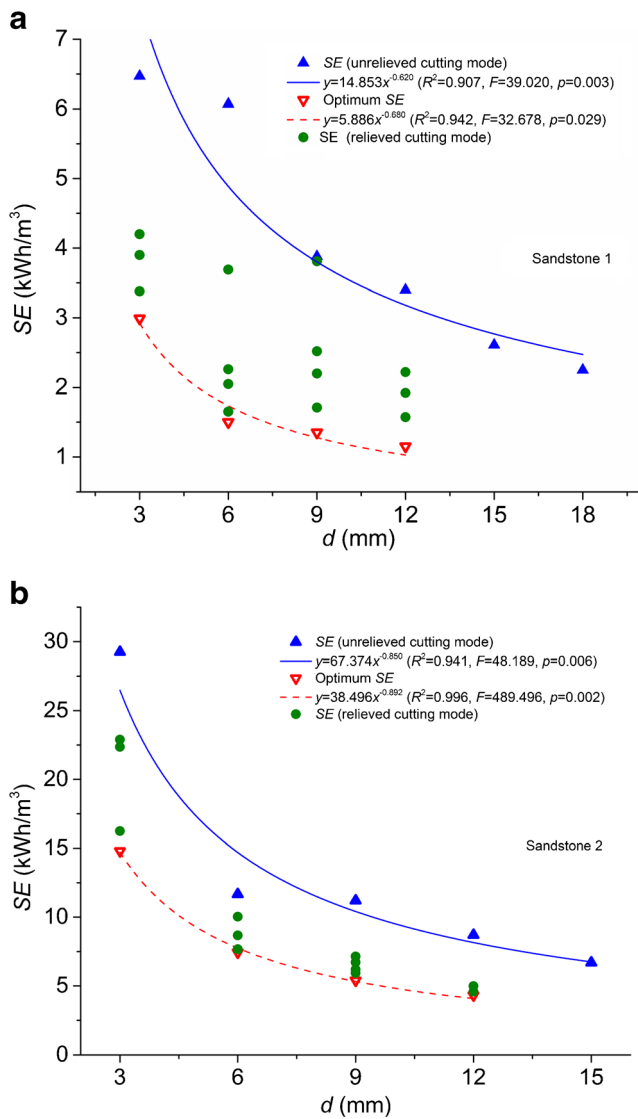


Fig. 13 Relationships between specific energy and cutting depth for sandstone 1 and sandstone 2

depth. Specific energy is also related to line spacing, which has a significant effect on the volume of rock chips and cutting forces. It has been attested that the ratio of line spacing to cutting depth also is a key factor in determining the specific energy. Thus, the effects of cutting parameters on the specific energy were also investigated.

Analysis of the cutting depth and line spacing

It is well-known that the cutting depth has a significant impact on specific energy. Bilgin et al. (2006) stated that specific energy in unrelieved cutting tests would not change effectively when the cutting depth is more than 9–10 mm. The variation of specific energy with the cutting depth can be seen in Fig. 13 for sandstone

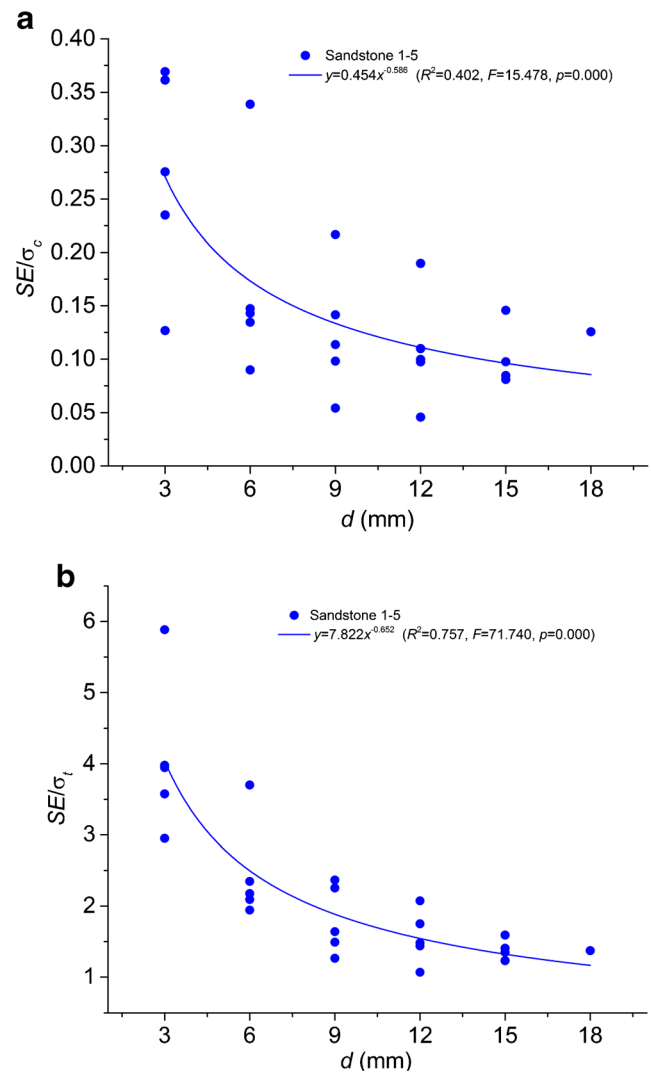


Fig. 14 Relationships between the ratio of specific energy to the compressive/tensile strength and cutting depth in unrelieved cutting mode

1 and sandstone 2, respectively. Regression analyses revealed that specific energy decreases with increasing cutting depth, which could be statistically described by strong exponential correlations for unrelieved and optimum relieved cutting at the confidence level of 95% ($R^2 = 0.907–0.996$, $F = 32.678–489.496$, $p = 0.002–0.029$). It can also be seen that the power value of the regression equation for unrelieved cutting is very close to that for optimum relieved cutting. However, it is important to note that no significant correlations were found between specific energy and line spacing data in this study.

On the other hand, it is a fact that rock strength is generally associated with rock cutting mechanisms. In addition, specific energy is also related to rock strength. In this context, Bilgin et al. (2006) demonstrated that there were strong linear relationships between optimum specific

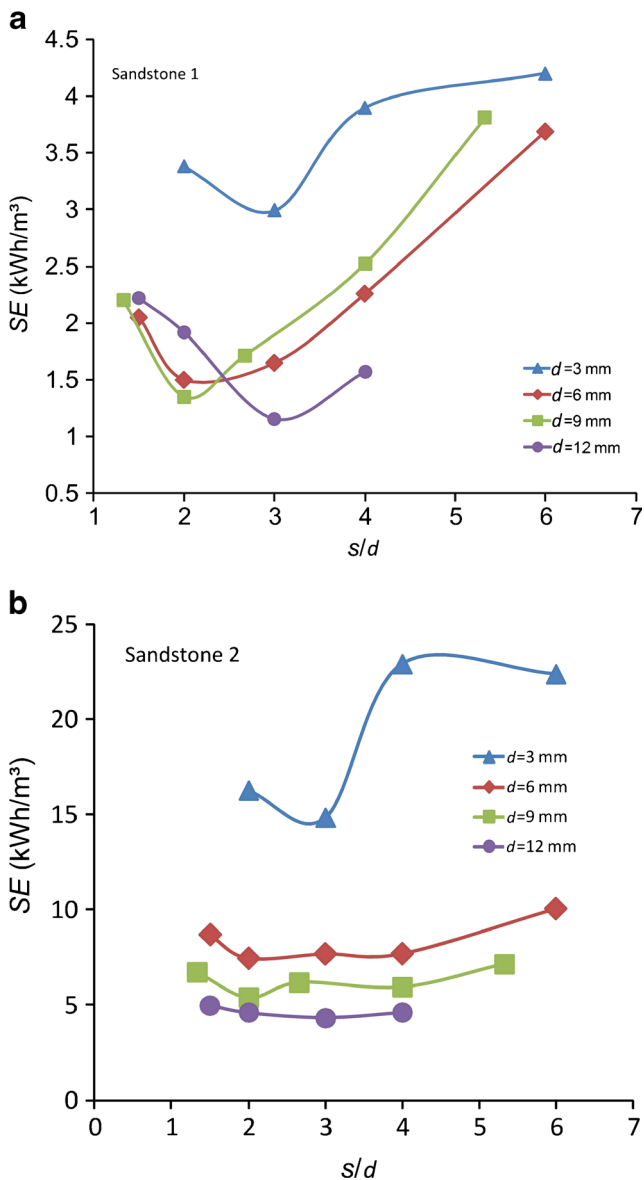


Fig. 15 Relationship between specific energy and the ratio of line spacing to cutting depth for sandstone 1 and sandstone 2

energy and the uniaxial compressive or tensile strength of rock. For this reason, the relationships between the ratio of specific energy to the compressive/tensile strength, which is a dominant cutting parameter, and cutting depth in unrelieved cutting mode were examined. In light of the statistical analyses presented in Fig. 14, there are significant exponential correlations between the specific energy ratios (SE/σ_c , SE/σ_t) and cutting depth ($R^2 = 0.402, 0.757$; $F = 15.478, 71.740$, $p = 0.000$). However, these results showed that tensile strength of the rock is relatively more dominant in rock cutting due to having higher correlation coefficient. The predicted equations of specific energy considering cutting depth and rock strengths in unrelieved cutting modes are given in Table 5.

Analysis of the ratio of line spacing to cutting depth

The ratio of line spacing to cutting depth is the key factor in obtaining the most efficient cutting condition. The optimum ratio of line spacing to cutting depth (s/d) is the ratio at which specific energy is in the minimum range. This parameter is widely used for the design of the conical tools on the excavators (e.g., shearer drums, cutting heads of roadheaders). The optimum s/d ratio for radial picks generally ranges between 1 and 5 as reported by Balci and Bilgin (2007) whereas for conical picks it lies between 2 and 5 according to Bilgin et al. (2006). Although rock cutting experiments indicate that the ratio is associated with the rock characteristics, significant relationships have not been found in Bilgin's tests so far. Copur et al. (2017) emphasized that there is a linear relation between optimum ratio of line spacing to cutting depth per revolution and uniaxial compressive strength of rocks in different cutting patterns.

Figure 15 shows the variation of specific energy versus the s/d ratio for sandstone 1 and sandstone 2. The optimum s/d ratios are in the range between 2 and 3 for the entire cutting depths. Moreover, no effects of cutting depth and line spacing on the ratio were observed in the present study. High specific energy values were obtained at very low s/d ratios due to the over-crushed rock pieces. Moreover, inefficient interactions occur between adjacent grooves at very high s/d ratios, especially for shallow cutting depths and large line spacings.

Conclusions

In this paper, a series of rock cutting tests by using a conical pick were conducted in relieved and unrelieved cutting mode. According to the tool forces recorded from tool-rock interaction, regression analyses were carried out. In this context, it was found that there exist statistically significant and strong correlations between tool forces and cutting depth based on linear and exponential function fitting, especially in unrelieved cutting mode. However, it was seen that the correlations are weak in relieved cutting mode. The ratio of normal to cutting force linearly decreases with increasing cutting depth. The ratio of peak to mean cutting force and the ratio of peak to mean normal force are found to be 2.02 ± 0.26 and 1.50 ± 0.09 , respectively, and they are not affected by the cutting depth and line spacing. There are strong and statistical between the cutting/normal forces in unrelieved cutting mode and cutting depth. Additionally, a reasonable agreement between the ratio of tool forces to the uniaxial compressive (and tensile) strength and cutting depth were obtained.

The results derived from relieved cutting tests clearly showed that line spacing has a significant influence on cutting and normal forces. Compared with unrelieved cutting mode, the tool forces in optimum relieved cutting mode are

approximately 29% lower for cutting forces and 36% lower for normal forces, based on the test data of the present study. The ratio of normal to cutting force decreases exponentially as the line spacing increases. Multiple linear regression analysis established statistically significant and strong relationships between tool forces and cutting depth and line spacing in relieved cutting mode.

The specific energy during the cutting process varied exponentially with the cutting depth in unrelieved and relieved cutting modes. However, no significant relationship exists between specific energy and line spacing. Specific energy reduced by approximately 50% in optimum cutting mode compared to unrelieved cutting mode for sandstone 1 and sandstone 2, respectively.

There are also strong exponential correlations between the ratio of specific energy to the uniaxial compressive/tensile strength and cutting depth in unrelieved cutting mode. On the other hand, specific energy corresponds well with the optimum s/d ratio ranging from 2 to 3 for sandstone 1 and sandstone 2.

As a result, it is emphasized that the models of this study would be more suitable to predict the tool forces and specific energy of the conical picks in soft and medium-hard strength sandstones.

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