Hindawi
Advances in Civil Engineering
Volume 2018, Article ID 6519029, 11 pages
https://doi.org/10.1155/2018/6519029

Research Article

Slant Angle and Its Influence on Rock Cutting Performance

Yong Sun and Xingsheng Li

CSIRO Energy, P.O. Box 883, Kenmore, QLD 4069, Australia

Correspondence should be addressed to Yong Sun; yong.sun@csiro.au

Received 21 February 2018; Accepted 23 April 2018; Published 13 June 2018

Academic Editor: Hang Lin

Rock cutting is an important aspect of the civil engineering, for example, tunnelling. To improve cutting efficiency, it is important to understand the rock failure (fracture) mechanisms and the influences of cutting parameters on rock fracture behaviour. This study identified that the relative position of a pick (rock cutting tool) to the rock surface is critical to the cutting performance of the pick during rock cutting process. However, the pick tilt angle commonly used by the industries is not sufficient to describe this relative position. To address this issue, a new angle named "slant angle" is introduced. The slant angle of a pick is determined by its tilt angle and the inclination angle of the rock surface. The calculation of the slant angle is presented. A series of laboratory rock cutting experiments were conducted to investigate the influence of the slant angle on cutting force and rock fracture pattern, and two new findings were made: (1) the rotational angle of the groove cut by a tilted pick was possibly different from the tilt angle and (2) all forces on a pick increased significantly with the increase of the slant angle. The findings of this study can help improve the rock cutting efficiency.

1. Introduction

Rock cutting plays an important role in the civil engineering which involves construction of tunnels [1] and road development [2]. Rock cutting performance is a major concern to the mining and construction industry [3]. Understanding rock fracture (breaking) behaviour under different cutting conditions is crucial for enhancing the cutting performance of excavating machines. Studies on rock failure mechanism have been used to analyse the rock cutting process [4, 5], although many studies on rock failures aimed at increasing the safety of the rock structure (e.g., see [6]). Two major factors considered in the analysis and evaluation of the cutting performance are forces acting on picks (a type of typically used rock cutting tool in the mining and construction industry) and rock fracture (breakout) conditions. Pick forces were often investigated by rock cutting tests [3, 7]. A pioneer work for developing a theoretical cutting force model was done by Evans [8]. Many factors can affect the forces acting on a pick and rock fracture condition cut by this pick, including rock characteristics such as rock compressive strength, tensile strength, and rock fracture behaviour; pick characteristics such as pick tip material properties and geometry; operational characteristics such as drum advance speed and drum rotational speed; frictional coefficient between pick cutting tip and rock surface; and cutting interaction between this pick and other picks [9–13]. Existing studies have largely focused on the effect of the attack angle, tilt angle, rake angle, and clearance angle on the cutting performance of a drum and the influence of the angle setting sequence on the final values of tilt and attack angles [14].

The rock fracture conditions (mainly breakout angle and direction) and the forces acting on a pick can be affected by the position of a pick relative to the rock surface, not only in the cutting plane but also in the normal plane. Cutting plane in this paper refers to a plane perpendicular to the rotational axis of the drum if the movement of the drum is parallel to this plane. Otherwise, this plane is the one formed by the instantaneous advance direction of the pick due to the drum advance movement and the instantaneous cutting direction of the pick due to the drum rotation. However, even in this case, as the influence of the drum's movement on the pick's cutting direction can generally be ignored, the cutting plane can also be treated as a plane perpendicular to the rotational axis of the drum. Normal plane in this paper refers to a plane containing the rotational axis of the drum and perpendicular to the pick cutting direction. Note that, for a particular pick, the positions of these two planes to its drum can be fixed by making them to contain the tip of the pick, but their positions relative to the rock being cut during a cutting process will still change with the rotation and movement of the drum. Obviously, the cutting planes and normal planes of individual picks on a drum are not all the same. Furthermore, the cutting direction of a pick rotates during a cutting process, resulting in the rotation of its cutting plane and normal plane. The gesture of the pick and its position relative to the rock surface can influence the breakout shape, force direction, and magnitude, as well as the cutting interaction.

Currently, various angles have been used to describe the relative positions of picks to their drum and rock surface cut by them and/or evaluate their individual and collective cutting performance, including the attack angle, clearance angle, rake angle, tilt angle, and wrap angle. Attack and tilt angles are defined in two orthogonal planes to determine the position of the pick axis [12]. Although their definitions are based on the cutting direction, they do not depend on the rock surface. On the other hand, clearance angle and rake angle are defined based on the tip profile and the rock surface in the cutting plane. The wrap angle is used to determine the arrangement of picks on the drum and not associated with the rock surface. Another angle used is the inclination angle, which depends on the wrap angle, but it is defined on the rock surface after cut [10]. The inclination angle is also related to the tilt angle. More details about the inclination angle are given in the next section.

Studies have revealed that the attack angle is a major factor affecting the forces acting on a pick [15]. Both tilt angle and inclination angle will also affect the force acting on a pick [10, 16, 17]. In the course of rock cutting with a drum, the positions of picks relative to the rock surface play an important role in the forces acting on the picks and rock breakout conditions. Forces acting on a pick and the rock breakout angle generated by this pick can be affected by this pick's relative position to the rock surface, not only in its cutting plane but also in its normal plane. Although changing the attack angle of a pick changes its relative position to the rock surface in the cutting plane, changing the tilt angle of a pick mainly changes its relative position in the normal plane. However, the tilt angle cannot solely determine this relative position because it is measured based on the drum axis rather than the rock surface, which does not have a fixed relationship with the drum axis.

To address the issue that there is not any parameter to define the relative position of a pick to the rock surface in the normal plane, a new parameter named "slant angle" is proposed and discussed in this paper. A series of laboratory rock cutting experiments were conducted to investigate the influence of the slant angle and the tilt angle on the rock breaking (fracture) behaviour in terms of rock breaking out angle, groove shape, and direction, as well as the forces on the cutting tools. No similar experiments have been reported in existing literature.

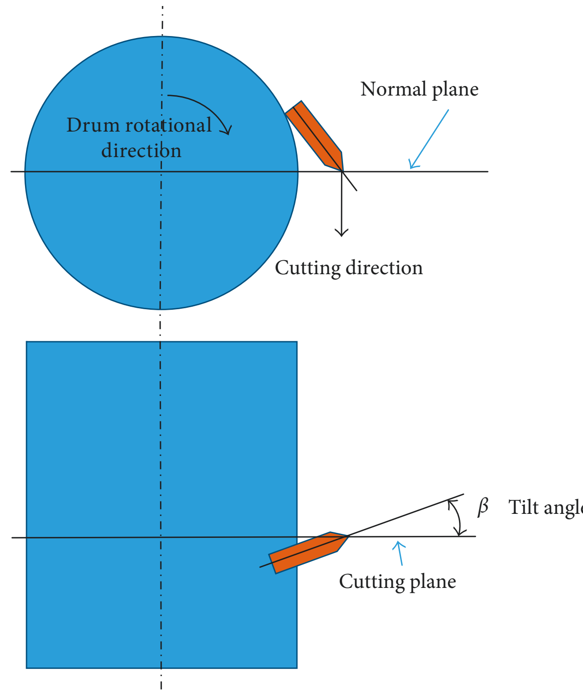


Figure 1: Definition of the tilt angle (β).

2. Concepts of Tilt Angle, Inclination Angle, and Slant Angle

Tilt angle, inclination angle, and slant angle, which are the focus of this study, are all defined in the normal plane.

2.1. Tilt Angle. Tilt angle is one of the key parameters that determine the location and gesture of a pick on a drum. It has been well defined and widely used in the drum design. According to Sun and Li [9], the tilt angle of a pick is typically defined as the angle between its cutting plane and the projection of the axis of the pick on its normal plane, as shown in Figure 1.

As one of the key pick arrangement design parameters, the tilt angle plays a critical role in the cutting performance of picks and drum. Research has shown that the tilt angle has a noticeable impact on the force acting on a cutterhead (drum) [16]. The experimental studies reported by Hekimouglu recently [17] revealed that the tilt angle of picks on road-headers has an optimal value, which was roughly the half of rock breakout angle for corner cutting picks.

2.2. Inclination Angle. While the tilt angle is defined relatively to the drum, the inclination angle is defined based on the rock surface that has been cut by the drum. According to Hekimoglu and Ozdemir [10], the inclination angle is defined as the angle of the slope of a cutting perimeter which is an envelope formed by the tips of picks in the same start on the same normal plane [10] (refer to Figure 2). Figure 2 shows a simulated rock breakout pattern for a simulated drum design. According to Hekimoglu and Ozdemir [10], the perimeter is a sloping straight line if these picks are

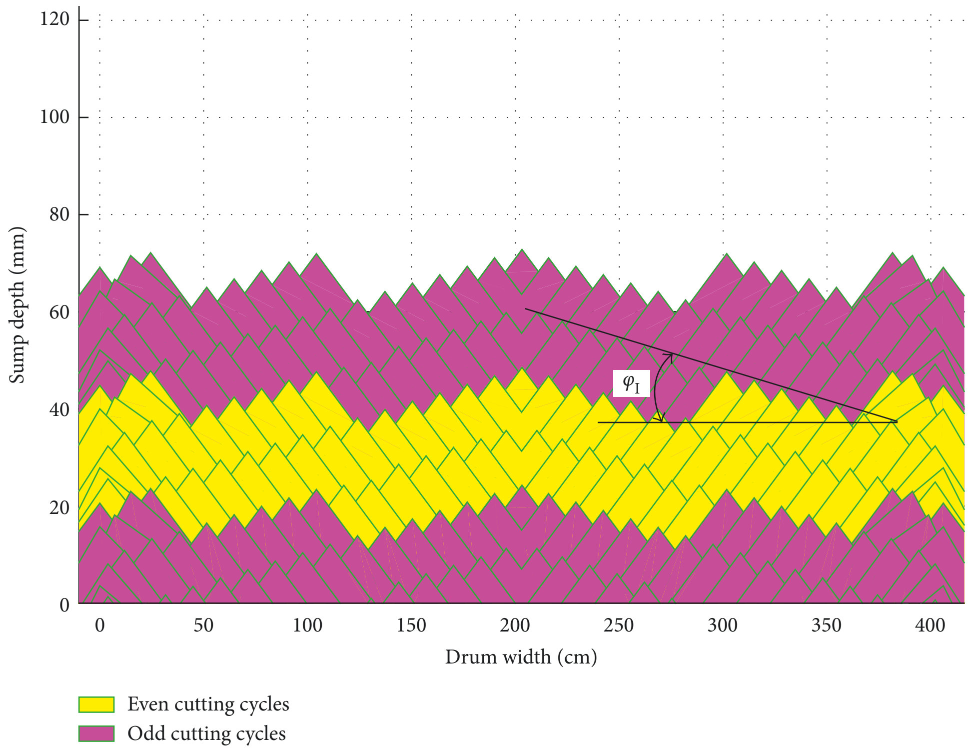


Figure 2: The definition of the inclination angle (advance speed = 1 m/min).

evenly distributed and their tilt angles are zero, as shown in Figure 2. The inclination angle is actually the angle between a cutting perimeter and the rotational axis of the drum on a normal plane. Obviously, the inclination angle could change with the rotation of the drum. In the following analysis, the inclination angle on the normal plane which is parallel to the drum advance direction (i.e., the breakout plane as defined in [12]) is considered because rock breakout pattern is defined in this plane [12]. Furthermore, the following formula to calculate an inclination angle given by Hekimoglu and Ozdemir in [10] is also based on this plane:

$$\tan\varphi_I = \frac{\theta v_n}{2\pi m S}, \quad (1)$$

where φ_I is the inclination angle, θ is the angular distance between two immediate neighbouring picks, S is the line spacing between these two picks, v_n is the advance per revolution of the drum, and m is the number of starts.

The maximum depth of cut (DOC) $D_{\max}$ is given by [11]

$$D_{\max} = \frac{v_n}{m}. \quad (2)$$

Equation (1) can be rewritten as

$$\tan\varphi_I = \frac{D_{\max}\theta}{2\pi S}. \quad (3)$$

Equation (1) indicates that the inclination angle increases with the increase in drum advance distance per revolution. It should be noted that (1) is used only for a special case: picks are evenly spaced without being tilted. The angular differences among picks are equal, and the calculated inclination angle has the maximum value. It is not suitable for calculating the inclination angle in other cases, for example, if picks are tilted. However, the analysis of the inclination angle in a general case will not be discussed further in this paper due to the scope of the paper.

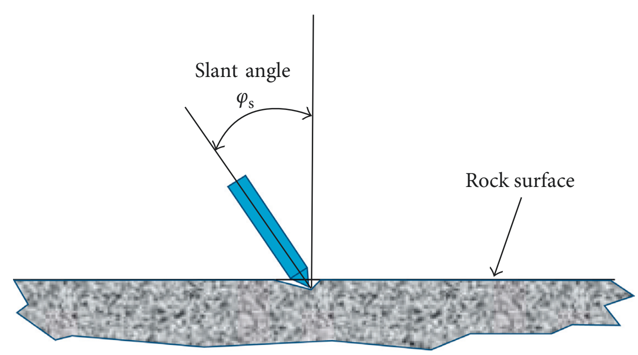


Figure 3: The definition of the slant angle.

Some investigation into the effect of the inclination angle on the performance of picks has been carried out although the influence of the tilt angle has not been considered; that is, existing studies on the effect of the inclination angle was conducted under the condition that the tilt angle was zero.

2.3. Slant Angle. The slant angle of a pick is defined as the angle between the axis of the pick and the normal direction of the rock surface being cut by the pick (Figure 3).

During a mining process with a cutting drum, the rock surface is normally curved. In this case, the slant angle is defined as the angle between the axis of the pick and the line

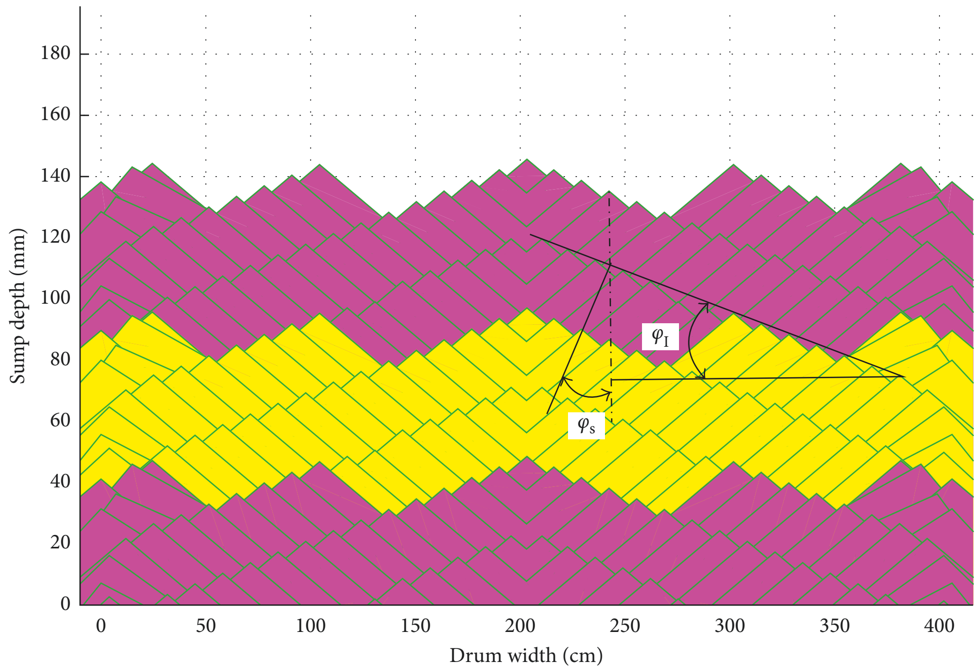


FIGURE 4: Slant angle of a pick in a cutting process (advance speed = 2 m/min).

perpendicular to the cutting perimeter, measured in its normal plane (Figure 4). Figure 4 shows another simulated rock breakout pattern for the same simulated drum design as used for Figure 2, but with a different drum advance distance per revolution. As mentioned in the previous section, the inclination angle increases with an increase in drum advance distance per revolution, which can also be observed by comparing Figures 2 and 4.

From Figure 4, it can be seen that the slant angle of a pick is equal to the inclination angle when its tilt angle is zero. In general, the slant angle of a pick is

$$\varphi_s = \beta - \varphi_I. \tag{4}$$

When using (4), one should ensure that the definitions of the directions of the inclination angle, tilt angle, and slant angle are the same. For example, if a positive inclination angle goes anticlockwise, both tilt and slant angles should also be measured anticlockwise. As shown in Figure 4, when φ_I is negative, φ_s is positive and β is zero. Obviously, when φ_I is zero, that is, rock surface being cut is parallel to the rotational axis of the drum, the slant angle of a pick is equal to its tilt angle. However, this is very rare in reality. The reason is that the angular distance between two immediate neighbouring picks θ in a real drum is normally not zero. According to (1), φ_I is also generally nonzero (also refer to Figures 2 and 4). As a result, one can find that the slant angle of a pick is generally not equal to its tilt angle in reality according to (4). This result is further illustrated in Figure 5.

The above finding is important for optimising drum design and operation because in current practice, force on a pick is often obtained from some linear rock cutting experiments. In this type of cutting experiments, when the tilt angle of a pick is set to zero, its slant angle is also normally zero. As a consequence, using the force data collected in these experiments to drum design without consideration of the influence of the slant angle can cause significant bias in the estimation of actual forces on picks and the drum in practice. The reason is that the slant angle has significant impact on forces and breakout pattern.

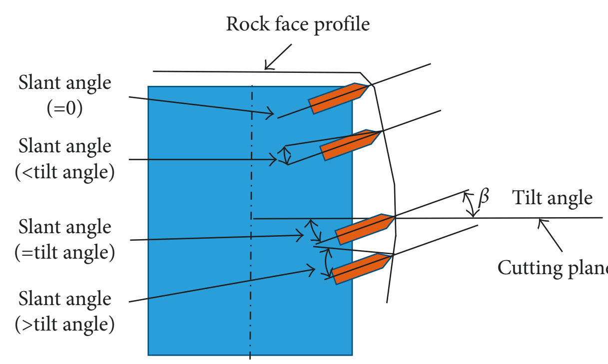


FIGURE 5: An example of the same tilt angle but with different slant angles.

3. Impact of the Slant Angle

A series of rock cutting experiments have been conducted in CSIRO Rock Cutting Laboratory to investigate the rock breaking (fracture) behaviour in terms of rock breaking out angle, groove shape, and direction, as well as the forces on the cutting tools.

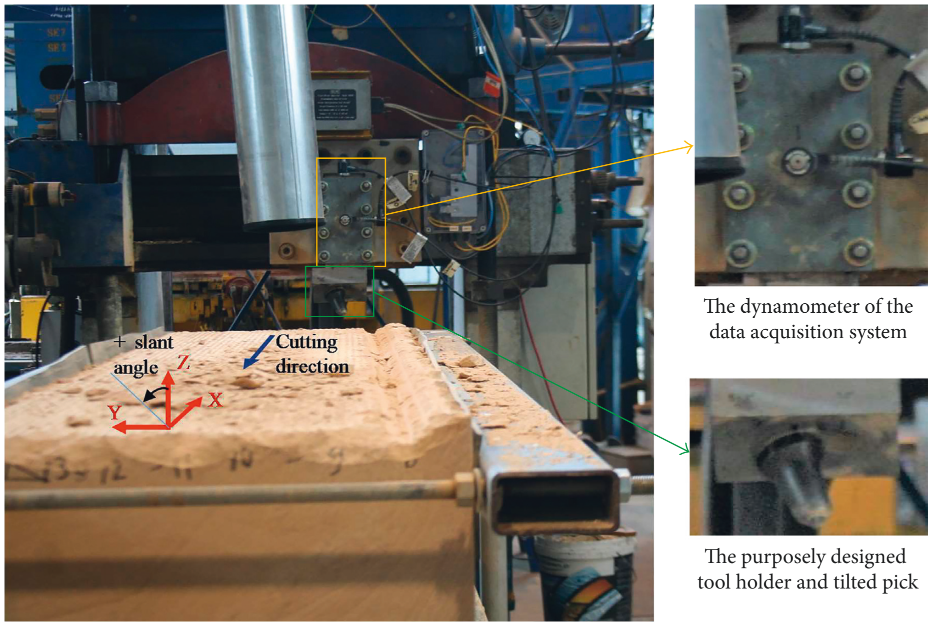


FIGURE 6: Test rig.

3.1. Experimental Rig and Method. Figure 6 shows the experimental rig used in the tests. It is basically a planer, which consists of a special tool holder, a pick, a data acquisition system, and a rock block. A series of special cutting tool holders were purposely designed and manufactured to generate different combinations of tilt angles and attack angles. During each test, the rock block travelled against the pick in a controlled speed, and the dynamometer of the data acquisition system simultaneously measured three forces acting on the pick, namely, force in the X direction, force in the Y direction, and force in the Z direction. The measured forces were recorded by a LabVIEW system in a PC. The X, Y, and Z directions are defined based on the coordinate system, as shown in Figure 6: the X axis is horizontal and its positive direction is opposite to the cutting direction which is toward the front; the Y axis is horizontal and perpendicular to the cutting direction with its positive direction pointing to the left; the Z axis is perpendicular to the XY plane with its positive direction pointing upward. Further information about this planer and its data acquisition system can be found in [16].

Test rock was a type of sandstone collected from Helidon, Australia, with UCS (uniaxial compressive strength) of 37–40 MPa and BTS (Brazilian tensile strength) of 4.6–4.8 MPa.

The slant angle was measured inside the YZ plane, starting from the Z-axis. Its positive direction is counterclockwise (Figure 6).

In the experiment, the rock surface was trimmed to be a horizontal plane; that is, it was parallel to the XY plane. A linear rock cutting with a single pick was adopted in the cutting tests. In each cut, the track of the pick tip was parallel to the X-axis. In this case, the inclination angle of the rock surface was zero, and the slant angle was equal to the tilt angle of the pick.

As the major purpose of this paper is to define the slant angle and test the hypothesis that the slant angle could significantly affect rock cutting performance, only the test results under the conditions shown in Table 1 is considered in the paper. In Table 1, only the slant angle is a variable.

TABLE 1: The test parameters.

Parameter	Value
Slant angle (degree)	0, 7.5, 15, 22.5, 30
Attack angle (degree)	60
Cutting speed (m/s)	2.5
Depth of cut (mm)	12

FIGURE 7: Grooves cut by a pick at different slant angles.

At least three cuts were conducted for each slant angle. Note that, in the tests, the slant angles were actually set to −7.5 degrees and −15 degrees, rather than 7.5 degrees and 15 degrees. In order to obtain the forces for a positive slant angle from the test results obtained based on its corresponding negative slant angle, the following assumption is made:

> If only the direction of a slant angle is reversed, the forces in X and Z directions will remain the same, and the absolute value (magnitude) of the force in the Y direction will also be the same. Only the direction of the force in the Y direction will be reversed.

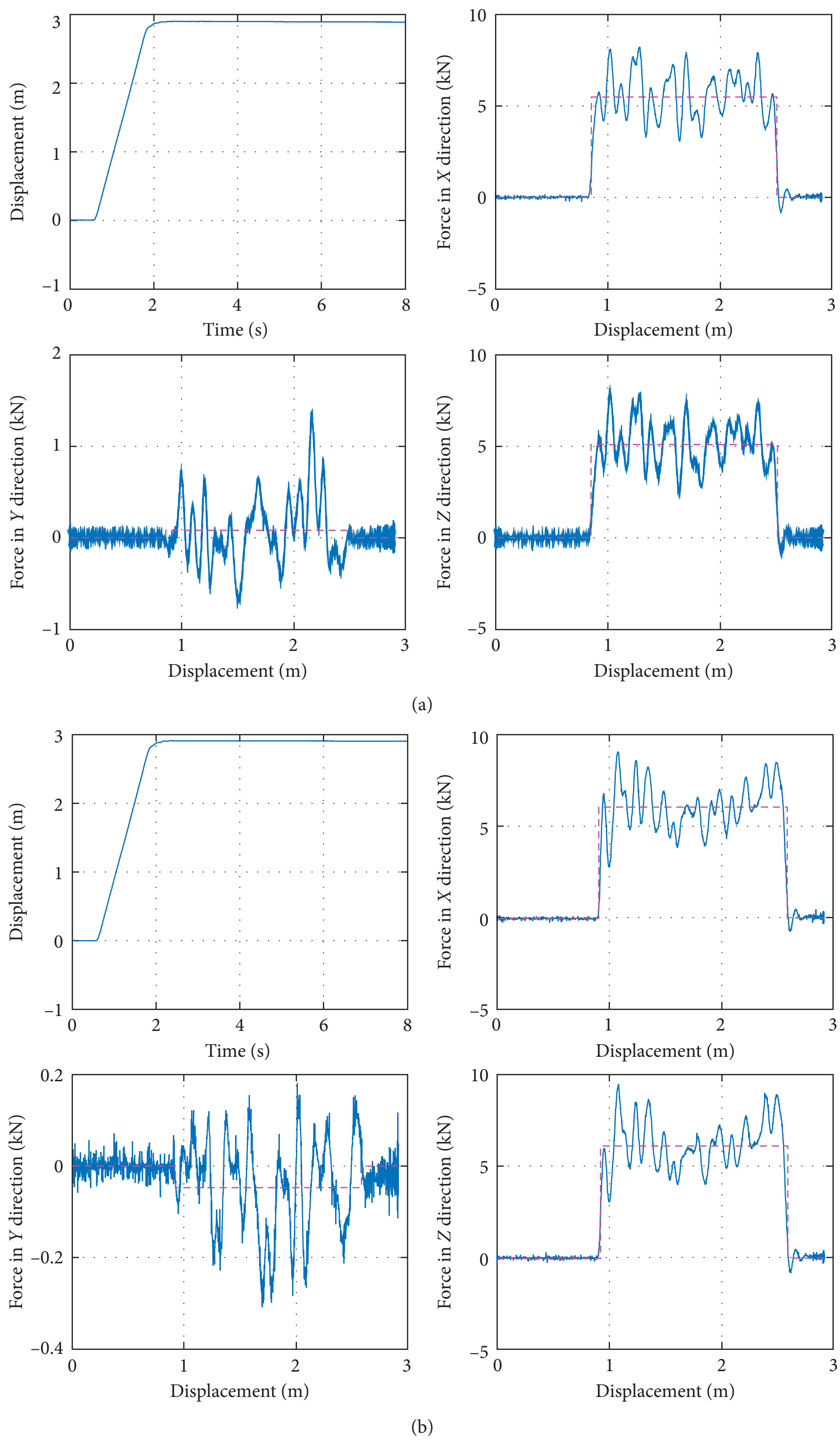
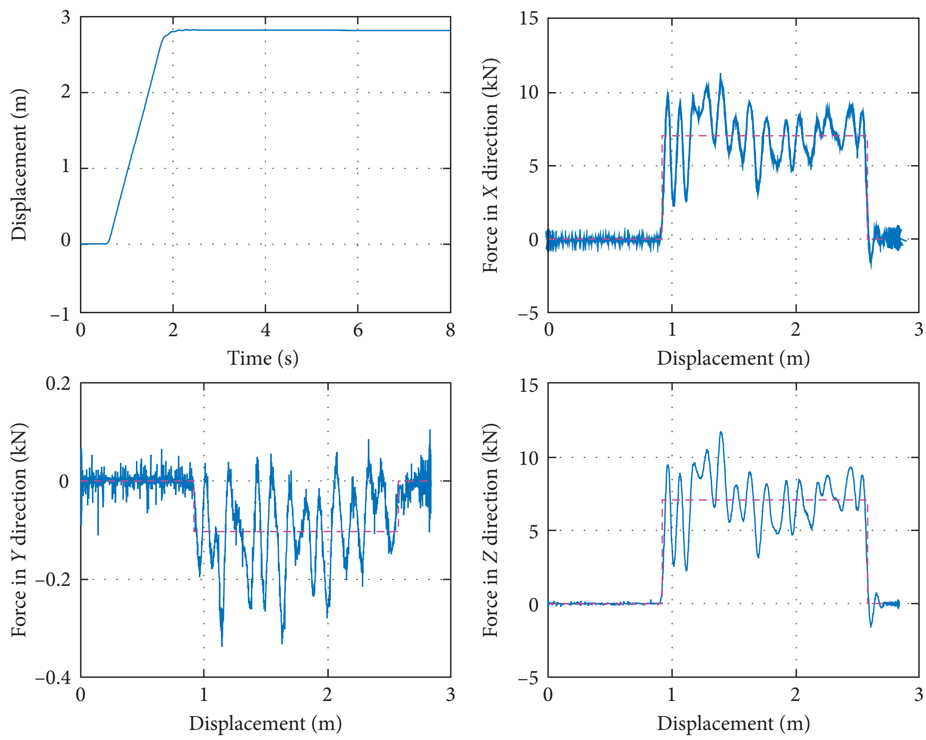
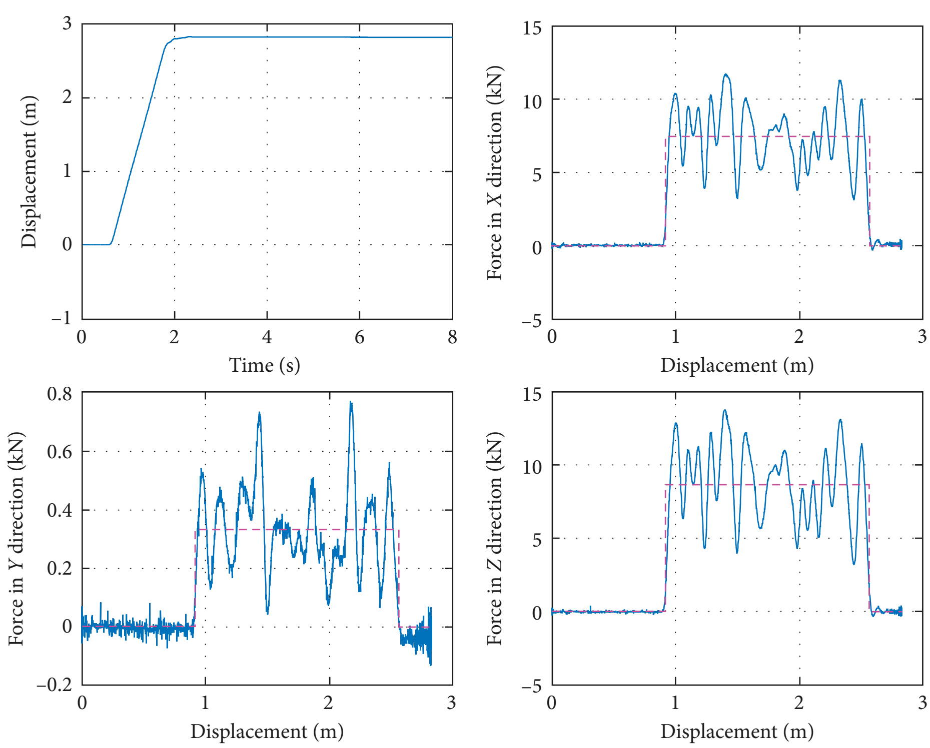


FIGURE 8: Continued.



(c)



(d)

FIGURE 8: Continued.

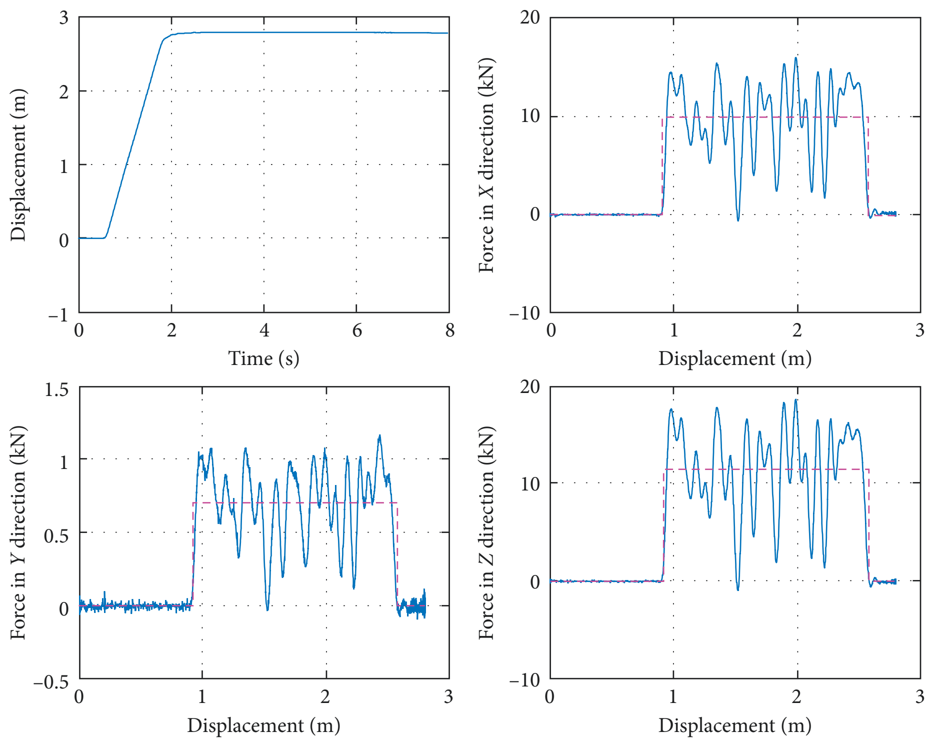


Figure 8: Pick forces during the cutting tests with different slant angles: (a) 0 degrees, (b) −7.5 degrees, (c) −15 degrees, (d) 22.5 degrees, and (e) 30 degrees.

This assumption is reasonable because the rock block was regarded as homogeneous.

3.2. Test Results and Discussion. Figure 7 shows an example of grooves cut by a pick at different slant angles (the slant angle for cutting Groove 16 was different from that for cutting Grooves 17, 18, and 19). In this figure, Grooves 17, 18, and 19 were cut by the pick set to an attack angle of 60 degrees, a slant angle of 15 degrees, and the DOC of 12 mm. It can be seen that the grooves were skewed; that is, the bisector of any groove cross-sectional area is not perpendicular to the rock surface in the YZ plane. More importantly, the rock cutting experiments revealed that although the grooves were skewed when the pick was tilted, it is likely that the rotational angle of the bisector of the groove cross-sectional area was not the same as the tilt angle. Therefore, assuming that the rotational angle of the bisector of the groove cross-sectional area is equal to the tilt angle could result in unacceptable errors. However, the influences of the slant angle on rock breaking shapes are not further studied here. The study on this type of influences will be reported in a separate paper. In the following analysis, only the impact of the slant angle on the forces generated during a cutting process is investigated in more detail.

The cutting tests revealed that the slant angle affected not only the rock breakout conditions but also the forces on the pick. Some examples of the planer displacement and the pick force data collected from the tests are shown in Figure 8. In Figure 8, blue continuous lines are the recorded forces and the pink broken lines are the mean values of the corresponding forces.

As shown in Table 1, the rock cutting tests were carried out with five different slant angles, and for each slant angle, the tests were repeated for three times to reduce the random errors in the test data. In total, 15 cutting experiments were implemented. Table 2 shows the test results.

The average values are used to identify the influences of the slant angle on individual forces. Figure 9 illustrates the average mean forces in X, Y, and Z directions versus the slant angle. To make the figures clearer, the original mean force data are not plotted in these figures. Table 3 summarises the R-squared values when different models are applied to fit the data in Figure 9.

Figure 9 shows that all the mean forces increased with the increase of the slant angle, but none of them changed with the variation of the slant angle in a linear way. From Figure 9 and Table 3, it can be found that the quadratic models fit the test results much better than the linear models. Within the tested range of the slant angles, the relationship between the forces and the slant angle can be modelled as follows:

$$\begin{aligned} F_x &= 0.0035\varphi_s^2 + 0.0216\varphi_s + 5.905, \\ F_y &= 0.0012\varphi_s^2 - 0.0145\varphi_s + 0.0805, \\ F_z &= 0.0048\varphi_s^2 + 0.0423\varphi_s + 5.6818, \end{aligned} \tag{5}$$

where, F_x, F_y, and F_z are the mean forces in X, Y, and Z directions, respectively.

Table 2: The test results.

Slant angle (degree)	Mean force in the X direction (kN)	Average (kN)	Mean force in the Y direction (kN)	Average (kN)	Mean force in the Z direction (kN)	Average (kN)
0	−0.071	0.064	6.327	5.628	6.550	5.914
0	0.195		5.421		5.643	
0	0.068		5.137		5.547	
7.5	0.046	0.084	6.229	6.445	6.082	6.260
7.5	0.008		6.465		6.281	
7.5	0.199		6.640		6.418	
15	0.103	0.090	7.054	7.180	7.057	6.993
15	0.105		7.212		7.126	
15	0.062		7.273		6.796	
22.5	0.332	0.357	8.770	9.157	7.520	8.235
22.5	0.399		9.691		9.055	
22.5	0.341		9.011		8.129	
30	0.704	0.710	11.478	11.234	10.018	9.722
30	0.758		11.399		9.900	
30	0.668		10.825		9.249	

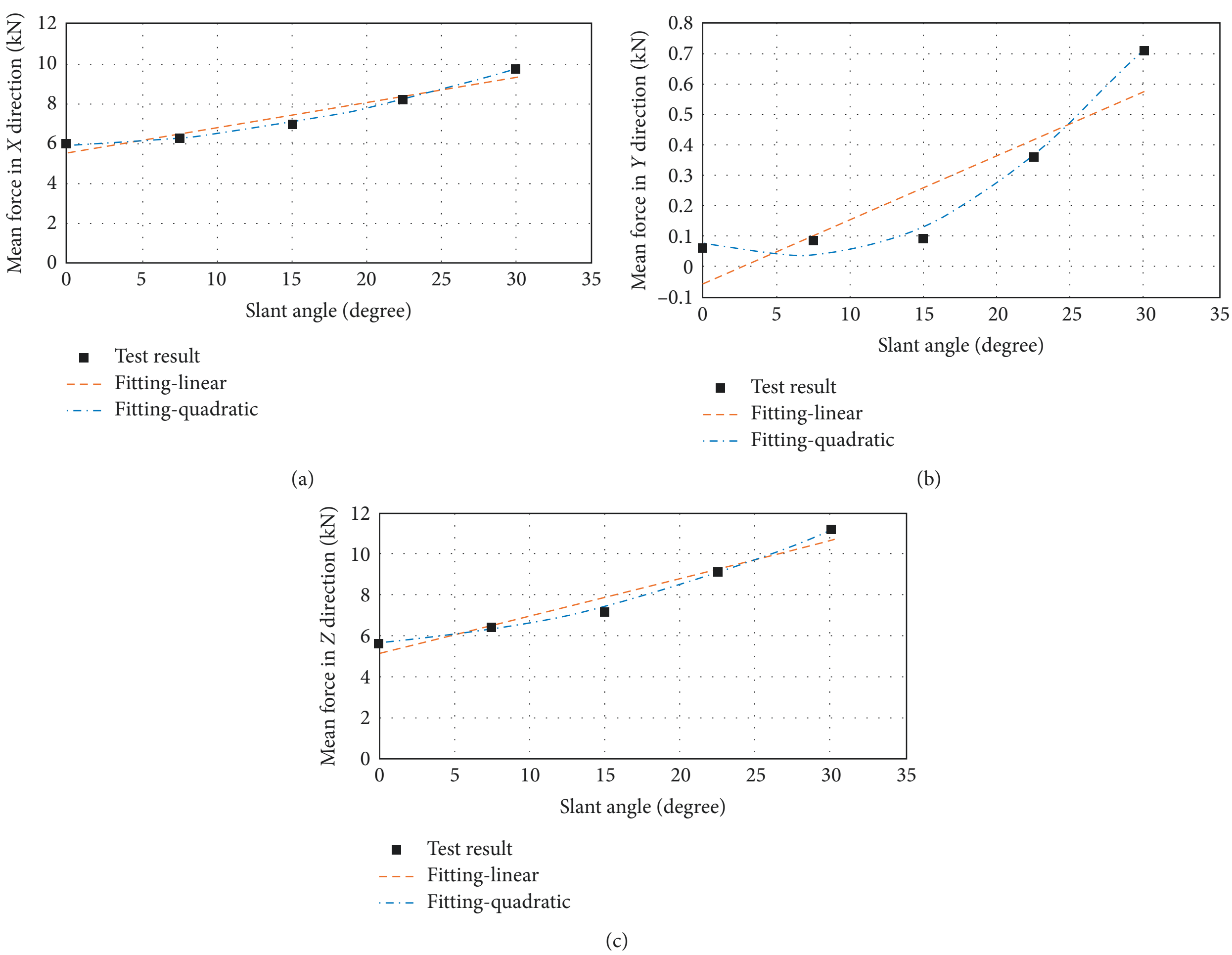


Figure 9: Mean forces in the (a) X, (b) Y, and (c) Z directions versus slant angle.

It is noted that, in pick force analysis, the forces acting on a pick during a cutting process are normally divided into cutting, normal, and lateral forces [2, 13]. The cutting force is the force opposite to the cutting direction; the normal force is the force perpendicular to the cutting direction and inside the plane formed by the tangent line of the instantaneous cutting tract and the pick axis; and the lateral force is the force perpendicular to the plane formed by the cutting and normal forces [2]. Therefore, the cutting force on the pick is always identical to the force in the

Table 3: R-squared values for the fitted models in Figure 9.

Force	Linear model	Quadratic model
Mean force in the X direction	0.9426	0.9996
Mean force in the Y direction	0.7894	0.9874
Mean force in the Z direction	0.9462	0.9956

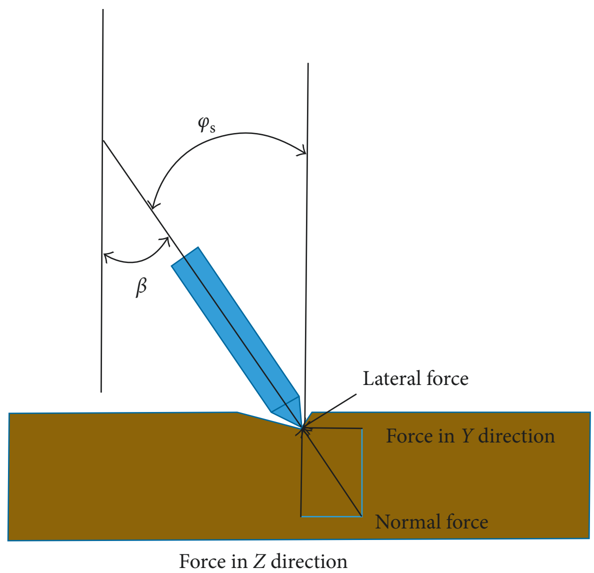


Figure 10: Relationship between forces in Y and Z directions and lateral and normal forces in the tests.

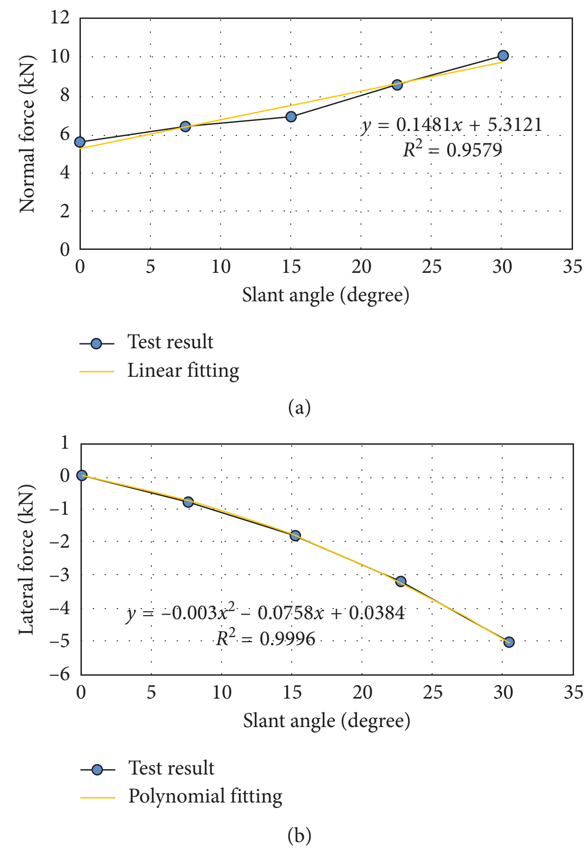


Figure 11: Mean lateral force (a) and normal force (b) versus slant angle.

X direction. When the slant angle is zero, the force in the Y direction is the lateral force on the pick, and the force in the Z direction is the normal force on the pick. However, when the pick is tilted in a cutting process, the force in the Y direction no longer represents the lateral force, and the force in the Z direction no longer represents the normal force (see Figure 10).

In general, the cutting, lateral, and normal forces on a pick can be calculated from the measured forces in X, Y and Z directions using the following equations:

$$\begin{aligned} F_c &= F_x, \\ F_l &= F_y \cos\varphi_s - F_z \sin\varphi_s, \\ F_n &= F_y \sin\varphi_s + F_z \cos\varphi_s, \end{aligned} \tag{6}$$

where, F_c, F_l, and F_n are the cutting, lateral, and normal forces on the pick, respectively.

Figure 11 depicts the changes of mean lateral force and mean normal force with the change of the slant angle.

From Figure 9(a), it can be seen that the cutting force acting on the pick increased significantly with the increase of the slant angle because the cutting force was the same as the force in the X direction. Figure 9(a) indicates that with the increase of the slant angle from 0 degrees to 30 degrees, the cutting force increased from 5.9 kN to 9.7 kN. From Figure 11, it can be found that the magnitude of both the lateral force and the normal force on the pick also increased significantly with the increase of the slant angle. When the slant angle increased from 0 degrees to 30 degrees, the lateral force increased from 0 kN to 5 kN, while the normal force increased from 5.6 kN to 10 kN. These results indicate that slant angle had a significant influence on the force acting on a pick in a rock cutting process.

4. Conclusions

A new angle named "slant angle" is introduced to determine the relative position of a pick to the rock surface to be cut in the normal plane of the pick. It is the angle between the axis of the pick and the normal direction of the rock surface; the slant angle depends on the tilt angle and inclination angle. It changes with the variation of drum advance per revolution. It is a better variable than the tilt angle for describing the relative position of a pick to the rock surface; laboratory rock cutting experiments were conducted to investigate the influence of the slant and tilt angles on cutting force and rock breakage (fracture) behaviour. The following major findings were obtained from the experiments:

(i) The rotational angle of the bisector of the groove cross-sectional area was likely to be different from the tilt or slant angle. Assuming that this rotational angle equals the tilt angle could result in unacceptable errors.

(ii) The magnitudes of the cutting, lateral, and normal forces on a pick all increased significantly with the increase of the slant angle. Assuming that the magnitudes of these forces are independent from the tilt or slant angle is unrealistic.

These findings are important for the improvement of the rock cutting efficiency and rock cutting tool life.

Only the slant angle on the normal plane parallel to the drum advance direction has been considered in this paper. The slant angle in more general situations will be studied in due course.

Data Availability

The data used in this manuscript were generated during the study and can be found at the CSIRO Rock Cutting Laboratory, QCAT, Australia.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

The authors are grateful for the technical support of Craig Harbers of CSIRO Energy in the rock cutting experiments and the financial support of CSIRO Strategic Program.

References

[1] T. Zhao, W. Liu, and Z. Ye, "Effective of water inrush from tunnel excavation face on the deformation and mechanical performance on shield tunnel segment joints," *Advances in Civil Engineering*, vol. 2017, Article ID 5913640, 18 pages, 2017.

[2] Y. Sun and X. S. Li, "A probabilistic approach for assessing failure risk of cutting tools in underground excavation," *Tunneling and Underground Space Technology*, vol. 70, pp. 299–308, 2017.

[3] N. Bilgin, M. A. Demircin, H. Copur, C. Balci, H. Tuncdemir, and N. Akcin, "Dominant rock properties affecting the performance of conical picks and the comparison of some experimental and theoretical results," *International Journal of Rock Mechanics and Mining Sciences*, vol. 43, no. 1, pp. 139–156, 2006.

[4] H. Guo, "Rock cutting studies using fracture mechanics principle," Ph.D. Thesis, University of Wollongong, Wollongong, NSW, Australia, 1990.

[5] Y. Nishimatsu, "The mechanics of rock cutting," *International Journal of Rock Mechanics and Mining Sciences*, vol. 9, no. 2, pp. 261–270, 1972.

[6] R. H. Cao, P. Cao, and H. Lin, "A kind of control technology for squeezing failure in deep roadways: a case study," *Geomatics, Natural Hazards and Risk*, vol. 8, no. 2, pp. 1715–1729, 2017.

[7] H. Copur, N. Bilgin, H. Tuncdemir, and C. Balci, "A set of indices based indentation tests for assessment of rock cutting performance and rock properties," *Journal of the South African Institute of Mining and Metallurgy*, vol. 103, pp. 589–599, 2003.

[8] I. Evans, "A theory of the cutting force for point-attack picks," *International Journal of Mining Engineering*, vol. 2, no. 1, pp. 63–71, 1984.

[9] Y. Sun and X. S. Li, "Determination of attack angle and tilt angle of a cutting pick," *Advanced Materials Research*, vol. 705, pp. 415–418, 2013.

[10] O. Z. Hekimoglu and L. Ozdemir, "Effect of angle of wrap on cutting performance of drum shearers and continuous miners," *Institution of Mining and Metallurgy Transaction, Section A: Mining Technology*, vol. 113, no. 2, pp. A118–A122, 2004.

[11] Y. Sun and X. S. Li, "Ineffective rock breaking and its impacts on pick failures," in *Proceedings of the 31st International Symposium on Automation and Robotics in Construction and Mining*, pp. 754–760, University of Technology, Sydney, Australia, July 2014.

[12] Y. Sun, X. S. Li, and W. Shao, "Influence of cutting parameters and interactions on the depth of cut in continuous mining operation," *Advanced Materials Research*, vol. 538–541, pp. 1422–1428, 2012.

[13] K. G. Hurt, C. J. Morris, and K. M. MacAndrew, "The design and operation of boom tunneling machine cutting heads," in *Proceedings of the Rock Breaking and Mechanical Excavation: 14th Canadian Rock Mechanics Symposium*, P. Baumgartner, Ed., pp. 54–58, Vancouver, BC, Canada, May 1982.

[14] Y. Sun and X. S. Li, "Impact of pick skew and tilt on cutting geometry," *Applied Mechanics and Materials*, vol. 851, pp. 216–220, 2016.

[15] W. Shao, X. S. Li, Y. Sun, and H. Huang, "Parametric study of rock cutting with SMART*CUT picks," *Tunnelling and Underground Space Technology*, vol. 61, pp. 134–144, 2017.

[16] O. Z. Hekimoglu and R. J. Fowell, "Practical aspects of rear pick arrangement on boom-type tunnelling machine cutting heads," *Mining Science and Technology*, vol. 10, no. 2, pp. 221–230, 1990.

[17] O. Z. Hekimoglu, "Investigations into tilt angles and order of cutting sequences for cutting head design of roadheaders," *Tunnelling and Underground Space Technology*, vol. 76, pp. 160–171, 2018.


Journal of Engineering
The Scientific World Journal
International Journal of Rotating Machinery
Journal of Sensors
Advances in Multimedia
Advances in Civil Engineering
Journal of Control Science and Engineering
Journal of Robotics
Hindawi
Submit your manuscripts at
www.hindawi.com
Journal of Electrical and Computer Engineering
Advances in OptoElectronics
VLSI Design
International Journal of Navigation and Observation
Modelling & Simulation in Engineering
International Journal of Aerospace Engineering
International Journal of Chemical Engineering
International Journal of Antennas and Propagation
Active and Passive Electronic Components
Shock and Vibration
Advances in Acoustics and Vibration