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A comprehensive roof bolter drilling control algorithm for enhancing energy efficiency and reducing respirable dust

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ABSTRACT: The drilling involved in the roof bolting operation in coal mining could not only generate excessive amounts of respirable coal and quartz dusts but also could encounter work interruption. Based on laboratory drilling tests, a comprehensive drilling control algorithm was developed to increase the drilling energy efficiency and to reduce the generation of respirable dust. The drilling rate deducted from test results is introduced in this study while considering the bit wear condition. The ratio between specific energy and rock uniaxial compressive strength is used as the index to determine the rational drilling control in this algorithm. In this paper, a drilling control algorithm for achieving a rational drilling bite depth is demonstrated. By adapting this drilling control algorithm, the drilling efficiency and bit condition can be monitored in real time, so the system can maintain a relatively high energy efficiency with less respirable dust generation and avoid drilling failure.

1 INTRODUCTION

Roof bolting has been the primary means to improve mine safety by preventing different types of roof falls in underground mines in recent decades. However, roof bolting operators exhibit a continued risk for overexposure to airborne levels of respirable coal and crystalline silica dust (size < 10 μm) from the roof drilling operation (Goodman and Organiscak, 2002). Inhaling these dusts can cause coal workers' pneumoconiosis (CWP) and another job-related lung disease, silicosis; both illnesses are disabling, irreversible, and even fatal, (Liu and Liu, 2020).

Currently, a dry vacuum dust collection system and canopy air curtain (Fletcher, 2013; Reed et al., 2019) have been developed to address the roof bolter operator dust exposure issue. But New cases of black lung and silicosis continue to be reported, even sometimes in young miners, because of the elevated respirable coal dust and respirable crystalline silica exposure levels that can occur dur-ing roof drilling.

Based on the findings from previous research, the amount of generated respirable dust is not only rock formation specific but also drilling parameter specific (Jiang et al., 2018a, b). In this study, a comprehensive drilling control algorithm is developed to enhance the drilling energy efficiency and to reduce the generation of respirable dust. By adapting this drilling control algorithm, the drilling efficiency and bit condition can be monitored in real time, so the system can maintain a relatively high energy efficiency while generating less respirable dust as well as reducing bit clogging and avoiding steel buckling failure.

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2 LABORATORY DRILLING EXPERIMENTS

In order to investigate the relationship between respirable dust generation with drilling parameters, including bit condition and rock type, 52 laboratory drilling tests have been conducted on a drilling test platform. This platform is equipped with a drilling control system, a data acquisition system, and a dust collection system. The drilling control system consists of a drill control unit and a drill head. This system attains the pre-set penetration and rotational rates for each drill hole event, which then automatically operates the drill to try to reach and maintain the pre-set parameters. The sensors of the data acquisition system attain the drill bit position, drilling penetration and rotational rate, drilling torque (T), and thrust (W), etc. The dust collection system includes a pre-cleaner cyclone and a dust collection box, which enables the collection of dust samples after each drilling test.

Since bolt-hole drilling in hard rock can produce more fine dust, faster bit wear, and unsafe working conditions than drilling in soft rocks, the drilling tests were performed on two rock blocks with different strengths. The uniaxial compressive strengths of the concrete and nonhomogeneous sandstone blocks are 55.16 and 132.13 MPa, respectively, to represent the medium and high strength rocks in the coal mine roof. The Kennametal® tungsten carbide spade bits commonly used for roof bolting operations in underground coal mines of 2.540 cm (1 inch) and 3.493 cm (1-3/8 inch) in diameter were used in the tests. For most of the tests, a new bit was used during drilling for each of the drill holes. For evaluating the effects of bit wear, a number of worn bits collected from the past drilling tests with varying weight losses were used in the tests, and a new bit was continuously used during drilling the holes until it was well worn.

The experiments were designed to drill the holes with a full range of bite depth according to the rock strengths, bit design, drilling safety, and available drilling power. The drilling system can be set at different penetration and rotation rates to achieve the pre-set bite depth for each test. The maximum allowable bite depth is limited by the available drilling thrust and the maximum allowable thrust on the drill steel to avoid it from bending failure (Luo et al., 2013). In this study, drilling bite depth (b), defined as bit penetration depth per revolution, was introduced to describe the roof bolter drilling process. Drilling bite depth can be calculated from penetration (v) and rotational rate (w), expressed by Equation 1.

$$b = \frac{60v}{w} \tag{1}$$

The detailed drilling parameters and conditions for the four groups are listed in Table 1. The first two groups were drilled with the larger bits (3.493 cm), while the smaller bits (2.540 cm) were used for groups 3 and 4. Test groups 1, 2, and 4 were conducted on concrete block, and group 3 was drilled on sandstone. It should be noted that for tests in group 1, a new bit was used for the first test and it was used continuously until it was substantially worn out after test 9. For tests 10, 11, and 12, three worn bits from past tests were used with a weight loss of 1.62g (1%), 25.31g (12%), and 27.54g (13%), respectively.

Prior to creating each drill hole, the dust collection system was cleaned. After each drill test, dust samples from the stages of the dust collection system were collected and their weights were measured and recorded. A specified quantity of dust representing each bulk sample is taken by the coning and quartering method (Zhu, 2014) so that the size distribution for the entire sample could be accurately determined. The main drilling test parameters and dust generation results are also listed in Table 1. The implementation rate in the table indicates the ratio of the achieved bite depth to the pre-set bite depth. It should be noted that an implementation ratio significantly smaller than 100% reflects a poor bit condition or the limitation of available drilling power.

Table 1. Drilling parameters and feedback results for each drill hole.

			Pre-set	Achieved			Implem. Rate	Total inhalable dust	Total respirable dust	Specific energy
			b	*v*	*w*	*b*				
Group	Test #	Condition	*cm/rev*	*cm/s*	*rev/ min*	*cm/ rev*	*%*	*g*	*g*	*MPa*
1	1	Concrete; 1-3/8"	0.152	0.83	299	0.167	109.6	1803.3	757.3	248.0
	2		0.102	0.85	434	0.117	116.0	1953.0	757.8	414.7
	3		0.091	0.83	454	0.110	120.3	2136.1	837.7	443.0
	4		0.122	1.06	507	0.126	102.5	2207.4	925.8	420.6
	5		0.152	1.05	522	0.121	79.2	1995.0	803.6	467.4
	6		0.396	2.05	517	0.238	60.1	2293.0	910.4	249.2
	7		0.427	1.54	500	0.185	43.3	2297.3	856.2	300.8
	8		0.457	1.60	499	0.193	42.1	2032.6	804.2	276.1
	9		0.406	1.00	301	0.200	49.1	2430.9	1083.3	202.4
	10		0.213	1.71	497	0.206	96.6	1738.0	607.1	229.5
	11		0.213	1.31	497	0.158	74.0	2593.5	1126.1	333.0
	12		0.213	1.19	500	0.143	66.9	2670.5	1356.1	349.1
2	13	Concrete; 1-3/8"	0.122	1.15	462	0.150	122.0	2268.6	839.6	292.6
	14		0.152	1.09	392	0.167	109.0	2023.2	710.3	288.2
	15		0.183	1.61	470	0.205	112.7	2068.3	753.0	215.9
	16		0.213	1.78	502	0.213	99.6	1902.2	677.4	213.6
	17		0.218	1.58	409	0.232	106.7	1970.6	703.7	214.2
	18		0.244	2.06	503	0.246	100.9	1820.4	619.0	183.2
	19		0.244	2.14	500	0.257	105.4			190.8
	20		0.244	2.14	503	0.255	104.8			265.3
	21		0.244	2.11	491	0.257	105.8	1984.7	709.0	184.4
	22		0.274	2.32	501	0.277	101.1	1917.6	768.1	176.5
	23		0.274	2.40	501	0.287	104.6			167.8
	24		0.290	2.04	425	0.288	99.3	1927.2	672.6	173.2
	25		0.305	2.51	515	0.292	95.9	1930.2	696.5	171.3
	26		0.305	2.70	510	0.318	104.2	1859.7	665.7	158.3
	27		0.366	3.33	503	0.398	108.5	1857.5	681.9	133.4
	28		0.406	2.91	453	0.386	94.8	1648.5	648.1	117.6
	29		0.457	3.06	441	0.416	91.0	1651.8	558.0	129.2
	30		0.427	3.67	504	0.437	102.3	1830.1	666.9	121.8
	31		0.427	3.53	499	0.425	99.4	1742.7	672.8	125.8
	32		0.488	4.24	458	0.556	114.0	1775.7	649.8	110.6
	33		0.533	3.73	398	0.562	105.3	1719.8	616.3	98.0
	34		0.579	5.07	505	0.602	103.9	1757.6	645.3	101.6
	35		0.610	4.25	399	0.640	104.7	1724.2	644.7	90.5
	36		0.762	5.46	427	0.767	100.8	1730.9	653.2	84.0
	37		0.686	5.06	397	0.765	111.6	1785.7	656.7	83.2
3	38	Sandstone; 1-3/8"	0.305	1.67	485	0.206	67.8	365.9	97.4	282.0
	39		0.305	1.78	485	0.220	72.2	369.7	97.3	252.3
	40		0.305	2.05	488	0.252	82.7	354.8	96.5	223.8
	41		0.381	2.28	399	0.343	90.0	353.9	103.1	143.8
	42		0.610	3.14	482	0.391	64.1	362.7	100.6	154.5
	43		0.508	4.09	583	0.421	82.9	366.4	101.7	152.2
	44		0.508	4.16	574	0.434	85.6	364.2	98.4	144.6
	45		0.610	3.74	482	0.465	76.4	347.3	95.7	132.4
	46		0.762	3.20	387	0.496	65.1	675.4	200.9	120.1
	47		0.762	3.22	388	0.497	65.3	675.1	217.2	118.7

(*Continued*)

Table 1. (*Continued*)

Group	Test #	Condition	Pre-set b cm/rev	Achieved v cm/s	w rev/min	b cm/rev	Implem. Rate %	Total inhalable dust g	Total respirable dust g	Specific energy MPa
4	48	Concrete;	0.127	1.20	591	0.121	95.7	1211.3	459.3	387.8
	49	1”	0.416	3.68	554	0.399	96.0	1012.2	398.6	140.5
	50		0.416	3.86	553	0.418	100.7	987.6	374.8	136.1
	51		0.457	4.74	589	0.483	105.6	917.9	344.0	116.5
	52		0.572	3.99	391	0.611	107.0	1049.9	441.8	82.6

*Drilling tests 19, 20, and 23 encountered the steel rope imbedded in the reinforced concrete block; no dust sample was collected.

The specific energy is used for evaluating the energy efficiency in this study. This parameter is widely used in drilling research for the evaluation of the drilling condition and bit selection (Farrelly and Rabia, 1987). The drilling specific energy is the amount of energy consumed to break a unit volume of rock, expressed in the amount of input energy divided by the rock volume drilled (Teale, 1964). Therefore, according to its definition, specific energy can be used as a drilling energy efficiency indicator, as higher specific energy means more energy was consumed during drilling of a unit volume of rock, indicating a lower energy efficiency. The specific energy for rotary drilling can be expressed mathematically in terms of drilling bite depth, penetration rate, torque, and thrust, as shown in Equation 2 (Luo, 2004).

$$\varepsilon = \frac{2\pi T}{A_b \cdot b} + \frac{W}{A_b} \tag{2}$$

In the equation, A_b is the borehole area in cm^2, b is the drilling bite depth in cm/rev, and T and W are the torque and thrust in Nm and N, respectively. It should be noted that all these parameters were monitored and recorded in real time by the drilling control system.

3 OPTIMIZATION OF THE DRILLING PARAMETERS

3.1 *Rational drilling bite depth determination*

Figure 1 shows the relationship between the main results (i.e., drilling specific energy, noise dose, inhalable and respirable dust weight), and the achieved bite depth. The noise dose data plotted in Figure 1 are from a previous research project (Li, 2015), and the specific energy and dust generation data are based on results from tests 13 to 37 in this research as these tests were conducted under the same conditions as in the noise research project. It shows that in the drilling tests with larger bite depth the drilling specific energy reduced significantly, indicating a better drilling energy efficiency. The drilling specific energy decreased by 70% by increasing the bite depth from 0.152 to 0.732 cm/rev. The noise dose rapidly decreases as the bite depth increases until it reaches its minimum value at a bite depth that equals 0.541 cm/rev. Afterwards, the noise dose value keeps almost constant.

For the dust weight results, the plot in Figure 1 shows the same trends as noise versus bite depth. Both amounts of the inhalable and respirable dusts decrease as the drilling bite depths increase before the bite depth reaches 0.551 cm/rev. Then, the amount for inhalable dust becomes stable while an increasing trend is shown for the respirable dust. The inhalable dust weight has reduced by 550g from the highest to lowest drilling bite depth. Meanwhile, the respirable dust weight has decreased by 200g.

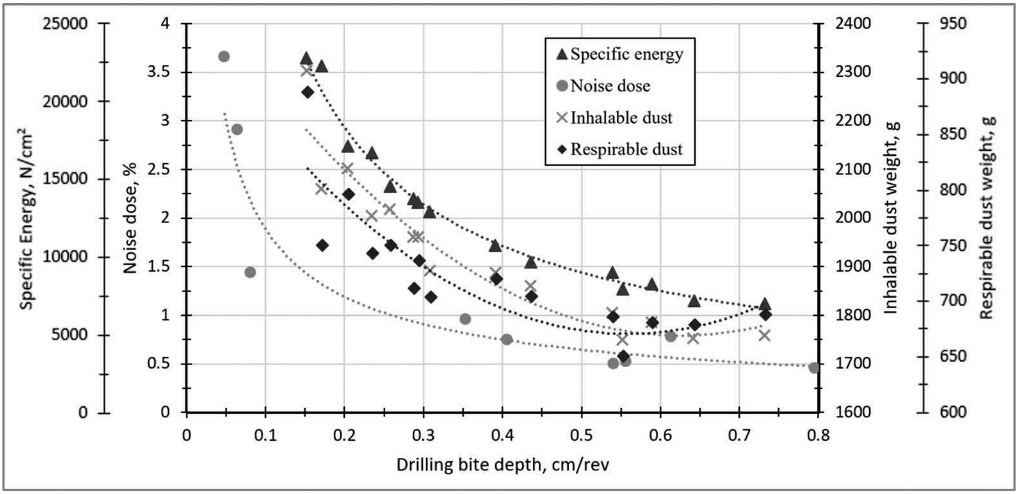

Figure 1. The relationship of drilling bite depth with noise dose, dust weight, and specific energy.

The previous discussion shows the benefits of drilling with a high bite depth in noise reduction, dust control, and energy efficiency. Since noise and dust curves level off around a bite depth of 0.55 cm/rev and the further reduction in specific energy is insignificant after this point, the bite depth from 0.50 to 0.60 cm/rev is recommended based on the particular rock and drill bit for the purpose of dust reduction while maintaining a good drilling efficiency.

3.2 *Drilling performance considerations*

Drilling in different materials may encounter different operational and safety issues. Drilling hard materials normally requires a greater thrust, while an excessive thrust could bend the drill steel which can lead to its buckling failure and unsafe working environment. In addition, the excessive thrust, along with a high rotational rate, could accelerate the bit wear, which in turn prevents the bit from penetrating into the rock material but causing considerable rubbing action. When dealing with soft rocks with excessive bite depth, large cuttings can be generated, and these cuttings could clog the drill bit and steel. The clogging could slow down the drilling cycle, and even worse, it can create a burst of dust backwards out of the drilling hole. The dust burst exposes the operator to a high concentration of respirable dust and worsens the working environment.

The roof bolter drilling performance was analyzed using the field test data in four Central Appalachian coal mines with different roof conditions, as shown in Table 2 (Cotton et al., 2015). For each mine, two sets of drilling control parameters are listed. The upper row is the original operating parameter, while the lower row shows the adjusted parameter.

The frequency of clogging in drilling soft rocks in Mines A and C is significantly reduced after rationally increasing the bite depth. Drill stalling when drilling hard material in Mine A also was eliminated with lifted bite depth, and similar outcomes were shown from Mines C and D. Meanwhile, by applying a higher bite depth, bit life was extended significantly from the observations.

In addition, based on the soft material drilling performance from Mine A and C, it is found that reducing rotation rate is very effective in abating bit clogging problems. To avoid drill stalling, a higher penetration rate combined with a lower rotation rate is recommended, and performance improvements can be found from the tests in Mine C and D. To explain this phenomenon, a higher penetration rate with a lower rotational rate combination can achieve a higher cutting efficiency. Even though a higher penetration rate requires higher thrust input, the increase in effective thrust acting on rock reduces the thrust load on steel. Evidence of

Table 2. Roof bolter drilling performance in different roof conditions.

	Strata	Rotation rate, rpm	Penetration rate, cm/s	*b*, cm/rev	Clogging	Stalling	Bit life, cm/bit
Mine A	29% soft shale71% hard shale	645	4.32 soft 2.03 hard	0.402 0.189	Always	Sometimes	251
		487	4.45 soft4.06 hard	0.548 0.500	Rarely	Never	315
Mine B	Medium hard	580	5.08	0.526	Never	Never	1 row/bit
		475	4.45	0.562	Never	Never	3 row/bit
Mine C	42% soft shale58% med. hard	670	6.10	0.546	Frequently	Frequently	1585
		500	6.10	0.732	Rarely	Rarely	1585
Mine D	Extremely hard material	650	3.30	0.305	Rarely	Always	91
		650	4.06	0.375	Never	Rarely	366

*Frequency expressions for clogging and stalling event from high to low: Always, frequently, sometimes, rarely, never.

more efficient drilling in hard material can be found from the extended bit life in Mine D. Therefore, in order to provide a more efficient and safer drilling process, a higher torque and thrust combination are recommended to provide a rational high bite depth for the specific rock material.

4 DEVELOPMENT OF A COMPREHENSIVE DRILLING CONTROL ALGORITHM

Based on the results from the drilling energy and dust generation analysis, the rational drilling bite depth should be in the range from 0.50 to 0.60 cm/rev for the tested concrete blocks or rocks with similar strengths. For safe and smooth drilling performance, the rational strategy is finding a rational bite depth by reducing the rotation rate first and then increasing the penetration rate.

The rational bite depth range is dependent on the rock strength, bit design and machine power. Uniaxial compressive strength (UCS) is a key physical parameter for estimating rock mass strength and is useful in determining the penetration rate in drilling performance prognosis across the drilling industry (Gong, 2006). Therefore, it is good to develop a normalized specific energy against bite depth graph based on the UCS of the rock to be drilled as shown in Figure 2. In this chart, both the vertical axis (specific energy) and the horizontal axis (bite depth) are normalized by UCS. This chart can be referred to when determining the rational drilling bite depth, which is the optimum bite depth when the other limitations are considered as the strength of rock strata changes.

In the chart in Figure 2, the horizontal axis shows the UCS weighted drilling bite depth (*b'*) defined by Equation 3. It takes into account both the UCS of the tested concrete block and of the rock to be drilled. On the vertical axis, the UCS normalized specific energy shows the potential for further reduction in drilling specific energy caused by increased bite depth. The rational bite depth is determined when the reduction of specific energy is no longer significant, while the further increase in bite depth will be limited by drill steel safety, available drilling power (stalling), or clogging condition.

$$b' = b \cdot UCS_c / UCS_r \tag{3}$$

In Equation 3, *b'* is the weighted drilling bite depth (cm/rev), UCS_c is the UCS for concrete block used in this test (MPa), and UCS_r is the UCS for the rock to be drilled (MPa).

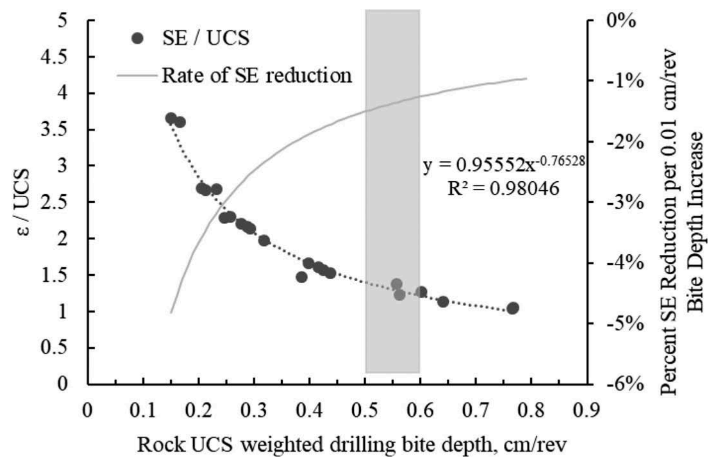

Figure 2. The relationship between weighted drilling bite depth with two different parameters.

The UCS normalized specific energy versus weighted bite depth from our drilling experiments shown in Figure 2 can be well fitted with a negative power function. By substituting the ε and b' into the resulting regression equation in the figure, the relationship between ε, USC_r and b is expressed by Equation 4. According to Equation 2, ε could be affected by bit size, bit type, and drilling condition, so it should be noted that a drilling coefficient α needs to be applied in order to accurately calculate the ε when drilling under different conditions.

$$\varepsilon = 0.0444 \cdot \alpha \cdot UCS_r^{1.76528} \cdot b^{-0.76528} \tag{4}$$

As stated before, the optimum bite depth is the one when the specific energy reaches the minimum. However, it is impractical to achieve the optimum bite depth due to the safety and power limitations. A rational bite depth is that for which the further increase in bite depth will only result in an insignificant reduction in drilling specific energy. The rate of ε reduction is the first derivative of ε with respect to b (Equation 5). The percent reduction in ε per 0.01 cm/rev bite depth increase is plotted in Figure 2.

$$\frac{d\varepsilon}{db} = -0.03398 \cdot \alpha \cdot UCS_r^{1.76528} \cdot b^{-1.76528} \tag{5}$$

Figure 2 shows that as the bite depth increases, the specific energy decreases, indicating a better energy efficiency. The less specific energy means less energy is used for over-breaking the rock and for generating noise. According to analyses on the experiments for drilling dust and noise research on concrete blocks, the recommended bite depth range is between 0.5 and 0.6 cm/rev. The rate of ε reduction plotted in Figure 2 also confirms that in the recommended rational bite depth range, the ε reduction per every 0.01 cm/rev bite depth increase is less than 1.5%. Therefore, the δ value is determined to be between 1.35 and 1.60. This range of δ value is applicable to all rock materials to be drilled other than wet and soft rocks with significant plastic behavior in which excessive bite depth can cause frequent clogging. A similar approach was used and proved to be effective in the optimization of the drilling parameters for rotary downhole drilling (Chen et al., 2016). Therefore, this ratio could provide an objective tool to determine whether the drilling was conducted in its rational performance range.

The recommended drilling control algorithm is shown in Figure 3. In a real-time drilling process, the drilling parameters (i.e., penetration and rotational rates, thrust and torque) acquired are used with bite design and wear condition to determine rock strengths. The rock strength is then used to determine the rational bite depth. Since a higher rotation rate (RPM)

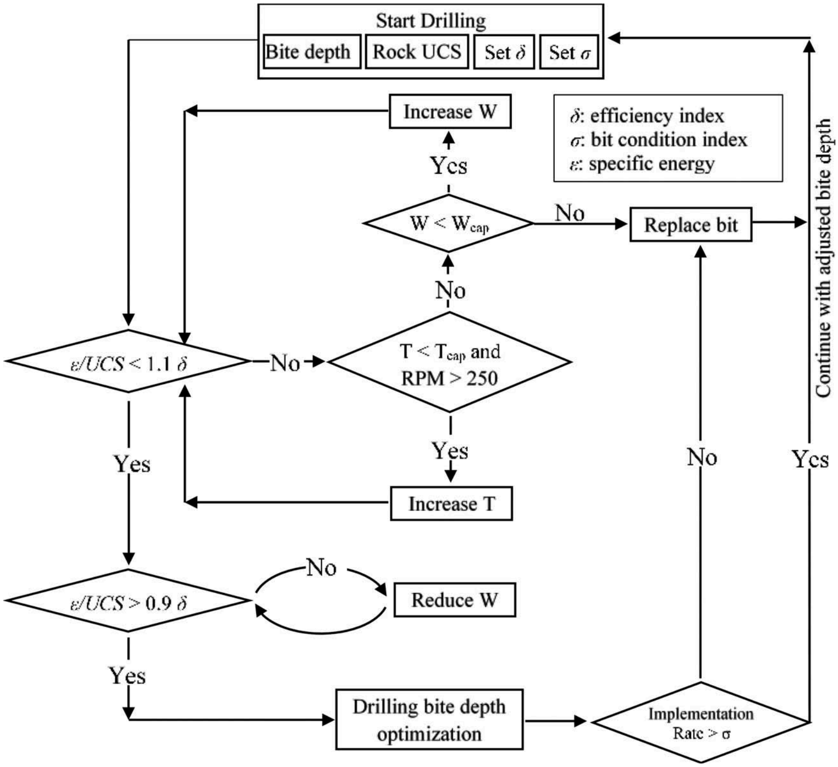

Figure 3. Schematic diagram of the drilling control algorithm.

would accelerate bit wear, a lower RPM combined with a correlated penetration rate (ROP) is preferable to reach a targeted drilling bite depth. In addition, an excessively worn drill bit prevents the system in achieving the targeted bite depth and can increase the respirable and inhalable dust generation rate by as much as 61.5% (respirable) and 43.6 % (inhalable). The overall drilling specific energy using a worn bit is higher than a new bit due to the increased rubbing area and friction between the drill bit and the rock. Therefore, a bit wear condition check is included in the algorithm according to the implementation rate (achieved versus targeted bite depth).

When the drill penetrates a different rock layer with its determined strength significantly different from the previous layer, a rational bite depth is determined based on the rock UCS and bit wear condition and implemented. As the drilling progresses, the specific energy is monitored, and the ratio can be calculated simultaneously. If the ratio is within 10% off the efficiency index, then the system will continue drilling with the initial bite depth. However, the algorithm still needs to evaluate the bit condition using the implementation rate. If the implementation rate is lower than the bit condition index, the system will stop, and a new bit needs to be installed to continue drilling.

In the first place, if the ratio between specific energy and material UCS is higher than 110% δ, then the system will first try to reduce the rotational rate to lift the bite depth in order to reduce the specific energy to meet the criteria until the torque has reached its cap value. Then, the system will increase the penetration rate by raising the thrust power. However, when thrust is increased to its cap value and the ratio is still beyond 110% δ, the most likely reason is that the effective thrust is too low, which is caused by excessive bit wear. Therefore, it will trigger a bit replacement alert and require a new bit to be replaced to avoid steel buckling.

By adapting this drilling control algorithm, the drilling efficiency and bit condition can be monitored in real time, so that at any point of the drilling, the system can stay in a relatively high energy efficiency with less respirable dust production and also reduce the chance to encounter bit clogging and steel buckling event, which can expose a tremendous safety and health hazard to the operator. Due to the limitation of data source, to improve the algorithm's prediction accuracy for respirable dust and noise production rate, more dust and noise results from drilling different types of rock need to be collected for the calibration process.

5 CONCLUSIONS

Fifty-two laboratory drilling tests with two different bit sizes and rock types were conducted in this study. The particles generated from each drilling were sampled and analyzed. The energy input was analyzed for the efficiency evaluation and used to determine the optimal drilling parameters. Regardless of bit size, on average, from one concrete drilling with a new bit, 20.9% of the total generated particles can be respirable and 56.5% can be inhalable. For sandstone drilling, the respirable and inhalable dust generation percentage is 20.9 and 74.4 % respectively.

By analyzing the effect of drilling bite depth on energy and dust generation rate, decreasing trends were observed for each parameter when increasing the bite depth. Based on the drilling safety performance, in order to provide a more efficient and safer drilling process, a higher torque and thrust combination to provide a rational high bite depth for the specific rock material are recommended.

An integrated drilling control algorithm was developed to improve the drilling efficiency and reduction of respirable dust. The rational bite depth range is correlated with the rock material that has been drilled, and this range can be determined by monitoring the drilling specific energy. The ratio between specific energy and the UCS was determined to be the indicator to identify the rational drilling bite depth for different rock materials.

This algorithm can monitor the drilling efficiency as well as the bit wear condition. Therefore, the algorithm can help to keep the drilling operation under a high efficiency while maintaining the dust generation rate at a lower level and reduce the chances of bit clogging and steel buckling events.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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