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Research Article

Theoretical Study and Experiment Validation on Drilling Cutting Weight during the Whole Process of Drilling

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In mining engineering, coal and gas outburst is extremely dangerous dynamic disaster, which will cause serious casualties and property losses. As a method to predict coal burst, the drilling cutting method has been widely used in coal mines. The drilling cutting weight is an important index of the drilling cutting method. In theoretical calculation, scholars usually assume that the coal is isotropic and homogeneous before drilling to deduce the formula of drilling cutting weight. However, in actual mining engineering, drilling cutting is usually carried out in the plastic coal body in front of the working face. Therefore, in the present study, the theoretical formula of the drilling cutting weight in the plastic coal mass is deduced, as well as in the elastic coal mass. The results show that the drilling cutting weight calculated based on the deduced formula increases with the increase of drilling depth in the plastic coal mass, which is consistent with the field measurement results. The fragmentation degrees of coal around the drilling hole are also considered by introducing cohesion, which changes linearly along the radial direction of the drilling hole. The results show that the smaller the cohesion, the greater the drilling cutting weight. The calculation formula for drilling cutting in elastic coal mass is also given. The dilatancy effect of coal around the drilling hole is also considered by introducing expansion coefficient n, which changes linearly along the radial direction of the drilling hole. There is a good match between the theoretical calculation results and the laboratory test results. The obtained results are helpful for the prediction and prevention of coal burst.

1. Introduction

As the most serious engineering disaster in coal mine, coal and gas outburst is an extremely complex dynamic phenomenon of coal, rock, and gas. With the gradual depletion of shallow coal resources and the increase of coal mining depth, the frequency of coal and gas outburst will continue to increase, so it is urgent to accurately predict and prevent them [1–10]. The drilling cutting method is widely used in mining because of its low cost, simple operation. It is the main method of prediction and prevention of coal and gas outburst [11–14].

Many researchers have studied the correlation between coal burst and drilling cuttings. Yin et al. deduced that there is a positive correlation between the drilling cutting and mine pressure, which provides a basis for evaluating the coal burst [15]. Based on the analysis of monitoring data in coal mine and numerical calculation, Qu et al. established the relationship among the drilling cutting, abutment pressure, and drilling stress and developed a real-time monitoring and early warning system for coal burst [16]. Gu et al. studied the relationship between drilling powder amount and stress, and the rock burst risk index was determined [17]. These studies mainly focus on the relationship between the drilling cutting and the stress in front of the working face.

On the other hand, the drilling cutting weight is an important index of drilling cutting method. Many scholars have carried out the theoretical and laboratory experimental research on the drilling cutting weight. Brona divided the drilling cutting weight into two parts, one is the weight of drilling cutting of the cylindrical coal body with the same diameter as the drilling hole and the other is the weight of drilling cutting caused by the displacement of the inner wall of the drilling hole [18]. The relationship between the total amount of drilling cuttings and the stress of coal body is obtained. Petuhov considered the dilatancy phenomenon in the inelastic deformation zone around the drilling hole and took Mohr–Coulomb criterion as the yield condition to obtain the relationship between the drilling cutting weight and coal body stress [19]. Pan put forward a dilatancy softening model which is closer to the constitutive properties of coal, and based on this, an analytical solution of drilling cutting weight is obtained [20]. Zhao and Zhang considered the softening property of coal after strength limit and its dilatancy in inelastic deformation and deduced the theoretical solution of drilling cutting weight, which is close to the actual situation [21, 22]. Considering that the horizontal stress cannot be ignored under deep mining, Tang et al. deduced new formula for drilling cutting weight based on the effective stress [23]. Therefore, it is of great significance for coal and gas outburst prediction and prevention to study the change regularities of drilling cutting weight.

In addition, some progress has also been made in the laboratory study of drilling cutting weight. In the process of drilling, the drill pipe is not only affected by the drill torque and thrust but also by the drill force and chip removal resistance [24, 25]. Therefore, some researchers studied the influence of drilling speed and torque on the drilling cutting weight. They show a positive correlation [26, 27]. Tang et al. revealed that the average value and maximum value of drilling cutting weight increase with the increase of drill pipe diameter, showing a parabola increasing relationship [28].

To sum up, scholars at home and abroad have carried out a lot of research in the application of the drilling cutting method and achieved certain results. In terms of theoretical calculation on drilling cutting weight, researchers assume that the coal before drilling is a homogeneous isotropic elastic body. After drilling, the calculation problem is transformed into an infinite plane strain problem with a circular hole. However, in practical engineering, the stress state of the coal body in front of the working face is in the order of plastic, elastic, and original rock stress. Moreover, drilling cutting is usually carried out in the plastic zone of coal mass. Therefore, in this study, we will deduce the theoretical formula of the drilling cutting weight in the plastic zone, as well as the formula in the elastic zone. The theoretical calculation results are compared with those of field and laboratory experiments to verify the validity of the formula.

2. Theoretical Study on Drilling Cutting Weight

On-site, the drilling cutting weight is calculated according to the weight of drilling cutting per unit length, in kg/m. The research shows that the drilling cutting weight is mainly composed of static drilling cutting weight and dynamic drilling cutting weight, which will be analyzed, respectively, in the following.

2.1. Static Drilling Cutting Weight. The static drilling cutting weight S_1 is the weight of solid coal with drilling radius r.

$$S_1 = \pi r_0^2 \rho, \tag{1}$$

where ρ is the density of coal, kg/m^3.

2.2. Dynamic Drilling Cutting Weight

2.2.1. Stress Zones Experienced by the Drilling Hole. Under the influence of mining, the stress of coal body in front of the working face will redistribute, and the drilling hole will go through plastic zone, elastic zone, and origin stress zone in turn, as shown in Figure 1. However, in engineering practice, it is difficult for the drilling hole to cross the maximum abutment pressure. Therefore, in the following, we will focus on the analysis of the drilling cutting weight in the plastic zone, as well as in the elastic zone.

2.2.2. Dynamic Drilling Cutting Weight in Plastic Zone. In the plastic zone, as the coal body in this zone is relatively broken before drilling, after drilling the surrounding rock mass of the drilling hole is mainly divided into the fracture zone and plastic softening zone, as shown in Figure 2. Therefore, in the plastic zone, the dynamic drilling cutting weight is mainly the additional cutting weight M_1 caused by the plastic deformation of coal body in the plastic fracture zone of the drilling hole.

According to the elastic-plastic mechanics, the stress-strain relationship in the three-dimensional state meets the requirements [29]:

$$\begin{aligned}
\varepsilon_r &= \frac{1+\mu}{E}\left(\sigma_r - \sigma\right) + \varepsilon,\\
\varepsilon_\theta &= \frac{1+\mu}{E}\left(\sigma_\theta - \sigma\right) + \varepsilon,\\
\varepsilon_z &= \frac{1+\mu}{E}\left(\sigma_z - \sigma\right) + \varepsilon,
\end{aligned} \tag{2}$$

where μ is Poisson's ratio, E is Young's modulus, σ is the average stress, and ε is the average strain.

$$\begin{aligned}
\sigma &= \frac{1}{3}\left(\sigma_r + \sigma_\theta + \sigma_z\right),\\
\varepsilon &= \frac{1}{3}\left(\varepsilon_r + \varepsilon_\theta + \varepsilon_z\right).
\end{aligned} \tag{3}$$

The stress-strain relationship in the plastic fracture zone can be multiplied by a plastic modulus ψ on the basis of the above formula. In the elastic zone, $\psi = 1$. Let the average deformation modulus in the plastic fracture zone be E_0 and the transverse deformation modulus be μ_0, volume unchanged ($\varepsilon = 0$). As this is an axisymmetric problem, the stress-strain relationship in the plane of the plastic fracture zone is $\sigma_z = 0$ and $\varepsilon_z = 0$. Therefore, $\sigma = (\sigma_\theta + \sigma_r)/2$. The relationship between stress and strain under plane strain is [27]

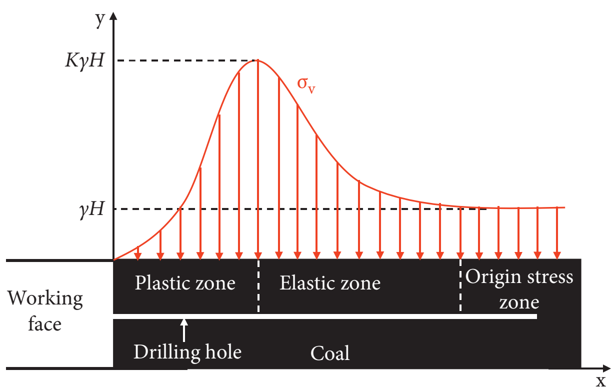
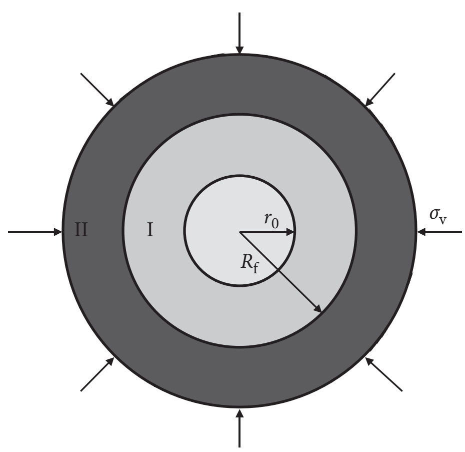


Figure 1: Stress zones in front of the working face.



I: Fracture zone
II: Plastic softening zone

Figure 2: Mechanical model for plane strain surrounding the drilling hole in the plastic zone.

$$\begin{aligned}\varepsilon_r &= \frac{\psi(1+\mu_0)}{E_0}(\sigma_r-\sigma_\theta),\\ \varepsilon_\theta &= \frac{\psi(1+\mu_0)}{E_0}(\sigma_\theta-\sigma_r),\end{aligned} \tag{4}$$

$$\psi = \frac{\sigma_v(\xi-1)+\sigma_c}{\xi+1(\sigma_\theta-\sigma_r)}\cdot\frac{2R_f^2}{r_0^2}, \tag{5}$$

$$\xi = \frac{1+\sin\varphi}{1-\sin\varphi}, \tag{6}$$

$$\sigma_c = \frac{2c\cos\varphi}{1-\sin\varphi}, \tag{7}$$

$$R_f = r_0\left[\frac{2\sigma_v(\xi-1)+2\sigma_c}{\sigma_c(\xi+1)}\right]^{1/\xi-1}, \tag{8}$$

where φ is the internal friction angle, and c is the cohesive force. In previous studies, cohesive force c is often taken as a constant value. However, in practice, the closer to the inner wall of the borehole, the smaller the cohesion, as shown in Figure 3. We assume that the cohesion c varies linearly in the fracture zone and keeps constant in the plastic softening zone. Therefore, in the process of calculation, the average value $c_1/2$ can be taken for relevant calculation. The radial displacement in the plastic fracture zone is

$$\begin{aligned}u &= r_0\varepsilon_\theta = r_0\frac{\psi(1+\mu_0)}{E_0}(\sigma_\theta-\sigma_r)\\ &= \frac{\sigma_v(\xi-1)+\sigma_c}{\xi+1}\cdot\frac{2R_f^2}{r_0}\frac{(1+\mu_0)}{E_0}.\end{aligned} \tag{9}$$

In conclusion, the dynamic drilling cutting weight M_1 in the plastic zone is

$$\begin{aligned}M_1 &= 2\pi r_0\rho\cdot\frac{\sigma_v(\xi-1)+\sigma_c}{\xi+1}\cdot\frac{2R_f^2}{r_0}\frac{(1+\mu_0)}{E_0}\\ &= 4\pi\rho R_f^2\cdot\frac{\sigma_v(\xi-1)+\sigma_c}{\xi+1}\cdot\frac{(1+\mu_0)}{E_0}.\end{aligned} \tag{10}$$

2.2.3. Dynamic Drilling Cutting Weight in Elastic Zone. In the elastic zone, the surrounding rock mass of the drilling hole is mainly divided into the fracture zone, plastic softening zone, and elastic zone, as shown in Figure 4. The dynamic drilling cutting weight includes the weight of coal cutting S_2 produced by elastic deformation of drilling hole, the weight of coal cutting S_3 produced by plastic deformation of drilling hole, and dilatancy.

The weight of coal cutting S_2 produced by elastic deformation of the drilling hole can be expressed as follows [23]:

$$S_2 = 2\pi r_0^2\rho\sigma_v\frac{1+\mu}{E}. \tag{11}$$

The strain softening constitutive equation of coal is [21, 22]

$$\sigma = \begin{cases} E\varepsilon, & (\varepsilon\le\varepsilon_c),\\ \sigma_p\left(\dfrac{\varepsilon}{\varepsilon_c}\right)^m, & (\varepsilon\ge\varepsilon_c),\end{cases} \tag{12}$$

where m is the plastic softening coefficient of coal, σ_p is the uniaxial compressive strength (MPa), and ε_c is the strain corresponding to the uniaxial compressive strength.

Taking the Coulomb–Mohr criterion as the yield condition, the equilibrium equation is

$$\begin{aligned}&\frac{d\sigma_r}{dr}+\frac{\sigma_r-\sigma_\theta}{r}=0,\\ &\sigma_\theta = q\sigma_r+\sigma_p.\end{aligned} \tag{13}$$

The boundary condition is $r = r_0$, $\sigma_r = 0$. The stress must be continuous on the boundary between elastic and plastic softening zones. Thus, the analytical formula of the radius R_0 of the plastic softening zone is obtained [21, 22].

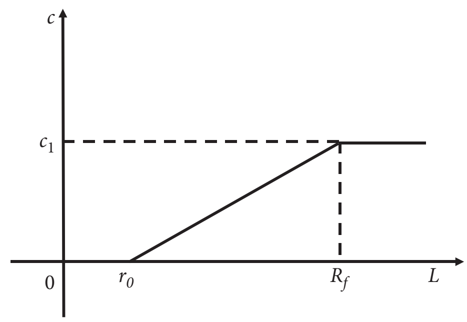


Figure 3: Variation of cohesive around the drilling hole in the plastic zone.

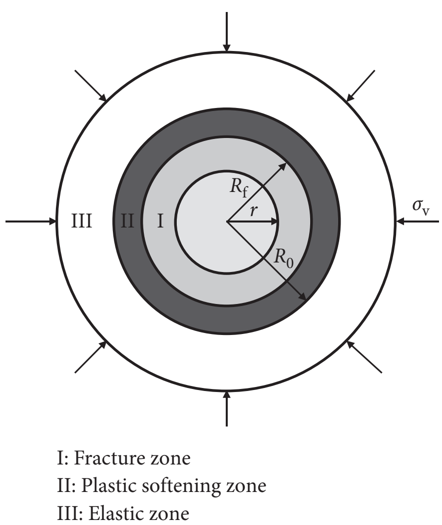


Figure 4: Mechanical model for plane strain surrounding the drilling hole in the elastic zone.

$$R_0 = r_0 \left[1 + \frac{(2m + \xi - 1)\left(2\sigma_v - \sigma_p\right)}{\sigma_p^{1-m} \left[\sigma_p + (\xi - 1)\sigma_v\right]^m (\xi + 1)} \right]^{1/2m+\xi-1}. \quad (14)$$

If the dilatancy effect is not taken into account, the radial displacement at the junction of the elastic zone and plastic softening zone is u_{R0} [21, 22]:

$$u_{R_0} = \frac{1+\mu}{2E} R_0 \left[\sigma_p + \frac{\xi - 1}{\xi + 1} \left(2\sigma_v - \sigma_p\right) \right]. \quad (15)$$

The radial displacement of the inner wall of the drilling hole is obtained by the condition of constant volume:

$$u_r = \frac{u_{R_0}}{r_0} R_0. \quad (16)$$

In the previous studies, scholars usually use average dilatancy coefficient or loose coefficient to consider the influence of dilatancy [21, 23, 28]. However, the closer to the inner wall of the borehole, the larger the expansion. Therefore, we assume that the dilatancy coefficient n changes linearly along the radial direction of the drilling hole in the fracture zone and plastic softening zone, as shown in Figure 5. Then, the radial displacement caused by dilatancy is

$$\begin{aligned} &\frac{\int_{r_0}^{R_0} 2\pi l \left[n_1 - 1/r_0 - R_0 (l - r_0) + n_1\right] \mathrm{d}l - \pi\left(R_0^2 - r_0^2\right)}{2\pi r} \\ &= \frac{(n_1 - 1)(R_0 - r_0)(R_0 + 2r_0)}{6r_0}. \end{aligned} \quad (17)$$

Therefore, the radial displacement u_r including dilatancy is

$$u_r = \frac{u_{R_0}}{r_0} R_0 + \frac{(n_1 - 1)(R_0 - r_0)(R_0 + 2r_0)}{6r_0}. \quad (18)$$

The weight of coal cutting S_3 produced by plastic deformation of the drilling hole and dilatancy is

$$\begin{aligned} S_3 &= 2\pi r_0 \rho u_r = 2\pi r_0 \rho \left[\frac{u_{R_0}}{r_0} R_0 + \frac{(n_1 - 1)(R_0 - r_0)(R_0 + 2r_0)}{6r_0} \right] \\ &= 2\pi\rho R_0 u_{R_0} + \frac{1}{3}\pi\rho (n_1 - 1)(R_0 - r_0)(R_0 + 2r_0) \\ &= \pi\rho R_0^2 \frac{1+\mu}{E} \left[\sigma_p + \frac{\xi - 1}{\xi + 1}\left(2\sigma_v - \sigma_p\right) \right] + \frac{1}{3}\pi\rho (n_1 - 1)(R_0 - r_0)(R_0 + 2r_0). \end{aligned} \quad (19)$$

In conclusion, the dynamic drilling cutting weight in the elastic zone is

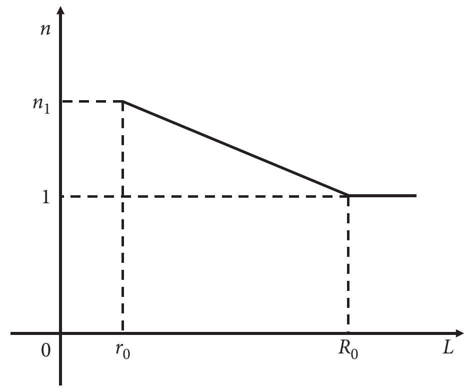


Figure 5: Variation of dilatancy coefficient around the drilling hole in the elastic zone.

$$S_2 + S_3 = 2\pi r_0^2 \rho \sigma_v \frac{1+\mu}{E} + \pi \rho R_0^2 \frac{1+\mu}{E}\left[\sigma_p + \frac{\xi - 1}{\xi + 1}\left(2\sigma_v - \sigma_p\right)\right] + \frac{1}{3}\pi\rho\left(n_1 - 1\right)\left(R_0 - r_0\right)\left(R_0 + 2r_0\right). \quad (20)$$

3. Verification of Drilling Cutting Weight Formula

3.1. Field Verification of Drilling Cutting Weight Formula in Plastic Zone. Taking the field drilling cutting weight of Xinglongzhuang Coal Mine as the research object, we will verify the rationality and validity of the theoretical formula of drilling cutting weight in the plastic zone by comparing the calculated cutting weight with the field measured cutting weight.

Xinglongzhuang Coal Mine is located in Yanzhou District, Jining City, Shandong Province. The total geological reserves of the whole mine are 789.83 million tons and the recoverable reserves are 381.7 million tons. Among them, the geological reserves of 3 coal in the main coal seam are 569.5 million tons and the recoverable reserves are 254.02 million tons, accounting for 66.55% of the recoverable reserves of the mine. The 3 coal seam is stable in the whole area, with an average thickness of 8.65 m. The mechanical parameters of coal body in Xinglongzhuang Coal Mine are given in Table 1.

A number of boreholes with 42 mm in diameter were drilled, along the coal wall in No. 10304 tail way. Borehole drilling is located near the center of wall in the direction altitude. In order to meet the need of pressure relief for rock burst prevention at the same time, the trail stations were arranged 15, 45, 75, and 105 m away from the working face, separately, as shown in Figure 6. Drillings were performed once a day and cuttings were collected to be weighed out in time. Drilling works were moved forward in turn with the advance of the working face. The results are given in Table 2.

The maximum drilling depth is 14 meters ahead of the working face. After that, it is hard for the bit to drill forward. Therefore, the maximum coal body stress is about 14 meters ahead of the working face. The mining depth of Xinglongzhuang Coal Mine is 490 m, and the average unit weight of rock mass is 25 kN/m^3; therefore, the overburden stress is 12.25 MPa. If the stress concentration factor K (Figure 1) is 2.5, then the maximum stress is 30.625 MPa. Assuming that the stress ahead of the working face changes linearly and the stress at the working face is about the overburden stress, then the stress values at various points ahead of the working face are given in Table 3.

The drill pipe radius is 0.021 m. For cohesion c_1, we take it as 0.8, 1.0, and 1.2 MPa, respectively. Then, the fracture radii R_f obtained from formula (8) are given in Table 4.

Let the average deformation modulus E_0 in the plastic zone be 21.24 GPa and the transverse deformation modulus μ_0 be 0.45, and the drilling cutting weight caused by the plastic displacement at various points ahead of the working face is given in Table 5.

According to formula (1), the static drilling cuttings weight is 1.988 kg/m. The total drilling cutting weight at various points ahead of the working face is given in Table 6.

The comparison of actual field cutting weight and theoretical cutting weight is shown in Figure 7. The drilling cutting weight increases with the increase of drilling depth, which is consistent with the field monitoring results. We can see that cohesion has significant influence on calculated drilling cutting weight. The smaller the cohesion, the greater the drilling cutting weight. Therefore, when using the above formula to calculate the cutting weight, cohesion must be determined first.

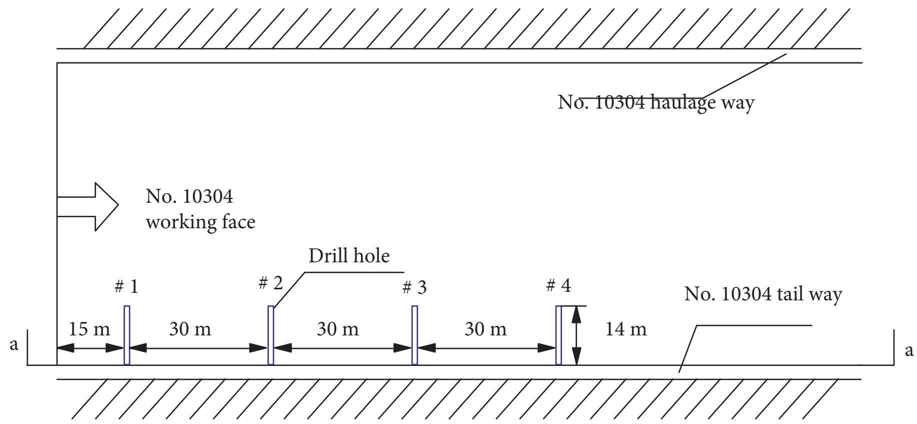
3.2. Verification of Drilling Cutting Weight Formula in Elastic Zone. The drilling cutting weight under different stress is calculated and compared with experimental results to verify the validity of the formula in the elastic zone, taking Longfeng Coal Mine as the research object.

The thickness of main coal seam in Longfeng Coal Mine is 10–20 m, the direct roof and floor are coal seams, the main roof is thick oil shale, and the old floor is tuff and basalt. Zhao and Zhang carried out laboratory experiment of drilling cutting, and the coal sample is taken from Longfeng Coal Mine [21]. The results are given in Table 7.

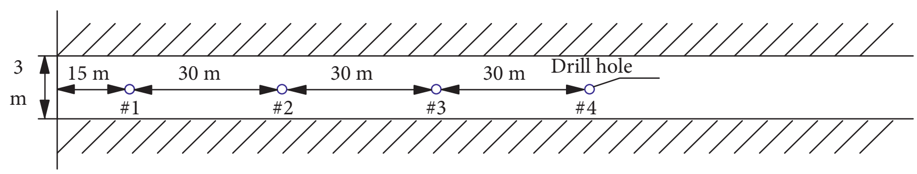
The mechanical parameters of coal body in Longfeng Coal Mine are given in Table 8. The weight of coal cutting S_2 produced by elastic deformation of the drilling hole is

Table 1: The mechanical parameters of coal body in Xinglongzhuang Coal Mine.

UCS (MPa)	Young's modulus (GPa)	Poisson's ratio	Internal friction angle	Cohesion (MPa)	Density
19.34	38.62	0.342	23°	1.2	1435.94 kg/m^3



(a)



(b)

Figure 6: Layout of drilling holes in No. 10304 tail way. (a) Layout plan. (b) Layout section.

Table 2: Statistics of drilling cutting weight in Xinglongzhuang Coal Mine (kg/m).

Monitoring point	Distance ahead of working face (m)												
	2	3	4	5	6	7	8	9	10	11	12	13	14
1	2.2	2.5	2.7	2.8	3.0	3.1	2.5	3.6	2.8	3.9	3.5	4.1	4.0
2	1.9	2.1	1.8	2.5	2.6	2.4	2.8	2.0	2.4	2.7	3.2	3.0	2.7
3	2.2	2.0	1.8	2.6	1.9	2.3	2.9	2.4	2.6	2.5	2.0	2.3	2.8
4	1.8	1.8	2.3	2.1	2.2	2.4	2.5	2.4	3.2	2.4	2.8	3.3	3.4
5	2.0	1.9	2.3	2.3	2.5	2.7	2.3	3.0	2.9	2.6	2.7	3.4	2.9
6	2.1	1.8	2.0	2.3	2.3	2.4	2.7	2.1	2.8	2.6	2.0	2.0	2.7
7	2.0	1.9	2.5	2.1	2.3	2.6	2.7	2.1	2.5	2.7	2.2	2.5	2.5
8	1.8	1.8	2.1	2.4	2.3	2.0	1.9	2.4	2.2	1.8	2.4	2.0	2.4
9	2.7	2.6	2.8	2.5	2.4	3.2	3.6	3.7	4.1	4.3	4.5	3.2	3.8
10	2.3	2.0	1.8	1.8	2.7	2.6	2.3	2.2	3.5	3.0	3.3	3.0	2.7
11	1.9	2.4	2.5	2.0	2.3	2.5	2.3	2.0	2.8	2.5	2.1	2.8	3.1
12	1.7	2.0	1.8	2.2	2.5	2.0	1.8	2.3	2.2	2.4	2.5	2.3	2.6
13	1.8	2.4	2.8	2.0	2.7	2.9	3.0	2.6	3.5	2.9	3.1	3.4	3.1
14	2.0	1.8	2.4	2.1	2.6	2.2	1.9	2.3	2.7	2.4	2.5	2.5	3.0
15	1.7	1.9	1.9	2.3	2.0	2.2	2.5	2.1	2.7	2.3	2.1	2.1	2.5
16	2.0	2.6	2.3	1.9	2.4	2.5	2.2	2.6	2.1	2.7	2.8	2.5	2.7
17	1.7	1.9	2.3	2.1	2.0	2.4	2.2	2.5	2.7	2.7	2.9	3.1	3.3
18	1.5	1.9	2.1	2.0	1.8	2.3	1.9	2.1	2.3	2.5	2.4	2.4	2.6
19	1.6	1.6	1.9	2.1	2.1	2.0	2.3	1.9	2.4	2.1	2.3	2.1	2.0
20	1.9	2.3	2.1	2.0	2.1	2.1	2.3	2.4	2.1	1.9	2.3	2.4	2.1
Average	1.940	2.060	2.210	2.205	2.335	2.440	2.430	2.435	2.725	2.645	2.680	2.720	2.845

Table 3: The stress values at various points ahead of the working face (MPa).

Distance ahead of working face (m)												
2	3	4	5	6	7	8	9	10	11	12	13	14
14.22	15.53	16.84	18.16	19.47	20.78	22.09	23.41	24.72	26.03	27.34	28.66	29.97

Table 4: The fracture radii R_f at various points ahead of the working face (m).

c_1 (MPa)	Distance ahead of working face (m)											
	2	3	4	5	6	7	8	9	10	11	12	13	14
0.8	0.145	0.156	0.166	0.176	0.187	0.197	0.207	0.217	0.227	0.236	0.246	0.256	0.265
1.0	0.122	0.130	0.139	0.148	0.156	0.164	0.173	0.181	0.189	0.197	0.205	0.213	0.221
1.2	0.106	0.113	0.120	0.128	0.135	0.142	0.149	0.156	0.163	0.170	0.177	0.184	0.191

Table 5: The drilling cutting weight caused by plastic displacement at various points ahead of the working face (kg/m).

c_1 (MPa)	Distance ahead of working face (m)												
	2	3	4	5	6	7	8	9	10	11	12	13	14
0.8	0.153	0.192	0.236	0.286	0.342	0.404	0.473	0.550	0.633	0.724	0.823	0.930	1.046
1.0	0.110	0.137	0.167	0.202	0.242	0.285	0.333	0.387	0.445	0.508	0.577	0.651	0.731
1.2	0.084	0.104	0.127	0.154	0.183	0.215	0.252	0.291	0.335	0.382	0.433	0.488	0.548

Table 6: The total drilling cutting weight (kg/m).

c_1 (MPa)	Distance ahead of working face (m)												
	2	3	4	5	6	7	8	9	10	11	12	13	14
0.8	2.141	2.180	2.224	2.274	2.33	2.392	2.461	2.538	2.621	2.712	2.811	2.918	3.034
1.0	2.098	2.125	2.155	2.190	2.230	2.273	2.321	2.375	2.433	2.496	2.565	2.639	2.719
1.2	2.072	2.092	2.115	2.142	2.171	2.203	2.240	2.279	2.323	2.370	2.421	2.476	2.536

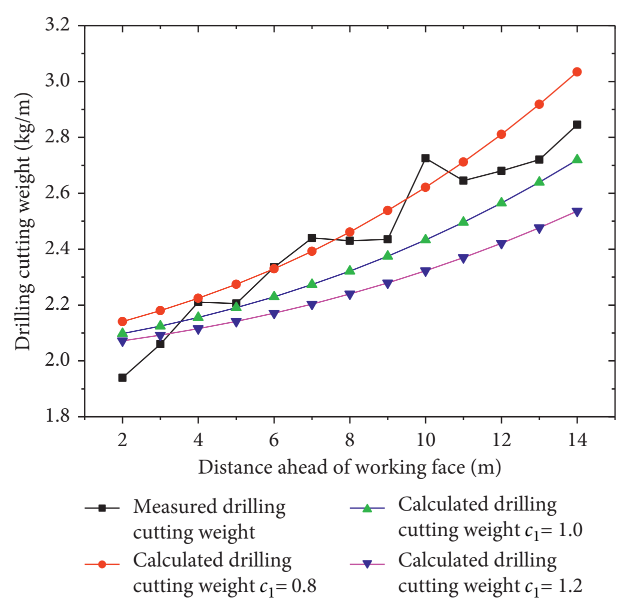


Figure 7: Comparison of actual field measured cutting weight and theoretical calculated cutting weight.

Table 7: The total drilling cutting weight under different stress in laboratory experiment.

σ_v (MPa)	10.4	15.6	20.8	26.0
TDCW (kg/m)	3.16–3.22	3.11–3.20	3.18–3.29	3.15–5.29
Aver (kg/m)	3.190	3.155	3.235	4.22

TDCW, total drilling cutting weight.

Table 8: The mechanical parameters of coal body in Longfeng Coal Mine.

UCS (MPa)	Young's modulus (GPa)	Poisson's ratio	Internal friction angle	Density	n_1	m
12.0	0.26	0.45	30°	1240.0 kg/m^3	1.1	−0.45

Table 9: The calculated total drilling cutting weight under different stress.

σ_v (MPa)	10.4	15.6	20.8	26.0
TDCW (kg/m)	2.229	2.754	3.587	4.850
Ratio	0.70	0.87	1.11	1.15

Ratio, ratio of theoretical calculation results to average value of experimental results.

$$S_2 = 2\pi r_0^2 \rho \sigma_v \frac{1+\mu}{E} = 4.345 \times 10^{-5} \sigma_v r_0^2. \quad (21)$$

The weight of coal cutting S_3 produced by plastic deformation of the drilling hole and dilatancy is

$$\begin{aligned} S_3 &= \pi \rho R_0^2 \frac{1+\mu}{E}\left[\sigma_p + \frac{\xi - 1}{\xi + 1}\left(2\sigma_v - \sigma_p\right)\right] + \frac{1}{3}\pi\rho\left(n_1 - 1\right)\left(R_0 - r_0\right)\left(R_0 + 2r_0\right) \\ &= 2.173 \times 10^{-5} R_0^2\left[\sigma_p + \frac{1}{2}\left(2\sigma_v - \sigma_p\right)\right] + 129.79\left(R_0 - r_0\right)\left(R_0 + 2r_0\right), \\ R_0 &= r_0\left[1 + \frac{(2m + \xi - 1)\left(2\sigma_v - \sigma_p\right)}{\sigma_p^{1-m}\left[\sigma_p + (\xi - 1)\sigma_v\right]^m (\xi + 1)}\right]^{1/2m+\xi-1} \\ &= r_0\left[1 + \frac{1.1\left(2\sigma_v - \sigma_p\right)}{4\sigma_p^{1.45}\left(\sigma_p + 2\sigma_v\right)^{-0.45}}\right]^{10/11}. \end{aligned} \quad (22)$$

The drill pipe radius is 0.021 m. According to formula (1), the static drilling cuttings weight is 1.717 kg/m. The calculated total drilling cutting weight under different stress is given in Table 9. The calculated results are in a good match with the experimental results, which prove the validity of the formula.

4. Conclusion

In the present study, we deduce the theoretical calculation formula of the drilling cutting weight in the process of drill pipe drilling in the coal body in front of the working face. The formulas are verified by field and laboratory experiments. The conclusions are as follows.

Considering that the coal body near the working face is mainly in plastic state, we first derive the theoretical calculation formula of the drilling cutting weight in the plastic coal mass. In the plastic zone, the drilling cutting weight calculated based on the formula increases with the increase of drilling depth, which is consistent with the field measurement results. The fragmentation degrees of coal around the drilling hole are also considered by introducing cohesion, which change linearly along the radial direction of the drilling hole. The results show that the smaller the cohesion, the greater the drilling cutting weight.

In the elastic zone, the dynamic drilling cutting weight includes the cutting weight S_2 produced by elastic deformation of the drilling hole and the cutting weight S_3 produced by plastic deformation of the drilling hole and dilatancy. The dilatancy effect of coal around the drilling hole is also considered by introducing expansion coefficient n, which changes linearly along the radial direction of the drilling hole. There is a good match between the theoretical calculation results and the laboratory test results.

It should be pointed out that there are still many factors affecting the drilling cutting weight, such as horizontal pressure, gas pressure, and drill pipe advancing speed, which need to be further studied.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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