# Reliability analysis on bolt support structure of coal roadway under the influence of mining

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**Abstract**: Based on the features of the serious deformation of coal roadway, many random variables of the mechanics of the surrounding rocks and the influence of mining, the reliability analysis model of the support structure of coal roadway under the influence of mining is established, and the calculating formulas of reliability of the support structure is obtained with the engineering structure reliability theory. And the reliability is calculated based on the method of Monte Carlo to the coal roadway which is exampled on the influence of mining or not. The relationship between support parameters and reliability, the mining influence coefficients and reliability is established, which provides theory foundations for the design of the coal roadway bolt support.

**Key words**: coal roadway; influence of mining; bolt support; structure reliability; the method of Monte Carlo

## 1 Introduction

Recently, in China, the deeper coal mining is gradually transferring to, the more difficult is the support of roadway. Especially in seam roadway, the sides are relatively softer, and it usually suffers from mining influence, which can cause further damage to the roadway[1,2], even the roof fall and caving of the whole roadway, and roadway support failure. The experiments and engineering practices in bolt support of coal roadway indicate that there are two main reasons why the support fails. Firstly, the failure in taking the dynamic parameters and discreteness of support resistance into consideration while designing for the roadway may cause the irrational selection of bolt support parameters[3]; secondly, without considering mining influence before face mining, the amount of roadway deformation is small, and roadway keeps well, while suffering from mining influence, intense deformation of roadway occurs, which usually results in support failure. Therefore, it is of theoretical and practical significance to research into the reliability on bolt support structure of coal roadway under the influence of mining.

## 2 Reliability calculated by the method of Monte Carlo and Matlab

### 2.1 Basic principles

The basic principle of the method of Monte Carlo is described as follows[4]: according to the theorem of large numbers, let $x_1, x_2, \cdots, x_n$ be $n$ separated random variables, assuming that they belong to the same maternal, with same distribution, finite mean($\mu$) and variance($\sigma^2$), then, for any $\varepsilon > 0$, there exists

$$\lim_{n\to\infty} P\left\{ \left| \frac{1}{n}\sum_{i=1}^{n} x_i - \mu \right| \geqslant \varepsilon \right\} = 0 \qquad (1)$$

In addition, assume that the occurring probability of a random event $A$ is $P(A)$, that in $n$ independent test, the occurring frequence of event $A$ is $m$, frequency is expressed as $W(A) = \frac{m}{n}$, then, for any $\varepsilon > 0$, there exists

$$\lim_{n\to\infty} P\left\{ \left| \frac{m}{n} - P(A) \right| < \varepsilon \right\} = 1 \qquad (2)$$

The basic idea of Monte Carlo is that, first, random variables which affect reliability of structure are bulk sampled , and then, samples are substituted into the expression of structural performance function group by group to determine whether the structure work or not, finally, the reliability of structure are obtained.

### 2.2 Solution procedure

Matlab is able to generate random variable arrays which are subjected to their own probability distribution functions; it simplifies programming process, and provides with array operation orders which avoid using loop statements and speeds up operation velocity[5].

Let performance functions be $g(X_1, X_2, \cdots, X_n)$, $X_i(i = 1, 2, \cdots, n)$ are random variables which are subjected to their own probability distribution functions.

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Firstly, $m' \times n'$ random variable arrays, whose expression is $x_i(k,l)$, $(i=1,2,\cdots,n; k=1,2,\cdots,m'; l=1,2,\cdots,n')$, are generated by corresponding random arrays generator instructions. Secondly, the elements of each array are correspondingly substituted into performance function one after anther. Finally, the result arrays of performance functions come up. According to the number $R$ of elements that are not less than 0 in statistical result arrays, reliability is shown in Eq. (3):

$$P_R = \frac{R}{m' \times n'} \tag{3}$$

## 3 The limit status equation and reliability of steady bolt support structure of coal roadway under the influence of mining

According to the destruction types of bolt support structure, criterion for stability, and the limit status equation, which are studied in Ref. [1] and Ref. [3], the analysis on bolt support structure of coal roadway under the influence of mining can be carried out as follows.

### 3.1 Reliability of roof support in coal roadway under the influence of mining

The influences, brought by mining stress for roof reliability in mining process, are the increase of roof press, rock fractures and damage degree of rock, the increase of height and weight of potential caving rock blocks as well. Assume that the height of caving rock is $D$, and that of potential caving block under mining is $D_c$, then, the expression $k_d = D_c/D$ is defined as the height coefficient of potential caving block under mining influence, which can be taken by numerical simulation calculation, experiment or experience value. And under the influence of mining, the steady values of Maximum horizontal stress ($\sigma_{1\max}$) is $\sigma_{TC}$, the lateral-load-depth-ratio ($n$) is $n_{TC}$.

#### 3.1.1 Nonoccurrence reliability of roof shear failure

When shear failure doesn't occur under mining influence, the limit status equation of roof stability is shown in Eq. (4)

$$g(N,W,\varphi) = \tan\varphi - \frac{k_d W S_c - 2N\sin\theta}{\sigma_{TC} n_{TC} k_d D S_c - 2N\cos\theta} = 0 \tag{4}$$

In Eq. (4), $k_d$ means the height coefficient of potential caving block under mining influence; $\sigma_{TC}$ means maximum horizontal stress in the potential caving scope under mining influence; $n_{TC}$ means steady lateral-load-depth-ratio under mining influence; $N$ means anchoring force of vertex angle bolts out the caving scope; $W$ means the weight of potential caving block; $D$ means the height of original caving block; $\varphi$ means equivalent internal frictionangle after roof bolting; $\theta$ means installation angle of vertex angle bolts; $S_c$ means distribution distance between two bolt rows. $N$, $W$ and $\varphi$ are random variables, usually, subjected to normal distribution.

According to solution procedure of Monte Carlo, when the shear failure doesn't occur, the reliability of roof stability ($P_{djc}$) can be work out.

#### 3.1.2 Nonoccurrence reliability of roof compressive failure

When compressive failure doesn't occur under mining influence, the limit status equation of roof stability is shown in Eq. (5)

$$g(N_{\max}, C^*, \varphi^*) = K_m \frac{N_{\max}}{S_c S_1} + \frac{2C^* \cos\varphi^*}{1-\sin\varphi^*} - \sigma_{TC} = 0 \tag{5}$$

$\sigma_{TC}$ means stable value of maximum horizontal stress in the potential caving scope under mining influence; $N_{\max}$ means the maximum anchoring force of single bolt; $S_c$ means distribution distance between bolt rows; $S_1$ means distribution distance between bolts; $C^*$ means residual cohesion of anchorage body; $\varphi^*$ means residual internal friction angle; $K_m$ means strengthening coefficient of equivalent bolt stress acting on reinforced unit at axial direction in residual stage. $N_{\max}$, $C^*$ and $\varphi^*$ are random variables and subjected to normal distribution.

According to solution procedure of Monte Carlo, when the compressive failure doesn't occur, the reliability of roof stability ($P_{dyc}$) can be work out.

#### 3.1.3 Reliability of bolt support structure for roof

Here, reliability of bolt support structure for roof under mining influence is defined as $P_{dc}$.

Based on $P_{dic}$ and $P_{dyc}$, $P_{dc}$ can be worked out with Eq. (6).

$$P_{dc} = \min\{P_{djc}, P_{dyc}\} \tag{6}$$

### 3.2 Reliability of coal side support structure under mining influence

As far as coal side, the influences, brought by mining, are mainly the obvious increase of roof stress, that of stress concentration coefficient and that of plastic area radius of coal side, the radius is expressed in Eq. (7).

$$R_c = \frac{mA}{2\tan\varphi_0} \ln \left( \frac{k_c \gamma H + \dfrac{C_0}{\tan\varphi_0}}{\dfrac{C_0}{\tan\varphi_0} + \dfrac{P_x}{A}} \right) \tag{7}$$

In Eq. (7), $k_c$ means stress concentration coefficient under mining influence; $R_c$ means the width of plastic area; $P_x$ means supporting resistance of bolts in coal side; $m$ means thickness of coal seam that is under mining; $\varphi_0$ means internal friction angle of coal *seam*; $A$ means lateral press coefficient; $C_0$ means cohesion of coal seam; $H$ means mining depth; $\gamma$ means bulk density of roof rocks.

### 3.2.1 Reliability of single bolt

The limit status equation of single steady bolt under mining influence is shown in Eq. (8).

$$g(R_c, C, \varphi) = \varepsilon_m - \frac{1}{2G}(\gamma H \sin\varphi + C\cos\varphi) \cdot \left\{ \frac{2R_c^{\alpha+1}}{\beta+1} \left[ \frac{1}{L} \cdot \frac{(a+1)^{\beta} - a^{\alpha}}{a^{\beta}(a+L)^{\alpha}} + \frac{\alpha-\beta}{\alpha+1} \cdot \frac{1}{(\alpha+L)^{\alpha+1}} \right] - \frac{a-1}{a+1} \right\} = 0 \quad (8)$$

In this expression, $\varepsilon_m$ means strain of bolt; $R_c$ plastic area radium of coal side under mining influence; $C$ means cohesion of coal; $\varphi$ means internal friction angle; $G$ means shear elastic modulus of coal; $\gamma$ means average bulk density of overlying strata; $H$ means mining depth; $a$ means radium of roadway; $L$ means the length of bolt; $\alpha$ and $\beta$ mean dilation coefficient of coal or anchorage body after broken. $R_c$, $C$ and $\varphi$ are random variables and generally belong to normal distribution.

According to solution procedure of Monte Carlo, the reliability of single bolt ($P_{bc}$) can be work out.

### 3.2.2 Reliability of bolt support structure for coal side

Under mining influence, reliability of bolt support structure for coal side follows the $k$-out-of-$n$ model, thus, reliability of bolt support structure for coal side ($P_{1b}$) can be worked out with Eq. (9).

$$P_{1b} = \sum_{i=0}^{k-1} \binom{n}{i} P_{bc}^{n-i} (1 - P_{bc})^{i} \quad (9)$$

## 3.3 Reliability of bolt support structure of coal roadway

Under mining influence, bolt support structure of coal roadway is a series-wound system; its reliability can be worked out with Eq. (10).

$$P_c = P_{dc} P_{1b}^{2} = \min\{P_{djc}, P_{dyc}\} \left[ \sum_{i=0}^{k-1} \binom{n}{i} P_{bc}^{n-i} (1 - P_{bc})^{i} \right]^{2} \quad (10)$$

# 4 Instance analysis

## 4.1 The conditions of roadway surrounding rock, actual support schemes and parameters value

For calculation, here gives an instance which is of haulageway of fully mechanized caving face in one certain coal mine. In this coal mine, the overall thickness of coal seam varies from 5.45 m to 6.15 m, average thickness is 5.86 m, mining depth($H$) is 450 m, the width of roadway ($b$) is 4.5 m, the roadway section is 4.5 m × 2.8 m (width × height), average bulk density ($\gamma$) of overlying strata is 0.023 5 MN/m$^3$, shear elastic modulus($G$) is 840 MPa, the height of potential caving block, the internal friction angle of original rock, residual cohesion of anchoring body which can be calculated by combining with unidirectional compressive residual strength of original rock, and the maximum anchor-hold of single bolt are subjected to normal distribution.

$H \sim N(1.93\ \text{m}, 0.33\ \text{m})$,

$\varphi \sim N(31.9°, 3.4°)$,

$C^* \sim N(0.073\ \text{MPa}, 0.007\,9\ \text{MPa})$,

$N_{max} \sim N(0.090\ \text{MN}, 0.010\ \text{MN})$.

Full-length anchor with the resin and rebar bolts is taken. The rebar are disposed on roof of roadway, the diameter ($\Phi$) is 22 mm, the length ($L$) is 2.0 m, and the strain ($\varepsilon_m$) is 0.06 m, distribution distance between bolt rows($S_c$) is 1.0 m, distribution distance between bolts($S_1$) is 1.0 m, the installation angle of roof bolts ($\theta$) is 75, let $\alpha = 1.5$, let $\beta = 1.5$.

As far as the value of stress concentrated coefficient, lots of academicians, home or abroad, have done lots of researches on it, for example, A. Gedibinse, in Poland, put forward that when $\delta_c$ is more than 25 MPa, $k = 3$; when $\delta_c$ is less than 25 MPa, $k = 2.5$[6]. S. S. Peng put forward that $k$ varies from 1.5 to 5 in Ref. [7]. In single face mining, the change of $k$ in different place forward coal wall is researched in Ref. [8]. The way to value $k$ is also proposed in Ref. [9]. Referring to the researches above, according to the concrete condition of this coal mine, from the angle of safety, here, let $k = 2.5$, and let $k_c = 4.5$.

Based on result of FLAC numerical simulation calculation, here, let $k_d = 4.5$.

## 4.2 Calculation result

Based on the method of Monte Carlo, the reliability of roadway bolt support structure is calculated by means of million-direct-sampling.

1) Reliability ($P$) is 0.993 6, without mining influence.

2) Reliability ($P_c$) is 0.697 4, under mining influence.

In this roadway, according to structural safety criterion, the reliability of bolt support structure is high without mining influence; it can fully satisfy the reliability of project. But under mining influence, the reliability is down rapidly from 0.993 6 to 0.697 4. For common project structure, 0.697 4 is too low to satisfy the reliability of project. Some corresponding parameters have to be modified to enhance system's reliability, to guarantee that there is enough reliability when roadway is under mining influence, and to keep roadway in safety.

### 4.3 The relationship between Mining influence coefficient and reliability

Based on least square method, multinomial curve-fitting is used to get relationship between caving height mining influence coefficient and reliability, and to get relationship between stress concentration factor and reliability. The results are as follows.

$$P = 2.832\,2k_d^3 - 12.369\,9k_d^2 + 16.489\,4k_d - 5.961\,3$$

$$P = -0.001\,1k_c^3 - 0.032\,4k_c^2 + 0.204\,8k_c + 0.705\,4$$

**Table 1 The calculating data of relationship between the mining influence coefficients and reliability**

| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Height-of-potential-caving-block mining influence coefficient $k_d$ | 1.0 | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 |
| Reliability | 0.993 8 | 0.971 1 | 0.908 8 | 0.799 0 | 0.650 7 | 0.494 4 | 0.353 2 | 0.240 7 | 0.157 2 |
| Under mining influence, stress concentrated coefficient $k_c$ | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 |
| Reliability | 0.998 1 | 0.994 6 | 0.981 4 | 0.947 0 | 0.872 9 | 0.763 4 | 0.665 2 | 0.558 9 | 0.357 0 |

The relationship curves are shown in Fig. 1 and Fig. 2.

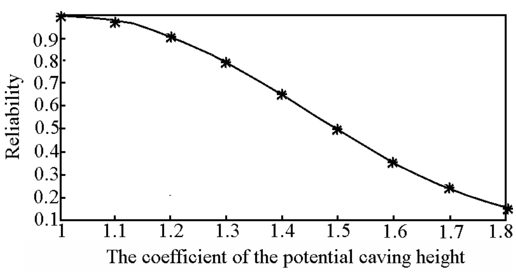


**Fig. 1 Relationship between the coefficient of the potential caving height and reliability**

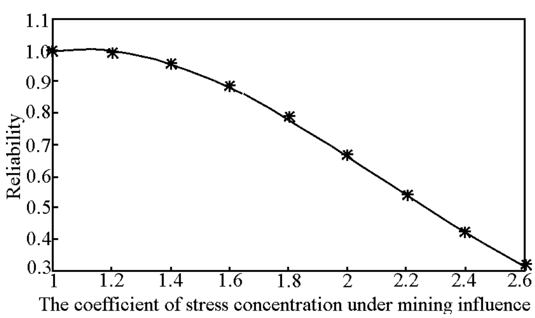


**Fig. 2 Relationship between the coefficient of stress concentration under mining influence and reliability**

### 4.4 The relationship between support parameters and reliability

Based on least square method, multinomial curve-fitting is used to get relationship between anchor-hold of bolt and reliability, to get relationship between variance of anchor-hold and reliability, to get relationship between row space and reliability, and to get relationship between tensile strain and reliability (which the roof is taken as an example for $N_{max}$, $\sigma_N$, and $S$ and the coal wall is taken an example for $\varepsilon_m$ to calculate). The results are as follows.

$$P = 218.814N_{max}^3 - 154.628\,2N_{max}^2 + 28.559\,3N_{max} - 0.575\,6$$

$$P = 5\,143.1\sigma_N^3 - 275.056\,9\sigma_N^2 + 0.735\,4\sigma_N + 0.859\,4$$

$$P = -0.279\,2S^4 + 1.786\,9S^3 - 3.939\,8S^2 - 2.989\,7S + 0.282\,2$$

$$P = 1\,352.8\varepsilon_m^3 - 567.107\,1\varepsilon_m^2 + 62.612\,7\varepsilon_m - 1.047\,7$$

The relationship curves are shown from Fig. 3 to Fig. 6.

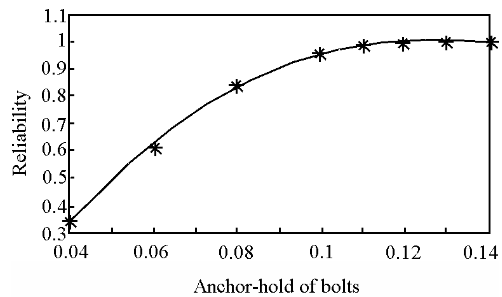


**Fig. 3 Relationship between anchor-hold of bolts and reliability**

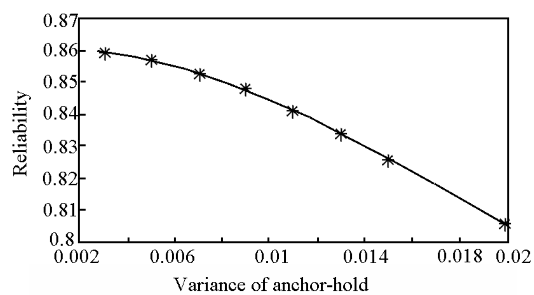


**Fig. 4 Relationship between variance of anchor-hold and reliability**

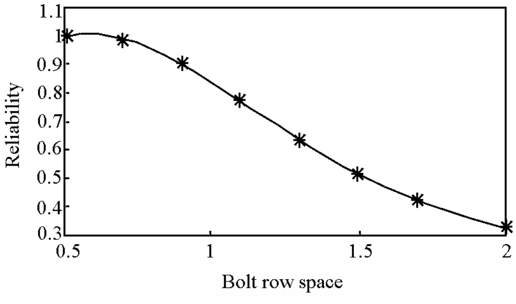


**Fig. 5 Relationship between bolt row space and reliability ($S_c = S_l$)**

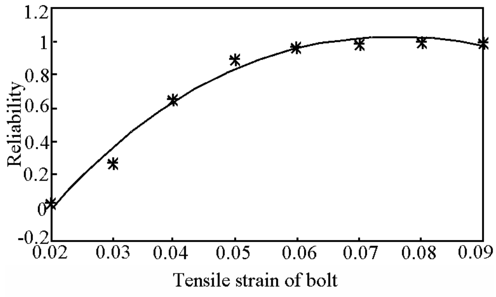


**Fig. 6 Relationship between tensile strain of bolt and reliability**

### 4.5 Results of analysis

1) Anchor-hold, row space and tensile strain of bolts are the main parameters which affect reliability, the increase of anchor-hold, reduction of row space, and enhancement of tensile strain of bolts can quickly promote reliability.

2) The variance of anchor-hold of bolts has certain effect on reliability, reduction of variance can enhance reliability, but effect is not obvious.

3) Reliability of roadway support structure decreases rapidly under mining influence, mining stress affects it a lot, thus, in design of coal gateway; the mining influence on reliability of support structure must be counted in.

4) Roadway bolt support structure is a relatively complex series-wound system, under the circumstance of greatly reduction of reliability suffering from mining influence, it is hard to enhance systematic reliability to a satisfying extent by improving single parameter of bolt, if wanted to be of satisfying systematic reliability, the reasons why reliability is low must be analyzed comprehensively, and corresponding parameters must be modified.

5) Priority selection of extendible and big anchor-hold bolts can enhance reliability, reduce row space and save cost.

## 5 Conclusions

1) According to the uncertainty of dynamic parameters of roadway surrounding rock and load effects of support structure, reliability model, which is good for process random variables, is applied to bolt support structure of roadway; based on analyzing limit status of support structure, under mining influence, reliability model for bolt support structure of roadway is established, calculation formulas are deduced, both of them can guide the design of bolt support.

2) Mining has intense influence on support structure of coal gateway, with increase of mining influence, the reliability of roadway support structure decreases quickly. Therefore, in design of bolt support structure of roadway, if roadway may be affected by mining, reliability of bolt support structure of roadway must be calculated with expression under mining influence.

3) Through calculation result of project instance, the change of roadway reliability under mining influence is analyzed, relationship between support parameters and reliability is established, as well as the relationship between mining influence coefficient and reliability, it provides parameters design and the thought to enhance reliability of support structure with scientific basis.

4) Reliability of root structure of roadway needs further research.

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