

Spatial Variability of Elastic Modulus of Rock Mass and Response Analysis of Roadway Deformation

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Abstract

Based on the viewpoint that the rock and soil are not homogeneous materials, the spatial variability of its mechanical parameters should be considered, and the influence of the spatial variability of the elastic modulus of the rock mass on the roadway deformation should be considered. Taking a coal mine roadway as the background, the spatial variability of elastic modulus of rock mass is characterized by means of random field theory. The random field data is simulated by Matlab software and the random field is discretized. The random field data is imported into each grid in the Abaqus model through Python language, and then the numerical model is operated in batches to obtain the displacement data of key points of the roadway and surrounding rock, which is consistent with the actual engineering. The displacement data is analyzed and processed based on the reliability method, and the β contour map of the roadway surrounding rock reliability index is calculated. Through the analysis, it can be concluded that the simulation accuracy of this method meets the engineering requirements, and the isoline distribution of the reliability index β conforms to the engineering practice, which is a good way to analyze the reliability of the roadway structure.

Keywords

Roadway Surrounding Rock; Spatial Variability; Random Field; Abaqus; Secondary Development.

1. Introduction

Coal is a main disposable energy in our country, and the mining of coal is very important to economic development. Due to the complex occurrence condition of coal seam in our country, the pressure and stability of surrounding rock of the roadway should be studied for the safe mining of coal resources. Surrounding rock pressure, surrounding rock properties and surrounding rock support are the basic factors affecting the stability of roadway, and the surrounding rock properties are mainly represented by the mechanical parameters of surrounding rock. In recent years, a large number of scholars have paid attention to the influence of mechanical parameters of surrounding rock on roadway stability [1-6], but most studies regard geotechnical materials as homogeneous materials and study the influence of mechanical parameters of geotechnical materials on roadway. In fact, due to deposition and post-deposition, Lumb considers geotechnical materials as heterogeneous materials [7]. The influence of the difference of mechanical parameters at different points in the rock formation on the roadway should be considered. There are many researches on geotechnical spatial variability in the field of slope [8]. In terms of underground structure, Xianjun Han [9] took into account the influence of geotechnical spatial variability on underground cavern earlier, especially in recent years, many scholars have considered the influence of geotechnical spatial variability on underground structure: Jianbin Li [10] studied the influence of spatial variability of elastic modulus on tunnel formation deformation based on random field theory. Jinzhang Zhang [11] considered the influence of spatial variability of parameters on tunnel structure deformation. Xuejun Liu [12] considered the influence of spatial variability of shear strength of

surrounding rock on tunnel deformation. Haitao Yu [13] studied the dynamic response of tunnel structure under seismic action considering the spatial variability of stratum medium along the tunnel. Changhong Wang [14] introduced random field theory into reliable index analysis of surface settlement of shield tunnel considering spatial variability of geotechnical parameters. In this paper, the spatial variability of rock mass mechanical parameters is characterized based on random field theory by referring to previous studies on spatial variability of rock mass. In addition, random field is realized through Abaqus and tunnel engineering simulation calculation and reliability analysis are carried out.

2. Random Field Theory of Rock and Soil Parameters

In the early stage of geotechnical parameter research, geotechnical parameters were regarded as a single random variable according to the classical probability theory and treated as mutually independent random variables. In fact, due to the influence of deposition history and consolidation by gravity or pressure, the mechanical parameters of geotechnical in spatial distribution not only showed variability, but also showed structure to some extent. It can only be regarded as independent random variables that lose the structure of geotechnical parameters in space. In the random field theory proposed by Vanmarcke [15], soil parameters are regarded as random functions related to spatial position coordinates, and the randomness and structure of geotechnical parameters are taken into account, which can better describe the spatial variability of geotechnical parameters. Random field theory regards rock mass mechanics parameters distributed in three-dimensional space as random variables, and takes position $P(x, y, z)$ as the domain Ω of the basic parameter. The random variable system generated by this theory is called random field $X(P) = X(x, y, z)$. The random field data of rock mass mechanical parameters are simulated by means of the mean, standard deviation and correlation distance of statistical data.

The mean value of random field is also called mathematical expectation, and mechanical parameters of all points in rock mass are not identical. To facilitate mechanical calculation, the mean value E is used to represent the size of mechanical parameters of rock mass by statistical processing, and the deviation degree between mechanical parameters of all points in rock mass and their mean value is represented by variance Var and standard deviation σ . The covariance Cov of P_i and P_j represents the second order mixing central moment between two points in random field:

$$\text{Cov}[X(P_i), X(P_j)] = E \left\{ \{X(P_i) - E[X(P_i)]\} \times \{X(P_j) - E[X(P_j)]\} \right\} \quad (1)$$

Autocorrelation coefficient can be used to describe the degree of correlation between parameter values at one point and other points in space. The sample autocorrelation function can truly and accurately describe the correlation between points, and the parameter sample autocorrelation coefficient can be directly calculated by the theoretical formula (2).

$$\rho[X(P_i), X(P_j)] = \text{Cov}[X(P_i), X(P_j)] / \{\sigma[X(P_i)]\sigma[X(P_j)]\} \quad (2)$$

Where, $\sigma[X(P_i)]$ and $\sigma[X(P_j)]$ respectively represent the mean standard deviation of local space where P_i and P_j are located. In mine engineering, the survey cost is extremely expensive, and the fitting of sample autocorrelation function requires a large number of measured data. In order to reduce the cost, the theoretical autocorrelation function is generally used to approximately replace the real sample autocorrelation function in practical engineering. The common forms of theoretical autocorrelation function include exponential type, Gaussian type, second-order autoregression type, exponential cosine type, triangle type, etc [16]. Since the calculated results are not very sensitive to the type of autocorrelation function, the exponential autocorrelation function that is easier to calculate is generally adopted in practical engineering. The three-dimensional exponential autocorrelation function is shown in Equation (3).

$$\rho[X(P_i), X(P_j)] = \exp \left[- \left(\frac{\tau_x}{L_x} + \frac{\tau_y}{L_y} + \frac{\tau_z}{L_z} \right) \right] \quad (3)$$

Type of $\tau_x = |x_i - x_j|$, $\tau_y = |y_i - y_j|$, $\tau_z = |z_i - z_j|$ respectively P_i, P_j two points of the X, Y, Z axis relative distance, L_x, L_y, L_z said the X, Y, Z axis of relative distance. Correlation distance L means that there is a strong correlation between two random field points within the correlation distance. If the distance between two points exceeds the correlation distance, it is considered that there is basically no influence between two points. Fuqiang Ren [17] introduced the exponential model of the theoretical variation function to obtain the correlation distance of the exponential function types of rock mass, and believed that there was a strong correlation within 4.5m. Generally, the correlation distance is only applicable within the same rock layer, and the mechanical parameter variability of adjacent rock layers is no longer considered, namely $L = 0$. The random field data of rock mass mechanical parameters need to be obtained first through statistical data and the above mathematical characteristics of random fields. The calculation methods include moving average method, rotating strip method, local average subdivision method, Cholesky decomposition method, etc. Cholesky decomposition method is simple and easy to implement, and is often used in geotechnical parameter random field simulation. In this paper, Cholesky decomposition method is used to calculate random fields.

3. Reliability Analysis based on Finite Element

As a powerful finite element software, Abaqus is widely used in geotechnical field due to its efficient nonlinear solving ability. The problems encountered in the numerical simulation are relatively complex. When the built-in functions of Abaqus cannot be satisfied, a large number of built-in subroutine interfaces provided by Abaqus can be used for secondary development. Therefore, Abaqus is selected to simulate the roadway.

In this paper, according to the method of realizing the reliability analysis process with the non-invasive finite element method, the simulation process of the elastic modulus of rock mass random field and the finite element analysis process are run independently. The statistical data and mathematical characteristics of random field were used to simulate random field data through Matlab. The center point method was adopted when the random field data was discretized to random field unit, that is, the material attribute of the center point of random field unit was regarded as the material attribute of the whole random field unit. Then, on the basis of the existing Abaqus calculation program, the secondary development of the finite element program is realized based on the underlying language of Abaqus, Python, so as to import the elastic modulus of rock mass into the corresponding finite element of the finite element model with the field, realize the spatial variability of the material parameters of the numerical model, and automatically call the calculation program to realize batch calculation. Reduce human workload, improve computing efficiency.

The specific steps to realize the response quantity of random field simulation in finite element software are as follows:

- (1) Establishment of finite element model: establishment of rock mass and roadway model according to site conditions.
- (2) Establishment of random field model: Based on known statistical data of geological exploration, covariance decomposition method is adopted to generate random field data of elastic modulus of rock mass with Matlab.
- (3) Random field embedding finite element model: With the help of Python language, material parameters are assigned to the grid according to the spatial correspondence between random field elements and finite elements, as shown in Figure 1, and then *.inp file is generated.

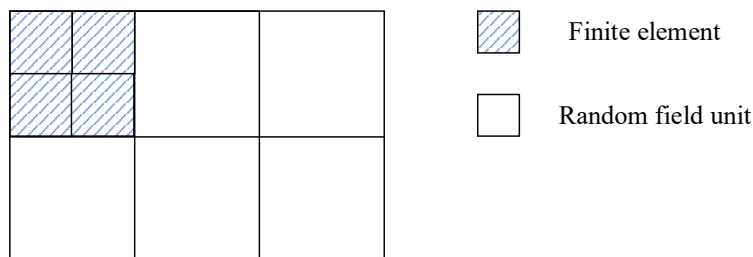


Figure 1. Flow chart

(4) Batch operation: make batch operation of Abaqus model with Python language, call Matlab to generate random field data within one operation, call Abaqus to generate and calculate *.inp file of random field embedded model, get and read *.odb file and write the calculation results into *.txt file.

4. Engineering Example

This study takes the roadway of a coal mine as the background, and calculates and analyzes the roadway on both sides of a working face without considering the influence of other roadway. The upper part is another working face that has finished mining, with a distance of 40 m, without considering the influence on it.

4.1. Roadway Modeling

According to the actual size of the roadway in coal mine, the model was established by using Abaqus. The cross-section shape of the roadway was a large cross-section oblique rectangle with a clear width of 4 500 mm, a upper side height of 3 700 mm, a lower side height of 2 600 mm and a middle height of 3 150 mm. Considering the influence of the model size on the roadway, the model size was established as 170×60×8 m, and the rock dip Angle of the model was 13°. The bottom surface of the model is completely fixed and normal displacement is limited around it. The buried depth of the roadway is about 500m, and the overlying rock mass is imposed on the upper surface of the model in the form of load. According to the actual working conditions, each step of excavation is 0.8m, and three steps of 2.4m are excavated in total. Eight-node linear hexahedral element (C3D8R) is used for rock mass, and two-node spatial linear beam element (B31) is used for anchor bolt. The number of model elements is 42310, and the number of nodes is 48323. The model is shown in Figure 2. Since the model grid is not a regular hexahedral element, when the random field data is imported, the centroid coordinates of the finite element grid are located in the random field element, and the finite element grid is considered to belong to the random field element, then the material properties of the random field element are imported into the finite element grid.

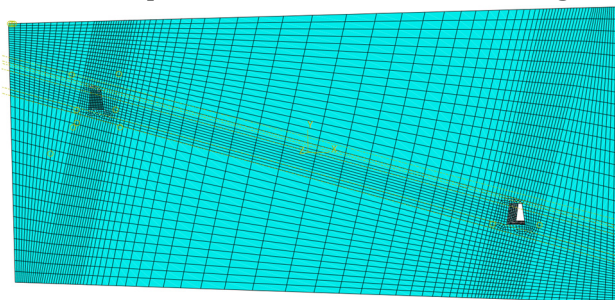


Figure 2. Model diagram

Mohr-Coulomb strength criterion can better simulate the strength characteristics and failure behavior of rock and soil materials, so the constitutive relation of rock mass in this paper adopts Mohr-Coulomb elastoplastic model. The main mechanical parameters of rock mass obtained according to the geological exploration report are shown in Table 1.

Table 1. Rock mass mechanical parameters

Rock layer	$\rho/(\text{kg} \cdot \text{m}^{-3})$	$E/(\text{GPa})$	μ	$c/(\text{MPa})$	$\varphi/(\text{°})$
Rock layer 1	2450	1.5	0.25	3.6	38
Rock layer 2	1800	0.83	0.23	2.3	29
Rock layer 3	1200	2.8	0.22	1.2	20
Rock layer 4	2450	4	0.25	2.2	44
Rock layer 5	2600	1.5	0.39	3.3	37

Note: The elastic modulus data in the table represent the mean elastic modulus of rock mass.

The roadway is supported by bolt, 7 $\Phi 22 \times 2$ 200mm bolts are used for roof support, and the two sides are of different specifications. 4 $\Phi 22 \times 2$ 200 mm bolts are used for the side near the working face, and 6 bolts are used for the side far from the working face. The specifications are $\Phi 43 \times 1$ 900 mm, and the row spacing between the top and side bolts is 700 \times 700mm.

The elastic density of bolt is 7 800 kg/m³, the modulus is 2.1×10^{11} GPa, and Poisson's ratio is 0.25.

4.2. Determination of the Number of Simulations

According to the results of theoretical analysis and a deterministic analysis, the deformation of the lower roadway is greater than that of the upper roadway, the displacement of the two sides is the largest, the relative displacement of the two sides is greater than the relative displacement of the roof and floor, and the relative displacement of the two sides is the key parameter of roadway deformation. It is considered that when the relative displacement of the two sides converges, other monitoring points should have converged. Therefore, the convergence of the relative displacement of the two sides of the lower roadway characterizes the convergence of the surrounding rock of the roadway. When the number of Monte-Carlo simulations reaches 200 times, the convergence mean and standard deviation of the relative displacement of the two sides calculated based on the random field are shown in Figure 3. When the number of simulations reaches 50 times, the mean and standard deviation curves fluctuate greatly. As the number of simulations increases, the mean and standard deviation will eventually approach a fixed value. When the number of simulations reaches 150 times, the mean and standard deviation curves are obviously gentle. After calculation, it is found that the final change of mean and standard deviation is less than 1%. Therefore, the number of Monte-Carlo simulations N required to study roadway deformation can be determined to be 200.

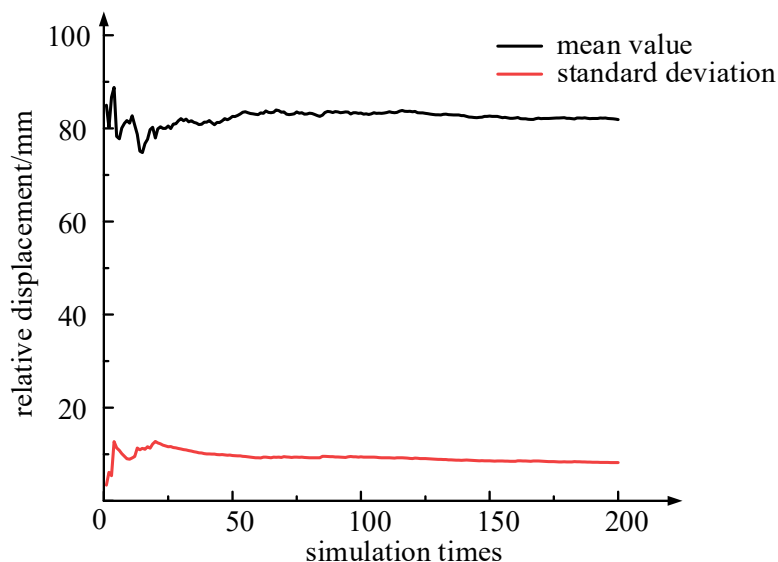


Figure 3. Convergence of relative movement of two lanes in roadway

4.3. Stress Results

Because this paper focuses on the influence of roadway deformation on stability, the stress information is not extracted in batches, and the stress field distribution is analyzed with one of the deterministic results. As shown in Figure 4, the stress value of the lower roadway is significantly greater than that of the upper roadway, and the Mises stress is affected by the coal seam at the upper and lower sides of the roadway. The stress value is greater than the roof and floor, and the stress value is the largest at the arch foot of the roadway, where there is obvious stress concentration. The stress results are basically consistent with the engineering practice.



Figure 4. Overall, Mises stress cloud diagram

It can be seen that the stress of surrounding rock affected by gravity load increases gradually from top to bottom. The stress concentration phenomenon occurs at the arch foot of surrounding rock of roadway, and the maximum stress can reach 3.67 MPa. The roof and floor of roadway have obvious stress release phenomenon, and the stress value is smaller than that of the two sides of roadway.

4.4. Displacement Results

In order to obtain the deformation of roadway and surrounding rock, the following monitoring points are arranged in the upper and lower roadways as shown in figure 5. Five monitoring points are arranged in the two sides of the roadway and the roof and floor respectively. In the surrounding rock of the 15 × 15 m roadway, 24 monitoring points are evenly distributed, and the horizontal and vertical displacements are extracted.

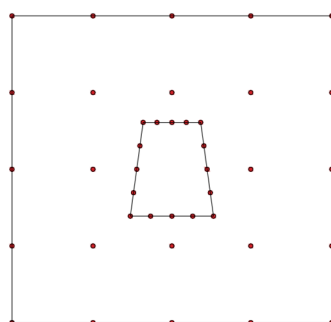


Figure 5. layout of monitoring points

In order to analyze the influence of random field of spatial variability of rock elastic modulus on the failure probability of roadway excavation, Monte Carlo simulation method is used to calculate the stability of roadway and surrounding rock. According to the maximum allowable deformation of the roadway section not exceeding 5 %, the relative displacement of the two sides is not more than 100 mm, and the maximum settlement of the vault is not more than 50 mm. The function of roadway and surrounding rock can be expressed as

$$f(x) = S_0 - S(x) \tag{4}$$

In the formula, $S(x)$ represents the deformation calculated by the numerical model, and S_0 represents the maximum allowable deformation.

In this study, the displacement information of the two sides and the roof and floor of the upper and lower roadways and the displacement information of the surrounding rock were obtained through 200 batch calculations. The deformation of the lower roadway was slightly larger than that of the upper roadway under the influence of buried depth. The distribution histogram of the relative displacement of the two sides is shown in Figure 9 and Figure 10. It can be seen that under the condition of considering the spatial variability of the elastic modulus of the surrounding rock, the maximum settlement of the upper roadway roof is 46 mm, which does not exceed the limit state value of 50 mm. The maximum relative displacement of the two sides of the upper roadway is 100 mm, and only one time reaches the limit state value of 100 mm, and the deformation size is consistent with the engineering practice. It shows that under the condition of considering the uncertainty of surrounding rock, roadway support can effectively control roof settlement and two-side displacement. The deformation of roadway is within the allowable range, and the failure of roadway can be considered as a small probability event.

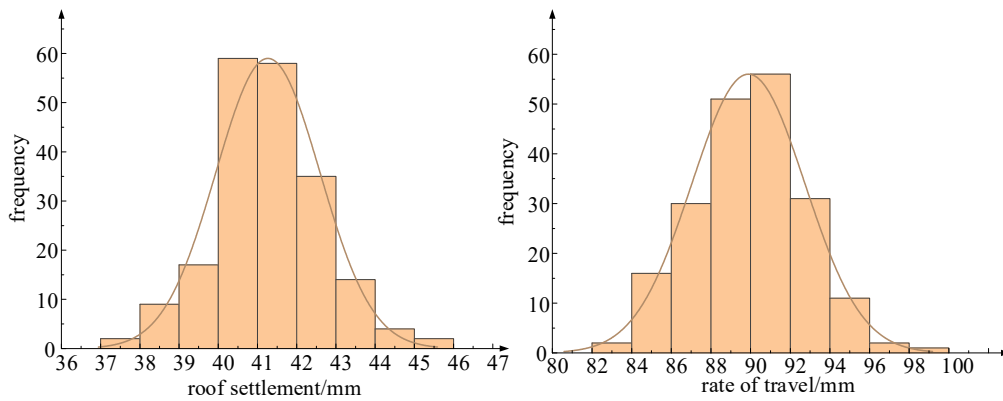


Figure 6. Roadway deformation distribution map

It can be seen from Figure 6 that when the Monte-Carlo simulation number N is 200, the mean and standard deviation of the displacement have reached convergence. With the increase of the number of simulations, the probability distribution of the displacement will not change greatly. It is considered that the fitted probability distribution function is in line with the real situation. The distribution function of roadway surrounding rock deformation is fitted by 200 times of simulation data. With the distribution function, the reliability of surrounding rock can be calculated by reliability theory. According to the reliability theory, the reliability index contour map of the lower lane is shown in figure 7.

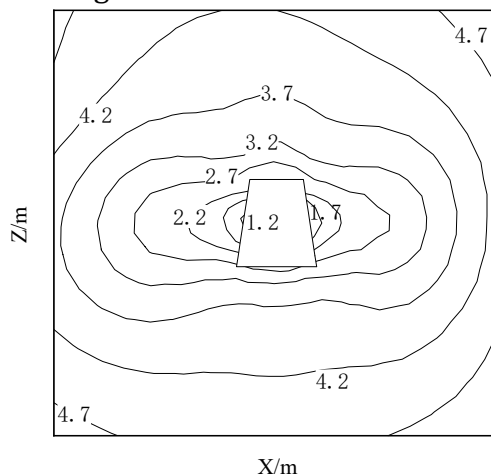


Figure 7. Reliability Index β Contour Plot

In general, the reliability index β generally increases from the roadway to the outside, and its value varies from 1.2 to 4.7. The minimum value of β is in the middle of the two sides of the roadway, and the maximum value of β is outside the surrounding rock. The rock strata of the two sides of the roadway are weak in mechanical properties of the coal seam, resulting in the β value of the two sides of the roadway is significantly smaller than that of the roof, and the β value distribution is elliptical. Because the left bolt support strength is weaker than the right bolt support strength, the β value of the left surrounding rock of the roadway is slightly smaller than that of the right surrounding rock, but the distribution law is basically symmetrical. The amount of floor arching in roadway is obviously less than that of roof settlement, which also leads to the value of floor β being significantly greater than that of roof β . The distribution of the reliability index β value is consistent with the actual project.

5. Conclusion

In this paper, a coal mine roadway is taken as the engineering background. Based on the random field theory, the random field of rock mass elastic modulus is generated to describe the spatial variability of rock mass parameters. The generated random field is imported into Abaqus numerical model in batches. The reliability of roadway surrounding rock is simulated by Monte-Carlo, and the following conclusions are drawn:

- (1) Based on the random field theory, this paper considers the influence of spatial variability of rock mass elastic modulus on roadway deformation. The example analysis shows that the accuracy meets the actual engineering requirements, and the simulation efficiency is high.
- (2) The statistical data of batch simulation is calculated by the reliability method to calculate the reliability index β value, which can consider the influence of uncertain parameters of rock and soil, and evaluate the deformation response of roadway system and the reliability of roadway structure more scientifically.
- (3) In this paper, the influence of spatial variability of elastic modulus parameters of rock mass on the stability of roadway is considered, but the strength of rock mass is affected by multiple parameters. The spatial variability of multiple parameters needs further study.

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