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FUZZY OPTIMIZATION METHOD AND ITS APPLICATION OF SIMILAR MATERIAL RATIO IN 3D GEO-MECHANICAL MODEL

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Abstract

The similar material plays an important role in Geo-mechanical model test, and the proportion influences the test results directly. According to the physical and mechanical properties of the prototype, the cementitious material with good elastic-plastic for iron crystal sand (ISBM) was chosen as the similar material for the research on failure mechanism of surrounding rock under the environment of excavation and high geo-stress in deep tunnel. Three mixing proportions that matched with similar conditions were got from more than 300 groups of matching test. Relying on the specific indoor test data, and the main physical and mechanical parameters of the original rock were taken as the evaluation index system, the improved fuzzy optimization mathematical model of similar material was established. It might help you make your decision in cases where several solutions seem to be able to fit the bill. The optimal proportion of the similar material was got by using the model, and the optimization result was applied to the true 3 d geological mechanical model test for similar material, and simulated successfully the process of excavation in high geo-stress environment deep tunnel. The reappearance of the zonal disintegration phenomena of surrounding rock under excavation in high geo-stress environment deep tunnel of Dingji coal mine.

Key words: *Geo- Mechanical Model(GMM); Similar Material Ratio(SMR); Gray Fuzzy Optimization(GFO); Deep Tunnel(DT)*

1. INTRODUCTION

The model is a representative object that imitates the prototype and copied by following some proportional relations, it has part or the whole characteristics of the prototype[1]. So geo-mechanical model test should be exactly called "engineering geology mechanical model". The geological environment of the deep underground caverns will be very complex under the condition of "three highs and one disturbance", and the surrounding rock mass will appear significant nonlinear deformation and strength failure. However, the prototype test has been proven difficult to realize for suffering from the disadvantages of difficulty in sampling, long cycle, and high cost. On the contrary, the model test leap into fame with the characteristics of simulation, macrography, reality, low cost and short cycle, and became an important tool for researching on the nonlinear deformation and strength failure of underground engineering[2-3]. Meanwhile, what similar material and what proportioning choice influences the physical and mechanical properties of model materials, and has a great impact on the success of the model test[4-5].

At present, with the development of similar material [5-10], more and more experimental methods and data processing theory have been gradually applied to the research. Cui Xi-min[11] analyzed the test errors by theory, and improved the test methods and precision from terms of the similarity material, similarity criterion, boundary conditions, the influence range and controllability. Fan He[12, 13] screened two proportions that conformed to the similarity condition through the orthogonal test, but in the choice of final proportion only security was single taken into account, and the theoretical basis is not sufficient. Chen Lu-wang[14] also took a generalized formula as the basis of selecting the optimal proportion.

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Cheng Sheng-guo[15] presented a fuzzy linear weighted transformation formula according to the similarity criterion, so as to choose the optimal proportion in similar material, however, there was no complete theoretical system and no application in engineering. From the above, there have no agreement about how to choose the optimal proportion among some proportions that match with the similar conditions in the similar material research. Therefore, it is time to establish a standard mode, and form a set of perfect theory system. Given all of that, relying on the specific indoor test data, the improved fuzzy optimization mathematical model of similar material was established based on the grey theory and fuzzy mathematics theory. The model took the main physical and mechanical parameters of the original rock as evaluation index system, and took consideration of the complexity, uncertainty of the preparation for similar material in geo-mechanical model test. Using this model to evaluate the three proportions that match with the similar conditions integrally and synthetically, the optimal proportion was got and applied in the geo-mechanical model test. The phenomena and data of the model test closely matched with the data from field monitoring. It indicates that the similar material used in the model test can be well simulated the characteristics of deformation failure in high geo-stress environment deep tunnel of Ding-ji coal mine, and lay the foundation for further study of the failure mechanism.

2. ENGINEERING PROJECT AND THE SIMILAR MATERIAL IN MODEL TEST

2.1 general situation of engineering and mechanical properties

Ding-ji coal mine lying in the northwest of Huai-nan city with the distance 14.75 km east–west and 11 km north-south is the important coal base in central China. The geological reserves of the field are about 1.279 billion tons with 9 minable seam, and the recoverable reserves are 640 million tons. The place of field monitoring was in the track tunnel, south of the mining area, -910 m, 11-2[16-18].

According to the characteristics of deformation failure from field monitoring and analysis of the results, the basic physical and mechanical parameters' values of the original rock are shown in table 1. According to the similarity principle and the basic parameters of prototype material, the physical and mechanical parameters' values can be calculated for the similar scale 1:50, shown in table 1.

Table 1. The Physical Mechanics Parameter Value Of The Original Rock And The Similar Material

	Unit weight γ **(KN/m^3)**	**Compressive strength** σ_c**(Mpa)**	**Elastic modulus** E**(Mpa)**	**Tensile strength** σ_t**(Mpa)**	**Cohesion** C**(Mpa)**	**Internal friction angle** φ**(°)**	**Poisson's ratio** μ
Prototype	2.62	88.55	12.97×10^3	14.01	10～15	40～43	0.268
Similar material	2.62	1.771	259.4	0.2802	0.2～0.3	40～43	0.268

2.2 The Preparation Of The Similar Material

The cementitious material with good elastic-plastic for iron crystal sand (ISBM) was chosen as the similar material, that has obtained the patent of invention[1]. The process of making specimen is as follows: (1)Mix the iron concentrate, barite powder and quartz sand together proportionately, and then mix this with the rosin alcohol solution, after stiring well, fill it into a mould.(2)Place the mould in the press, compact the mixture by a constant strength of 5 Mpa, remove the mould and take out the test-piece, so a standard cylinder size 100×50 mm is finished. (3) Dry the cylinders for 3 to 4 days, make the alcohol fully volatile, also air-blower can be used to accelerate the drying. For the purpose of testing the influence of the components on test parameters under combination of different ratio, we made more than 300 groups of matching test, and 4 specimen for each group, so more than 1200 cylinders were made to test the material mechanical parameters. The mould and part of the specimen are shown in figure 1.

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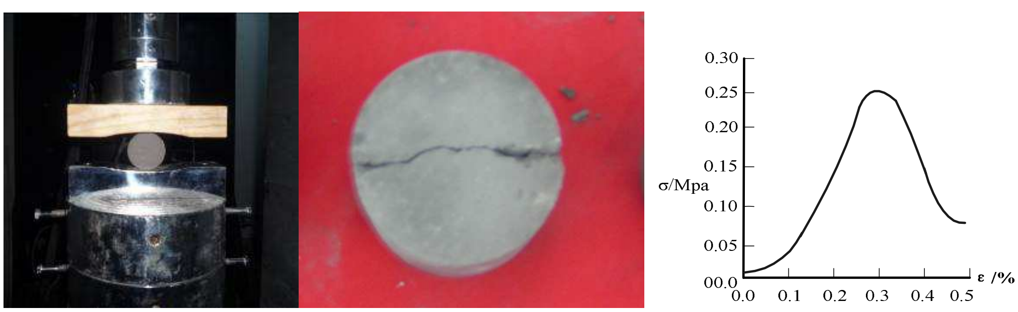
Figure 1. The mould and the similar material specimen

2.3 Tests of physical and mechanical parameters for similar material

The tests of elastic modulus, poisson's ratio, compressive strength and tensile strength were performed in the rock rigid compression-testing machine made by Shandong university. And the tests of internal friction angle and cohesion were performed in conventional triaxial compression testing machine and direct shear apparatus. The process of the physical mechanical parameters test for the similar material are shown in figure 2.

***(A)** Compressive Strength Test*



***(B)** Tensile Strength Test*

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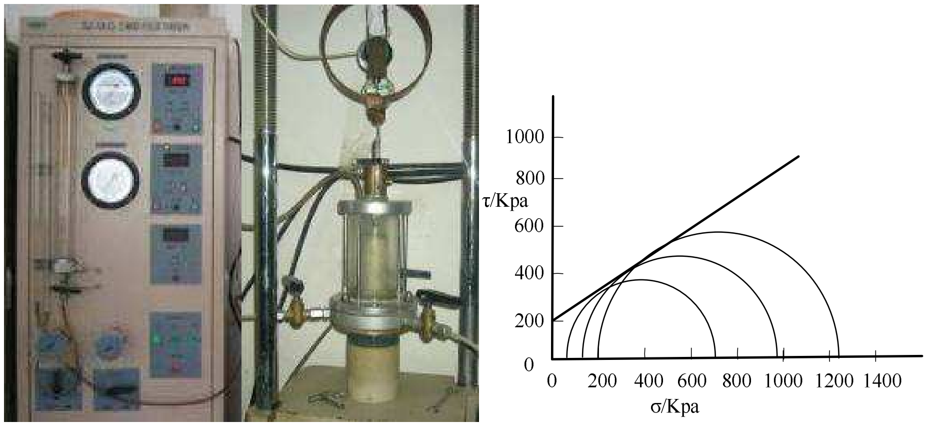

***(C)** Triaxial Test*

***(D)** Direct Shear Test*

Figure 2. *The Physical Mechanical Parameters Test Of The Similar Material*

We tested the influence of the components on mechanics properties of the similar material under combination of different ratio, so as to obtain the appropriate proportions that match with the similar condition.

□Concentration of rosin alcohol solution(RA)

As the cementing agent of the material, rosin need to be dissolved in alcohol to form solution, and the adhesion to the mixture would be increased efficiently.

The compressive strength and elastic modulus of the material are determined by the concentration of rosin alcohol solution. We plot the relationship between the concentration of the rosin alcohol solution and the compression strength and elastic modulus of the material, shown in figure 3.

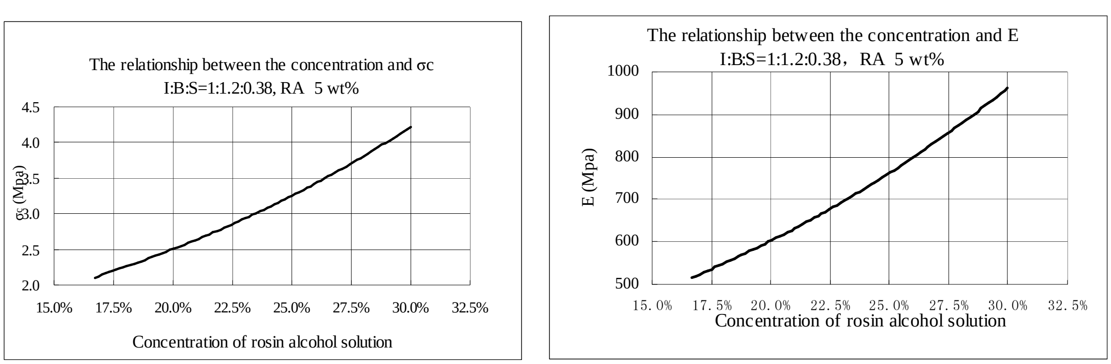

Figure 3*. The Relationship Between The Concentration Of The Rosin Alcohol Solution And The Compression Strength*

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And Elastic Modulus Of The Material

□The ratio of the quartz sand(QZ)

Quartz sand is a coarse aggregate, and plays the role of the skeleton in iron crystal sand similar material, which is equivalent to the stones in the concrete. The compressive strength and elastic modulus of the material are determined by the ratio of the quartz sand. We plot the relationship between the ratio of the quartz sand and the compression strength and elastic modulus of the material, shown in figure 4.

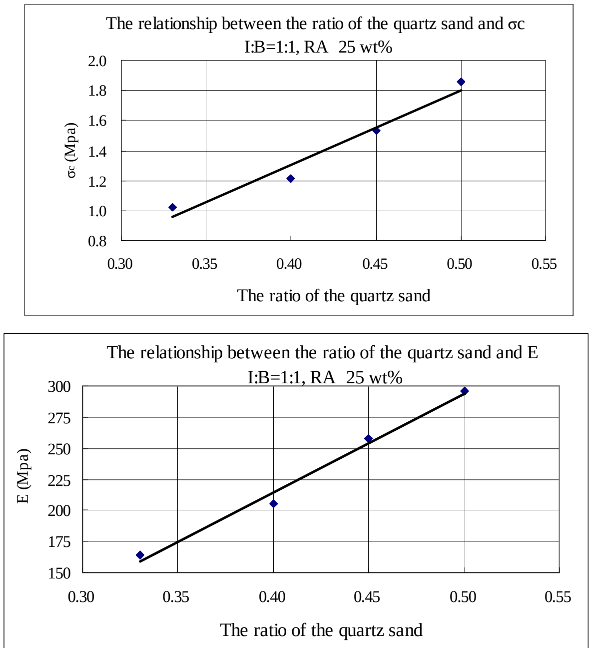
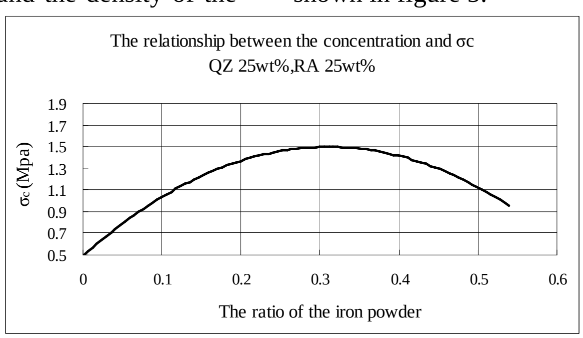


Figure 4. *The Relationship Between The Ratio Of The Quartz Sand And The Compression Strength And Elastic Modulus Of The Material*

□The ratio of the iron powder

As the fine aggregate of iron crystal sand similar material, on one hand, the iron powder can meet the requirements of high density for rock because of its high density, and the density of the similar material can be effectively improved by increasing its ratio. On the other hand, the ratio of the iron powder can also influence the mechanics parameters to some extent. The relationship is shown in figure 5.



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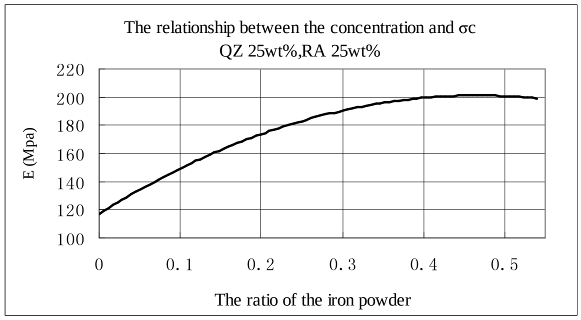

***Figure 5**. The Relationship Between The Ratio Of The Iron Powder And The Compression Strength And Elastic* modulus of the material

Three mixing proportions that matched with similar conditions were got from more than 300 groups of matching test, shown in table 2. Geo-mechanical model test requirements the simulation environment and the similar material to be as close to the actual situation as possible, so for the accuracy of similar material, the higher the better. Therefore, it is time to establish a mathematical model to optimize the best proportion of the similar material.

Table 2. Physical Mechanics Parameter Value Of Similar Material And The Ratios

Parameters	**Unit weight γ (KN/m^3)**	**Compressive strength $\sigma_c(Mpa)$**	**Elastic modulus $E(Mpa)$**	**Tensile strength $\sigma_t(Mpa)$**	**Cohesion $C(Mpa)$**	**Internal friction angle $\varphi(°)$**	**Poisson's ratio μ**
Ratio	2.62	1.3	263.35	0.234	121.21	44.135	0.273
Ratio Ⅱ	2.62	1.4	278.06	0.244	204.065	43.02	0.276
RatioⅢ	2.62	1.76	295.29	0.26	263.77	41.775	0.271

3. FUZZY OPTIMIZATION METHOD AND ITS APPLICATION

3.1 Selection Of Indices

Under the environment of high geo-stress, and in the test for failure mechanism of surrounding rock in deep tunnel, basic physical and mechanical parameters, such as the unit weight γ, compressive strength σc, elastic modulus E, tensile strength σt, cohesion C, internal friction angle φ, and poisson's ratio μ are the main parameters, which needs to be satisfied the similar conditions. Therefore, the seven parameters mentioned above were taken as the evaluation indices to establish the evaluation index system.

3.2 The Grey Fuzzy Membership Degree Of The Index System

There are many groups of matching test in the similar material geo-mechanical model, the number is recorded as m. And also many mechanical parameters which constitute the evaluation index system, recorded as n. The sign xij expresses the ith mechanical parameter in group jth. And then the expression of characteristic value matrix can be expressed as $\{X=(x_{ij})_{m\times n} \big| i=1 \quad n, j=1 \quad m\}$. The

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original data needs to be standardized for the difference of dimension and magnitude. The formulas is as follows:

$$r_{ij} = x_{ij} \big/ (x_i^{\max} + x_i^{\min}) \quad (1)$$

Where, r_{ij} expresses the ith mechanical parameter in group jth after standardization. $x_i^{\max}$ expresses the maximum of the ith mechanical parameter, and $x_i^{\min}$ expresses the minimum。

The standardization mentioned above can make the optimization index keep the changing information of its value and reflect the trend of optimization[16]. The standard value of optimization index are listed in table 3.

Table 3. The Standard Value Of Optimization Index

Parameters	γ	σ_c	E	σ_t	C	φ	μ
Similar material	0.500	0.577	0.468	0.545	0.649	0.485	0.493
Ratio Ⅰ	0.500	0.423	0.475	0.455	0.315	0.515	0.502
Ratio Ⅱ	0.500	0.456	0.501	0.474	0.530	0.502	0.507
Ratio Ⅲ	0.500	0.573	0.532	0.506	0.685	0.488	0.498

The same density plays no role in the optimization results, so the index γ can be ignored. The standard matrix of the other indices is as follows:

$$R = \begin{bmatrix} 0.425 & 0.471 & 0.474 & 0.315 & 0.514 & 0.499 \\ 0.458 & 0.498 & 0.493 & 0.530 & 0.501 & 0.505 \\ 0.575 & 0.529 & 0.526 & 0.685 & 0.486 & 0.495 \end{bmatrix}$$

3.3 Grey Fuzzy Membership Degree

As the comparison sequence of each scheme, the standardization index set is recorded as $R = (r_{j1}, r_{j2}, \cdots, r_{jn})\ j = 1, \cdots, m$,and the optimal scheme sequence is $R^0 = (r_1^0, \cdots, r_n^0)$. The gray correlation analysis was made with R and R0 referencing the grey correlation degree analysis theory, and acquired the grey correlation coefficient about scheme j and the optimal scheme.

$$\delta_{ij} = \frac{\min_j \min_i |r_i^0 - r_{ij}^{'}| + \rho \max_j \max_i |r_i^0 - r_{ij}^{'}|}{|r_i^0 - r_{ij}^{'}| + \rho \max_j \max_i |r_i^0 - r_{ij}^{'}|} \quad (2)$$

Where, δ_{ij} is the correlation coefficient，and it represents the difference of the comparison sequence and the optimal scheme sequence concerning index i th. $\rho \in [0,1]$ is the resolution ratio，and its role is to weaken the impact of distortion arising from the maximum absolute difference, and improve the significance of difference among the correlation coefficients. Generally, the reasonable value of ρ is 0.5.

Generally,the grey correlation coefficient and fuzzy membership degree is similar in geometry, therefore, the grey correlation coefficient was used as the grey fuzzy membership degree to determine the membership degree. It can reflect the integrity of the scheme by taking into account the influences of all aspects . So the discriminant matrix of membership degree can be acquired by using equation (2) as follows:

$$\Delta = (\delta_{ij})_{m \times n} \quad (3)$$

For the particularity of the study object, the mechanical parameters of the prototype for similar material,that is, the actual parameters of rock mass is mining area are the optimal value in the evaluation model, therefore, the optimal sequence can be expressed as follows:

$$R^0 = (0.577 \quad 0.468 \quad 0.545 \quad 0.649 \quad 0.485 \quad 0.493)$$

The grey fuzzy membership degree matrix can be acquired by using equation (3).

$$\Delta = [\delta]_{3\times 6} = \begin{bmatrix} 0.532 & 0.978 & 0.663 & 0.340 & 0.861 & 0.966 \\ 0.592 & 0.849 & 0.714 & 0.595 & 0.921 & 0.937 \\ 0.998 & 0.735 & 0.827 & 0.840 & 1.000 & 0.987 \end{bmatrix} \quad (4)$$

3.4 Determination Of Weight

The common methods for weights are AHP, entropy, principal component analysis, binary contrast and combination method, etc. And

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different calculation methods are suitable for different research object.

The AHP and the entropy method are introduced into the calculation for the particularity of the study object. And only the final results were shown duo to space limitations.

$$\omega=[0.157 \quad 0.093 \quad 0.092 \quad 0.489 \quad 0.085 \quad 0.084]$$

3.5 Optimization Results

The grey fuzzy membership degree was then weighted to calculate the membership degree vector for each scheme.

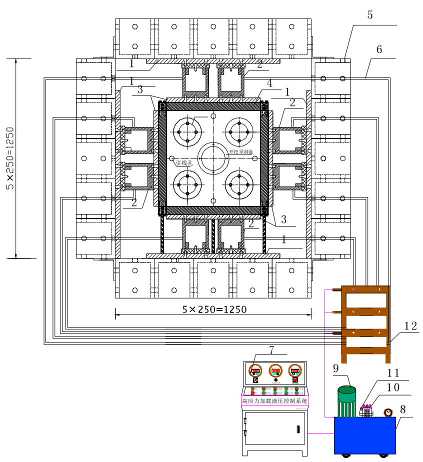
$$A=\omega\circ\Delta=[0.262 \quad 0.323 \quad 0.415]$$

According to the principle of the maximum membership degree, the optimal scheme is Ratio □, and the optimal membership is in the following order: Ratio □> Ratio □ > Ratio □. So the similar material of Ratio □ was applied in geological mechanical model test.

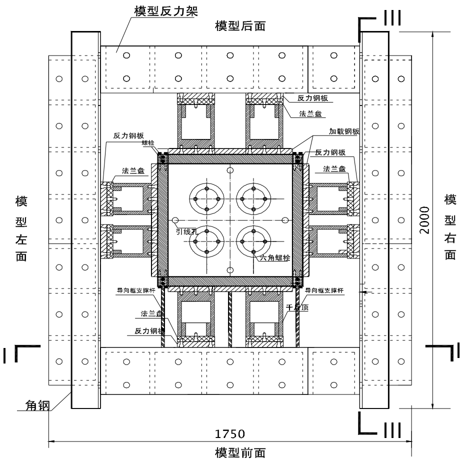
4. ENGINEERING APPLICATION FOR THE OPTIMIZATION RESULTS

4.1 Model Test System

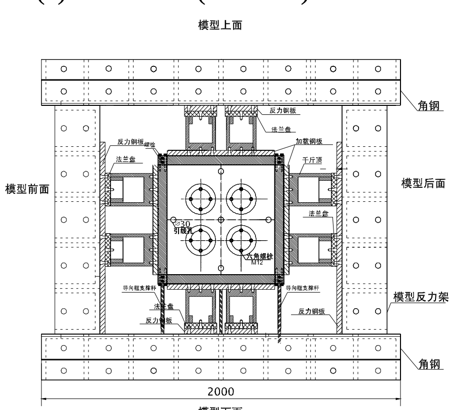
In order to simulate the environment of high geo-stress for surrounding rock in deep tunnel accuratly, and develop the model test effectively, our team developed a kind of true 3D model test system that can be digital,synchronous, independent when loading high geo-stress (patent no. ZL200810016641.0). The equipment uses the high stress and large size model system, and improved the insufficient in current model effectively, such as lacking high stress, smaller size and the rough control accuracy. The design drawing and the 3D visualization are shown in figure 6. And figure 7 shows the finished model test system.



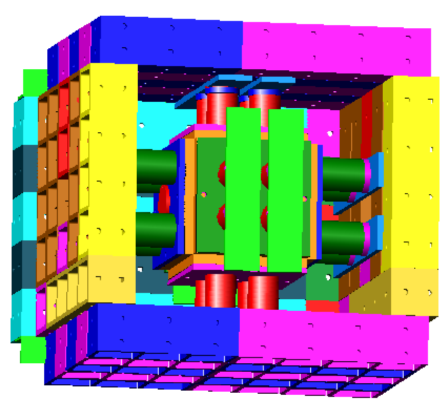
(a) front view (unit:mm)



(b) top view (unit:mm)



(c) side view (unit:mm)



(d) 3D visualization

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***Figure 6**. The design drawing of the high geostress-true triaxial model test system*

(A) The Finished Model Test System (B) Front View Of Internal System (C) Top View Of Internal System

***Figure 7**. The True Triaxial High Geostress Loading Model Test System*

4.2 Analysis For The Damage Of Model Test

The geo-mechanical model test made by the similar material of Ratio □ appeared zonal disintegration phenomena around the tunnel, where the fractured zone and the non-fractured zone spaced at regular intervals. The observed damage phenomena of the rock around the tunnel[9]are shown in figure 8. In their outward order from the entrance in the direction of the axis , the distance are 10cm、20cm、30cm and 40cm, corresponding to (a), (b), (c) and (d) respectively. The phenomenon is very close to the monitoring field of Dingji coal mine, where the extension of the fractured layer and the fractured zone are similar. It indicates that the model test can reflect the mechanism of the zonal disintegration of the surrounding rock in deep tunnel effectively.

(a) (b) (c) (d)

Figure 8. Damage phenomena of model test

4.3 Analysis Of Monitoring Results

By the comparison of the model test results to be converted into the prototype and the distribution of the fractured zone in-situ monitoring, we found that the laboratory simulation coincided with the monitoring field. The comparison of fractured zone extension between the results of model test(converted into the prototype) and in-situ monitoring are shown in table 4.

Table 4. The Comparison Of Fracture Zone Extension Between The Results Of Model Test And In-Situ Monitoring

	Fracture Zone Extension			
Fractured layers	1	2	3	4
Results of in-situ monitoring /m	0～1.7	2.3～3.2	4.8～5.8	6.2～6.5
Results of model test /m	0～1.6	2.4～2.7	4.4～4.6	6～6.2

From the comparative analysis of the results listed in table 4, we can see that the optimal proportion of similar material used in geo-mechanical model test can acquire the similar phenomenon coincided with the monitoring field. It indicates that the optimal proportion of the similar material meets the test requirements, and the result of the optimization is reasonable.

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5. CONCLUSION

(1) With recent advancements in experimental techniques, the improved grey fuzzy optimization model can be applied in the true 3d geo-mechanical model test for optimizing similar material. The method was easy, convenient and quick, and can save a lot of time spending on the test. However, the model needs to be a further development.

(2) The optimal proportion of the similar material was got by using the model, and the optimization result was applied to the true 3 d geological mechanical model test for similar material, and simulated successfully the process of excavation in high geo-stress environment deep tunnel. The reappearance of the zonal disintegration phenomena of surrounding rock under excavation in high geo-stress environment deep tunnel of Dingji coal mine. It indicates that the optimal proportion of the similar material meets the test requirements, and the result of the optimization is reasonable.

(3) As the precondition of the optimization, the establishment of the evaluation index system is complicated. It should be pointed out that the index system is not unchangeable,

it should be different according to the different or specific geological mechanical model test.

6. ACKNOWLEDGEMENT

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