ISSN: 2688-8645

Experimental Study on Zonal Disintegration of Surrounding Rock of Deep Rock Masses

Leyang Zheng[1, 2, a, *], Qiangyong Zhang[1], Zhongxian Li[1], Qiang Gao[1], Xun Zhao[1]

[1]Shandong University, Shandong, China;

[2]Shandong Shixin Construction Co.,Ltd, Shandong, China.

[a]Email: 868389126@qq.com

Abstract

In deep rock mass excavation and support engineering field, foreign and domestic scholars are unclear about zonal disintegration formation mechanism of deep tunnel. Therefore, generation, development and formation process of zonal disintegration should be studied through geomechanical model test of similar materials. With monitored zonal disintegration phenomenon of Fengji Coal Mine in Anhui Mining Area as engineering background, a new similar rock material, iron crystal sand cementing material is used for geomechanical model test of similar material with excavated material from deep roadway on 3D high ground stress condition by self-developed high ground stress 3D loading geomechanical model test system. Zonal disintegration phenomenon of surrounding rock in deep roadway and nonlinear deformation change law inside surrounding rock of tunnel are simulated effectively, which lays solid test foundation for studying nonlinear deformation failure mechanism of surrounding rock in deep roadway.

Keywords

Deep rock masses; 3D geomechanics; nonlinear failure; geomechanics.

1. Introduction

In recent years, as economic construction grows fast in our country, demand for energy increases day by day, and exploitation strength increases constantly. As shallow resource decreases gradually, mining develops toward deep constantly. According to resource mining situation at present, coal mining depth increases at the speed of 8m to 12m in our country. In recent years, some coalmines have entered deep mining. For example, the exploitation of Anhui Fengji Coal Mine, Xinwen Suncun Mine, Shenyang Caitun Mine, Kailuan Zhaogezhuang Mine, Xuzhou Zhangxiaolou Kuang, Biaopiao Guanshan Mine, Beijing Mentougou Mine has extended to nearly 1000m underground. In addition, to meet the demand, many metal and nonferrous metal mines have shifted to deep mining. For example, 1# Mine in Jinchuan Mining area has been mined to 1250m underground, the mining depth of Tongling Shizishan Copper Mine has reached 1100m, and the mining depth of Fushun Hongtoushan Copper Mine has entered 900m to 1100m. It is predicted that many metal and nonferrous metal mines will enter 1000m to 2000m deep mining in our country. According to incomplete statistics, there are over 80 metal mines abroad with mining depth exceeding 1000m, and most of them are in South Africa. Mining depth of a majority of gold mines in South Africa is below 1000m. Where, the depth of three ones exceeds 2400m. In addition, the mining depth of some nonferrous metal mines exceeds 1000m in Russia, Canada, USA and Australia.

With constant increasing of mining depth, when tunnel or roadway is excavated in deep rock masses, alternative fracture zone and non-fracture zone will happen to surrounding rock on both sides and forward, and such phenomenon is called zone facture phenomenon. Zonal disintegration phenomenon is verified using multiple physical detection approaches in exaction of many foreign and domestic deep tunnel projects. In 1980s, E.I. Shemyakin et. al. discovered zonal disintegration phenomenon using resistivity meter at Taimyrskii mining site of deep mine (see Fig. 1).

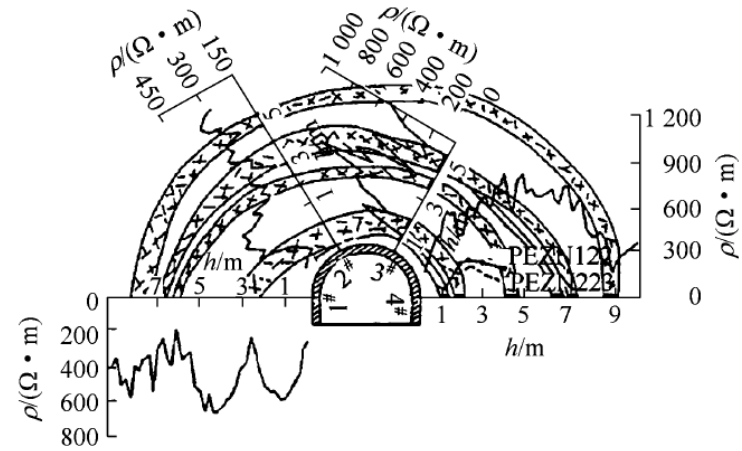


Fig 1. Zonal disintegration phenomenon of Taimyrskii Mine

G. D. Adams and A. J. Jager monitored roof spacing fracture at 2000m to 3000 deep of Witwatersrand gold mine in South Africa with borehole periscope. Fang Zulie monitored deformation of surrounding rock in one deep roadway of Jinchuan Ni Mine area with multipoint displacement meter, and obtained zonal disintegration phenomenon of surrounding rock as shown in Fig. 2. Liu Gao et. al. obtained the measured surrounding rock stress result along radial direction of drill hole perpendicular to side wall of tunnel in the 1200m middle section of Jinchuan 2# Mining Area. The result is greatly different from surrounding rock stress distribution law of shallow tunnel (See Fig. 3). Li Shucai et. al. probed and observed zonal disintegration phenomenon from surrounding rock of deep roadway in Dingjiao Coalmine of Huainan Mining Area with borehole tester, and recorded it with a video recorder, which confirmed zonal disintegration effect existing in surrounding rock of deep roadway.

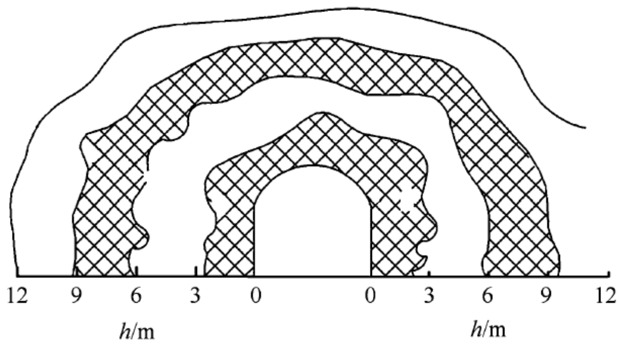


Fig 2. Zonal disintegration phenomenon of deep roadway in Jinchuan Ni Mining Area

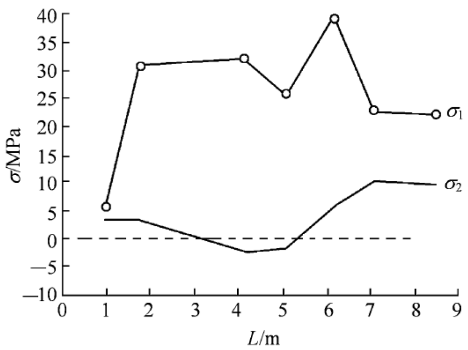


Fig 3. Measured surrounding rock stress result of one test tunnel in the 1200m middle section of Jinchuan 2# Mining Area

Zonal disintegration phenomenon of surrounding rock in deep roadway is greatly different from successively arranged fracture zone, plastic zone and undisturbed elastic zone appearing around the tunnel during excavation of shallow underground tunnel, which attracts experts' and scholars' great attention in international rock mechanics engineering field and becomes research topic of such field in recent years. In theoretical exploration of zonal disintegration formation phenomenon, Wang Ming Yang et. al. studied "quantization" effect of geomechanical energy of surrounding rock of deep roadway, and pointed out appearance of surrounding rock spacing fracture of deep tunnel. To this end, support form, tunneling method, and support scope should be reconsidered. Zhou Xiaoping and Qian Qihu deemed excavation of deep roadway as dynamic problem, used displacement potential function as equation of motion, and applied elastic mechanics and fracture mechanics to determining residual strength of rock mass in fracture zone and generation time of fracture zone, and further determined width and quantity of fracture zone and non-fracture zone. In test study of zonal disintegration phenomenon, E. I. Shemyakin et. al. verified zonal disintegration phenomenon discovered at Taimyrskii mining site of deep mine. According to model observance, it was found out the load change was rather slow and could be deemed to be static when surrounding rock zone was broken. Thus, spacing fracture phenomenon was deemed to be formed when external condition did not change or change slowly, and it lasted a longer time. E. J. Sellers and P.Klerck studied the impact of discontinuous surface of surrounding rock of deep tunnel on spacing fracture and observed that discontinuous surface might become one of surrounding rock spacing rapture sources of tunnels when a certain requirement was met. Tang Chun'an and Zhang Yongbin analyzed numerical simulation of fracture process in parallel on the 3D loading condition with RFPA and zonal disintegration phenomenon reappeared. Results show that spacing facture phenomena is the outcome of annular tension failure of surrounding rock along roadway under the effect of main stress.

In recent years, many experimental studies have been made on zonal disintegration phenomena by domestic scholars. Pan Yishan et. al. made a 30cm×30 cm×10 cm model with gypsum, a 6cm drillhole was preserved at the center of model. Such test was loaded in the form of planar stress, but only crack extended along loading direction was observed in the test, zonal disintegration phenomenon did not appear. Gu Jincai et. al. [19] made a cylinder compression model test of preserved tunnel with mortar and found many cracks appeared on surrounding rock of tunnel under axial high ground stress effect of paralleled tunnel, and there was no failure zone among cracks. They verified the existence of zonal disintegration with model test. However, such test was not similar material model test with engineering as background. Similarity of material was not considered, neither excavation process of tunnel. Moreover, loading adopted planar strain loading, high ground stress 3D loading process of deep tunnel was not simulated. In addition, the test focused on observing fracture phenomena, but no

ISSN: 2688-8645

measuring gage was distributed in the test model to analyze surrounding rock deformation change law of tunnel.

2. Principle of Similitude and Selection of Similar Material

2.1. Principle of Similitude

Similitude principle of model test refers to the returned physical phenomenon on the model should be similar with prototype. Model material, model shape and load should follow a certain law. Physical quantity between prototype (P) and model (M) with the same dimension is called similar scale, expressed with letter C. L is length, γ is volume weight, δ is displacement, σ is stress, ε is strain, E is modulus of elasticity, tσis tensile strength, c σ is compressive strength, c is cohesion, ϕ is frictional angle, μ is Poisson's ratio, and f is friction coefficient. According to principle of similitude, prototype and model should meet the following similarity relation:

(1) Stress similitude scale Cσ, volume weight similitude scale Cγ and geometric similitude scale LC should meet the following similarity relation:

$$C_\sigma = C_r C_L \tag{1}$$

(2) Displacement similitude scale Cδ, geometric similitude scale Cσ and strain similitude scale Cε should meet the following similarity relation:

$$C_\delta = C_\varepsilon C_L \tag{2}$$

(3) Stress similitude scale Cσ, elasticity modulus similitude scale C_E and train similitude scale Cε should meet the following similarity relation:

$$C_\sigma = C_\varepsilon C_E \tag{3}$$

2.2. Selection of Similar Material

According to similitude principle of model test, a new similar rock material is developed. It is a composite formed by mixing and compacting a specified proportion of refined iron mine powder, blanc fixe, quartz sand, gypsum, and rosin alcohol solution and thus called similar iron crystal sand cemented material. According to physical mechanics parameters of similitude principle and prototype materials, model similitude scale is 1:50. Thus, physical mechanics parameters of roadway model material could be computed (See Table 1).

Table 1. Physical mechanical parameters of primary rock and model materials

Type of Material	Volume Weight /($\mathbf{KN} \cdot \boldsymbol{m}^{-3}$)	**Modulus of Deformation** /MPA	Cohesion /MPA	Internal Friction Angle /（°）	Compressive Strength /MPA	Tensile Strength /MPA	Poisson's Ratio
Primary Rock Material	26.2	12620.2	10.0	44	88.62	14.12	0.266
Model Material	26.2	258.2	0.2	44	1.76	0.29	0.266

ISSN: 2688-8645

3. Processing and Making of Deep Roadway Test Model

The model test takes deep roadway project of Anhui Fengji Coalmine as research object. The roadway section form is semicircle arch, the sectional dimension is 5000mm×3880 mm, and burial depth is 910m. The roadway is mainly in medium sandstone and fine sandstone stratum, and stress field of mining area is mainly horizontal tectonic stress.

3.1. Model Simulation Scope

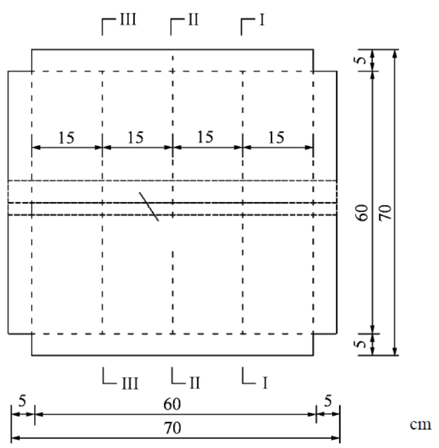
The prototype simulation scope is: length (along axis of tunnel, namely X-axis) x width (perpendicular to tunnel axis, namely Y-axis) x height (along height, namely Z-axis)= 30m×30m×30m. considering 1:50 geometric similitude scale, the simulation dimension of the model is LxWxH=0.6m×0.6m×0.6m, and sectional dimension of model is 100.0mm×77.6mm.

3.2. Modeling Process

3D model of deep tunnel is made using hierarchical compaction method. Basic process is below: weigh and prepare material according to the given proportion→ mix materials evenly with a mixer → pave materials on testbed by layers from bottom to top → compact materials evenly with a compression board → accelerate air flow with a fan to air dry the compacted materials → lay measuring elements by layers around the tunnel according to designed elevation (including strain brick, grating scale multipoint displacement meter and FBG strain transducer), pave, compact, air dry next layer of materials, bury measuring elements until completing of modeling.

3.3. Layout of Model Measuring Elements

To observe zonal disintegration phenomenon of surrounding rocks effectively, multiple measuring elements are buried in the area that might have zonal disintegration around model tunnel according to site zonal disintegration observation record of deep roadway at Fengji Coalmine of Anhui Mining Area, mainly including strain bricks (stuck with strain gage), minitype high-precision grating scale multipoint displacement meter, FBG strain transducer.



I-I and III-III is strain measurement section; II-II is displacement measurement section

Fig 4. Model monitoring section layout diagram

4. Model Excavation Test

Gravity stress of model roadway is deemed as γh, and ground stress perpendicular to tunnel axis is 1.5γh. Where, h is burial depth of roadway, and ground stress paralled with tunnel axis is imposed according to 1.7 times of compressive strength of model material. Model boundary loading is controlled by hydraulic control system, and model boundary loading increased by proportion until set value. After completing load, the load keeps constant, and model roadway is excavated using full-section manual drilling way. whenever a footage (2m is a footage for the prototype, 40cm is a footage for the model) is excavated, excavation stops, the reading change of model should be measured and recorded with sensor. Then, excavation, test and record of next footage proceeds until completion of tunnel excavation.

5. Model Test Result Analysis

5.1. Test result with Grating Scale Multipoint Displacement Meter

After completing exaction, displacement value on measured points around tunnel is marked around the model tunnel. Then, value of each point is connected with a smooth curve to get displacement change law of measured points around the model (see Fig. 5).

Through analysis of Fig. 5, it is known:

(1) After excavation, displacement on each measured point of test line around tunnel shows wave-shape change with crest and valley distributed at interval. Such change law is totally different from the law that displacement around shallow tunnel decreases gradually as the distance from wall of tunnel increases. It indicates that zonal disintegration exists in surrounding rock of tunnel after excavation, crest position with great displacement is surrounding rock failure zone, and valley position with small displacement is surrounding rock non-failure zone.

(2) Displacement of left and right side wall in symmetric position is not fully symmetric, indicating that zonal disintegration zone is not always the concentric circle of the excavated tunnel, and ehre might be offset.

(3) Displacement on measuring point 1 on vault, arch bottom, left and right side wall that is nearest tunnel wall is relatively great, indicating that zone near the tunnel wall is surrounding rock fracture zone in traditional sense, and it is consistent with surrounding rock failure observed in the test.

(4) Displacement of the measured point 6 at farthest end of left and right side wall is smaller than that of other measuring points on test line of left and right side wall. It indicates that such part is close to critical range of zonal disintegration. However, displacement on measured points farthest from vault and arch bottom is greater than that of measured points near the valley, indicating that such part is most outer fracture zone of zonal disintegration.

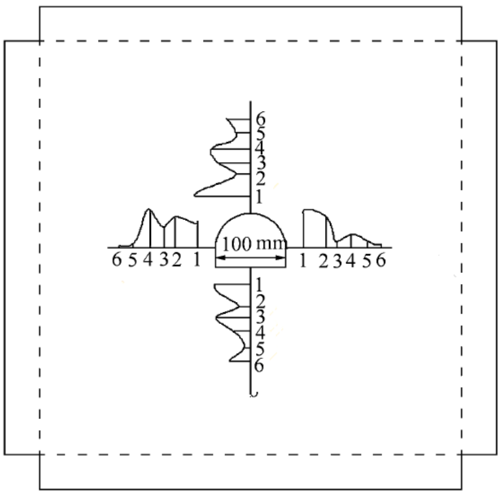


Fig 5. Displacement change law on measured points around the model tunnel

ISSN: 2688-8645

Through checking fracture distribution 10cm, 20cm and 30cm from entrance of tunnel along axial direction of tunnel, it is known:

(1) With increasing of depth, zonal disintegration phenomenon is more obvious, obvious fracture and non-fracture spacing distribution, namely zonal disintegration appeared. It is consistent with test analysis result of displacement around tunnel.

(2) Four-layer fracture zone and four-layer non-fracture zone around model tunnel are arranged at interval. Where, fracture zone nearest tunnel wall is surrounding rock crushing zone in traditional sense, the distance of fracture zone in outmost layer from tunnel entrance is about 7m if converted into prototype, and it is identical to measured fracture layers and fracture zone of Anhui Fengji Coalmine, indicating that the model test reflects zonal disintegration phenomenon of surrounding rock of deep roadway.

5.2. FBG Strain Transducer Test Result

Fig. 6 presents FBG strain transducer layout diagram. After all the tunnel excavation is completed, radial strain change of FBG measuring points is drawn along test line (see Fig. 7). According to Fig. 7, it is known that radial strain change law of left wall of tunnel measured with FBG strain transducer is consistent with that measured with grating scale multipoint displacement meter. In other words, the radial strain around the tunnel also shows waveform change with crest and valley distributed at interval. Such change law is totally different from the law that radial strain around shallow tunnel decreases gradually with the increasing of the distance from tunnel wall. It indicates that crest position with greater radial strain is surrounding rock failure zone, the valley position with smaller radial strain is surrounding rock non-failure zone. Moreover, zonal disintegration phenomenon alternated by fracture and non-fracture is also measured with FBG strain transducer.

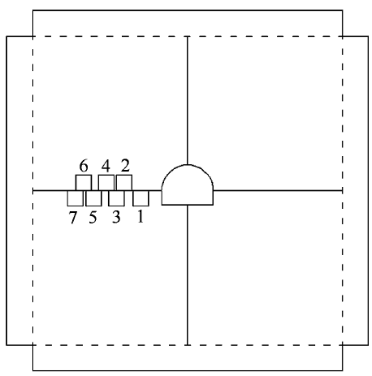


Fig 6. FBG strain sensor layout scheme

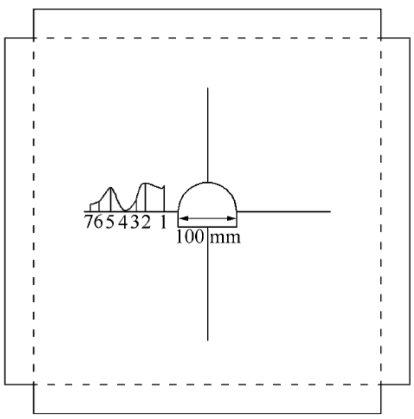


Fig 7. Radial strain change law on measured points measured with FBG strain transducer

ISSN: 2688-8645

5.3. Strain Gage Measurement Result

Fig. 8 shows strain brick layout diagram around the tunnel. Fig. 9 shows radial strain change of measuring points around tunnel measured with strain bricks. According to Fig. 9, it is known that radial strain around tunnel measured with strain brick also shows waveform change with crest and valley distributed at interval. Such change law is identical to test change law of previous grating scale multipoint displacement meter and FBG strain transducer, indicating that zonal disintegration phenomenon alternated by fracture and non-fracture existed around the excavated tunnel.

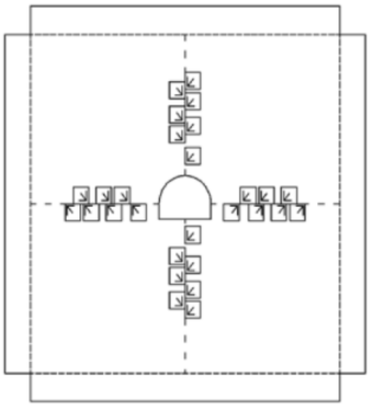


Fig 8. Layout of strain bricks

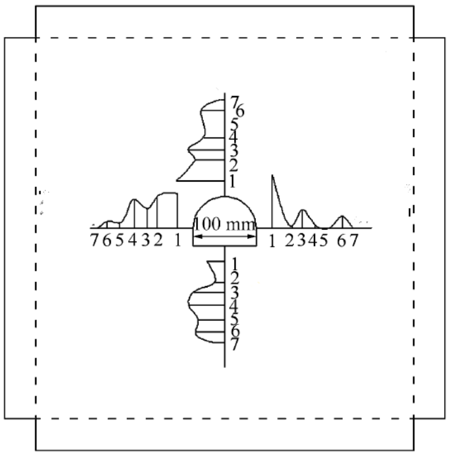


Fig 9. Radial strain change law on measured points around the tunnel measured by strain bricks

6. Conclusion

Through similar material 3D geomechanical model test of deep roadway at Anhui Fengji Coalmine on high ground stress condition, the following conclusions are drawn:

Using new iron crystal sand cemented similar rock material and self-developed high-ground stress true 3D loading model test system, zonal disintegration phenomenon of surrounding rock of deep roadway firstly reappears through 3D geomechanical model test.

Multiple testing methods like high-precision grating scale multipoint displacement meter, FBG strain transducer and strain bricks are adopted to obtain displacement and radial strain waveform change of surrounding rock of deep roadway with crest and valley distributed at interval on high ground stress condition. Such change law indicates that zonal disintegration

ISSN: 2688-8645

exists around the tunnel. It is consistent with zonal disintegration alternated by fracture and non-fracture of the crosswise cut-through model along axis of tunnel.

Test results indicate that higher excavation stress along axis of tunnel is the main reason for zonal disintegration of surrounding rock of deep roadway.

Zonal disintegration layers of surrounding rock around tunnel and fracture zone distribution scope disclosed by the model test is consistent with the field measured results, indicating that geomechanical model test could simulate nonlinear deformation characteristics and failure law of deep roadway on high ground stress condition, which lay solid test foundation for nonlinear deformation failure mechanism of surrounding rock of deep roadway.

References

[1] Fang Zulie. Maintenance Principle and Control Measures of Soft Rock Tunnel [C]// Edited by He Manchao. Theory and Practice of Soft Rock Tunnel Support of Coalmine in China. Beijing: Coal Industry Press, 1996: P64 to P70.

[2] He Manchao, Xie Heping, Peng Suping, et. al. Study on Deep Mined Rock Mass Mechanics [J]. Chinese Journal of Rock Mechanics and Engineering, 2005, 24(16): P2803 to P2813,

[3] Zhu Jie, Wang Renhe, Lin Bin. Study on Frequent Fracture Phenomena and Fracture Opening of Surrounding Rock of Deep Roadway [J]. Journal of China Coal Society, 2010, 35 (6): P887 to P890.

[4] Gu Jincai, Gu Leiyu, Chen Anmin, et. al. Experimental Study on Layered Fracture Filure Mechanism Model of Surrounding Rock of Deep Excavated Tunnel [J]. Chinese Journal of Rock Mechanics and Engineering, 2008, 27(3): P433 to P438.

[5] Li Jianfeng, Cheng Jianlong, Feng Chaochao. Zonal Disintegration Simulation Experiment of Surrounding Rock of Deep Soft Rock Roadway [J]. Journal of Liaoning Technical University (Natural Science)

[6] Yuan Pu, Xu Ying, Xue Junhua. Experimental Study on Anchor Supported Deep Roadway Blasting Excavation Model [J]. Chinese Journal of Rock Mechanics and Engineering, 2016,35(09):P1830 to P1836.