The 6th International Conference on Mining Science & Technology

Exploration of numerical simulation on paleo-tectonic stress field

Zhou Chun-mei\textsuperscript{a}, Zhang Ze-jun\textsuperscript{b}, Wang Sheng-wei\textsuperscript{b}, Li Xian-fu\textsuperscript{a,}\textsuperscript{*}

\textsuperscript{a} School of Environment and Civil Engineering, Wuhan Institute of Technology, Wuhan 430073, China

\textsuperscript{b} Faculty of Earth Sciences, China University of Geosciences, Wuhan 430074, China

Abstract

This paper analyzed the numerical simulation method of Paleo-tectonic stress field from three aspects: tectonic simulation target, establishment of the tectonic model, and tectonic modeling. Taking Chengzhuang coal mine of Jin city in Shanxi Province as an example, based on field investigations on macro and micro tectonic features, we established plane-stress model and 3d geological model at first, and selected mechanical parameters of rock mass, boundary condition and failure criterion of rock, then, determined the magnitude of paleo-tectonic stress and the loading sequence of stress by using of large scale numerical simulation software ANSYS and FLAC. The simulation results show that two stages of large tectonic movement should have taken place at Chengzhuang coal mine in history, that is it is in east-west direction at first, and then turned to south-north direction; and the magnitudes and directions of tectonic stress are 60Mpa, east-west direction, and then 110 Mpa, south-north direction respectively. This tectonic action could meet most shear joints on the earth and in the 3# coal rock taken place simultaneity. The region with a weak resistance capacity to deformation is easily destroyed in uniform stress field, because the shearing resistance capacity of rock mass namely internal friction angle was different. This analysis has an important significance to risk zoning and gas outburst regional predicting in coal mine.

Keywords: paleo-tectonic stress, tectonic simulation, plan-strain, shear joint

1. Introduction

Simulation of Paleo-tectonic stress field can recover or inverse the process of tectonism, which includes the action mode, direction, magnitude and boundary condition of Paleo-tectonic stress, the environment where medium are situated and the mechanical properties of medium, according to structural features left behind by tectonic in geological history. Key problem in numerical simulation analysis to Paleo-tectonic stress field is how to understand the magnitude and the loading order of stress in boundary conditions, in geological modeling. Meanwhile, numerical simulation volume and geological model must keep similarity with each other\textsuperscript{[1][2]}. Tectonic simulation can be approximately divided into three parts, tectonic simulation target determining, abstract or establish tectonic modeling and tectonic simulating.

Target of tectonic simulation can be defined as an important symbol to judge a tectonic simulation is successful or not. Usually, it determines the final result of deformation or style which includes structural deformation sequence and successive deformation process, mainly by field geological investigation and the synthesis of other geological
information. It needs to be explained that the way to realizing the results or style of final deformation is not unique. We can only regard it as a possible process of geological function, a rational explanation. The basis for establishing a tectonic model is tectonic simulation target, abstract a numerical model, including morphology of medium (or geological body), acceptance or rejection of mechanical parameters, relationship and boundary condition between different dielectric bodies, and the determination of action mode, direction and magnitude of tectonic stress. As for issues of multiple stage tectonic deformation, we should consider the boundary condition and the action mode, direction, magnitude of external force by stages. Whether tectonic model can be established reasonably is the key to tectonic simulation.

Tectonic simulation was that, based on the idea of replace uneven with even, used finite element method and finite difference method, and then obtain quantitative simulation data (principal stress, stress and displacement) by using calculations of different stages or process of tectonic model with the tool of massive or computer at different stages.

The thinking of tectonic simulation was proposed in the process that exploring tectonic stress field numerical simulating to Chengzhuang coal mine, Jincheng city, Shanxi Province. It should be point out is that the tectonic simulation methods and achievements we have summarized are both innovative, that’s because tectonic deformation formed in geological history has two characteristics, one is the rate of tectonic deformation is extremely slow, it is a long process \[3-5\], elastic deformation state transformed into rheology state, which related with time, in this long deformation process. Another is that, most of the tectonic deformations are large deformation problems, these rheology and the large deformation problems related with time, are difficult topics need further exploration in numerical simulation up to now.

2. Tectonic simulation target

Jincheng Chengzhuang coal mine in Shanxi Province, located in south section of ne-trending, Zhanshang-Wuxiang-Yangcheng fold belt, is north north eastern secondary tectonic unit in Qingshui block col, Lviang-Taishang fault block, north China fault block. There only outcropped quartz sandstone in upper paleozoic under Hezi group (P1x) to siltstone and fine sand interbedded in Shiqianfeng group (P2sh) on the mining area ground surface. The general trend of mining area was a monoclinal structure, which trending was north-ne (Northern), gradually turned to ne-trending (Southern), formation was gentle (Dip angle:3°-15°, generally within 10°), and the tendency was northwestwards. Though the tectonic deformation was relatively weak and there was no evidence of magmatism in this monoclinal structure, fold and fault in different time of stage, especially the joints deforming information, still relatively developed, and it is similar to regional tectonic.

Macroscopic tectonic information, namely fold and the fault which not developed relatively high, show that, there existed very gentle tectonic style of interphase fornix-basin, which with pan bottom downward and upward simultaneously, it reveals that the direction of early maximum principal pressure stress was nearly east-westward, and the direction of advanced maximum principal pressure stress adjusted to nearly south-northward. The joints can be determined as three different tectonic sequence or three periods joint according to intersected relations and ordered fine observations and systematic measurements of more than 80 ground surface joint points. The direction of early joints maximum principal pressure stress was early nearly east-westward, the second phase was north-southward, and the advanced is northwest-southeast (Fig 1). Among them, joints in the first and second phase developed relatively, they are associated products of early similar to south-north folds and advanced similar to east-west folds respectively, the later only fragmentary in distribution, the folds deformation corresponding to it was not obvious. There still was the same deformation information downwards 500m from ground surface, namely the roof and floor of 3# coal seam. According to above mentioned, the final deformation result was mainly about tectonic superposition of early nearly south-northward and advanced nearly east-westward, corresponding to early nearly east-westward and advanced nearly south-northward respectively. Undoubtedly, that is the target model reconstructed by tectonic simulation.
We established a plane stress model, by simplifying three-dimensional medium as plane homogeneous body, only considering the parts of ground surface, namely with the target of simulating reconstruction by the model of Fig 1, mainly according to the field investigation results, that is, the tectonic stress field formed simultaneously reconstructed joints and folds of each observation points in this region are the optimum results of this simulation, which under the action of early nearly east-westward maximum principal stress $\sigma_{ew}$ and south-northward principal stress $\sigma_{sn}$, and determined boundary conditions according to related principle. Then stress concentration regions and weak deformation regions in stress field could provide function of forecasting. Another method is three-dimensional tectonic model, it abstracted geological issues as a three or multiple layers to processing, the surface layer was the same to the former model, the difference was that three-dimensional tectonic model not only should satisfy with ground surface reconstruct target(Fig 1), but also should reconstructed the deep part of basic conditions such as a part or most of joints in different time of stage, in 3#coal seam.

3. Tectonic models

3.1. Geological model

Plane stress model containing irregular boundary conditions were easy to generate additional moment, which would cause the model imbalance, so we extend the research scope of Fig 1 to rectangle (as fig2).

3.2. Determination of boundary conditions

Load condition: according to the test results of different parts in 3# coal seam roof and bottom, we calculated out that $\sigma_{ew}$ changes between 59-61 Mpa, and tends to a constant value of 60Mpa, test result $\tau_{0}$ approximated as a constant value of 20Mpa, adjusted $\sigma_{sn}$ to generate joints in study area as shown in Fig. 1. The $\sigma_{sn}$ is the final result of tectonic simulation when shearing rupture occurred in most points at the same time.
Constraint conditions: The first period tectonic deformation, loaded \(\sigma_{cw}\) to east-westward and constrained in south-northward, equivalent to the displacement is 0 in infinite point. The surface on vertical direction was free surface, and the displacement in infinite point downwards was 0. The second period tectonic deformation, we took the style of the first period tectonic deformation terminate as original shape, that was on the basis of the first period tectonic deformation terminate, simulated superimposed tectonic deformation, loaded \(\sigma_{sn}\) to south-northward, and constrained in east-westward, equivalent to the displacement was 0 in infinite point. The surface on vertical direction was free surface, and the displacement in infinite points downwards was 0.

3.3. Determination of rock rupture criterion

Joints in this area mainly presented as a brittle shear one, according to mohr-coulomb criterion. According to mohr-coulomb strength theory and limit equilibrium condition, the angle between normal direction \(k\) of shear failure plane and maximum principal stress \(\sigma_1\) was \(45^\circ + \varphi/2\), and satisfied the following formula:

\[
\sigma_1 = \sigma_3 \tan^2 (45^\circ + \varphi/2) + 2\varepsilon \tan (45^\circ + \varphi/2)
\]

where friction angle \(\varphi\) in formula 1 is an important parameters that reflect geological body capacity of resist shear failure geological body, namely absolute value of angle difference value, \(N\) groups conjugated shearing rupture plane 1 and 2 by field geological investigation. Internal friction angle showed nonlinear variation, that is because the medium has obvious heterogeneity, or the variation of temperature and pressure environment in different periods of a medium. Introduced friction angle \(\varphi\) into formula (1), relation formula between \(\sigma_1\) and \(\sigma_3\) can be obtained. Maximum principal stress \(\sigma_1\) corresponding to the geological body failure, calculated by formula 1, in which \(\sigma_3\) was the result of numerical simulation, compared the value of \(\sigma_1\) with numerical simulation \(\sigma_1\), when \(|\sigma_{\text{limit state}} - \sigma_{\text{numerical simulation}}| \leq 10\) Mpa, geological body at a critical state, when \(\sigma_{\text{limit state}} - \sigma_{\text{numerical simulation}} > 10\) Mpa, geological body at a safety state. When \(\sigma_{\text{limit state}} - \sigma_{\text{numerical simulation}} < -10\) Mpa, geological body is at a dangerous state. Critical state expressed that, investigation points just generated shear fracture joints under the tectonic, joint trend consistent with field investigation.

4. Tectonic simulation

4.1. Plane stress simulation

Plane stress model could be decomposed (Fig. 3) into independent actions of east-westward tectonic stress \(\sigma_{cw}\) (issue 1) and south-northward tectonic stress \(\sigma_{sn}\) (issue 2), according to principle of superimposed stresses, then superposed the actions. That is we should introduce node force calculated from east-westward load in issue 1 into
issue 2, and used initial stress at nodes in issue 2, then added south-northward tectonic stress to issue 2. The essence of this operation was make the load of east-westward and south-northward act on the model boundary as two phases, if loading to east-westward and south-northward but with no constraint at the same time, it is easy to result in non-convergence of calculation. Choose loading by stages was comparatively suitable, the result equivalent to effect of loading at the same time. Nodes, unit division and mechanical parameters of issue 1 and issue 2 are the same, there were differences in force and boundary condition only when independent effect on individually, numerical simulation is by using large-scale finite element analysis software ANSYS 8.1. Change loading sequence and stress magnitude, tectonic simulation was carried out respectively.

(1) Firstly loading $\sigma_{ew}=60$MPa to east-westward, and then loading $\sigma_{en}=110$MPa to south-northward (Fig 3). Stress calculating result showed that shearing rupture occurred at 51 nodes in 80, among them, 29 nodes were at critical state, 22 at dangerous state, and 29 at safety state.

Conclusions as follow can be obtained through different loading sequence and loading mode of tectonic stress:

(1) When magnitude of tectonic stress unchanged, loading sequence made great effects on the stress calculation result, and the result was mainly influenced by the magnitude of final loading.

(2) When magnitude of tectonic stress changed, loading sequence made a certain effect on the stress calculation result, and the result was mainly influenced by the functional range magnitude of final loading.
(3) According to lamination relationship of structural features, in this area, the loading sequence and the magnitude of tectonic stress is suitable, when first loading $\sigma_{ew}=60$ Mpa to east-westward, and then loading $\sigma_{ns}=110$Mpa to south-northward.

Simulating results showed that, principal stress distributed uniformly, except for the stress non uniformity caused by boundary effect in boundary, the reasons are analyzed as following:

(1) Rock strata showed nearly horizontal, we took the average of rock mass parameters in each units (in 3#coal seam and the overlying, mulching of rock strata) in the calculation, however, geological body is a complex multiphase-orthotropic one, physical property parameters are inhomogeneous.

(2) Without considering temperature field, however, the rock mass were embedded underground for a long time, thermal effect generated by temperature can cause a change in stress field of rock mass.

(3) The model was a complete and uniform global, without considering the faults and joints in it, in fact, the structural plane existed in the rock mass can cause a change in stress state.

(4) Load distributed uniformly acted on boundary of model, without considering loading by stage in history and the load changed with depth.

(5) Considered to thickness of overlying rock strata is according to present borehole data, without calculating the denuded rock strata thickness and the pressure is subjected of surface layer.

4.2. Tectonic simulation results

Plane stress tectonic results showed that, with the loading mode of loading $\sigma_{ew}=60$ Mpa to east-westward firstly, and then loading $\sigma_{ns}=110$ Mpa to south-northward, most of the nodes in the study area will be at critical states, among them, Liuhe, Dongpo, Luotuozhang, Beiluo, Zhongjie, and Dajianshan belongs to dangerous area, Houhe, Hexi, Yangzhuang, Shizhuang, Yuanjiejing, Gouxi, Fanzhuang, and Getao belongs to critical area, Duanhe,Guohe, Laoyanzhuang, and Jizhuang belongs to safety area (Fig 6).

![Fig. 6. Simulation results of plane-stress model](image)

The main reason of rock mass deformation failure in the uniform stress field resulted from the inconsistent capacity (internal friction angle) to resistant shear failure, it can be drawn by calculating the rock mass internal friction angle according to the joints conjugate angle by ground surface investigation, we can draw that the distribution of minimal internal friction angle namely heavy deformed was consistent with dangerous area (Fig 6).

5. Conclusions

(1) By taking Chengzhuang coal mine in Shanxi Province as an example, we put forward a Paleo-tectonic numerical simulation thought consisted of tectonic simulation target–establish tectonic model-tectonic simulation. We established geological model (plane stress model and three-dimensional model), selected rock mass mechanical parameters, boundary conditions and rock mass fracture criteria, then determined the magnitude of palaeo-tectonic stress as the boundary condition of model and the loading sequence of palaeo-tectonic stress by using large
numerical simulation analysis software ANSYS and FLAC, calculated the maximum and minimum principal stress of certain points, judged whether the points were at dangerous state, critical state, or safety state by using of mohr-coulomb criterion, according to the judgment to field tectonic trace.

(2) The position with weak capacity to resistant deformation would rupture under the action of uniform stress field because the capacity (internal friction angle) of rock mass to resistant shear failure was inconsistent.

(3) Tectonic simulation well revealed the main tectonic motion law and drive mechanism of Chengzhuang coal mine, Jin city, Shanxi Province, it indicated that, there ever occurred two stages of tectonic motion, first along east-westward, later south-northward. Mode and magnitude of loading was that, first loading 60Mpa to east-westward, and then loading 110~180 Mpa to south-northward, which satisfied that most of shear joints and the known joints in 3#coal seam occurred at the same time. These laws has an important significance in hazard division and prediction to gas outburst area, in Chengzhuang coal mine, Jin city, Shanxi Province.

Acknowledgement

The research result is a collective effort and the datum is from professor Wang Shengwei. The support by National Natural Science Fund (No: 40672187, 50874080) and Wuhan Institute of Technology Youth Fund Project (Q200805) were gratefully acknowledged.

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