Nonlinear Analysis of a Reverse Fault

Qiong Wang
Harbin University, Harbin150086, China.
Corresponding Author e-mail: wangqiong1127@163.com

Gang Chen
Heilongjiang Provincial Key Laboratory of Underground Pressure Control & Methane Treatment for Deep Mining, Heilongjiang University of Science and Technology, Harbin 150022, China
e-mail: chengang0607@163.com

ABSTRACT

In order to study the character of cross-fault mountain tunnel under reversed-slip fault dislocation, the inter-action model between the rock and the tunnel is made on the basis of the principle of the finite element and the pseudo-static method. The method for analyzing the nonlinear responses of the cross-fault tunnel under load of fault dislocation is also developed. The analysis is performed by using the displacement function of finite element soft-ware. The effect of fault dislocation is simulated by imposing displacement load on the hanging wall rock.

The values of displacement load are imposed by 100 steps to describe the loading process. With the increase of fault dislocation the stress states of the tunnel under the condition of reversed fault are analyzed. By the computation, some meaningful results have been obtained: (1) The tunnel is under safe state, when the fault dislocation is smaller than 20 cm. (2) The bottom of tunnel is the easiest to be damaged, then the roof, and the damage to the roof is at the last.

KEYWORDS: tunnel, strike-slip fault, pseudo-static method, numerical simulation, nonlinear analysis

INTRODUCTION

In the past, people thought that "the tunnel moves with foundation in the earthquake ", it is generally believed that the damage of earthquake on the tunnel is very small; However, in recent years, a large number of earthquake damage investigations showed that earthquake of shallow buried tunnel, unsymmetrical loading tunnel, fault zone of the tunnel body and tunnel portal section influence larger [1-3]. According to the research results of the earthquake damage of Yoshikawa's Japanese railway tunnel, the conclusion shows that if the tunnel is located in the earthquake fault zone, it will be likely to be destroyed [4-6].

EQUILIBRIUM EQUATIONS BETWEEN SURROUNDING ROCK AND MASS SYSTEM

In order to describe the failure of the tunnel lining caused by the movement of the surrounding rock along the fault, the nonlinear contact model is adopted to analyze the stress form of the tunnel lining.

In the loading process, the surrounding rock movement along the fault is employed as dynamic load, and then it is transferred to the lining through the nonlinear contact model between surrounding rock and tunnel. Internal force and deformation in the lining unit will occur under above load, a new equilibrium comes out again. The system dynamic equilibrium equation [7] can be expressed as formula 1.

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F\} \tag{1}$$

At the same time, the main reason for damage to the tunnel lining is the permanent deformation of surrounding rock under fault movement, so dynamic part in formula 1 can be neglected, all the stress and strain should be calculated on the basis of the pseudo static method calculation [8]. According to the finite element theory, after ignoring the acceleration and velocity terms, the motion equations of the tunnel lining structure can be simplified as formula 2 and 3.

$$[K_r]\{X_r\}=\{F_r\} \tag{2}$$

$$[K_t]\{X_t\}=\{F_t\} \tag{3}$$

where X_r is displacement vector of surrounding rock, F_r is external force of surrounding rock, X_t is displacement vector of tunnel lining, F_t is external force of tunnel lining.

When the displacement is applied on the boundary of surrounding rock, according to formula 2, the equivalent load of surrounding rock distribution can be obtained. Based on the assumption that the contact part between surrounding rock and lining has no displacement or deformation, above distribution equivalent displacement load will be transferred to the lining, and then the final tunnel lining internal stress will be solved by displacement.

THE FINITE ELEMENT MODEL AND LOADING MODE

The object of this study is a long mountain tunnel, the definition of which length must be longer than 1000 meter [9]. It is not necessary to analyze such a large length, because it will increase the computation time. In order to obtain a reasonable tunnel lining calculation model length, a number of trials are conducted, in the calculation process the mathematical model of the length is increased gradually, the fact is that within a certain range near the fault, the lining reaction changes very little, the length is the reasonable length, which is 400 meters.

The size of element model is of a 400-meter length, 106.2-meter width and 80-meter height. Model consists of surrounding rock (granite), fault fracture zone (sandstone), and tunnel concrete lining. The tunnel lining is simulated by plate element, and the surrounding rock and fault fracture zone are simulated by solid element. The fault zone is a weak rock, which thickness is 5m, its dip angle is 45°. Coordinate origin of model is located at the center of the cross section in the hanging wall of the tunnel entrance, the X axis is perpendicular to the tunnel axis, Y axis direction is along the horizontal direction of the tunnel, Z axis is the vertical direction. The element model is shown in Figure 1, the yellow parts are surrounding rocks, and the green part is fault zone.

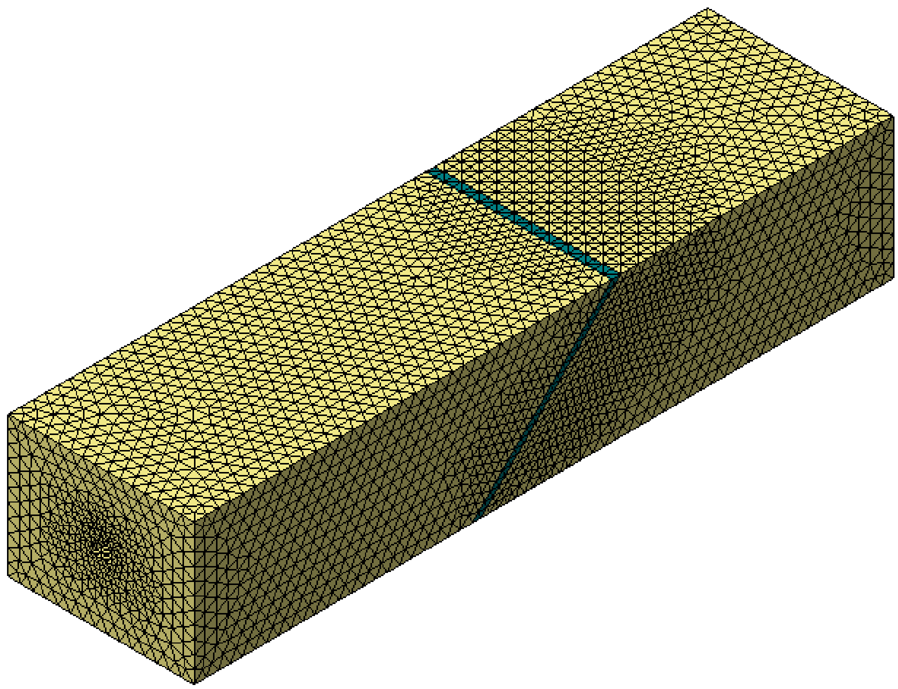

Figure 1: the finite element calculation model

The movement of surrounding rock is simulated by applying a force displacement along the fault on the hanging wall. The displacement loads are along two directions, one is horizontal, and the other is vertical. Each maximum displacement is 2 meters, and it is loaded by 100 steps. Because the dip angle is 45 degree, the reversed fault movement can be simulated by the means of applying vertical and horizontal displacement at the same time. The tunnel deformed as Figure 2.

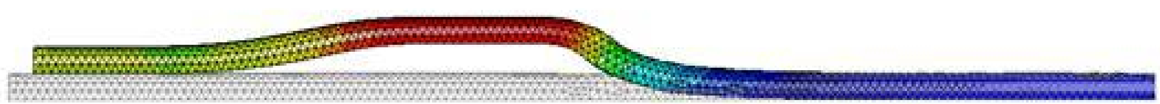

Figure 2: tunnel deformation under reverse fault displacement

DATA ANALYSIS AND DISCUSSION

Starting point is from the tunnel entrance in hanging wall, and abscissa is along tunnel axis, which is described as l, the fourth main stress under forced displacement load is used as vertical ordinate, which is expressed as P.

The location of the tunnel in surrounding rock can be determined according to the horizontal coordination. In the hanging wall, the coordination points for tunnel bottom are from 0 to 129, those for roof are from 0 to 138, and those of side wall are from 0 to 133. In the fault zone, the coordination of bottom is from 129 to 134, that of tunnel roof is from 138 to 142, and for the side wall is from 133 to 138. In the reversed fault footwall, the horizontal coordination of bottom is from 134 to 400, for the roof, it is from 138 to 142, and that of side wall is from 138 to 400.

The displacement loads are applied step be step, the maximum step is 100 and displacement is 2 meters. The stress distributions at displacement of 10cm, 20cm, 50cm, 100cm, 150cm and 200cm are analyzed separately.The high stress area is near the fault zone under reversed fault movement, so the tunnel points near fault are employed to analyze.

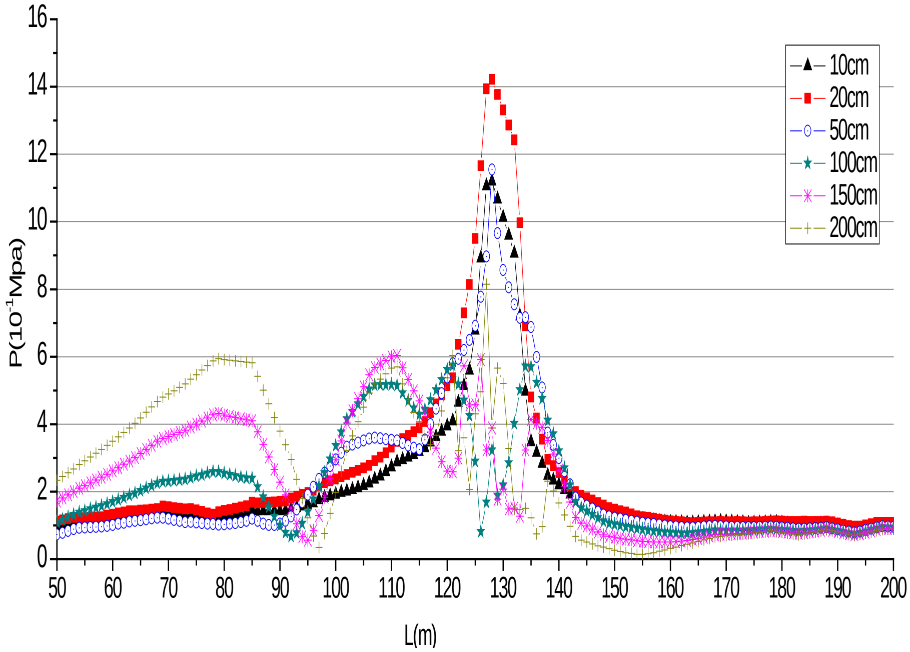

Figure 3: stress distribution of tunnel bottom

There are three high stress areas in tunnel bottom, one is at fault zone, a second one is at the area in hanging wall, which is 20 meters to fault, a third one is 50 meters to the fault zone.

In the scope from 10 meters in hanging wall to 5 meters in foot wall, the maximum stress is 1.12MPa with the10-cm displacement on surrounding wall. When the displacement increases to 20cm, the highest stress gets to 1.42MPa, the other points at this area also higher than those at 10-cm displacement. But when the displacement reaches 50cm, the highest stress decrease to 1.15MPa, which is less than that with lower displacement, this phenomenon shows that stress begins to yield at this range. In the process of loading 100cm to 200cm, the stress of lining plate decreases further more. The tunnel bottom stress in the foot wall area begins to be reduced after applying 100cm displacement, but the value is not to the damage ones, so the scope of internal stress decreased mainly because of faults' lining plate damage, leading to release stress and the stress transfer decreases.

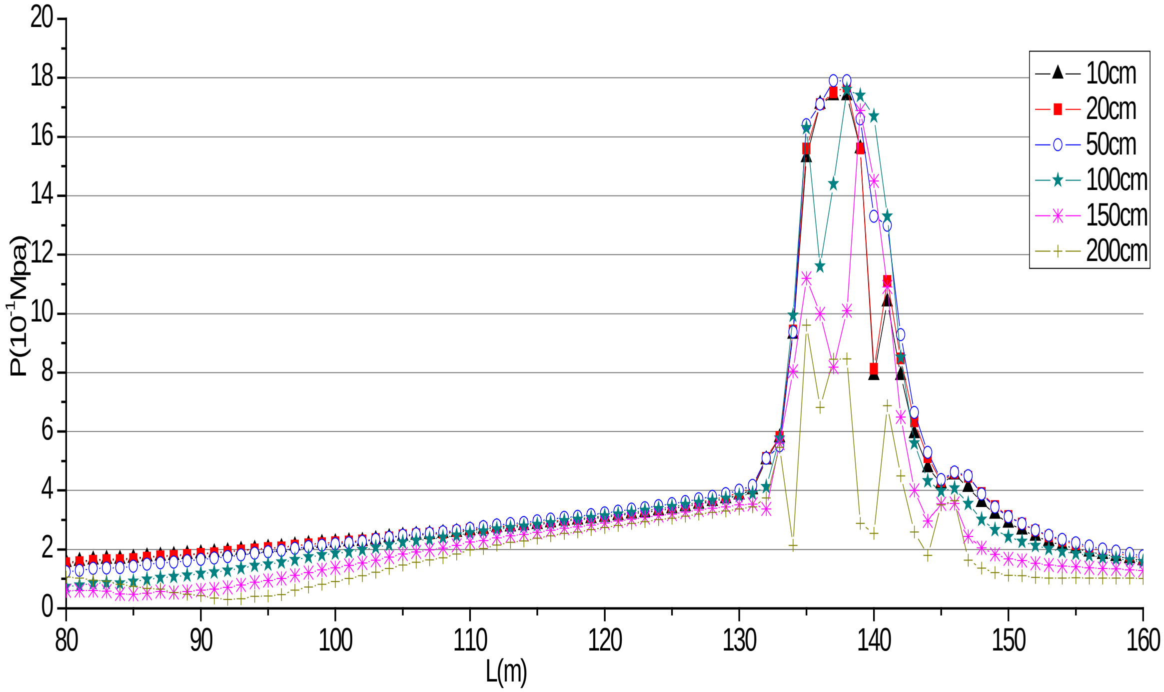

Figure 4: stress distribution of tunnel roof

The highest tunnel roof stress occurs at the fault zone, and is changing with more and more displacement load, which is 1.75MPa with 10cm displacement and 1.77MPa with 20 cm displacement, 1.78MPa with 50cm movement, but when the movement increases to 100cm, the stress maximum is 1.76MPa, which means the stress begins to yield. The range of stress decreased increases with the larger displacement load. Stress at location in the foot wall, which is 10 meters to fault, is reduced after 150cm load, but its reason is that the effect of damage on the fault blocks transfer of stress in the process of loading.

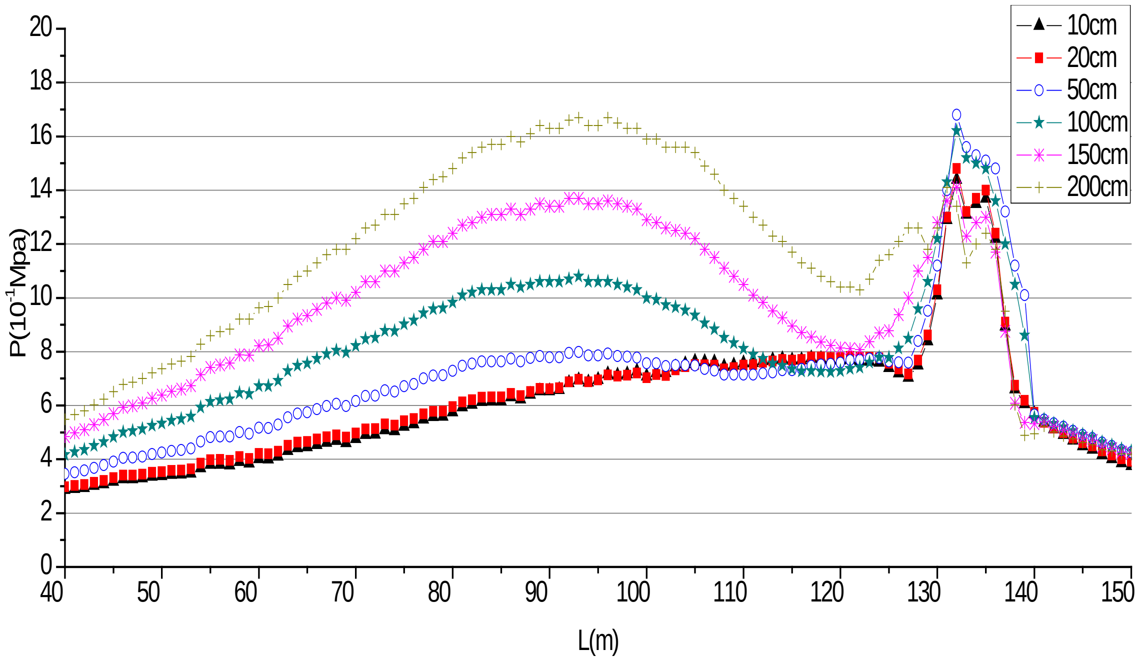

Figure 5: stress distribution of tunnel side wall

There are two high stress areas, one is in fault, and the other is in the scope of 10 meters to 80 meters away from fault in hanging wall. In the fault zone, the stress is changing from 1.37MPa at 10cm displacement, and 1.48MPa at 20cm displacement, then to the highest stress of 1.68MPa at 100cm. But when the displacement gets to100cm, the principle stress switches to 1.62Mpa, which suggests that the stress begins to yield. In the case of 150cm loading displacement, the stress at side wall decreased significantly, and decreasing is enlarged to the entire fault and 2 meters distance in the hanging wall. When loading 200cm, the stress value in the side wall is reduced further more, but its damage range is not changed. The other high stress area is at the 10 to 80 meters far away from fault in the hanging wall. In the process of loading 10cm to 200cm, side wall stress value increases with the larger displacement load. With the loading displacement of 200cm, stress value has reached 1.63MPa, which suggests that if the forced displacement load continues to increase, there is a risk of damaging.

CONCLUSIONS

The finite element principle and pseudo-static method are employed to analyze the tunnel nonlinear reaction when it is cross fault zone in mountain under reversed fault displacement. The conclusions are as following.

(1) When the displacement loading is under 20cm, the stress is small and tunnel lining is at the safe state.

(2) In the reverse fault condition, with the constant increase of the forced displacement, the bottom plate is destroyed, and then the damage extends to the side wall and roof.

(3) The high stress area are mainly located in fault zone and hang wall from 60 meters range, which parts we should give more attention in the design and construction.

ACKNOWLEDGMENTS

This research is supported by Heilongjiang province natural science foundation of China (NO. QC2014C057) and Key Laboratory of Mining Engineering College of Heilongjiang Province foundation of China (NO. 2013-kf07)

REFERENCES

1. Jiang Hua 1, Jiang Shuping, Wang Xiaowen: “Study on Transverse Seismic Response of Highway Tunnel in Fault Region" Tunnel Construction, 2009, 29: 14-18.
2. J.S.Yang, M.C Wang: “Evaluation of Tunneling-induced Downdrag on End-bearing Piles” *Electronic Journal of Geotechnical Engineering*, 2002, 7: 358-368.
3. Evangelos I. Stavridakis: “Strengthening the Soil Engineering Characteristics by Using Anchors During an Earthquake Impact” *Electronic Journal of Geotechnical Engineering*, 2005, 10:1676-1685.
4. Zheng Xilai, Yang Delin, Li Wenyi, "anti-earthquake of underground structure" Shanghai: Tongji University Press, 2005.
5. Qian Qihu, He Chuan, Yan Qixiang, "Dynamic Response Characteristics of Tunnel Project and Analysis and Enlightenment of Earthquake Damage in Wenchuan Earthquake Tunnel" Chengdu: Analysis and Research on Wenchuan Earthquake Damage, 2009:608-618.
6. Li Tianbin: Failure Characteristics and Influence Factor Analysis of Mountain Tunnel at Epicenter Zone off Great Wenchuan Earthquake" *Journal of Engineering Geology*, 2008, 16:742-750.
7. Wang Mingnian: “Research on Damping Technology Principle of Underground Structure in High Seismic Zone" Chengdu: Southwest Jiao Tong University, 1999.
8. Guo Endong, Feng Qimin: “A Seismic Analysis Method for Buried Steel Pipe crossing Fault” *Earthquake Engineering and Engineering Vibration*, 1999, 19: 43-47.
9. Bardet, Linos J P. "A Non-linear finite element program for geomechanics and Geotechnical engineering", Los Angeles: User's Manual, University of Southern California, 1991:3(21)22-29.

Editor’s note.
This paper may be referred to, in other articles, as:
Qiong Wang and Gang Chen: “Nonlinear Analysis under Reverse Fault” *Electronic Journal of Geotechnical Engineering*, 2016 (21.12), pp 4413-4419. Available at ejge.com.