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Finite element modeling of a tunnel affected by dislocation of faults

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Abstract

Many tunnels built in mountainous areas go through active faults whose dislocation can severely affect the stability, strength and serviceability of the tunnels. In this study, finite element method was used to simulate the dislocation of the faults, and we investigated the effects of main factors such as fault dip angle and tunnel lining segment length on the internal stress and deformation of lining structures of the tunnels. Failure mechanism of the lining structures was studied, and the sensitivity of the main factors was analyzed. It is found that the optimal lining segment length of the tunnel was 5m.

Keywords: Finite element method, Tunnels through faults, Lining structures, Dislocation of faults, Internal stress, Deformation.

Introduction

Faults are often encountered in highway tunnel constructions. It is a normal way to avoid faults in highway tunnel constructions in existing design standards[1]. But with the rapid development of Chinese national economy and the exploitation of land resources, a number of tunnels constructions projects inevitably encounter faults problems, Especially, in strong earthquake areas. In these areas the faults which the tunnels go through are often active faults. The tunnels go through active faults are hugely impacted by the dislocation of the faults, which have direct impacts on the constructions and operation safety of the tunnels.

The impacts of the faults fracture zone on the tunnel structures are mainly manifested in below two aspects. The first is that the faults fracture zone take place dislocation along the faults surfaces which are often called dislocation problems. The second is that dynamic response characteristics of tunnels in the faults fracture zone under the earthquake which are often called vibration problems. After investigating the designs and studies on tunnels engineering which go through active faults, a lot of studies are concentrated on the anti-seismic of tunnels. Appropriate engineering measures of anti-seismic are relatively mature, but the measure of anti-relatively dislocation is very little.

John Caulfield, et al (2004) designed the tunnel in southern California Claremont water pressure tunnel by expanding its section size and reducing the length of the lining segments. A lot of shear seams in the lining of the tunnel were set in southern California Claremont water pressure tunnel projects[2,3].

Russo M, et al (2002) proposed to build relatively flexible connections in Turkey Bolu highway tunnel projects.[4-6].

In China in the construction of WuXiaoLing tunnel (2004) also met the same problem. The tunnel go through an activities fault. The design of the tunnel taken a way of expanding section size and set aside shear displacement seams in the lining of the tunnel[7].

A R Shahidi, et al (2005), in Greece Koohrang-Ⅲ water pressure tunnels project also adopted a relatively flexible connection design. Numerical calculations was used to certificate that the tunnel was safe when the fault take place dislocation[8].

Jiang Shuping, et al (2008), respectively discussed both of the methods of overexcavation design and hinged design of the tunnels[9].

Hinge design is a way which minimize the length of lining segments. A certain range of the lining segments structures besides the faults become relatively independent after the tunnels which adopted hinge design. The rigid linings of the tunnels are connected by flexible connectors. When the fault take place dislocation the mechanical behavior are concentrated on the flexible connectors or part of the structures, which will cause localized structural damage and not lead to an overall destruction of the whole tunnel structures.

In order to fully reveal the mechanics, deformation and failure characteristics of the lining structures of the tunnels under the dislocation of faults. Numerical simulation of finite element method was adopted to analyze the mechanical and deformation behavior of the tunnel structures under the activity of the dislocation of the faults. Horseshoe-shaped section tunnels are the most widely used in tunnels engineering, so horseshoe-shaped section tunnels were chosen in numerical simulation of the tunnels which go through the faults. In order to reveal better the deformation and failure mechanisms of the dislocation of the faults on the lining structures of the tunnels, we carried out study on the mechanical behavior of the faults.

Engineering geology and tectonic

According to the regional geological data, geological survey and geophysical drilling results, the engineering geology of tunnel zones were below successively: Quaternary Holocene strata colluvium (Q4c+dl), Quaternary Holocene alluvial (Q4al+pl), Fourth Department of Holocene debris accumulation layer (Q4sef) and the Triassic Feixianguan group (Tf), Permian Yangxin group (Py), Liangshan group (Pl) and Carboniferous Zongchanggou (Cz)[10].

Folds traces were not obvious in this tunnel area. The occurrence of the rock in the entrance of the tunnel was 121°∠49°. The occurrence of the rock in the exit of the tunnel was 321°∠71°. The inclination and incidence were subject to effects of the tectonic, and they change quickly in the tunnel area. There were two kinds of faults respectively named F22 and F22-1 going through the tunnel area. Fault F22 go through the tunnel near the entrance of the tunnel, and Fault F22-1 go through the tunnel at the middle of tunnel area. Fault F22-1 and Fault F22 were secondary faults in Longmen Central Fault in China. The two faults active in the 5·12 Earthquake in China and formed cracks in the body of the mountain. A 3-8m width fracture can be seen in Fault F22, and this fracture formed a groove ground subsidence. The large sinking height was approximately 2m. The fracture extends continuously.

Finite element model establishment and parameters selection

Modeling and model size

The study on the stress and deformation of tunnels structures were strict and complex three dimensional problems in condition of faults taking place dislocation. The longitudinal of tunnels was the largest impacted by the activity of the dislocation of the fault. Therefore, the fault and the tunnel structures could be set orthogonal relation in space when establishing a 3d finite element model. In order to fully reveal the longitudinal deformation and mechanical behavior of the tunnel lining structures under the dislocation of the tunnel and reduce the impact of the boundary of the tunnel, the finite element model size was below: Length×Width ×Height = 120 m ×80 m × 80 m, namely vertical length of the tunnel was 200 m, the lateral width of the tunnel was 60 m, the depth of the tunnel was 40 m and the depth of the top of tunnel was 100 m.

Boundary conditions and fault activity simulation implementation

On the left and the right sides of the finite element calculation model, X direction and Y direction horizontal displacement were restricted respectively. Z direction displacement of the lower plate of the fault was restricted, while its upper plate could active. The fault was a thrust fault. The active pattern was the upper plate of the fault move up while its lower plate kept stable. In the model a displacement was added on the upper plate to simulate the vertical dislocation of the fault. The average dislocation on the fault was 0.5m. The basic conditions of the model were below:
A. The model was composed of bedrock, concrete lining of the tunnel and fault fractured zones.
B. The tunnel went through the faults fractured zones in the model. The left part of the fault was called the lower plate, and the right part of the faults was called the upper plate. The two parts could dislocate along the fault surface. The dislocation pattern was reverse faulting.

Material constitutive and calculations parameters

As geotechnical materials have heterogeneity, anisotropy, strength-difference effect and other characters. Any one model can not fully accurately represent these characteristics of geological materials. There are three categories of constitutive models which are respectively elastic model, plastic model and elastic-plastic model currently in rock and soil. In this analysis model soil and tunnel lining were assumed to be ideal elastic-plastic material. D-P yield criterion and the associated flow rule were adopted because D-P yield criterion could take into account the effects of principal stress and hydrostatic pressure on yield and destruction of the tunnel. Its yield surface smooth and non-angular. It help to determine the direction of the increment of plastic strain and numerical calculations. The material parameters are less and easy to be test or conversed by the Mohr-Coulomb criterion and its material constant. D-P parameters can be conversed as follow formulas.

$$\sigma_y = \frac{9c\cos\varphi}{\sqrt{9+3\sin^2\varphi}} \qquad \alpha = \frac{\sin\varphi}{\sqrt{9+3\sin^2\varphi}}$$

Contact surface was set between the upper plate and the lower plate of the fault. Between soil and the lining structure a contact surface was also set. Contact analysis was made on these surfaces in the model. Friction coefficient of the contact surface between the upper plate and the lower plate was 0.3. Friction coefficient between strata and tunnel lining structures was 0.7. Coulomb friction model was adopted in the numerical analysis. The inter force and deformation laws of the lining of the tunnel were analyzed under different amount of dislocation in this model. The average calculation dislocations amount was 50cm.

Rock, lining and fracture zones were simulated by solid element. The material of initial support and secondary lining of the tunnel adopted elastic-plastic constitutive. Rock adopted D-P yield criterion and incremental elastic-plastic constitutive. Calculation parameters and calculation model are shown in Table 1 and Figure 1.

Table 1 Calculation parameters of rock, fracture zone and lining of the tunnel

Material's name	Modulus /GPa	Poisson's ratio	G /kN.m^{-3}	Friction angle / ^{o}	Cohesion /MPa
Rock	0.5	0.38	22	34	0.3
Fracture zone	0.05	0.4	18	30	0.1
Lining	28	0.20	25	58	3

Finite element numerical model of cross-fault tunnel under the dislocation of fault is shown in Figure 1.

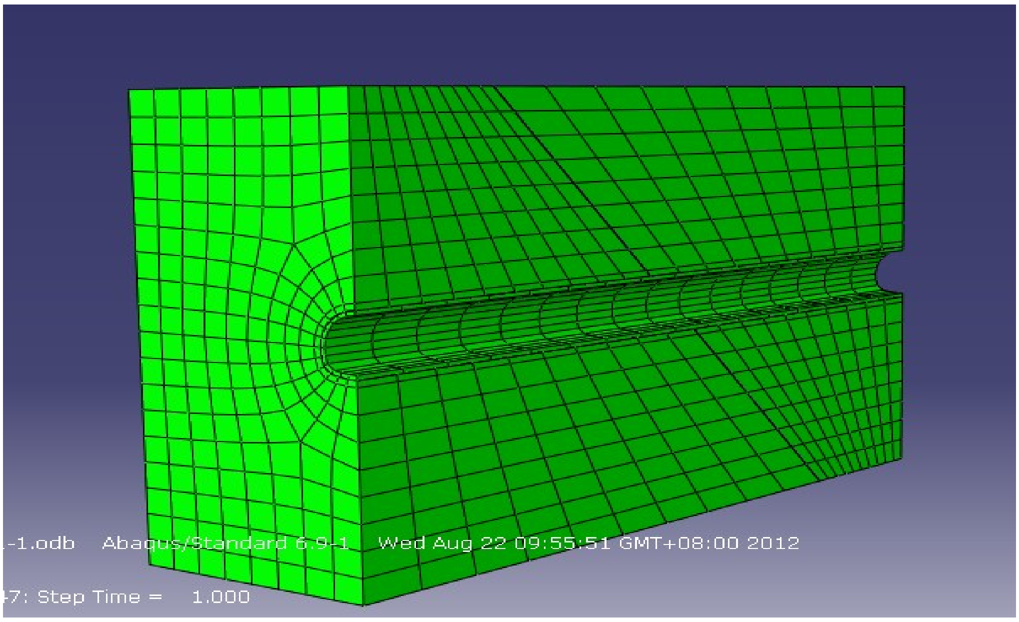

Figure 1 Finite element numerical model of cross-fault tunnel under the dislocation of the fault

FEM numerical results

Four kinds of lining segment lengths of the tunnel were taken into account in FME calculation model. They were respectively 15m, 10m, 5m and no shear seam in tunnel which was mean the tunnel was continue. Tunnel lining segment length could be optimized according to FEM calculation.

Response results contrast of different lining segments lengths of the tunnel are shown in Fig.2- Fig.6.

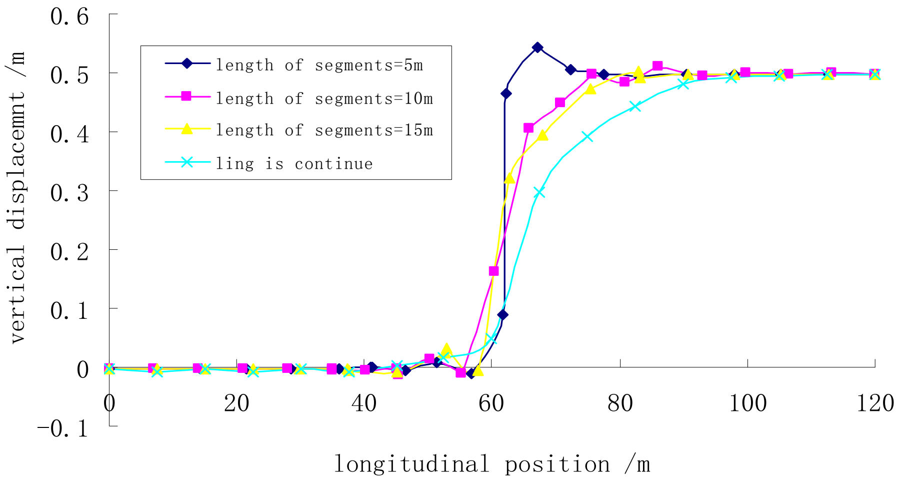

Figure 2 Vertical displacement of the arch top of the tunnel for different lining segment lengths along longitudinal

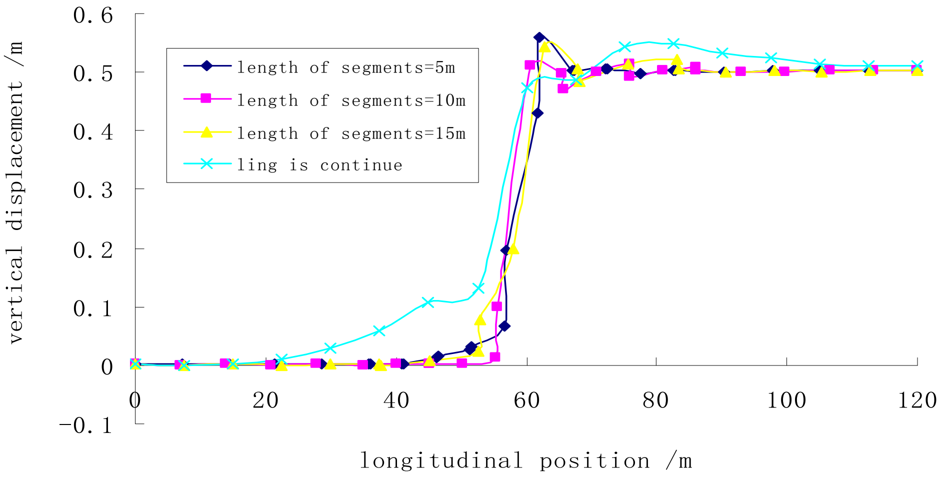

Figure 3 Vertical displacement of the arch bottom of the tunnel for different lining segment lengths along longitudinal

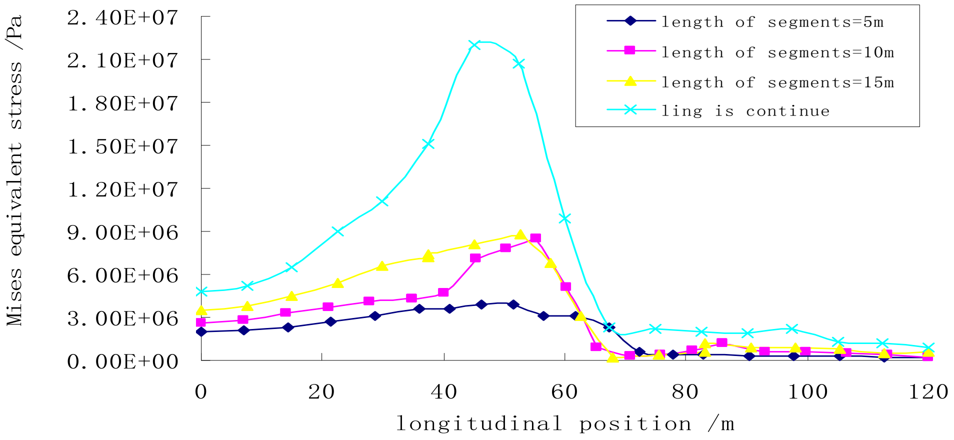

Figure 4 Mises equivalent stress of the arch top of the tunnel for different lining segment lengths along longitudinal

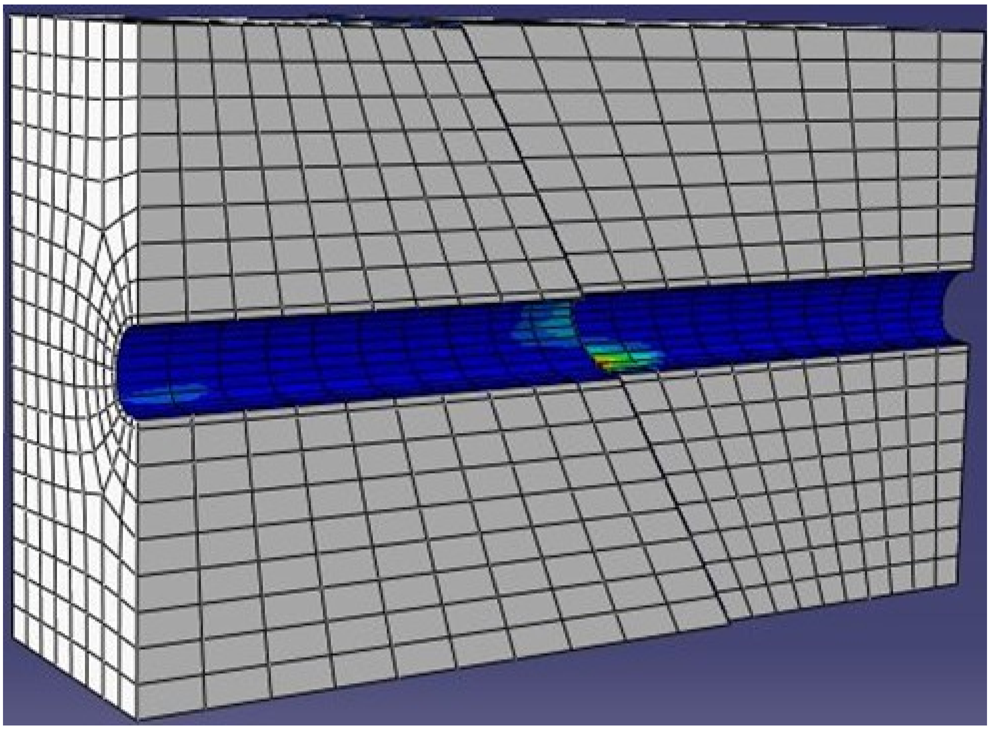

Figure 5 Contact stress of the tunnel which the length of segment is 10m under the dislocation of the fault

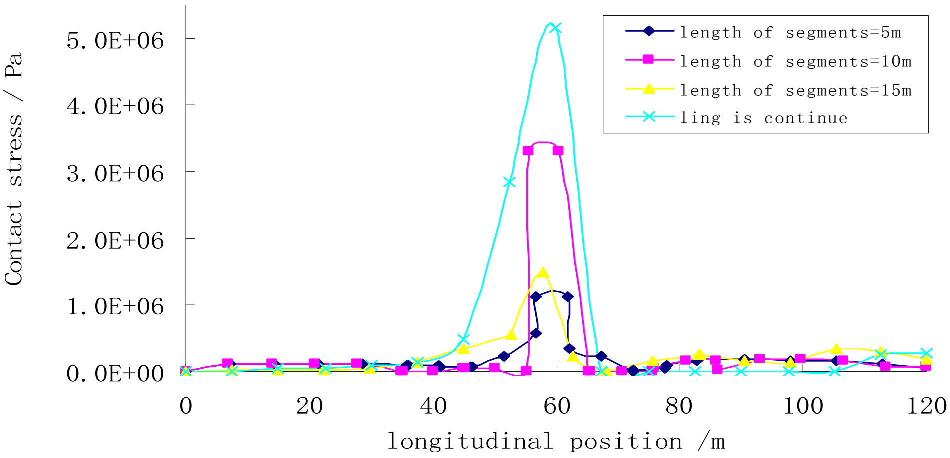

Figure 6 Contact stress of the arch bottom of the tunnel for different lining segment lengths along longitudinal

Table 2 Maximum Mises stress of the tunnel for different lining segment lengthss

Lining segment length	Maximum Mises stress /MPa
No shear seam in tunnel	21.91
15m	20.98
10m	17.5
5m	13.12

Conclusions

According to dynamic response calculations and the comparison charts of the tunnel structures for different lining segment lengths below conclusions can be get.

(1) It is better to adopt chain segmented structures than non-segmented structures in tunnel engineering. Chain segmented structures tunnel can reduce the influence of the dislocation of the fault on the tunnel structures.

Although vertical displacement along tunnel longitudinal increase with the lining segment length of the tunnel decrease, but the affect zone of the displacement mutation was significantly reduced. The affected zone of dislocation of the fault on the tunnel was 40m when there was no shear seam in the ling structures. When the lining segment length was 5m, the affected zone was the minimum, and the affected length along tunnel longitudinal was shorter than the lining segment length.

(2) After adopting chain segmented structures, the maximum Mises stress of the tunnel lining reduced and the stress reduced more quickly when the lining segment length become shorter. The maximum Mises stress was13.12MPa when the lining segment length was 5m, and it was 59.88% of the Mises stress of the tunnel with no shear seam . While the maximum Mises were almost the same between the tunnel which the lining segment length was 15m and the tunnel with no shear seam.

The distribution of Mises stress was more uniform with the lining segment length decrease. The maximum stress was mainly concentrated on the lining arch waist of the tunnel near the fault. Contact stress in the tunnel lining reaches maximum near the surface of the fault. With the lining segment length decreases, contact stress of the tunnel lining decrease. Contact stress of the tunnel changed abruptly from the tunnel with no shear seam to the tunnel which the lining segments length was 15m.

(3) The plastic zone significantly reduced when the tunnel adopt chain segmented structures than no-chain segmented structures. When the lining segment length was 15m, the plastic zone of the lining was mainly distributed in one lining segment length range near the fault surface. When the lining segment length was 10 m, the plastic zone of the lining was mainly distributed in one-two lining segment length range near the fault surface. It can be seen the plastic zone of chain segmented structures significantly reduced with the lining segment length decreases. The maximum equivalent plastic strain decreased with the decrease of the lining segment length.

Based on the above analysis, when chain segment structures were adopted in tunnel engineering, the maximum stress, the distribution of the plastic zone and the maximum equivalent plastic strain of the lining significantly reduced. With the decrease of section length, the stress significantly reduced, and it become more uniform. The plastic zone and the maximum equivalent plastic strain were also significantly reduced. When the lining segment length was 5m, the tunnel could adapt to the dislocation of the better than that of the lining segment length was more than 5m.The tunnel which segment length was 5m give full play to the lining of carrying capacity and had good resistance. If the segment length is too short the project costs will increase and it will cause no necessary waste. Also it will increase the construction process and increase the difficulty of construction control when the lining segment length is too short. Therefore the lining segment length of chain segment structures tunnel was recommended 5m.

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