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Research on reasonable anti-fault fortification length and effect of different deformation joint spacing for Urumqi metro line 2 tunnel through reverse fault fracture zone

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ABSTRACT: This paper presents a method of determining reasonable anti-fault fortification length and studies the effect of different deformation joint spacing for tunnels within the active faults region. The length determination criterion is based on the law that the internal force and stress of lining gradually decrease and then remain stable along the fault fracture plane. Besides the determination of fortification length, the deformation joint spacing is set to 6m, 9m and 12m respectively within the fortification length to study and compare their effect on the internal force and stress of lining. These analyses indicate that the anti-fracture fortification length is determined to be 90m, setting the deformation seam can significantly reduce the internal force and stress of lining and with the decrease of deformation joint spacing, the anti-fault effect is better.

1 INTRODUCTION

The damage to the underground tunnels and transmission pipes dates back to 1923 when the Kanto earthquake occurred (Kawashima, 2000). After that time and during the past decades, many accidents have been observed and numerous studies made to reveal the failure mechanism of tunnels or pipes under the action of ground motion or permanent ground deformation (Ohki et al. 1989, Anastasopoulos. 2008; Yu et al. 2011, He et al, 2014). Generally speaking, the damage induced by permanent ground deformation is more serious than that of ground motion, so some accurate and detailed analysis for the tunnels lining or buried pipes have been considered to minimize the influence of unwilling deformation (Kiyomiya et al. 1999, Shahidi. 2005). In-depth studies on the impact of fault movement on underground tunnels based on field studies, numerical approaches and experimental analysis using scale models have been carried out. Table 1 presents a summary of results of these studies. In these studies, all the types of faults including thrust fault, strike-slip fault and normal fault are dealt with, both sandy and clayey soils have been studied. The failure mechanism of the tunnel's transverse and longitudinal section is analyzed.

Nevertheless, there are not much published methods or standard codes for this problem in the text books of tunneling, so the present research attempts to further explore the following issues for the future design of tunneling crossing fault on the basis of these previous studies:

1. Determining the anti-fault fortification length based on the law that the farther from the fault fracture plane, the smaller the tunnel response.
2. Setting deformation joints within the fortification length to study their effect on tunnel response.

Table 1. Summary of the existing studies for the fault movement on underground tunnels

Methodology	Author/year	Fault type	Deformation
Field studies	Prentice and Ponti (1997)	Strike–slip fault	Longitudinal
	Kontogianni and Stiros (2003)	Strike–slip/thrust fault	Longitudinal
	Konagai (2005)	Strike–slip/normal fault	Cross-sectional
Numerical analysis	Shahidi (2005)	Thrust fault	Longitudinal
	Lin et al. (2005)	Thrust fault	Cross-sectional
	Chung et al. (2005)	Thrust fault	Cross-sectional
	Zhao et al (2016)	Normal faults	Longitudinal
Model experiment	Burridge et al. (1989)	Thrust fault	Longitudinal
	Lin et al. (2006b)	Thrust fault	Cross-sectional
	Liu (2011)	Thrust fault	Longitudinal
	Liu (2014)	Normal fault	Cross-sectional and Longitudinal
	Sun (2018)	Thrust fault	Cross-sectional and Longitudinal

2 URUMQI METRO LINE 2 TUNNEL

One of the subway tunnels under construction in the region of northwest china is Urumqi metro line 2 tunnel, which is supposed to be completed during the few coming years. This metro tunnel is 19.1km long with 6.7m diameter, which tightly connects the urban central area and the recent key development areas of the city. The site is located within the Tian Shan region which contains many problematic areas including water bearing strata, severely tectonized and faulted zones. There are four faulted sections along the tunnel axis, the focus of this paper is Xi Shan fault which affects about 52m long along the tunnel.

A longitudinal profile of geological formations along the tunnel axis is shown in Figure 1, in which the Xi Shan fault is indicated. As it can be seen from the profile, except for the fracture zone and surrounding rocks on both sides, a 12-meter overburden soil layer exists. To decrease the effect of fault displacement on tunnel as much as possible and meanwhile satisfy the requirement of ground loads, the metro tunnel is built at a height of 0.7m above the fault zone. The long time and more important aim is to keep the tunnel working for a life period of 100 years, i.e. during this time the tunnel lining should stand safe and be strong enough to

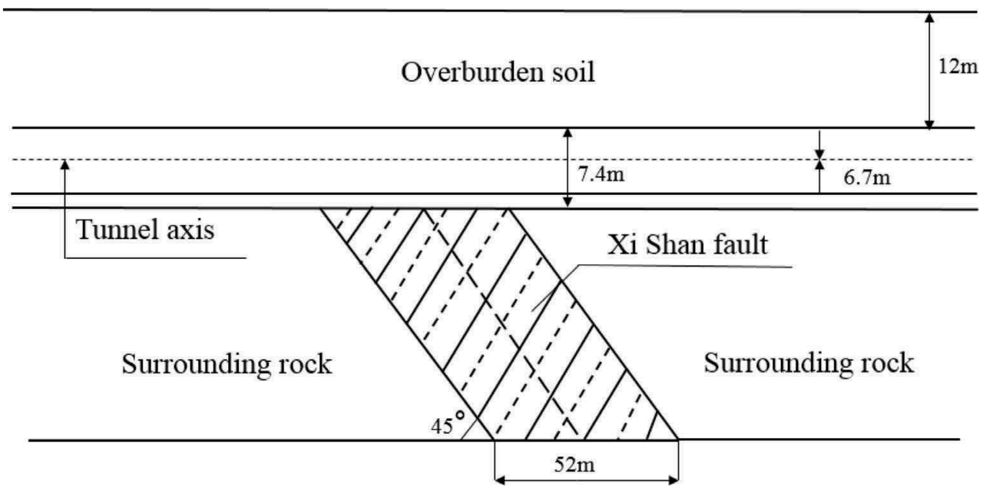


Figure 1. Sketch of geological profile

tolerate the predicted transverse deformations caused by tectonic activities and fault movements. Hence, the design is based on probable maximum vertical fault displacement 16.5cm according to the seismic reports.

3 FINITE DIFFERENCE MODEL

Figure 2 shows finite difference models of the tunnel crossing Xi Shan fault, the stratum length along the tunnel axis is 252m, whereas the dimensions in the directions *x* and *z* are 82m which is about 12 times tunnel diameter and 60m about 9 times tunnel diameter. All soil layers are simulated by solid elements and the Mohr-Coulomb yield criterion is used for their constitutive models. The shield method is adopted during the construction process, C45 concrete is used for initial support simulated by liner element with its thickness 35cm and C50 concrete is used for secondary lining simulated by shell element with its thickness 25cm, considering the focuses of this paper are the determination of anti-fault fortification length and effect of different deformation seam spacing on tunnel lining, therefore the tunnel lining is simplified and modeled as an elastic beam element. Three-dimensional soil-structure model is established and the physico-mechanical properties of soil layers and tunnel linings are shown in Table 2. Based on the above mentioned conditions, the pattern of longitudinal deformations is determined by means of the finite difference model, FLAC^{3D}.

4 RESULTS AND DISCUSSIONS

4.1 *Determination of reasonable anti-fault fortification length*

The damage to the underground tunnels caused by fault displacement is very huge, but the damage is mainly concentrated near the fault rupture plane, so it's necessary and possible to identify a reasonable disaster area for the anti-fault design. Based on the law that the internal

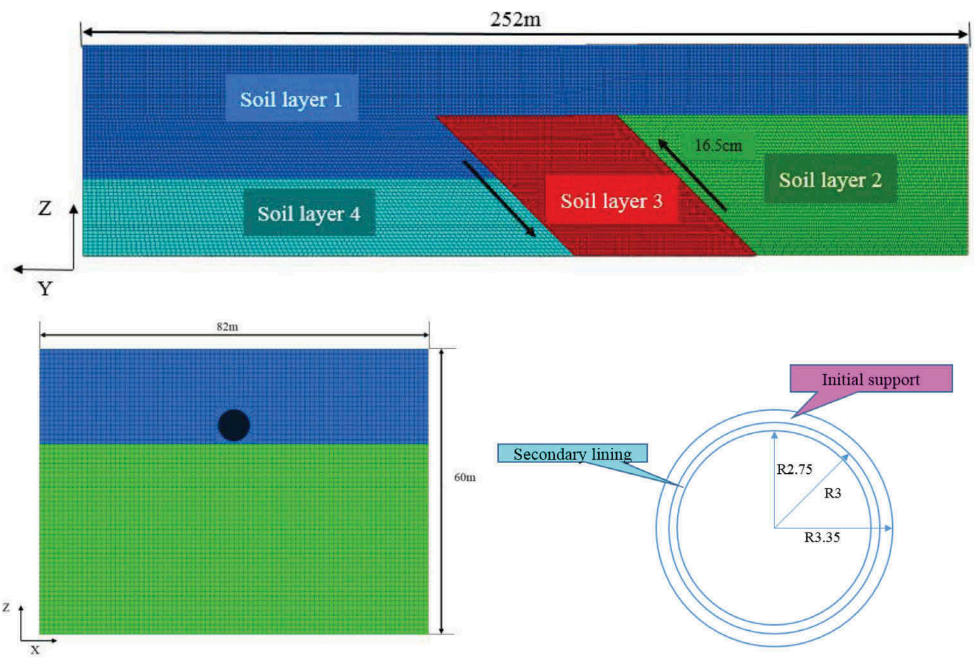


Figure 2. Finite difference model of tunnel and soil layers

Table 2. Physico-mechanical properties of soil layers and tunnel linings

Name	ρ kg/m^3	E (MPa)	μ	φ (degree)	c (kN)
Soil layer 1	2010	13.6	0.33	18	21
Soil layer 2	2470	2500	0.25	27	90
Soil layer 3	1800	47	0.17	18	30
Soil layer 4	2100	2000	0.25	40.8	4
Initial support	2500	33.5	0.2	-	-
Secondary lining	2500	34.5	0.2	-	-

force and stress of tunnel lining gradually decrease and then remain stable along the fault fracture plane, the bending moment, first and third principal stress are chosen to envelop various adverse conditions for determining the reasonable anti-fault fortification length. The anti-fault lengths of hanging wall and footwall are determined respectively, for the hanging wall, the third principal stress (tensile stress) at the location of vault, the bending moment and the first principal stress (compressive stress) at the location of tunnel bottom are chosen to describe the trend of internal force and stress because the values of the three indicators are the largest at the above mentioned positions, for the footwall, the third principal stress at the location of tunnel bottom, the bending moment and the first principal stress at the location of vault are chosen for the same reason. In Figure. 3a, b and c, the variations of chosen bending moment, first and third principal stress are shown, respectively, along tunnel length,“0” represents the location of fault fracture plane.

First, the anti-fault length of hanging wall is analyzed. As can be seen, the maximum values of the bending moment, first and third principal stress are 733kN.m, 45MPa and 7.4MPa, respectively. When the distance along fault fracture plane is not less than 27m, the value of bending moment tends to be stable, when the distance along fault fracture plane is not less than 40m and 20m respectively, the first and third principal stress showing a law similar to bending moment, combined with the above analysis, the anti-fault length of hanging wall is taken as 40m. Then the anti-fault length of footwall is analyzed, the maximum values of the bending moment, first and third principal stress are -682 MPa,35.2 MPa and 5.1MPa, respectively. When the distance along fault fracture plane is not less than 22m, the value of bending moment tends to be stable, when the distance along fault fracture plane is not less than 50m and 30m respectively, the first and third principal stress showing a law similar to bending moment, therefore the anti-fault length of footwall is taken as 50m. So the total anti-fault length is determined as 90m.

In Figure. 3a, b and c, it can be easily concluded that the first principal stress has the largest influence range among the three indictors. However, what needs to be pointed out is that the tunnel lining is mainly subjected to shearing, stretching and bending damage in the disaster area, so after determining the anti-fault length by the variations of the first principal stress along the tunnel length, the shear, tensile and bending bearing capacity of tunnel lining should be paid more attention. The following part will discuss some measures to decrease the above internal force.

4.2 *Study on the effect of setting deformation joint*

Looking through relevant cases, it may be easily concluded that the current methods of designing the safe sections for the probable deformation along the anti-fault length can principally be classified in three kinds of approaches, i.e.:

- the isolation technique, which means filling the space gap between the ground and the lining by some soft materials
- excavating a larger diameter section in order to provide enough space for the conditions of earthquake or faulting
- the method of flexible joints, between the adjacent parts of the main parts of rigid lining.

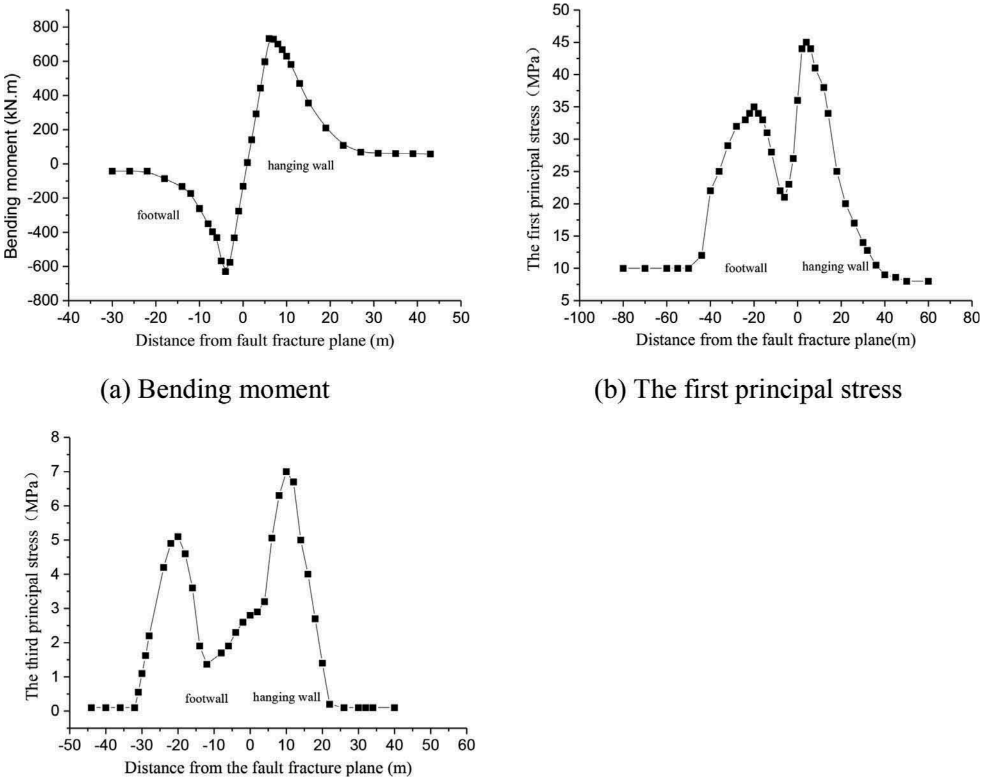


Figure 3. The variations of internal force and stress along the tunnel length

The method of setting deformation joints is applied for the present study. Omega gasket allowing 5-8cm displacement is used in this engineering which can be simulated by directly disconnecting adjacent linings. The deformation joint spacing 6m, 9m and 12m are selected to analysis the anti-fault effect based on the following reasons:

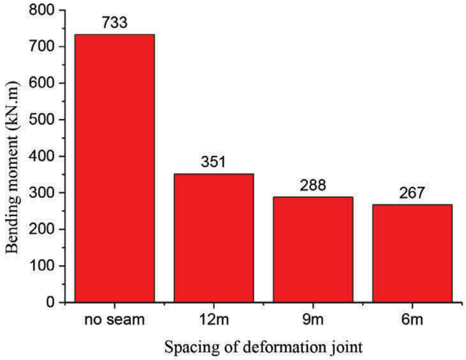
- at present, the length of concrete trolley in tunnel construction is generally 6 to 12 meters.
- single ring of shield tunnel structure consists of six types of segments and its width is 1.5m.
- considering the waterproof requirements, the spacing cannot be set too small.

The maximum bending moments, the first and third principal stresses under different working conditions are computed and compared in Figure 4a, b and c.

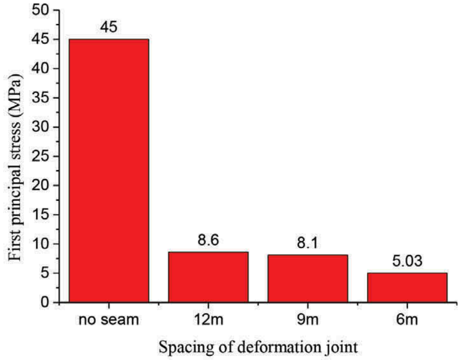
In Figure 4a, b and c, compared with the “no seam” condition, the bending moment, first and third principle stress of setting deformation spacing as 12m decrease by 52.1%, 80.8% and 76.1%, respectively, which indicates that setting the deformation seam can significantly reduce the internal force and stress of lining. Comparing the three conditions of setting deformation joint spacing 12m, 9m and 6m, it’s found that the internal force and stress decreases with the reduce of the spacing. Therefore, in order to improve the anti-fault ability of the tunnel, the spacing of deformation joints should be as short as possible under the condition of meeting waterproofing and construction requirements.

5 CONCLUSIONS

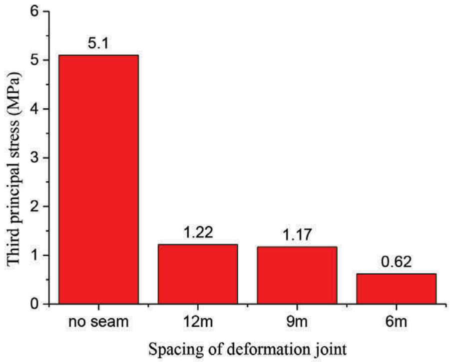
Determining the disaster area and taking measures to improve the anti-fault ability of the tunnel crossing fault are the two key issues in the design. The anti-fault length is determined as 90m in the Urumqi metro line 2 tunnel engineering based on the law that the internal force



(a) Bending moment



(b) The first principal stress



(c) The third principal stress

Figure 4. The maximum bending moments, the first and third principal stresses under different working conditions

and stress of lining gradually decrease and then remain stable along the fault fracture plane, the method of setting flexible joints proves to be an effective way to improve the anti-fault ability of the tunnel and the spacing of deformation joints should be as short as possible. The above analyses are only in the elastic phase and further study about the plastic analysis of structure should be carried out in the future. However, the research results are expected to provide reference for similar engineering design.

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