The seismic behavior of the tunnel across active fault

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SUMMARY:
The tunnel may have to be constructed across a faulted zone as it is not always possible to avoid crossing active faults. In these situations, the tunnel must tolerate the expected fault displacements and seismic action, and allow only minor damages for the assumed life time. The seismic behavior of the tunnel across the active fault is analyzed and a method of designing flexible lining for tunnels across active fault is put up. The effects of the method are analyzed by numerical simulation. The results show the tunnel lining with flexible joints allows the tunnel to distort into S-shape through the fault zone without rupture and thus it can provide reference to the design and construction of tunnels located in the active faulted zones.

Keywords: tunnel; flexible joint; active fault

1. GENERAL INSTRUCTIONS

Tunnels built in areas subject to earthquake activity must withstand both seismic and static loading. Historically, tunnels have experienced a lower rate of damage than surface structures. Nevertheless, some tunnels have experienced significant damage in recent large earthquakes, including the 19995 Kobe, Japan earthquake, the 1999 Chi-Chi, Taiwan earthquake and the 2008 Wenchuan, China earthquake. Failure of these tunnels during earthquake proposes a deeper consideration in detail design of tunnels. Several studies have documented earthquake damage to tunnels. ASCE (1974) describes the damage in the Los Angeles area as a result of the 1971 San Fernando Earthquake. JSCE (1988) describes the performance of several tunnels, including an immersed tube tunnel during shaking in Japan. Dowding and Rozen (1978), Owen and Scholl (1981), Kaneshiro. (2000), and Wang(2009) et al all present summaries of case histories of damage to tunnels. Among various phenomenon happening to the lining of tunnels by earthquake, the shear deformation of cross section passing through the faulted zone has the major effect.

The tunnel may have to be constructed across a fault zone as it is not always possible to avoid crossing active faults. In these situations, earthquake-induced fault movement may subject the tunnel to differential displacements and generate stress concentrations.

Looking through the previous studies and relevant cases, it can be concluded that the current methods of designing the safe sections for the cases of probable deflection along the longitudinal profile of tunnels can principally be classified into fourth kinds of approaches, i.e.:

(1) excavating a larger diameter section in order to provide enough space for the conditions of earthquake or faulting.

(2) The grouting reinforcement technique, which means grouting the ground in order to increase the strength and ductility of the faulted zones.

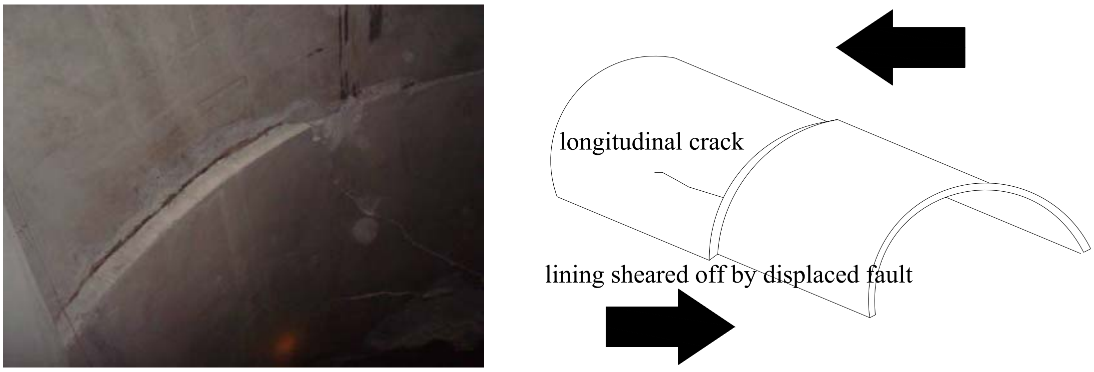
(3) The isolation technique, which means filling the space gap between the ground and the lining by some soft materials.

(4) the use of flexible joints, which may be considered to increase longitudinal flexibility of the tunnel.

The fourth method is applied in this paper. The seismic behavior of the tunnel across the active fault is analyzed and a method of designing flexible lining for tunnels across active fault is put up. The effects of the method are analyzed by numerical simulation.

2. OVERALL FEATURES OF DAMAGE TO TUNNELS ACROSS FAULTS

On May 12 2008, at 2:28 pm (local time), a strong earthquake with a magnitude of 8.0 (Ms) struck Wenchuan town, in the eastern Sichuan area of west China(N31.0, E103.4), at a depth of approximately 19km. Damage investigation was conducted on 18 tunnels located in the Du (Dujiangyan)-Wen(Wenchuan) highway. Firstly, quick visual inspections were performed to gather preliminary information on tunnel damage. Detailed surveys were performed for tunnels that were significantly damaged, using lining crack mapping, photo recording, and measuring of the major crack characteristics (including width, depth and relative displacement). Various types of tunnel damages were observed, including portal failure, sheared off lining, concrete lining spalling, groundwater inrush, rockfalls, and lining cracks. Among the 18 tunnels investigated in Du-Wen highway, all of the tunnels suffered various degrees of damages. Meanwhile, 1 tunnel (5%) is classified as lightly damaged, 4 tunnels (22%) moderately damaged and 13 tunnels (73%) severely damaged. Tunnels passing through the displaced fault zone and fractured zones suffered heavy damage by the relative shear deformation imposed by surrounding rock, as illustrated in Figure 1.



(a) (b)

Figure 1. Sheared off lining due to displaced fault. (a) sheared off damage observed in tunnel; (b) sketch of lining damage due to shear deformation imposed by surrounding ground

3. THEORETICAL ANALYSIS

The main loading of tunnels is the deformation imposed by the surrounding ground. For design purpose, this deformation must be somehow predicted. This is a very difficult tast called seismic hazard analysis. Prediction can be attempted based on deterministic or probabilistic analysis. In either case the results are highly uncertain but possibly still the best achievable assumption.

We consider harmonic waves with the circular frequency **w**. Non-harmonic waves can be decomposed into harmonic ones. Let the unit vector **I** denote the direction of wave propagaion and let a be the amplitude of oscillation. Then the displacement **u** of a point with spatial coordinates **x** is given by the following expressions. Herein, $\mathbf{u_p}$ and $\mathbf{u_s}$ denotes the p-wave and s-wave displacement vectors, respectively.

$$u_p = a_p I \exp[i\varpi(t - \frac{I \cdot X}{c_p})] \quad (2.1)$$

$$u_s = a_s I \exp[i\varpi(t - \frac{I \cdot X}{c_s})] \quad (2.2)$$

$\mathbf{c_p}$, $\mathbf{c_s}$, $\mathbf{a_p}$ and $\mathbf{a_s}$ are the corresponding propagation speeds and amplitudes, respectively. Let **t** be the unit tangential vector at a particular point P of the tunnel axis. Then, the earthquake-induced longitudinal strain and the change of curvature of tunnel can be obtained as:

$$\varepsilon_{\max} = \frac{\varpi}{c} a \cos^2 \alpha \quad (5.3)$$

$$\kappa_{\max} = (\frac{\varpi}{c})^2 a \cos^2 \alpha \quad (5.4)$$

With **α**being the angle between **I** and **t**.

Thus, a joint between two rigid tunnel segments will suffer the elongation **s** and the rotation **θ**(see Figure 2) as follows:

$$s = L\varepsilon \quad (5.5)$$

$$\theta = L\kappa \quad (5.6)$$

L is the length of each tunnel segment.

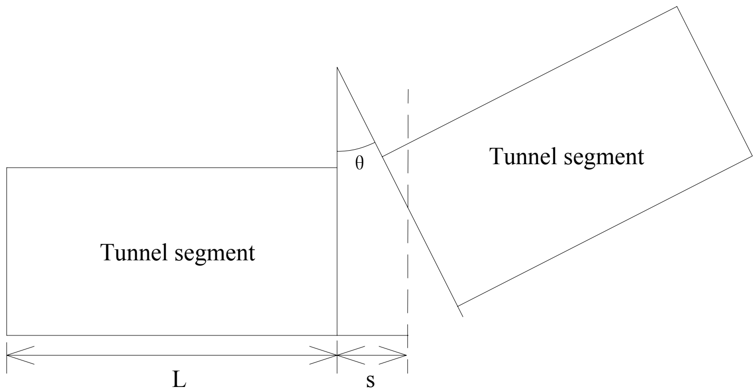


Figure 2. Distortion between two rigid tunnel segments

4. DESIGNED DETAILS OF THE FLEXIBLE JOINT FOR TUNNELS

4.1 considerations for design

The design of seismic joint must begin with a determination of the required and allowable differential movements in both the longitudinal and transverse directions and relative rotation. The joint must also be designed to support the static and dynamic earth and water loads expected before and during an earthquake, and must remain watertight.

In the design of the flexible joint for tunnels in active faulted zones, it can logically be accepted that the designed structure cannot be strong enough to bear the fault displacements, because the amount of the assumed forces from this accidents are significant large. Because of this fact, the design of the flexible joint for tunnels to be safe cannot be based on the working loads, but alternatively the probable maximum credible displacement.

4.2 locations of the flexible joints

the flexible joints should be located in the zones where the differential displacements are significantly large. So setting up some flexible joints between two consequent rigid parts of lining (see Figure 3) can make it flexible enough to be able to tolerate the moment and shear force which may happen in it.

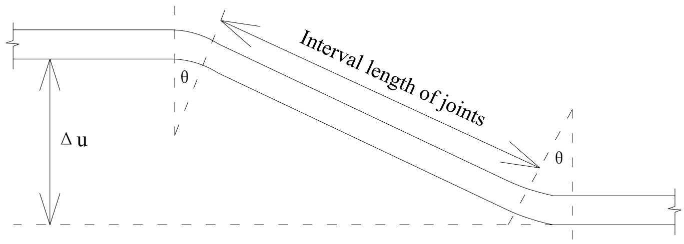


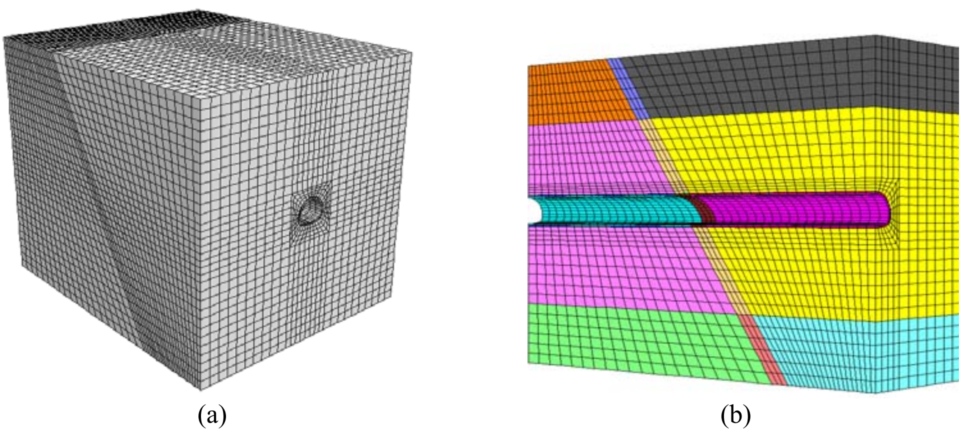
Figure 3. Locations of the flexible joints

5. NUMERICAL ANALYSIS

5.1 Model for a coupled tunnel-ground-fault system

Numerical analysis was performed by FLAC^{3D}, a finite differential program. The ground behaviour and ground-structure interaction have been modeled for the present computations under the conditons of Mohr-Coulomb criterion and the tunnel linings, including the primary lining and the secondary lining, are also considered and modeled as three dimensional elastic elements. A longitudinal profile of the model system along the tunnel axis is shown in Figure 4, in which the fault zone is indicated and whole differential displacement due to the fault movement is assumed to be 20cm.

The geomechanical parameters of the tunnel, the fault and the joints are assumed as shown in Table 1. The layout of the isolation joints is shown in Figure 5. which are modeled by joint elements.

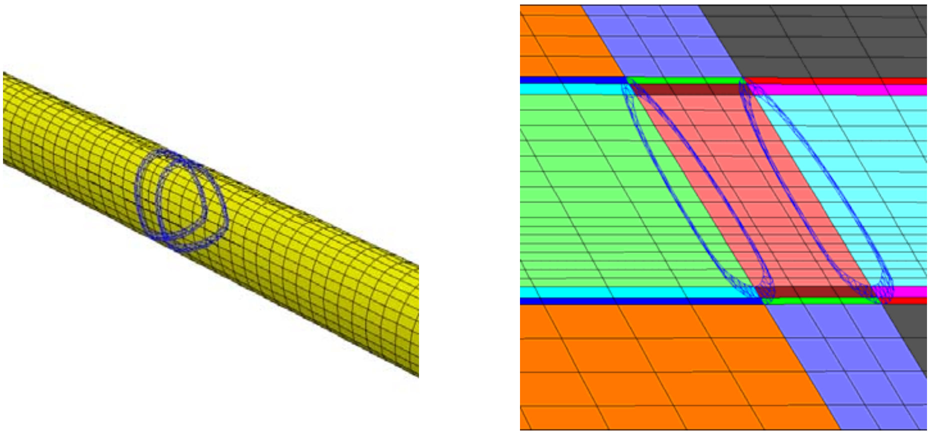


(a) (b)

Figure 4. The longitudinal profile of an assumed tunnel with a faulted zone. (a) General model (b) Partial model along the tunnel axis

Table 4.1. Geomechanical parameters of the ground and tunnel

Position	E(GPa)	μ	γ(kN/m^3)	C(MPa)	φ(°)
Hanging wall	30	0.2	25	1.2	40
Footwall	30	0.2	25	1.2	40
Faulted zone	3	0.3	20	0.6	25
Tunnel	35	0.2	26	/	/

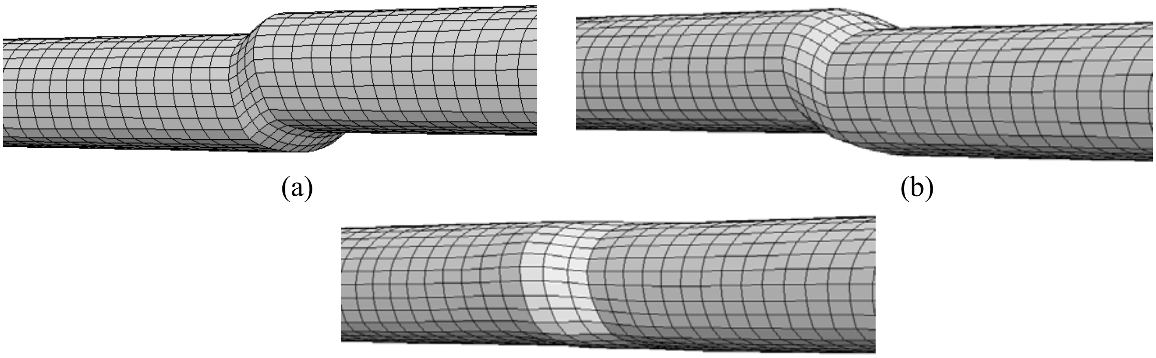


(a) (b)

Figure 5. Isolation joint model

5.2 numerical results and discussion

The effect of fault movements on tunnels is simulated by imposing forcible displacement on the hanging wall. The values of forcible displacement in horizontal and vertical directions are both 20cm. The deformation of the tunnel under three different fault movements is shown in Figure 6.



(c)

Figure 6. deformation of the tunnel under three different fault movements. (a) Reverse fault; (b) Normal fault; (c) Strike-slip fault

In Figure 7 and 8, The maximum principal stresses of tunnel roof and floor are shown, respectively, along the tunnel axis. It is found that the maximum principal stress of tunnel under normal fault movement is the biggest, but the damage range is smallest. The biggest damage range occurs in strike-slip fault condition. The influence degree of reverse fault is between the other two faults.

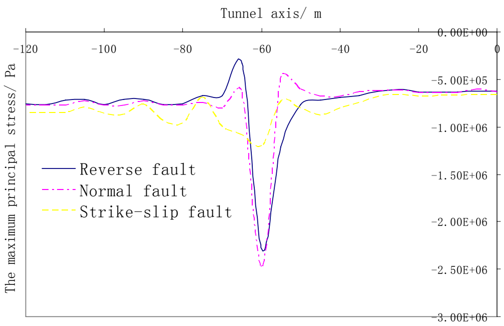


Figure 7. The max. principal stresses of tunnel roof

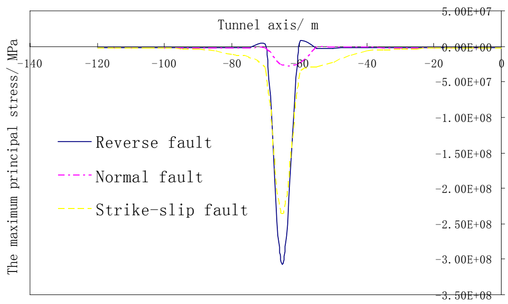
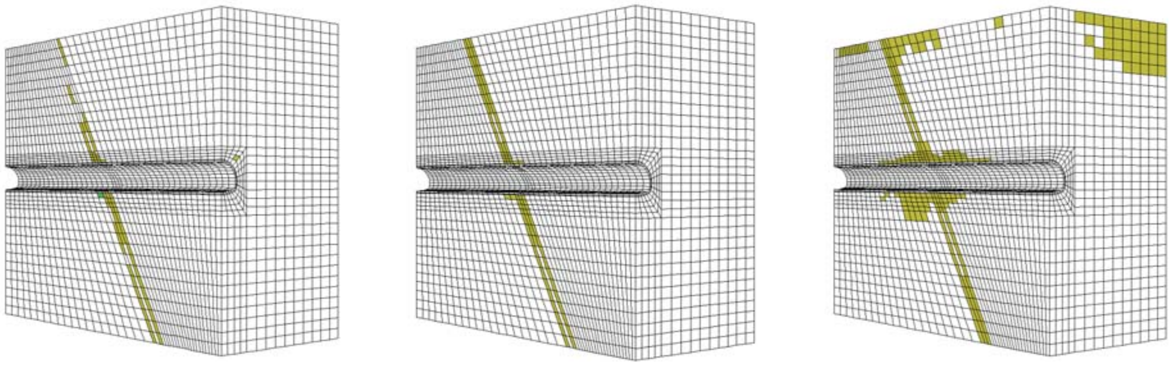


Figure 8. The max. principal stresses of tunnel floor

Figure 9 shows the plastic zones occurred along the surface of fault movement. It is also found that the surrounding rock near the tunnel across the fault is damaged seriously under the strike-slip fault movement. So it is can be concluded that the tunnel is liable to damage under the strike-slip fault movement.

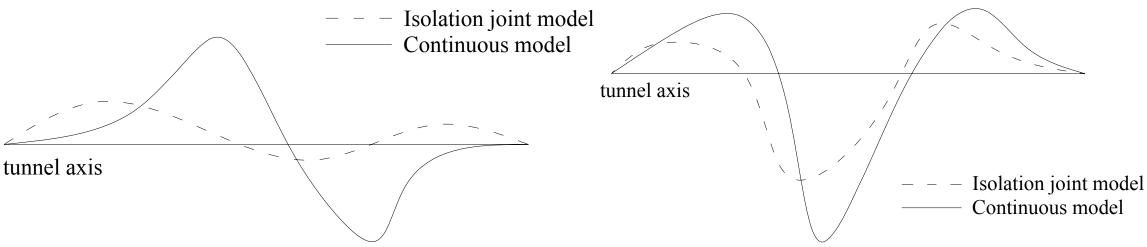


(a) (b) (c)

Figure 9. Plastic zone of sourrouding rock under three fault movements. (a) Reverse fault; (b) Normal fault; (c) Strike-slip fault

The tunnel lining is damaged seriously under strike-slip condition, so the continuous design of the tunnel across the faulted zone(no isolation joints) is analyzed under this condition. The results of the comparison between isolation model and continuous model are shown in Figure 10.

It is found that very large forces and moments will be generated if a continuous design is used. So introducing some flexible joints between two consequent rigid parts of lining can make it flexible enough to be able to tolerate the moment and shear force which may happen in it.



(a) (b)

Figure 10. Comparison of : (a) moment and (b) shear force of two models along the tunnel axis. (a) Bending moment; (b) Shear force.

6. CONCLUSIONS

The seismic behavior of the tunnel across the active fault is analyzed and a method of designing flexible lining for tunnels across active fault is put up. The effects of the method are analyzed by numerical simulation. The results show that the tunnel lining with flexible joints allows the tunnel to distort into S-shape through the fault zone without rupture and thus it can provide reference to the design and construction of tunnels located in the active faulted zones.

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