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Seismic tunnel response in jointed rock mass

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ABSTRACT: A series of pseudo-static discrete element analyses are performed to evaluate the effect of rock joint on the seismic response of tunnels. The parameters considered joint spacing, stiffness and strength, and dip. The results show that the joint stiffness and strength have the most critical influence on the tunnel response. Increase in the spacing of the joints results in localized concentration of shear deformation, and hence the moment and shear stress of the tunnel lining increase accordingly. The tunnel response is shown to be lowest for joints dipping at 45°, while the responses are largest for vertical and horizontal joints. In summary, it is shown that smooth, widely spaced joints with shear stiffness lower than 0.25 GPa/m can significantly increase the tunnel response under seismic loading. The tunnel linings are shown to be most susceptible to damage due to induced shear stress, and therefore should be checked in the seismic design.

1 INTRODUCTION

The underground space has become an integral part of the modern infrastructure due to the lack of urban surface space and increased need for infrastructure including tunnels for roads and railways. While the importance of underground space is well recognized, their response under seismic loading has not been extensively studied because the underground space is known to be resistant to earthquake induced damage. However, recent earthquakes demonstrated that even underground space is prone to damage under severe seismic loading (Asakura et al., 1996; Hashash, 2002; Wang, 1993).

Since tunnels are completely enclosed in the ground, they do not vibrate freely and comply to the movement of the ground. Therefore, it is a common practice to perform an analytical or numerical pseudo-static analysis, in which the maximum shear strain at the location of the tunnel calculated from a site response analysis is imposed. Previous studies assumed the ground to be continuous (Amorosi et al., 2009; Cilingir et al., 2010; Sedarat et al., 2009). Such assumption is valid in cases of tunnels surrounded by soil. However, it is not appropriate for tunnels built in rock mass, in which the characteristics of the joints may greatly influence the response of the tunnel. In this paper, a series of discrete element analyses (DE) were performed to evaluate the influence of the rock joints on the seismic response of tunnels.

2 NUMERICAL ANALYSIS

DE were performed with UDEC^{2D} (2004), whereas FLAC^{2D} (2002) was used to perform the finite difference analysis (FD). The computational domain and the boundary conditions are shown in Figure 1.

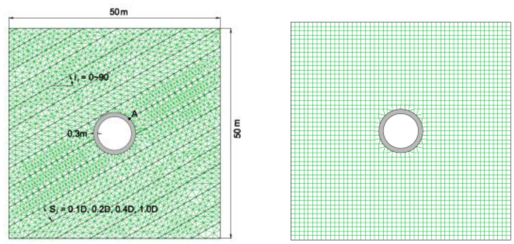


Figure 1. Computational model: (a) discrete element analysis model and joint layout, (b) finite difference analysis model.

Table 1. Properties for rock and tunnel lining.

	Density (kg/m^3)	Elastic modulus (GPa)	Poisson's ratio
Rock	2320	19.3	0.15
Tunnel lining	2000	15	0.2

The domain was 50 m × 50 m and the circular tunnel with a radius of 5 m and 0.3 m thick lining is located at the center of the domain. The lower boundary was fixed in vertical and horizontal directions, while the lateral boundaries were fixed only in the vertical direction. Plane strain condition was used in all analyses. The deformation is imposed in the form of inverted triangle along the lateral boundaries and constant displacement at the top boundary, as shown in Figure 2.

In both DE and FD, plane strain constant strain triangular elements were used to model the rock. The DE and FD models are shown in Figure 1a and b, respectively.

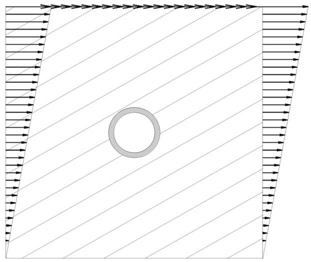


Figure 2. Application of displacement boundary.

Table 2. Properties applied for the rock joints.

Joint type	K_n (GPa/m)	K_s (GPa/m)	c (MPa)	ϕ (°)
Fresh to slightly weathered	20	2	0.2	49
Moderately weathered	5	1.3	0.1	40
Weathered	2	0.5	0.05	36
	1	0.25	0.04	35
Clay-in-filled	0.1	0.025	0.03	33

The tunnel lining was modeled with 2-node beam elements. Both the rock and lining were assumed to be linear elastic materials, whereas the Mohr-Coulomb model was used for the joints and the tunnel-joint interface. The properties for clastic sedimentary rock as recommended by (Kulhawy, 1975) were applied. The properties used for the rock and tunnel lining are listed in Table 1.

To investigate the effect of joints, various combinations of tunnel-joint spacing, stiffness and strength and dip were modeled, the matrix of which is given in Table 3. Parameters shaded in grey represent the reference properties. Joint spacings used were 1 m (0.1D), 2 m (0.2D), 4 m (0.4D), and 10 m (1.0D). A total of seven joint dips, ranging from 0° to 90° at an interval of 15° , were used. The properties for joint stiffness and strength were selected from Bandis et al. (1983) and FLAC^{2D} manual. Bandis et al. (1983) characterized the joint condition as 1) fresh to slightly weathered, 2) moderately weathered, and 3) weathered and recommended a range of normal (K_n) and shear stiffness (K_s) for each joint condition. K_s was suggested to be 1/4 – 1/10 of K_n. In Table 2, the values of stiffness and strength selected in the analyses are summarized. In addition, properties representative of a clay-infilled joint ($K_n = 0.1$ GPa/m, $K_s = 0.025$ GPa/m) were used. The shear strengths were calculated from the Barton-Bandis equation (Barton, 1976);

$$\tau = \sigma_n \tan[JRC \log(\frac{JCS}{\sigma_n}) + \phi_r] \tag{1}$$

where σ_n = normal stress, JCS = joint compressive strength, JRC = joint roughness coefficient. The recommended values for sandstone as suggested by Bandis et al. (1983) were applied. The Mohr-Coulomb parameters (c', ϕ') what fits the calculated shear strengths for σ_n range of 0.2∼2.0 MPa, were used, as listed in Table 2.

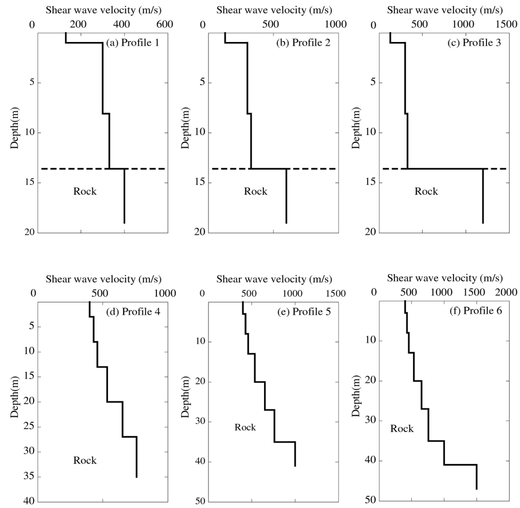


Figure 3. Vs profiles used to perform site response analyses for estimation of representative maximum shear strain in rocks.

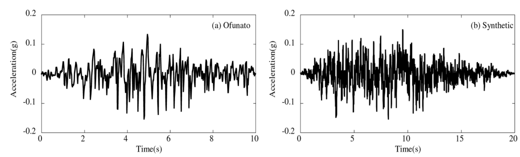


Figure 4. Input ground motion acceleration time series used to perform 1D site response analyses.

It was assumed that the rock is massless and the initial stresses caused by overburden and tunneling were not simulated. The calculated responses were solely induced by ovaling deformation of the tunnel. To determine the shear strain amplitude to be applied in the analysis, a series of one-dimensional equivalent linear site response analyses were performed using DEEPSOIL (Hashash and Park, 2001). A total of six profiles were used, are shown in Figure 3.

Figure 3a–c are soil columns underlain by weathered to weak rock. Figure 3d–f are rock profiles. The input motions used are shown in Figure 4.

Two motions widely used in Korea, which are recorded motions at Ofunato and synthetic motion, were scaled to a peak ground acceleration of 0.154g. It represents the maximum acceleration for an earthquake with a return period of 1000 years. The synthetic motion is response spectrum compatible motion generated by SIMQKE-II (Vanmarcke et al., 1999). The dynamic curves used are shown in Figure 5.

The mean curves of Seed & Idriss (1970) were used for all soil layers, while the default curve for rocks Schnabel et al. (1972) was used for rock profiles. The calculated maximum shear strain results showed that the range of calculated maximum shear strains in rock

Table 3. Matrix of analyses.

Parameters		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Joint spacing (m)	1	○													
	2		○												
	4			○		○	○	○	○	○	○	○	○	○	○
	10				○										
Joint stiffness (GPa/m)	K_N / K_S														
	20 / 2					○									
	5 / 1.3	○	○	○	○					○	○	○	○	○	○
	2 / 0.5						○								
	1 / 0.25							○							
	0.1 / 0.025								○						
Joint dip (°)	90									○					
	75										○				
	60											○			
	45												○		
	30	○	○	○	○	○	○	○	○						
	15													○	
	0														○

layers is between 0.002–0.024% using representative motions for Korea. The shear strain was lower than 0.01% for rock layers exceeding 1000 m/s in shear wave velocity, while shear strain up to 0.024 is calculated for softer layers. Based on the analysis results, the pseudo-static analyses in the following applied 0.01% shear strain. It should be noted that at regions of higher seismicity, the anticipated shear stain level can be higher.

3 ANALYSIS RESULTS

3.1 *Joint spacing*

The joint spacing modeled were 0.1D, 0.2D, 0.4D, and 1.0D, which correspond to Cases 1, 2, 3, and 4, respectively. The reference properties of joints were applied in all cases, as listed in Table 3. Since the location of the tunnel-joint intersection influences the response, the joints were laid out such that one joint always intersects the tunnel shoulder. The calculated responses are shown in Figure 6. It was shown that the responses generally increase with the spacing, due to concentration of the deformation. As the spacing decreased, the responses became more uniformly distributed along the tunnel lining.

The calculated thrust, moment, and shear force for 1.0D case were larger than 0.1D case by 50%, 79%, and 183%, respectively. The maximum responses of the DE and FD were compared to the allowable stresses. The bending stresses for Case 1 and FD were similar, the difference increasing with the joint spacing. In all cases, the calculated stresses were pronouncedly smaller than the allowable stress. The shear stresses calculated from the DE were significantly larger than the FD, but again, smaller than the allowable stress.

3.2 *Joint stiffness and shear strength*

The influence of the joint stiffness and strength, Cases 3 and 5 to 8, are illustrated in Figure 7. It should be noted that even though only the values of the joint stiffness are shown in the figures, the strength of the joints change with the stiffness, as summarized in Table 3.

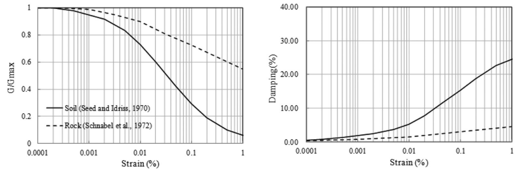
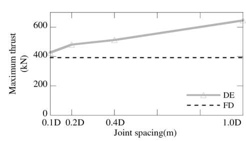
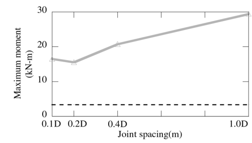


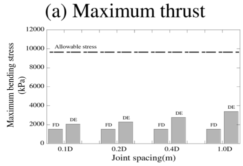
Figure 5. Dynamic curves used.



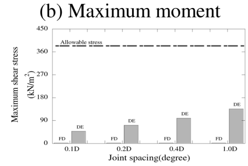
(a) Maximum thrust



(b) Maximum moment



(c) Maximum bending stress



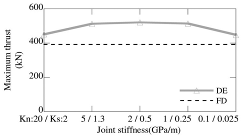
(d) Maximum shear stress

Figure 6. Effect of joint spacing on calculated (a) thrust, (b) moment, (c) bending stress, and (d) shear stress (Case 1, 2, 3, 4).

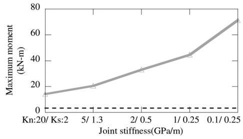
Figure 7 shows that the joint stiffness and strength has significant influence on the calculated response. With decrease in the joint stiffness and strength, the thrust was not greatly influenced, while both the moment and shear force showed pronounced increase. When properties representative of weathered and clay in-filled joints were applied, the bending stress became close to 50% of the allowable stress, while the shear stress approached the allowable stress. It was demonstrated that the tunnels intersected by weak joints are susceptible to damage under seismic loading.

3.3 *Joint dip*

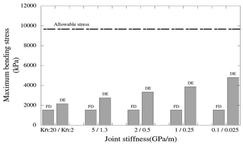
The joint dip was varied from 90° (vertical) to 0°, at an interval of 15°. In all cases, the joints were laid out such that one joint intersects the tunnel shoulder. The reference properties for the joint were applied. Figure 8. compares the DE, FD, and the allowable stresses. Similar trends to previous sections were observed. The moment and shear force were concentrated at the tunnel-joint intersection, whereas the thrust did not show such dependency. In line with previous analyses, it was shown that the moment and shear stresses were more sensitive than the thrust to change in the joint dip. The moment and shear force were lowest for joint dipping 45° and highest for vertical and horizontal joints. This was because when displacement boundary condition was applied, as shown in Figure 2 highest shear stresses were imposed at the vertical and horizontal boundaries. It was demonstrated that the shear deformation is largest for vertical and horizontal joints under vertically propagating shear waves.



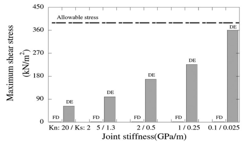
(a) Maximum thrust



(b) Maximum moment

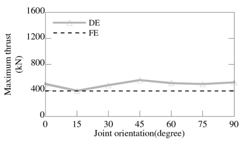


(c) Maximum bending stress

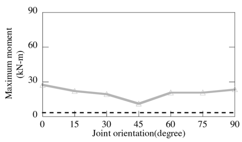


(d) Maximum shear stress

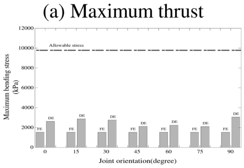
Figure 7. Effect of joint stiffness and strength on calculated (a) thrust, (b) moment, (c) bending stress, and (d) shear stress (Case 3, 5, 6, 7, 8).



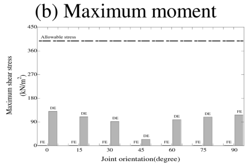
(a) Maximum thrust



(b) Maximum moment



(c) Maximum bending stress



(d) Maximum shear stress

Figure 8. Effect of joint dip on calculated (a) thrust, (b) moment, (c) bending stress, and (d) shear (Case 3, 9, 10, 11, 12, 13, 14).

4 CONCLUSIONS

This study evaluated the effect of joints on the seismic response of circular tunnels through a series of the discrete element (DE) and the finite difference (FD) analyses. The parameters considered were tunnel-joint spacing, stiffness and strength, and joint dip. The properties for the joint were selected from the literature and the applied shear strain amplitude was based on site response analyses.

The results demonstrated the following. The response of the tunnel was significantly influenced by the joint stiffness and strength. It was shown that weathered joints with shear stiffness lower than 0.25 GPa/m can result in high levels of moment and shear force, and should therefore be checked in the seismic design. Joint spacing also had important influence on the tunnel response. With increase in the joint spacing, the concentration of the deformation induced high levels of moment and shear stress. The vertical and horizontal joints resulted in the highest response.

In summary, the results of the DE indicate that widely spaced, vertical or horizontal, weathered and smooth joints with shear stiffness lower than 1.0 GPa/m can greatly increase the shear stress in the tunnel lining. It is therefore recommended that the effect of joints be evaluated in such cases.

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