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Numerical Analysis for Earthquake Dynamic Responses of Tunnel with Different Lining Rigidity Based on Finite Element Method

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Abstract: The damage to tunnel induced by intense earthquake is obviously. Thus, more and more attentions have been paid to the tunnel destruction induced by earthquake. So far, there are few study conducted on the influence that the parameter change of tunnel lining has upon the seismic dynamic response of lining. The study attempts to make a systematic analysis of the tunnel responses with different lining rigidity to the earthquake and seek out the rules governing the change of lining rigidity and the seismic dynamic response of tunnels. To find out the relationship between tunnel lining rigidity and seismic dynamic response, the finite element model of deeply buried tunnel have been set up based on the software of finite element and the responses about different rigidity of tunnel lining under earthquake's dynamic load has been analyzed by using elastic finite element law. The conclusions have been drawn that the change of displacement, velocity and acceleration of earthquake responses by increasing rigidity of tunnel lining is unobvious. Therefore, it is unfeasible and uneconomical to diminish the response of tunnels to seismic dynamic by increasing the lining rigidity.

Key words: Tunnel, rigidity of tunnel lining, earthquake dynamic response, finite element method

INTRODUCTION

With the rapid development of economy and society, tunnels have tent to be built in those areas where the earthquake happens frequently, namely high earthquake-intensity areas. A large number of investigations conducted after a quake indicate that the damage brought by the massive quake to tunnel lining is enormous and meanwhile the forms of damage are various (Li, 2008).

The problems of tunnel have been studied by many researchers and there are many studies have been published now (Li *et al.*, 2012; Hu *et al.*, 2012; Ding *et al.*, 2012). Okamoto and Tamura (1972) pointed out that great development has been made on the researches regarding the numerical analysis of the tunnel dynamic response at home and abroad; Goto *et al.* (1988) conducted a seismic model test for the tunnel and gained many valuable achievements. By means of translation, Shenghai (1989) introduced the structure calculation of lining, the soil tunnel, the seismic design of underground pipeline and seismological observation and model test of buried (hushed) pipeline etc. when non-circular rock mass tunnel was under earthquake loading. Genda and Wenhai (1990) studied the seismic resistance of the railway tunnel lining under massive quake loading and considerable achievements were obtained in the meantime. Changshi (1996) summarized the failure characteristics of tunnels and underground structures. He also studied the seismic response by using the mass-spring model and adopting the method of finite element. Based on the analysis of Osaka-Kobe earthquake, Ruimin and Qifeng (1998) held that the seismic behavior of underground structures was better than that of buildings on the ground. They further believed that study of the seismic behavior of underground structure should be deepened in terms of structure analysis, model test and even the revision of standard. Feng (2003) made a numerical simulation for the wave analysis of underground structure by adopting the method of Newmark implicit integration and viscous-spring artificial boundary. Based on the premise that different surrounding rock materials and lining types were assumed, he also studied the relation between seismic fortification length and surrounding rock of the tunnel portal part, the surrounding rock reinforced by grouting, the setting of the effect of shock absorbing layer as well as its application range. Songhong (2003) simulated the lateral and overall random seismic response of underground structures by taking the approach of impulse response function of random vibration. At the same time, by adopting the maximum random seismic response he also

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Corresponding Author: Xiaoping Cao, School of Civil Engineering, Lanzhou Jiaotong University, Lanzhou Gansu 730070, China analyzed the reliability of random seismic dynamic of underground structures and put forward the method investigating the dynamic reliability based on the theory of first excursion failure.

So far, there are few studies conducted on the influence that the parameter change of tunnel lining has upon the seismic dynamic response of lining. In order to find out the relation between tunnel lining rigidity and seismic dynamic response, a systematic analysis for the seismic responses of tunnel surrounding rock with different lining rigidity was presented. It is hoped that the present study is able to serve as a basis for the further study on the shock absorption measures of tunnels.

MOTION EQUATION

According to D'Alembert's theory, the motive equation of tunnel structural system can be:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=-[M]\{\ddot{x}_g\} \tag{1}$$

where, [M] is the whole mass matrix; [C] is the whole damp matrix; [K] is the whole stiffness matrix; $\{\ddot{x}\}$ is the systemic acceleration vector; $\{\dot{x}\}$ is the systemic velocity vector; $\{x\}$ is the systemic displacement vector; $\{\ddot{x}_g\}$ is the ground acceleration vector induced by earthquake.

The rayleigh damp matrix can be written as follows:

$$[C] = \alpha[M]+\beta[K] \tag{2}$$

Where:

$$\begin{aligned} \alpha &= \zeta_0 \cdot w_0 \\ \beta &= \frac{\zeta_0}{w_0} \end{aligned} \tag{3}$$

where, ζ_0 is the damping ratios, it can be 0.05 when calculating.

In this study, Newmark's step-by-step implicit integration method is adopted to solve the motion Eq. 1:

$$\dot{x}_{t+\Delta t} = \dot{x}_t+[(1-\delta)\ddot{x}_t+\delta\ddot{x}_{t+\Delta t}]\Delta t \tag{4}$$

$$x_{t+\Delta t} = x_t + \dot{x}_t\Delta t + \left[\left(\frac{1}{2}-\gamma\right)\ddot{x}_t + \gamma\ddot{x}_{t+\Delta t}\right]\Delta t^2 \tag{5}$$

where, $\dot{x}_{t+\Delta t}$ is the nodal velocity vector at time t+Δt, $x_{t+\Delta t}$ is the nodal displacement vector at time t+Δt, δ and γ are integral constant, they can determined by integral stability. Stability of Newmark's step-by-step implicit integration is with no conditions when $\delta = 1/2$, $\gamma = 1/4$.

After the nodal location and the nodal acceleration at time t are acquired together with the nodal velocity at time t+Δt, the nodal displacement at time t+Δt can be calculated by Eq. 5.

CALCULATION MODEL

The tunnel is located in the semi-infinite stratum, the tunnel border of the horizontal and below across the tunnel sections are further infinitely. The calculating model is eight times of the horizontal tunnel span and the spacing between two tunnels is 30 m. For the vertical direction of the tunnel, the top and bottom boundary is 75 m from the tunnel center each. Thus, the whole depth of calculating model is 150 m and the top surface is assumed as the ground. It can be simulate the tunnel and tunnel first lining through the four points element (i.e., tetrahedron element) and rectangular element for the tunnel second lining to present dynamic finite element analysis. The whole model partitions 16376 elements (including entity and plane elements). The model and finite element grid is shown in Fig. 1.

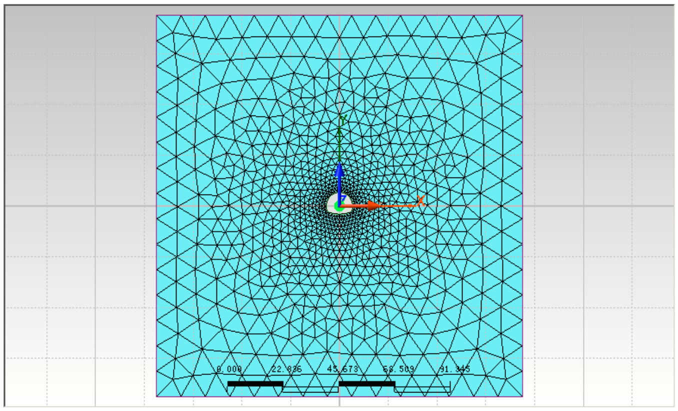

Fig. 1: Finite element grid of model

Since, the present study aims to find out the impact that the change of lining rigidity has on the earthquake response, acceleration of exceeded probability 2% (Fig. 2) into 50 years is imported through transverse direction.

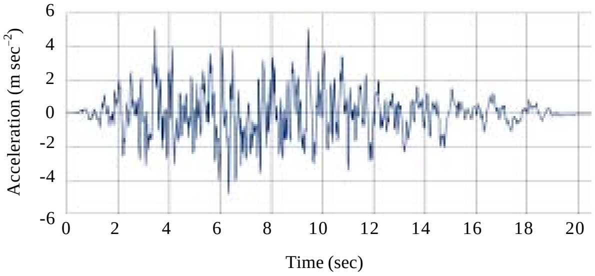

Fig. 2: Curve of time history of acceleration of exceeded probability 2% into 50 years

ANALYSIS OF CALCULATION RESULTS

The present study takes a certain highway tunnel that are under construction as an example. Various parameters of the tunnel system is shown in Table 1.

The model calculates, respectively the displacement, the velocity and the acceleration response of the tunnel secondary lining when the lining rigidity is 0.5 E, 1 E, 1.5 E, 2 E, 2.5 E, 3 E, 3.5 E and 4 E. The vault, spandrel and arch foot of the tunnel secondary lining are chosen as the feature points for study. The curve for the displacement, the velocity and the acceleration of the feature points along the transverse and vertical direction with different rigidity is shown in Fig. 3a-f.

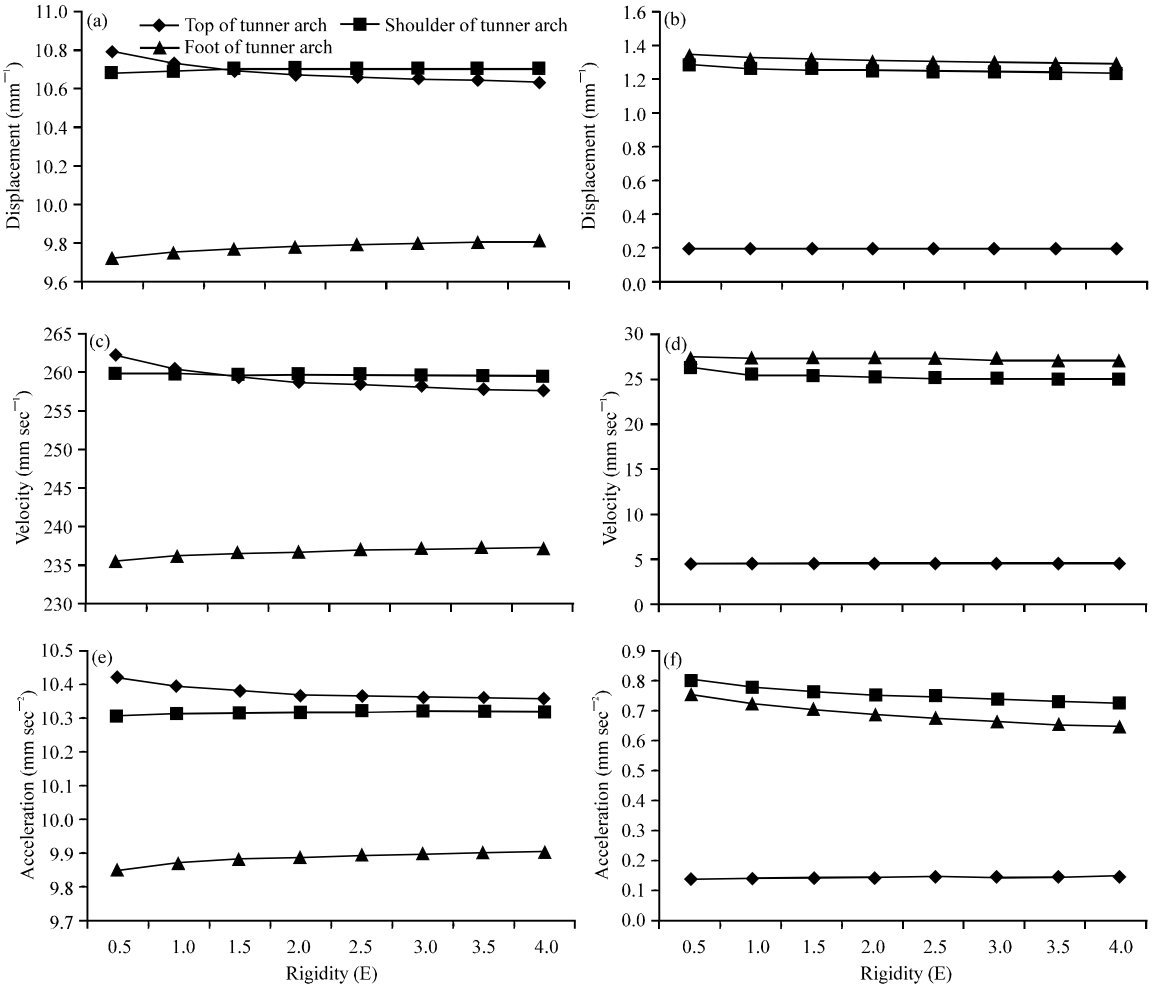

Fig. 3(a-f): (a-b) Curves of displacement, (c-d) Velocity and (e-f) Acceleration of characteristic dot under different lining rigidity

Along the direction of seismic wave propagation the value of displacement, velocity and acceleration in every point of tunnel secondary lining is far larger than that in the other direction.

The value of the maximum displacement, velocity and acceleration in the vault, spandrel and arch foot of the tunnel along the transverse direction is obviously larger than that along the vertical direction; Along the transverse direction, the value of the maximum displacement, velocity and acceleration in the vault and spandrel is obviously larger than that in the arch foot; Along the vertical direction, the value of the maximum displacement, velocity and acceleration in the spandrel and arch foot is obviously larger than that in the vault.

With the lining rigidity increasing, the maximum displacement, velocity and acceleration in the vault along the transverse direction presents a decreasing trend; The change of the maximum displacement, velocity and acceleration in the spandrel along the vertical direction is basically irrelevant to the change of rigidity; the maximum displacement, velocity and acceleration in the arch foot increases slightly.

No matter along the transverse direction or vertical direction, increase in the lining rigidity exerts little influence on the displacement, velocity and acceleration in the spandrel and the maximum displacement, velocity and acceleration in the spandrel is relatively larger than that in the vault and arch foot.

As is shown in Fig. 4a, the maximum axial force of lining appears in the spandrel; as is shown in Fig. 4b, the maximum bending moment of lining appears in the arch foot. Furthermore, the bending moment in the spandrel is

Table 1: Mechanical parameters of rock and tunnel lining

Material type	Specific gravity γ/kN m^{-3}	Young's modulus E/GPa	Poisson's ratio μ	Cohesion C/MPa	Interior frictional angle φ/°	Dynamic shear modulus G/GPa
Surround rock V	22	4.5	0.32	0.5	35	0.536
Second lining/C30 concrete	25	30.0	0.20	4.0	55	9.583

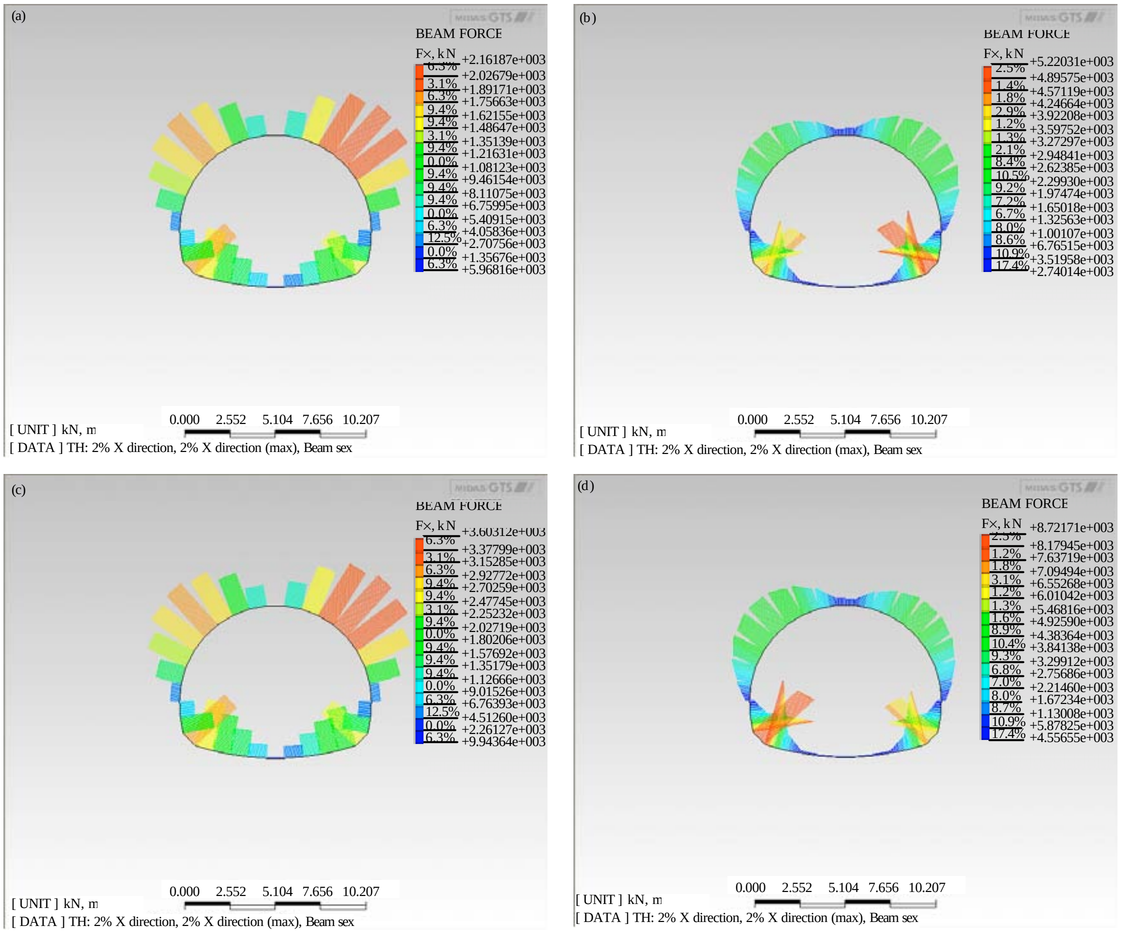

Fig. 4(a-e): Continue

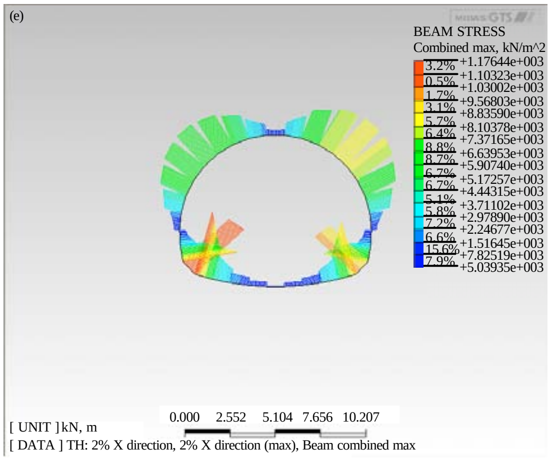

Fig. 4(a-e): Picture of internal force and stress under the rigidity is 4.0 E (a) Picture of axes force of element reference frame under the rigidity is 4.0 E, (b) Picture of Y directional bending moment of element reference frame under the rigidity is 4.0 E, (c) Picture of X directional axes stress under the rigidity is 4.0 E, (d) Picture of bending moment stress under the rigidity is 4.0 E and (e) Picture of combined stress under the rigidity is 4.0 E

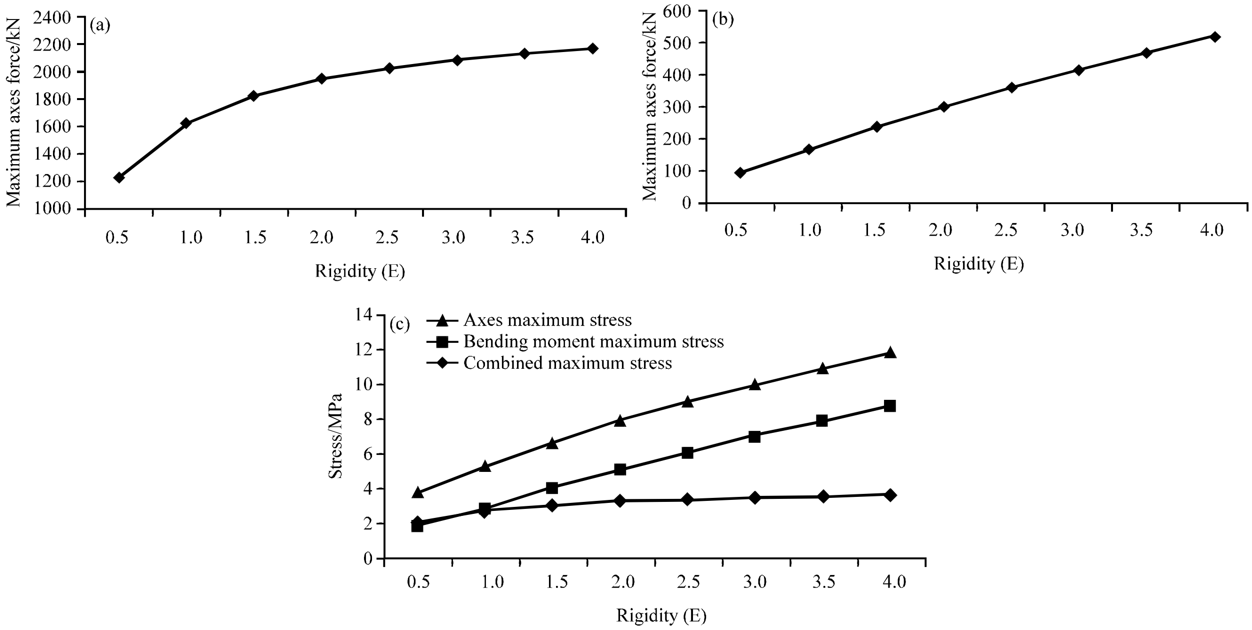

Fig. 5(a-c): Curves of internal force and stress (a) Maximum axes force, (b) Maximum bending moment and (c) Each stress and maximum combined stress under different tunnel lining rigidity

relatively larger, as is shown from Fig. 4c-e, the maximum axial stress of lining appears in the spandrel and the maximum flexural stress in the arch foot. On the whole, the maximum combined stress of lining (including axial and flexural stress) appears in the arch foot. In addition, the combined stress in the spandrel is relatively larger.

As is shown in Fig. 5a, under the impact of seismic wave in transverse direction, the maximum axial force of lining structure increases significantly as the rigidity increases in transverse direction of Element Coordinate System of which increase in the range from 0.5-2 E is relatively larger and increase following 2 E is found to be stable; as is shown in Fig. 5b, the maximum bending moment of lining structure increases evidently with the rigidity increasing in vertical direction of element coordinate system; as is shown in Fig. 5c, the maximum combined stress of lining structure increases in a stable manner as the rigidity does.

CONCLUSION

Under the impact of seismic dynamic loading, the maximum displacement, velocity and acceleration of tunnel lining structure is definitely larger in the direction of seismic wave propagation than that in the other direction. Therefore, the damage brought by earthquake to tunnel lining structure is directly connected with the direction of seismic wave propagation. As the tunnel lining rigidity increases, the displacement, velocity and acceleration of tunnel lining structure decrease and meanwhile they are decreased in a small scale.

First of all, under the impact of seismic loading, the maximum axial force of tunnel lining appears in the spandrel and the maximum bending moment of lining appears in the arch foot. Second, The bending moment in the ,spandrel is relatively larger. On the whole, the combined stress (including axial and flexural stress) of lining in the arch foot is the largest.

Under the impact of seismic wave, increase in the rigidity is consistent with increase in the maximum axial force, the maximum bending moment and the maximum combined stress of lining structure.

Therefore, it is unfeasible and uneconomical to diminish the response of tunnels to seismic dynamic by increasing the lining rigidity.

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