Numerical Simulations of Seismic Responses of Concrete Segments for Tunnel Linings in Shenyang City

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Abstract. In order to evaluate the influence of seismic action on internal forces on segments, the seismic responses of concrete segments for tunnel linings in Shenyang city are numerically simulated with finite element method. The seismic inputs acting on bottom of FEM model are modified in order to make peak value of accelerations on ground surface equal to 1m/s² based on code for seismic design of buildings. The investigations show that, by comparing with those of the seismic inputs on bottom of FEM model, the predominant frequency of ground surface movements is significantly modified because the soil has an important filtering effect. By comparing with the peak value of accelerations of seismic inputs on bottom of FEM model, the peak value of accelerations on ground surface is only amplified as 1.57 times because the elastic moduli in different soil layer have little different. The maximum bending moments on segment linings induced by static soil loading are 496kNꞏm. The maximum bending moments on segment linings induced by seismic loading are 58kNꞏm. The maximum bending moments on segment linings induced by static soil loading are located in roof, floor and two side walls. However, the maximum bending moments on segment linings induced by seismic loadings are located in left and right spandrels. On those sites, the bending moments induced by static loading approaches zero. By comparing with the maximum bending moment on segment linings induced by static soil pressure, the maximum bending moment superposed by static and dynamic loadings only increases 0.4%.

1. Introduction

Earthquake loadings acted on underground tunnel linings are often neglected because it is commonly believed that the underground tunnel linings move with surrounding soils during earthquake processing. However, some serious damage or even collapse examples of underground tunnels after earthquake has been reported[1]. Arnau investigated deformation properties of concrete segment tunnel by using three-dimensional computational model[2]. To investigate the seismic characteristics of the special subway tunnel under spatially varying earthquake ground motions with high efficiency, the concept of response displacement method was utilized and realized with a refined free-field model and a simplified soil-tunnel model by Miao[3]. Hashash described approaches used by engineers in quantifying the seismic effect on an underground structure. Deterministic and probabilistic seismic hazard analysis approaches were reviewed. The development of appropriate ground motion parameters, including peak accelerations and velocities, target response spectra, and ground motion time histories, was briefly described [4]. In order to study their effects on the dynamic tunnel-soil-aboveground building interaction, starting from
a real case-history regarding the Catania (Italy) underground network, and in particular a cross-section including an aboveground building, the depth of the tunnel, the position of the aboveground building and the seismic inputs were modified by Abate [5]. In order to describe strain rate dependence and fatigue damage of concrete material under cyclic loading, a dynamic constitutive model for concrete lining considering tension and shear anisotropic damage is presented, and the evolution equations of damage variables are derived by Wang[6]. Abate dealt with the dynamic interaction that occurs between a tunnel, the soil and an aboveground building, who also investigated the effects of the tunnel on the response of the soil and/or of the building[7]. Singh simulated the case of Delhi metro underground tunnels through PLAXIS 2D and studied their response to 1991 Uttarkashi earthquake of lower Himalaya and then conducted some parametric study [8]. The aim of the paper is to investigate the dynamic responses of concrete segment linings in tunnel, compute dynamic increments of bending moment of concrete segment linings, analyze variation of amplitude of horizontal acceleration versus embedded depth, and evaluate safety characteristics of concrete segments under the actions of static loading and earthquake loading.

2. FEM modelling for a tunnel with concrete segment linings
During earthquake processing, the concrete segments as tunnel linings move with surrounding soils, and its vibrating characteristics are governed by soil layer properties. A metro tunnel is located from Yunfeng north street to Shenyang railway station in Shenyang city and was excavated by EPB shield machine. The average embedded depth of tunnel is 16 m. The underground water table is 8.4 m. The outer-diameter of reinforced concrete lining is 6 m. The thickness of reinforced concrete segment is 350 mm. Grade C50 concrete was used to manufacture lining segment. The elastic modulus of concrete is 34.5GPa. The Poisson’s ratio of concrete is 0.2. Physical and mechanical parameters of soil layers are listed in Table 1. Based on the seismic code, magnitude of seismic precautionary intensity is 7 in Shenyang city, and the peak of horizontal acceleration is 1m/s2 (0.1g) based on code for seismic design of buildings.

| Parameters                  | Thickness/m | μ          |
|-----------------------------|-------------|------------|
| 1/Miscellaneous fill        | 2           | 0.32       |
| 2/silty clay                | 3           | 0.30       |
| 3/medium-coarse sand        | 3.5         | 0.28       |
| 4/gravelly sand             | 1.5         | 0.33       |
| 5/medium-coarse sand        | 3           | 0.30       |
| 6/pebble                    | 3           | 0.25       |
| 7/pebbles(tunnel location)  | 6           | 0.25       |
| 8/medium-coarse sand        | 7           | 0.30       |
| 9/silty clay                | 3           | 0.38       |
| 10/silty-fine sand          | 3           | 0.35       |
As shown in Figure 1, the horizontal displacements on left side and right side of FEM model are constrained, and the vertical displacements on bottom side of FEM model are constrained. The horizontal seismic loading inputs are applied on the bottom side of FEM model after scaling of amplitude and period.

In order to investigate seismic properties of the soil layer and concrete segment linings, dynamic characteristics of FEM model are numerically computed by using ANSYS software. Natural frequencies of FEM numerical model are listed in Table 2. The first order mode shape of the soil layer and concrete segment linings is shown in Figure 2.

![Figure 1. FEM model with boundary conditions and seismic loading inputs.](image)

![Figure 2. The first order mode shape of the soil layer and concrete segment linings.](image)

| order | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Natural frequencies/Hz | 0.796 | 0.887 | 0.893 | 0.961 | 1.142 | 1.308 | 1.416 | 1.555 |

Damping has been taken account using Rayleigh approach with damping proportional to stiffness and mass to the critical damping. Damping of the model was given as Rayleigh damping which is defined as

\[ C = \alpha M + \beta K \] (1)

Where \( \alpha \) and \( \beta \) are coefficient of the matrix. Here, \( \alpha \) and \( \beta \) were selected to conform the damping coefficient of the FEM model which correspond to its 1st and 2nd natural period of traverse motion. They are can be approached by
\[ \alpha \approx 2 \xi \omega_1 \]  
\[ \beta \approx 2 \xi / \omega_1 \]  

Where \( \xi \) is critical damping ratio, \( \xi = 5\% \) for soil and \( \xi = 2\% \) for concrete segments, \( \omega_1 \) is the angular frequency of the first natural mode of the structure.

3. Determination of seismic loading inputs on FEM model
Kobe horizontal earthquake wave is selected as basic wave shape of earthquake inputs. The scaled horizontal earthquake inputs on bottom of FEM model are so modified that the peak of horizontal accelerations on ground surface is equal to 0.1g which is based on seismic code, and the response spectrum of horizontal accelerations on ground surface can approach to the response spectrum determined by seismic code.

4. Dynamic response analysis of concrete segments
It can be found from Figure 4 that the natural frequencies of soil layers have important effect on predominant frequency of acceleration response on the ground surface. The soil layers are like as the filtering elements and modify predominant frequency of earthquake inputs.
Figure 5. Variation of amplitude of horizontal acceleration versus embedded depth.

It can be observed from Figure 5 that the amplitude of horizontal acceleration decreases with increase of embedded depth. The amplitude of horizontal acceleration at the ground surface is largest. Amplification ratio between amplitudes of horizontal acceleration at the ground surface and at bottom of FEM is 1.57.

Figure 6. Comparison of static and dynamic maximum bending moments of amplitude modulated horizontal seismic wave of Kobe along the perimeter of the segment.
Figure 7. Variation of bending moment superposed by static and dynamic loadings on spandrel versus time.

Figure 8. Variation of bending moment superposed by static and dynamic loadings on roof versus time.

Dynamic bending moment increments along perimeter of concrete segments are shown in Figure 8. It can be observed from Figure 8 that the dynamic bending moment increment at point E is largest. By comparing with static bending moment (496kN·m), the dynamic bending moment increases 0.4%.

5. Conclusion

1) The predominant frequency of ground surface movements is significantly modified because the soil has an important filtering effect. By comparing with the peak value of accelerations of seismic inputs on bottom of FEM model, the peak value of accelerations on ground surface is only amplified as 1.57 times because the elastic moduli in different soil layer have little different.

2) The maximum bending moments on segment linings induced by static soil loading are 496kNm. The maximum bending moments on segment linings induced by seismic loading are 58kNm. The maximum bending moments on segment linings induced by static soil loading are located in roof, floor
and two side walls. However, the maximum bending moments on segment linings induced by seismic loadings are located in left and right spandrels. On those sites, the bending moment induced by static loading approaches zero.

3) By comparing with the maximum bending moment on segment linings induced by static soil pressure, the maximum bending moment superposed by static and dynamic loadings only increases 0.4%.

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