Study on the Seismic Response of Long and Large Tunnel under Non-Uniform Excitations

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Abstract. In recent years, the underground tunnel engineering has developed rapidly, moving towards long, large, deep, new and complex structures. The seismic design of the tunnel should consider not only the conventional consistent excitation, but also the response of the non-uniform seismic excitation to the tunnel. Taking the actual Yellow River tunnel project as an example, the non-uniform seismic excitation analysis method is used to study the lateral and longitudinal seismic responses of the super-large tunnel, and the deformation characteristics of the top, bottom and waist of the tunnel are analysed. The study found that the longitudinal deformation and mechanical behavior of long tunnels are characterized by non-uniformity, inhomogeneity and asymmetry. Under the non-uniform excitation, the maximum response displacement of the top, bottom and waist of the tunnel section is larger than the displacement under the uniform action. Therefore, during the design of long tunnels, longitudinal seismic deformation should be emphasized, and the study of non-uniform load effect should be strengthened.

1. Introduction

Underground tunnel engineering has developed rapidly in recent years, many of which are located on or near the seismic zone. Initially, engineers believed that the seismic performance of underground structures was superior to the structures on the ground, but the Japanese Kobe earthquake in 1995 refreshed people’s perceptions. This earthquake severely damaged most of the stations and interval structures, especially Da Kai station which has been completely damaged\(^{[1]}\). The accident not only brought so enormous pain to people, but also sounded the alarm that the engineering community began to pay attention to the seismic performance of underground structures. Chen Guoxing\(^{[2,3]}\), Liu Jingbo\(^{[4]}\), Zhuang Haiyang\(^{[5]}\) and other scholars conducted vibration table test, reaction displacement analysis and numerical simulation on the seismic performance of underground tunnels. Yang et al\(^{[6]}\) conducted a centrifugal dynamic model test considering the seismic action under the George Massey immersed tunnel. The test results show that under the earthquake action, earthquake liquefaction will happen to the sand foundation, which causes the tunnel to take place displacement in different degrees. The effect of earthquakes on the tunnel can be reduced by means of gravel drainage piles or vibration-tight foundations. Liu Guanglei et al\(^{[7]}\) used a dynamic centrifuge with an acceleration of 50g to carry out model tests on shield tunnels embedded in saturated sand. Li Hongxuan et al.\(^{[8]}\) used large-scale finite difference software FLAC3D to calculate the seismic behavior of underwater highway tunnels on soft
soil foundations. What’s more, using time history analysis method, they concluded that the tunnel structure has a lower probability of shear failure and tensile failure. Besides, the tunnel performance meets the safety requirements. Chen Xianghong et al [9] did researches on the effect of hydrodynamic pressure on the tunnel when the earthquake occurred, using ANSYS large-scale finite element software to establish a water-soil-structure model based on Newmark implicit algorithm.

With the rapid development of numerical simulation, some problems are on the way, such as the inability to select appropriate boundary conditions, how to select the dynamic parameters of the soil, and how to simulate the spectral characteristics of the soil. At the same time, in the structural seismic response analysis, the input of seismic waves usually adopts the uniform excitation method. For the large-span structure, because the earthquake motion variability has obvious influence on the structure, the traveling wave excitation input method should be adopted. However, the study on earthquake motion law of tunnel under traveling wave excitation is not deep enough. Therefore, it is necessary to further study the dynamic response of the shield tunnel under traveling wave excitation. Based on the research of a Yellow River tunnel project, the dynamic time history analysis of the shield tunnel is carried out by consistent excitation loading and non-uniform excitation loading, and the seismic response of the long and large shield tunnel is analyzed.

2. Engineering background and analysis model
The analysis background of this paper is a tunnel project through the Yellow River. The tunnel is 3890m long, with an outer diameter of 15.2m, an inner diameter of 13.9m and a segment thickness of 650mm. So it is a long and large underwater tunnel. According to the position relationship between shield tunnel and stratum, the tunnel passes through the silty clay layer and clay layer where the upper part of the tunnel is in the silty clay layer, and the lower part is in the clay layer. The size of the established analysis model is X×Y×Z=141.6m×2516m×98.83m. The number of nodes of the model is 42265, and the number of zones is 196485. The dynamic boundary of the numerical model is free field boundary, the calculation time step is determined automatically according to the size of the element. The finite element model is shown in figure 1 (a) -(c).

![Model elevation](image1)

(a) Model elevation

![Model plan](image2)

(b) Model plan

![Tunnel model](image3)

(c) Tunnel model

Figure 1. Calculation model of tunnel project through Yellow River
According to the stratum parameters provided in the geological survey report, the stratum was comprehensively evaluated. In the numerical analysis, the Mohr-Coulomb model (M-C) was adopted for each soil layer. The calculation parameters are listed in table 1.

| Number | Name               | c   | \(\varphi\) | \(\gamma\) | E   | \(\nu\) | Constitutive model |
|--------|--------------------|-----|-------------|-------------|-----|--------|-------------------|
| 1      | silty clay         | 20  | 12          | 19          | 20  | 0.39   | M-C               |
| 2      | clay               | 24  | 17          | 19.7        | 25  | 0.34   | M-C               |
| 3      | silty clay         | 38  | 17          | 19.7        | -   | 0.32   | M-C               |
| 4      | clay               | 40  | 22          | 20          | -   | 0.32   | M-C               |
| 5      | strongly weathered gabbro | 70  | 38          | 22          | 200 | 0.24   | M-C               |

Shield tunnel segments adopt elastic elements, and the parameters are summarized in table 2.

| Name              | E(MPa) | \(\nu\) | \(\gamma\) (kN/m³) |
|-------------------|--------|--------|---------------------|
| C60 tunnel segment| 3.24\times10⁴ | 0.2    | 25                  |

Seismic waves were input from the bottom of the model. Considering the traveling effects of seismic waves, non-uniform loading method was adopted to simulate the propagation process of seismic waves in 7 different regions at the bottom of the model by controlling the time interval. The input seismic waves are illustrated in figure 2.

Three unfavorable sections along the length of the tunnel were selected for analysis, and the positions of the sections were shown in figure 3.
3. Response analysis of shield tunnel under non-uniform seismic excitation

Comparative analysis on the displacement response of the tunnel vault, arch bottom, left arch waist and right arch waist under the uniform and non-uniform excitation induced by E2 frequent earthquake are shown in Figure 4(a)-(d). It can be seen that under the action of non-uniform seismic waves, the tunnel vault, arch bottom and arch waist have a large displacement response.

![Figure 4. Time history of tunnel displacement under uniform excitation and non-uniform excitation](image)

(a) Time history of tunnel top displacement  
(b) Time history of tunnel bottom displacement  
(c) Time history of tunnel left waist displacement  
(d) Time history of tunnel right waist displacement

Figure 4. Time history of tunnel displacement under uniform excitation and non-uniform excitation

![Figure 5. Tunnel longitudinal displacement at different times](image)

(a) Tunnel longitudinal displacement at different position when t=4s  
(b) Tunnel longitudinal displacement at different position when t=12s  
(c) Tunnel longitudinal displacement at different position when t=12s

Figure 5. Tunnel longitudinal displacement at different times
Under the action of non-uniform compression wave excitation, the displacement changes of the tunnel along the longitudinal direction at different times are shown in Figure 5(a)-(c) above. It can be observed that the deformation along the longitudinal direction of the long and large tunnel is characterized by inconsistency, inhomogeneity and asymmetry. Near the longitudinal direction of 800m, the displacement amplitude of the tunnel has a large change. That is a position where the seismic resistance of the shield tunnel is relatively weak.

Table 3 summarizes the key indicators under uniform excitation loading and non-uniform excitation loading. It can be seen that the response of shield tunnel is more intense under non-uniform loading. The maximum transverse displacement increases by 14% compared with uniform loading, the longitudinal displacement increases by 15.9% compared with uniform loading, the axial force of tunnel increases by 4.8% compared with uniform loading, the shear force of tunnel increases by 65.7% compared with uniform loading, and the bending moment of tunnel increases by 5.5% compared with uniform loading.

4. Conclusion
The research was building on the real Yellow River tunnel project. The dynamic response of this shield tunnel was simulated under uniform excitation and non-uniform excitation. The following conclusions were summarized.

(1) The deformation of the long and large tunnel along the longitudinal direction has a character of inconsistency, nonuniformity and asymmetry. Under the non-uniform excitation, the displacement amplitude of the tunnel along the longitudinal direction has a maximum in a certain location. That is a position where the shield tunnel is prone to be damaged.
(2) Compared with uniform seismic loading, the shear force of tunnel increases by 65.7% under non-uniform loading, which is the largest one among the key indicators. So, the shear resistance design of tunnel ought to be strengthened.

(3) Under the non-uniform excitation, the maximum response displacement of the top, bottom and waist of the tunnel section is larger than the displacement under the uniform action. Therefore, in the design analysis of long tunnels, longitudinal aseismic deformation should be emphasized, and the study of non-uniform load effect should be enhanced. Non-uniform excitation method is more suitable for engineering practice analysis.

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