Seismic Response Analysis of Oblique Incident Angle of SV Wave on Immersed Tunnel

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Abstract. On the basis of viscous-elastic artificial boundary, the ground motion input is transformed into the equivalent node load to achieve the oblique incidence of seismic waves. The two-dimensional finite element model of Nanchang Honggu immersed tunnel section is established by using finite element software. The influence of different incident angles on the dynamic response of the immersed tunnel is analyzed under the oblique incident of the SV wave. The results show that the seismic response law of the immersed tunnel is significantly different from that of the vertical incident when the SV wave is obliquely incident. The structural stress of the immersed tunnel is larger at the corner of the immersed tunnel and the junction of the intermediate partition with the floor and the roof. As the incident angle increases, the vertical response of the immersed tunnel structure increases significantly. Therefore, when seismic design analysis of the immersed tunnel is carried out, the influence of the oblique incidence of the ground motion on the dynamic response of the immersed tunnel should be considered.

1. Introduction

Underground structures such as tunnels are always considered to have better seismic performance due to the constraints of surrounding rock masses or soil media. Therefore, seismic research on underground structures is far inferior to that of above-ground structures for a long time[1,2]. However, the examples of tunnel damage in recent years show that this understanding is one-sided[3], especially the Kobe earthquake in 1995, which overturns the conclusion that Japanese experts believe that the tunnel is strong and safe against earthquakes. Therefore, seismic research on underground structures such as tunnels has received more and more attention from the seismic engineering community, and numerical simulation technology is a feasible and effective means to study this major problem.

In the seismic research of underground structures such as tunnels, when the seismic source is far away, the incident direction of seismic waves can be assumed to be perpendicular to the surface[4]. When the source is relatively close, the seismic wave is not incident on the vertical surface of the earth, but transmits to the near field at an angle and presents different spatial variations[5]. Fu F et al. used the non-uniform ground motion input method to study the influence of SV waves on the overall dynamic response of the tunnel under different angles of incidence[6]. Huang J Q et al. considered the SV wave incident obliquely in the cross section and longitudinal section of the tunnel, and studied the seismic response of the tunnel section under the SV wave oblique incidence condition[7]. Wang J H et al. used ANSYS to analyze the seismic response of the mountain tunnel and studied the influence of the incident angle of the SV wave on the dynamic response of the tunnel[8]. Gao X J et al. analyzed the
dynamic response of subway tunnels under complex geological conditions of soft and hard soils with oblique incidence of seismic SV wave[9]. All the above studies have shown that the spatial non-uniform change caused by the oblique incidence of ground motion has a great influence on the seismic response of the site. Most of the researches on the seismic input from different angles are concentrated in the mountain tunnel and subway tunnel, but the influence of the seismic input from different angles on the seismic response of submarine immersed tunnel under soil-structure interaction is relatively small.

In this paper, based on the viscous-elastic artificial boundary, the ground motion input is transformed into the equivalent node load to achieve the oblique incidence of seismic waves. The two-dimensional finite element model of the Nanchang Honggu immersed tunnel section is established. The influence of different incident angles on the dynamic response of the immersed tunnel is analyzed under the oblique incident of the SV wave.

2. Material and method

2.1. Viscous-elastic artificial boundary

In order to eliminate the influence of reflected waves, this paper introduces artificial boundaries in the finite field of intercepted ground to simulate the radiation damping effect of far-field medium. The viscous-elastic boundary can not only simulate the absorption of scattered wave energy, but also simulate the elastic recovery ability of the infinite domain foundation, and overcome the low frequency instability caused by the viscous boundary[10]. The viscous-elastic boundary can be equivalent to a continuously distributed parallel spring-damper system, the normal and tangential spring stiffness and damping coefficient of the viscous-elastic boundary are calculated according to formula (1) and formula (2).

\[ K_{BN} = \alpha_N \frac{G}{R}, \quad C_{BN} = \rho c_p \]

\[ K_{BT} = \alpha_T \frac{G}{R}, \quad C_{BT} = \rho c_s \]

Where \( K_{BN} \) and \( K_{BT} \) are normal and tangential spring stiffness, \( C_{BN} \) and \( C_{BT} \) are the damping coefficients of normal and tangential dampers. \( R \) stands for the distance from the source to the artificial boundary point. \( c_p \) and \( c_s \) are P wave and SV wave velocity. \( G \) stands for shear modulus of the medium, \( \rho \) stands for medium density. \( \alpha_N \) and \( \alpha_T \) refer to normal and tangential viscous-elastic artificial boundary correction coefficients.

2.2. Ground motion input method

The finite element method combined with viscous-elastic artificial boundary to realize the input of seismic wave must meet the condition that the equivalent load applied on the artificial boundary should make the displacement and stress on the artificial boundary the same as the original free field. In this way, the seismic input problem is transformed into the problem of free-field motion on the artificial boundary node, and the free-field motion can be transformed into the equivalent nodal force processing on the artificial boundary node. The equivalent nodal force on the artificial boundary is treated according to equation (3).

\[ F_B(t) = \tau_0(x_B, y_B, t) + K_B u_0(x_B, y_B, t) + C_B \dot{u}_0(x_B, y_B, t) \]

Where \( \tau_0(x_B, y_B, t) \) refers to the stress generated by \( u_0(x, y, t) \) in the original continuous medium, \( u_0(x_B, y_B, t) \) is the displacement produced by the known free wave field \( u_0(x, y, t) \) on the boundary.
2.3. Mechanical model and parameters

Nanchang Honggu immersed tunnel is a two-hole and one-pipe corridor structure, with two holes for the roadway and one pipe corridor for a comprehensive corridor. The immersed tube has a section width of 30m and a section height of 8.3m. The upper part and both sides of the structure are covered with gravel soil, and the cover thickness is flush with the height of the original riverbed. C40 concrete is adopted for pipe joints of immersed tunnel, clay layer is adopted for soil layer, and parameters of soil and structural materials are shown in Table 1. The two-dimensional finite element model of the soil-immersed tunnel is shown in Figure 1, the total length of the transverse direction (x direction) of the model is 300m, and the total height of the vertical direction (y direction) is 60m. Considering the mutual dynamic interaction between the tunnel and the foundation soil in the actual working condition, the binding constraint between the tunnel and the soil is defined. Viscous-elastic boundary conditions are applied to both sides and the bottom surface of the finite element model.

![Figure 1. Finite element model of soil-tunnel](image)

2.4. Seismic wave input

The Kobe wave is selected as the input seismic wave. The typical 0~20s in the time history curve of the seismic wave are intercepted at a time interval of 0.02s. Figure 2 shows the acceleration time-history curve of the seismic wave. This seismic wave is incident as an earthquake SV wave obliquely from the lower left side of the model at an angle of 0°, 15°, and 30° respectively.

| Material              | Density (kg m$^{-3}$) | Elasticity Modulus (MPa) | Poisson Ratio |
|-----------------------|-----------------------|--------------------------|---------------|
| Concrete              | 2370                  | 32500                    | 0.2           |
| Soil                  | 2050                  | 45                       | 0.28          |
| Covered gravel soil   | 1500                  | 150                      | 0.15          |

![Figure 2. Acceleration time history curve of Kobe wave](image)

3. Results and discussion

3.1. Immersed tunnel stress state

The first principal stress of the immersed tunnel is shown in Figure 3.
Figure 3. The first principal stress contour of structure under different incident angles

When SV wave vertical incidence, the maximum of the first principal stress is 2.122 MPa, which is mainly located at the junction of the intermediate partition with the floor and the roof. When incident at 15°, the maximum value of the first principal stress is 0.508 MPa, mainly located at the right side wall. At 30° incidence, the maximum value of the first principal stress is 0.767 MPa, which is mainly located at the corner point of the floor and the side wall. It can be seen that when seismic waves are incident at different angles, the seismic response of the immersed tunnel structure is significantly different, and there are significant differences in the stress magnitude. The larger stress points appear at the corner of the immersed tunnel and the junction of the intermediate partition with the floor and the roof, which indicate that the middle partition wall on both sides of the middle pipe gallery and the corner points are more vulnerable than other points. It should be highly valued and corresponding reinforcement measures should be taken.

3.2. Seismic response of monitoring point

The midpoint of floor and roof of the immersed tunnel are used as monitoring points to observe the acceleration time history of the immersed tunnel under the oblique incidence of seismic waves. Figure 4 shows the acceleration time history curve of the monitoring point respectively.

(a) Vertical acceleration at midpoint of roof

(b) Horizontal acceleration at midpoint of roof
It can be seen from the figure that as the incident angle increases, the horizontal acceleration of the midpoint of the immersed tunnel roof and floor are continuously decreasing, especially between $0^\circ$ and $15^\circ$, the maximum horizontal acceleration is reduced from 8.741 m/s$^2$ to 7.267 m/s$^2$. The main consideration is due to the decrease of the horizontal component as the increase of the incident angle when the SV wave is incident obliquely. In the vertical direction, with the increase of the incident angle, the vertical acceleration peak of the midpoint of the immersed tunnel roof and floor increase significantly. The maximum vertical acceleration of the midpoint of floor is 0.032 m/s$^2$ at normal incidence, increased to 5 m/s$^2$ at $30^\circ$ incidence. And the main consideration is due to the increase of the vertical component as the incident angle increases when the SV wave is incident obliquely. Therefore, the vertical seismic response of the immersed tunnel under the SV wave oblique incidence is more significant than the horizontal direction, and the influence of vertical acceleration on the structure should be considered in the design.

4. Conclusion

Based on the viscous-elastic artificial boundary, the equivalent node load input method is used to simulate the oblique incidence of SV waves, and the influence of the incident angle of seismic waves on the dynamic response of the immersed tunnel is studied. The following conclusions are obtained:

(1) Under the oblique incident of seismic waves, the dynamic response of the immersed tunnel is significantly different from that of vertical incidence, mainly reflected in the stress distribution, horizontal and vertical acceleration.

(2) The maximum point of stress in the immersed tunnel appears in the corner of the immersed tunnel and the junction of the intermediate partition with the floor and the roof. These weak points should be considered in the seismic design.

(3) Under the oblique incident of seismic SV wave, the oblique incident angle has little effect on the horizontal acceleration, but is sensitive to the vertical acceleration.

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