Research Article

Effect of Oblique SV Wave on the Seismic Response of Mountain Tunnel

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In order to study the dynamic response of parallel mountain tunnels under the oblique incidence of seismic waves, based on the display finite element method and using viscoelastic artificial boundary, the oblique incidence of three-way seismic waves was realized by angular incident mode. The displacement and stress distribution characteristics of the tunnel lining under different propagation angles and vibration angles of SV waves were studied. The results show that the oblique incidence of SV wave has a certain effect on the displacement of the double tunnel, the forces in the tunnel are symmetrical and the axis displacement increases with the increase of incident angle, and the vertical displacement changes greatly. The stress of the tunnel lining under the oblique incidence of the SV wave is elliptical. The peak value of the maximum principal stress appears at the maximum span on both sides, and the maximum principal stress decreases with the increase of the vibration angle. The maximum principal stress of the right tunnel is flat. The minimum principal stress of the left and right holes decreases with the increase of vibration angle, and the minimum principal stress of the left hole is 90°~270°. The distribution of the minimum principal stress in the range is large. Mises stress increases with the increase of the incidence angle of seismic waves.

1. Introduction

The underground structure usually interacts with the surrounding rock, and the stress and deformation of the tunnel are closely related to the interaction between the surrounding rock. Because the tunnel structure gene really exists underground, the seismic performance is better than that of the above-ground structure, the tunnel has symmetry, and its stress has a great relationship with the symmetry, so there are a few studies. The earthquake resistance of underground structures has received attention, especially for some traffic tunnels located in earthquake-prone areas. It is difficult to repair the large damage to the tunnels caused by earthquakes, such as the Italian earthquake [1], studies the influence of earthquake on the tunnel in Italy, analyzes the seismic damage phenomenon and seismic records, and quantitatively analyzes the seismic damage based on the theoretical mechanical mechanism of the interaction between surrounding rock and tunnel on the basis of the simplified model, which provides guidance for the seismic design of the tunnel. However, there is a certain gap between the equivalent static load and the actual seismic load. Wang et al. [2], by investigating the damage of the tunnel caused by Taiwan Jiji earthquake and studying the damage forms of the tunnel lining and the distribution of cracks, it is found that each tunnel has been damaged to different degrees. The failure law of the tunnel is summarized, and the analysis is carried out based on the geological conditions of the tunnel, design documents, and maintenance records. The influence factors of the earthquake on tunnel damage are mainly related to the geographical location of the tunnel, whether the tunnel passes through the fault fracture zone, the distance of the epicenter, the type of tunnel lining, and so on. However, only the tunnel failure phenomenon was recorded, and the factors influencing the tunnel earthquake failure were analyzed, but the mechanism of seismic wave action
was not studied. Jiang et al. [3], by analyzing the various
damage phenomena of the tunnel after the earthquake, the
factors of the damage are analyzed, and the damage database
of the tunnel is established by using the geographic in-
formation system to evaluate the damage degree of the
tunnel that occurred in recent years and which caused great
damage to the tunnel. Therefore, it is necessary to study the
laws of tunnels under the action of earthquakes. In engi-
neering earthquake resistance, there is no authoritative
theoretical method for ground motion input. By Yan et al.
[4], using the fi nite element software, based on wave theory and
obliquely incident P and SV waves, the seismic response of
the tunnel under the interaction of soil structure is studied,
and the comparison with the analytical solution is carried
out to verify the accuracy, and the type of incident wave and
the incident angle are, respectively, studied. Only the ground
motion response of a circular tunnel is analyzed, and the
seismic damage of a noncircular tunnel is not analyzed.
However, most mountain railway and highway tunnels are
horseshoe-shaped tunnels, so it is of greater use value to
study the seismic response of noncircular tunnel burial
depth and tunnel diameter on the seismic response of the
tunnel. By Dana et al. [5], using the fi nite element method
and boundary element method to calculate the near fi eld and
far fi eld, the in fl uence of incident angle, terrain, and geo-
metric characteristics on the ground motion response of
valley terrain is analyzed.

This research can provide some reference for building
design on this terrain. By Davis et al. [6], the Fourier series is
used to deduce the free-form surface in half space, and the
analytical solution of the unlined tunnel is calculated. The
calculation results are compared with the previous research
results. The approximate solution of the hoop stress of the
tunnel when the incident wave is much larger than the
diameter of the tunnel is analyzed, and the research results
can provide a reference for the earthquake resistance of
small-diameter tunnels, according to Zhang et al. [7]. The
analytical solutions of the P wave and SV wave in the
composite lining are studied by the wave function expansion
method, and springs are set between the tunnel surrounding
rock and the support. The in fl uence of incident wave type
and isolation layer on the dynamic stress concentration
factor of the tunnel is analyzed, and it is obtained that the
dynamic stress concentration factor of the tunnel under the
action of SV wave is more signifi cant according to Zhang
et al. [8]. By analyzing the seismic responses of shafts and
tunnels receiving SH waves, in the case of obliquely incident
SH waves, the incident waves have a signifi cant impact on
the tunnel dynamics. In this paper, the stiffness matrix
method is used to solve the analytical solution of the dy-
namic response of the shaft and the tunnel. The in fl uence of
the shaft on the tunnel decreases as the distance between the
shaft and the tunnel increases according to Liao et al. [9]. The
seismic response of seismic waves written into the radio-
elastic half-space tunnel is studied. The transition matrix is
used to construct basis functions with the moving P wave,
SH wave, and SV wave, and the scattered wave fi eld and the
refracted wave fi eld are deduced according to Wolf et al. [10].
Based on the explicit fi nite element method combined with
the viscoelastic fi nite element method, the dynamic response of
the subway station under the oblique incidence of the SV
wave is analyzed, and some benefi cial conclusions are drawn.
Under the oblique incidence of seismic waves, the shear
force and axial force of the station pillars changed signifi-
cantly, and they increased with the increase of the incident
angle. At present, there are many researches on the two-
dimensional incidence of seismic waves, there are few three-
dimensional oblique incidence models, and there are no
relatively mature results. Although the above scholars have
conducted extensive researches on the seismic response of
tunnel, most of them regard the seismic wave as a vertically
incident on the underground structure, but, in fact, the
seismic wave is an oblique incident to propagate when the
earthquake occurs, and the study on the in fl uence of the
incidence angle of the seismic wave on the seismic response
of the underground structure is far from sufficient.

Based on the displayed fi nite element method, this paper
deduces the equivalent nodal load of the oblique incidence
of three-dimensional seismic waves, compiles the corre-
sponding program, and conducts the seismic response of
the double-hole tunnel in the mountains under the oblique
incidence of three-dimensional seismic waves in ABAQUS.

2. Three-Dimensional Viscoelastic Artificial
Boundary and Ground Motion Input

2.1. Viscoelastic Artificial Boundary. The viscoelastic artifi-
cial boundary can absorb the energy radiated from the computing
area, which can well simulate the in fl uence of in fl nite foundation
on the computing area. In the three-dimensional viscoelastic
artifi cial boundary, it is required to install springs and damping
elements in both directions of each node on the boundary of the
fi nite element model. The spring-damping elements are realized
by the Springs/Dashpots element in the ABAQUS software. The
schematic diagram is shown in Figure 1. Relevant studies have
shown that the accuracy of the viscoelastic boundary is relatively
high, and the recovery force of the soil in the later stage is
relatively good [11].

The viscoelastic artificial boundary can absorb scattered
waves and simulate the restoring force of semi-in fl nite
foundations. The spring and damping parameters of the
viscoelastic boundary are calculated by the following formu-
las [12, 13]:

\[
\begin{align*}
    k_N &= A_T \frac{1}{1 + A} \frac{\lambda + 2G}{r}, \\
    C_N &= A_T B \rho c_p, \\
    k_T &= A_T \frac{1}{1 + A} \frac{G}{r}, \\
    C_T &= A_T B \rho c_v.
\end{align*}
\]

In the formula, \( \rho \) is the density, \( G \) is the shear modulus, \( \lambda \)
The relevant literature \( A = 0.8, B = 1.1 \). Compile the cor-
responding program in Matlab, import the corresponding node information file and displacement velocity time history
file of the model, and generate the amplitude curve file, load file, and spring damping file. Then, write these three files into the inp file, and perform calculations in Abaqus. The seismic wave oblique incidence model is shown in Figure 2. The left and right boundaries and the bottom boundary are set with viscoelastic artificial boundaries, and the upper surface is a free boundary.

2.2. Earthquake Input Method. The total wave field motion equation of the finite element time domain method is shown as follows:

\[ m_i \ddot{u}_{li} + \sum_{k=1}^{n} \sum_{j=1}^{n} k_{ikj} \dot{u}_{kj} + \sum_{k=1}^{n} \sum_{j=1}^{n} c_{ikj} \ddot{u}_{kj} = A_i f_{li}. \]  

(3)

In the formula, \( m_i \) is the mass of the node; \( k_{ikj} \) is the stiffness of the node \( k \) direction \( j \) to the node \( l \) direction; \( c_{ikj} \) is the damping coefficient; \( \dot{u}_{kj} \) is the displacement of the node \( k \) direction \( j \); \( u_{kj} \) is the velocity; \( \ddot{u}_{kj} \) is the acceleration; \( f_{li} \) is the node \( l \) the force of the infinite far field at the direction \( i \) on the finite near field; \( A_i \) is the influence area of the node. In three-dimensional problems, \( n = 3, i, j = 1, 2, 3 \). The total wave field of the artificial boundary is decomposed into an inner field and an outer field. The inner field is denoted by superscript \( R \), and the outer field is denoted by superscript \( s \). The total wave field displacement and force can be expressed as follows:

\[ u_{li} = u_{li}^R + u_{li}^s, \]  

(4)

\[ f_{li} = f_{li}^R + f_{li}^s. \]  

(5)

The motion relation of artificial boundary stress in layman’s field is

\[ f_{li}^s = -k_{li} u_{li}^R - c_{li} \dot{u}_{li}^R, \]  

(6)

where \( k_{li} \) and \( c_{li} \) are the viscoelastic boundary parameters. Taking formula (4) into (6), then into (6) into (5), and then into (5) into (3), the finite element equation of motion of the viscoelastic boundary is obtained:

\[ m_i \ddot{u}_{li} + \sum_{k=1}^{n} \sum_{j=1}^{n} (c_{ikj} + \delta_{ik} \delta_{ij} A_i c_{li}) \ddot{u}_{kj} + \sum_{k=1}^{n} \sum_{j=1}^{n} \left( k_{ikj} + \delta_{ik} \delta_{ij} A_i c_{li} \right) \ddot{u}_{kj} = A_i \left( k_{li} u_{li}^R + c_{li} \dot{u}_{li}^R + f_{li}^R \right). \]  

(7)

2.3. Viscoelastic Boundary Displacement Field. It can be known from the wave theory that the wave is delayed in the process of propagation. The SV wave \( u_0(t - \Delta t) \) incident at angle \( \alpha \) on the left, the reflected SV wave \( A_3 u_0(t - \Delta t) \) at angle \( \alpha \), and the reflected P wave \( A_4 u_0(t - \Delta t) \) at angle \( \beta \) are composed of the left inner field displacement:

\[
\begin{align*}
    u_{l1}^R(t) &= u_0(t - \Delta t) \cos \alpha - A_3 u_0(t - \Delta t) \cos \alpha + A_4 u_0(t - \Delta t) \sin \beta, \\
    u_{l2}^R(t) &= -u_0(t - \Delta t) \sin \alpha - A_3 u_0(t - \Delta t) \sin \alpha - A_4 u_0(t - \Delta t) \cos \beta.
\end{align*}
\]  

(8)

The front and back inner field displacements are as follows:

\[
\begin{align*}
    u_{l1}^R(t) &= u_0(t - \Delta t) \cos \alpha - A_3 u_0(t - \Delta t) \cos \alpha + A_4 u_0(t - \Delta t) \sin \beta, \\
    u_{l2}^R(t) &= -u_0(t - \Delta t) \sin \alpha - A_3 u_0(t - \Delta t) \sin \alpha - A_4 u_0(t - \Delta t) \cos \beta.
\end{align*}
\]  

(9)
The displacement of the row field in the bottom edge is as follows:

\[
\begin{align*}
  u_{R1}^R(t) &= u_0(t - \Delta t_7) \cos \alpha, \\
  u_{R2}^R(t) &= -u_0(t - \Delta t_7) \sin \alpha,
\end{align*}
\]  

where \( \Delta t_1 - \Delta t_7 \) is the time for the incident wave to travel from the wavefront to the artificial boundary.

2.4. Viscoelastic Boundary Stress Field. The viscoelastic boundary stress is analyzed by references [14–16].

Left side:

\[
\begin{align*}
  f_{R1}^R &= \frac{G}{c_s} \sin 2\alpha \left[ u_0(t - \Delta t_1) - A_3 u_0(t - \Delta t_2) \right] + A_4 \frac{\lambda + 2G \sin^2 \beta_p}{c_p} u_0(t - \Delta t_3), \\
  f_{R2}^R &= \frac{G}{c_s} \cos 2\alpha \left[ u_0(t - \Delta t_1) - A_3 u_0(t - \Delta t_2) \right] - A_4 \frac{G \sin 2\beta_p}{c_p} u_0(t - \Delta t_3), \\
  f_{R3}^R &= 0.
\end{align*}
\]  

Front side:

\[
\begin{align*}
  f_{R1}^F &= f_{R2}^F = 0, \\
  f_{R3}^F &= A_4 \frac{\lambda}{c_p} u_0(t - \Delta t_6).
\end{align*}
\]  

Bottom:

\[
\begin{align*}
  f_{R1}^B &= \frac{G}{c_s} \cos 2\alpha u_0(t - \Delta t_7), \\
  f_{R2}^B &= -\frac{G}{c_s} \cos 2\alpha u_0(t - \Delta t_7), \\
  f_{R3}^B &= 0,
\end{align*}
\]  

where \( \lambda \) and \( G \) are Lame constants; \( c_p \) is the P wave velocity; \( c_s \) is the SV wave velocity.

3. Earthquake Input Validation

A finite element model is established in ABAQUS to verify the seismic response when SV wave 15° is obliquely incident in a three-dimensional half-space. The model size is 1000 m × 1000 m × 1000 m, the soil parameters are density \( \rho = 2000 \text{ kg/m}^3 \), elastic modulus \( E = 2 \text{ GPa} \), Poisson’s ratio is 0.3, and the displacement time-history curve of the incident wave is shown in Figure 3, and the center point A of the top surface of the model is taken as the analysis point.

Build the finite element model to SV wave 15°. The incident half-space field, as can be seen from the cloud in Figure 4, is the reflected wave that occurs after the seismic wave is incident. It can be seen from Figure 5 that the finite element model solution is consistent with the theoretical circle, which verifies the correctness of the model.

In the figure, (1) is the displacement nephogram of SV wave 15° oblique incident at 0.7 s, (2) is the displacement nephogram of SV wave 15° oblique incident at 1.5 s, and (3) is the displacement nephogram of SV wave 15° oblique incident at 2.5 s.

4. Influence of Oblique Incidence of SV Wave on Seismic Response of Parallel Tunnel

4.1. Computational Model. A three-dimensional finite element model of a parallel tunnel is established in ABAQUS, as shown in Figure 6. The longitudinal (Z) of the model is 100 m, the transverse (X) width is 200 m, the height (Y) is 100 m, the tunnel depth is 30 m, the distance between the...
two holes is 60 m, the soil adopts the Mohr–Coulomb constitutive model, the binding constraint is adopted between the soil and the primary lining, and the surface-to-surface contact between the primary lining and the secondary lining is adopted. The finite element model parameters are shown in Table 1.

4.2. Seismic Input. The American El-Centro wave is selected as the ground motion input, and the three-directional seismic wave is applied by means of the incident vector of the corner incident function. The acceleration time-history curve is shown in Figure 7. The seismic wave propagation angle $\theta$ is the angle between...
Table 1: Material parameters.

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (GPa)</th>
<th>Density (kg.m(^{-3}))</th>
<th>Poisson’s ratio</th>
<th>Internal friction angle (°)</th>
<th>Cohesion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>3</td>
<td>2100</td>
<td>0.33</td>
<td>30</td>
<td>0.1</td>
</tr>
<tr>
<td>Initial lining</td>
<td>30</td>
<td>2500</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second lining</td>
<td>31.5</td>
<td>2500</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EI–Centro acceleration time-history curve.

EI–Centro

**Figure 7:** EI-Centro acceleration time-history curve.

Vertical displacement (cm)

(a)

Vertical incident

15°

25°

(b)

**Figure 8:** Continued.
Figure 8: Comparison of the displacement of the left and right tunnels: (a) horizontal displacement of point A in the left tunnel, (b) vertical displacement of point A in the left tunnel, (c) horizontal displacement of the right tunnel A′ point, and (d) vertical displacement of the right tunnel A′ point.

Figure 9: Continued.
Figure 9: Amplitude distribution of principal stress when SV wave is incident at 15: (a) maximum principal stress and (b) minimum principal stress.

Figure 10: Continued.
the SV wave and the XY plane, which is taken as 0°, respectively, 15°, and 25°, for each propagation angle \( \theta_v \) corresponding to a vibration angle 0°, 30°, and 60°.

4.3 Influence of Incident Angle on Axis Displacement. As shown in Figure 6, the left and right double-hole tunnels are, respectively, determined at two points. The two points on the left tunnel are points A and B, and the two points on the right tunnel are points A' and B'. The distance between points A and B is 80 m. The distance between "point" and B' is also 80 m, and the SV wave is 15 m, respectively, 25°, and 90° oblique incidence double-hole tunnel. It can be seen from Figure 8 that the horizontal displacement of point A of the left hole increases with the increase of the incident angle of the seismic wave, but the increase is small; the relative vertical displacement of point A of the left hole increases with the increase of the incident angle. And the displacement in the case of normal incidence is significantly larger than the displacement in the other two incident angles and is 90°. The change curve of tunnel displacement peak when the incidence angles of seismic waves are 15° and 25°. The horizontal and vertical displacements of the right hole also increase with the increase of the incident angle, and the vertical displacement varies greatly, showing an obvious traveling wave effect. When the seismic wave is obliquely incident on the tunnel, there is an obvious traveling wave effect along the longitudinal direction of the tunnel. The nonuniform vibration effect of the seismic wave makes the movement of the tunnel along the longitudinal direction obviously different and accelerates the damage of the tunnel.

4.4 Influence of Incidence Angle on Lining Stress Distribution. The finite element model was established, and the SV was 15°, respectively, and 25°. The propagation angles are obliquely incident on the tunnel, and each propagation angle corresponds to three vibration angles of 0°, 30°, and 60°. The distribution curves of the absolute value of the maximum principal stress and the minimum principal stress of the double-hole tunnel are shown in Figures 9 and 10.

SV wave 15° can be seen as the maximum principal stress of the left and right holes of the tunnel is elliptically distributed under the incident, and the distribution is basically symmetrical. The maximum principal stress of the left hole is smaller at the vault (−60°~60°) and the inverted arch (150°~240°), and the maximum span on the left (240°~300°) and the right maximum span (90°~150°) are larger, the maximum value appears at the left and right maximum span, and the maximum principal stress decreases with the increase of the vibration angle; the maximum principal stress of the right hole is flat, the left and right sides are large, and the upper and lower ends are smaller, the maximum principal stress occurs at the largest span on the right side (90°~120°) and the largest span on the left (270°), the maximum principal stress at the vault (0°) and the bottom of the vault (180°) is the smallest, and the maximum principal stress in the right hole is the largest. The stress is less than the distribution of the maximum principal stress value of the left hole. The minimum principal stress of the left and right holes decreases with the increase of the vibration angle. The minimum principal stress of the left hole is larger in the range of 90°~270° and is smaller in the range of (~60°~60°), and the minimum principal stress is small. The stress appears at the largest span on the left and right. The distribution law of the minimum principal stress of the right hole is the same as that of the left hole, but the minimum principal stress of the vault of the right hole is greater than the minimum principal stress of the left hole.

When the seismic wave is incident at 25°, the maximum principal stress is large on both sides and small at the upper
and lower ends. The maximum value appears at the left and right maximum spans 90° and 270°, and the distribution range of the maximum principal stress in the left hole is larger than that in the right hole. The minimum principal stress is mainly distributed in the range of 90°–270°, and the minimum principal stress of the right hole is asymmetrically distributed, and the two largest spans on the left and right bear the greatest force.

The Mises stress at the longitudinal vault of the tunnel is extracted. It can be seen from Figure 11 that with the increase of the incident angle of the seismic wave, the Mises stress increases. Along the direction of the tunnel axis, the stress value changes due to the traveling wave effect, showing nonuniformity. The variation law of Mises stress in the right tunnel is the same as that in the left tunnel, the Mises stress in the right tunnel is significantly smaller than that in the left tunnel. It can be seen that under the action of seismic waves, the left tunnel receives a greater force.

5. Conclusions

(1) When the SV wave is obliquely incident on the double-hole tunnel, the displacement of the left and right tunnels increases with the increase of the incident angle, and the vertical displacement is significantly larger than the horizontal displacement value, showing the traveling wave effect along the longitudinal direction of the tunnel.

(2) SV wave 15°: The maximum principal stress of the left and right holes of the tunnel is elliptically symmetrically distributed under the incident. The maximum principal stress of the left hole appears at the left and right maximum spans, and the maximum principal stress decreases with the increase of the vibration angle; the maximum principal stress of the right hole is flat with the right maximum span (90°–120°). The maximum principal stress occurs at the maximum span (270°), and the maximum principal stress of the right hole is smaller than the distribution of the maximum principal stress value of the left hole. The minimum principal stress of the left and right holes decreases with the increase of the vibration angle, and the minimum principal stress of the left hole is larger in the range of 90°–270°. When the SV wave is incident at 25°, the maximum principal stress is large on both sides and small at the upper and lower ends. The maximum value appears at the left and right maximum spans (90° and 270°), and the distribution range of the maximum principal stress in the left hole is larger than that in the right hole. The minimum principal stress is mainly distributed in the range of (90°–270°), and the minimum principal stress of the right hole is axisymmetrically distributed, and the two largest spans on the left and right bear the greatest force.

(3) With the increase of the incident angle of the seismic wave, the Mises stress increases. Along the direction of the tunnel axis, the stress value changes due to the traveling wave effect, showing nonconsistency. The Mises stress of the right tunnel is obviously smaller than that of the left tunnel, which shows that the left tunnel is subjected to a larger force under the action of seismic waves.

(4) In this paper, a three-dimensional finite element model is established to analyze the seismic response of the tunnel under the oblique incident SV wave. The three-dimensional model can consider the longitudinal seismic response of the tunnel, which is more similar to the actual project.
**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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