Research Article

Analytical Solutions for a Deep-Buried Tunnel with Noncircular Cross Sections in Orthotropic Rock Mass

Shuhong Liu, Jiajun Duan, Chenhao Wu, and Yongquan Zhu

1Engineering Mechanics, Shijiazhuang Tiedao University, Shijiazhuang 050043, China
2Faculty of Engineering and Physical Sciences, University of Southampton, Southampton SO17 1BJ, UK
3School of Civil Engineering, Shijiazhuang Tiedao University, Shijiazhuang 050043, China

Correspondence should be addressed to Shuhong Liu; liush@stdu.edu.cn

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For the generalized plane strain problem of a deep-buried tunnel excavated in orthotropic rock mass under far-field biaxial compression, the stress and displacement are the most important basis for determining tunnel support design. First, by using the complex variable method, the conformal mapping and affine transformation functions are represented by the same variable. Two stress functions are obtained by the integral method, and thus, the analytical solutions for stress and displacement in orthotropic rock mass are obtained. Second, taking a horseshoe-shaped tunnel as an example, the stress and displacement distributions around the tunnel are given by using the analytical and the finite element method software ANSYS, respectively. The analytical and numerical results are in good agreement, especially at the tunnel edge. Finally, compared with isotropic rock mass, the results show that material constants of the rock mass have little effect on the stress and significant effect on the displacement.

1. Introduction

With the rapid growth in traffic demand, the number of tunnel construction has sharply increased. To ensure the safety of tunnel construction, the stress and displacement of surrounding rock during tunnel excavation have been widely concerned in academic and engineering circles. The deep-buried tunnel can be regarded as a hole in an infinite body, and the complex variable method is the most effective to solve hole and crack problems. For different tunnel shapes such as semicircle, circle, square, and straight-wall-top-arch, analytical solutions for stress and displacement were obtained by assuming isotropic rock mass [1–6]. Guo et al. [7] obtained the explicit form of analytical solution caused by a shallow circular tunnel and analyzed the secondary stress field with pile load combined with Mindlin’s solution. The exact solutions for two unequal cracks emanating from an elliptical hole were also given [8–10].

However, rock mass is not isotropic, and it is generally anisotropic. The process of solving analytical solution for anisotropic materials with a noncircular hole is much more complicated than that for isotropic materials. Chen [11] pointed out that there was an exact closed-form solution only for an elliptical hole in anisotropic materials. Gao and Long [12] and Gao and Tong [13] derived the stress (stress functions) and stress intensity factors for an orthotropic plane containing elliptical holes or cracks by series expansion and Cauchy integral methods, respectively. Zhang and Sun [14] supposed that the arbitrary cross section of tunnels was parallel to the isotropic plane and presented a closed-form solution for stress and displacement of transversely isotropic rock mass. They found that stress solution was the same as that of isotropic rock mass, while the displacement solution was distinct. Unlike Zhang and Sun [14], Manh et al. [15] supposed that the tunnel axis was parallel to the isotropic plane. They proposed analytical solutions for stress...
and displacement around arbitrary cross section tunnels in transversely isotropic rock mass and compared the analytical results along the tunnel edge with those calculated by numerical simulation software FLAC3D for semicircular and rectangular tunnels. Daoost and Hoa [16] obtained an analytical solution for stress distribution around a triangular hole in an orthotropic plate. Complex coordinates \( z_i \) (\( i = 1, 2 \)) of the affine transformation and \( z \) of the conformal transformation were all represented with complex curvilinear coordinate \( \zeta \) (i.e., \( z = \omega (\zeta) \)), \( z_1 = \omega_1 (\zeta_1) \), and \( z_2 = \omega_2 (\zeta_2) \), while the relationship between \( \zeta \) and \( z_1 \) or \( z_2 \) was determined by the numerical method. Based on Daoost and Hoa’s [16] solution, Ukadgaonker and Rao [17] developed a completely analytical solution for a triangular hole in an orthotropic plate under several loading conditions. Using the same method as Ukadgaonker and Rao [17], Zheng and Li [18] obtained an analytical solution for stress around rectangle holes in an orthotropic plate. Ukadgaonker and Kakhanki [19] obtained the analytical solution for stress distribution along the edge of irregular holes in an orthotropic laminate, which was in good agreement with a finite element solution. Li and Zheng [20] obtained stress distribution along the rectangle hole in orthotropic plates through the boundary integral equations. Zhang et al. [21] presented stress and displacement distribution around a shallow elliptical tunnel in anisotropic soil and found that anisotropic properties have a great effect on the displacement. Liu et al. [22] obtained the stress and displacement for an noncircular-lined tunnel in orthotropic surrounding rock.

Lu et al. [23] and Zhang et al. [24] transformed the outer regions of the tunnel in three physical planes \( z, z_1, \) and \( z_2 \) into the outer regions of the unit circle in three imaginary planes \( \zeta, \zeta_1, \) and \( \zeta_2 \) through three functions \( z = \omega (\zeta), z_1 = \omega_1 (\zeta_1), \) and \( z_2 = \omega_2 (\zeta_2). \) By the power series method, analytical stress distribution along the boundary of the noncircular tunnel in orthotropic rock mass was presented and verified by the ANSYS software solution. However, because the relationship between \( \zeta_1 \) or \( \zeta_2 \) and \( \zeta \) is too complex for an actual tunnel, the solution for stress or displacement may not be obtained in other points except those for the tunnel boundary.

From the above literature, there are several research results on isotropic rock mass with holes/tunnels. The closed-form solutions for stress and displacement are obtained and verified by numerical solutions. Considering that anisotropy of rock mass is much more complicated than the isotropic situation, for orthotropic rock mass, analytical solutions for stress and stress distribution along the tunnel edge have been mainly studied in the past years. The analytical distribution of stress and displacement around the hole is rarely given. In this paper, by mapping three physical planes \( z, z_1, \) and \( z_2 \) into one imaginary plane \( \zeta, \) the analytical distribution of stress and displacement around noncircular tunnels in orthotropic rock mass is given and compared with the numerical solution of ANSYS software. In addition, the influence of material constants of rock mass on stress and displacement is discussed by comparing with the isotropic solution.

2. Problem and Solution Process

The schematic diagram of a tunnel with noncircular cross sections in orthotropic rock mass is shown in Figure 1. The buried depth is so deep that the gravity is ignored, and then, the tunnel is assumed to be subjected to far-field stresses \( \sigma_{\infty} \) and \( \sigma_{\infty}^\circ. \) Rock mass is orthotropic, and the coordinate axes are coincident with the principal axes.

2.1. Transformation Functions. For the orthotropic problem, a conformal mapping function \( z = \omega (\zeta) \) and two affine transformation functions \( z_1 = \omega_1 (\zeta) \) and \( z_2 = \omega_2 (\zeta) \) are used to transform the outer region of the tunnel in the three physical planes \( z, z_1, \) and \( z_2 \) into the outer region of the unit circle in the mathematical plane \( \zeta. \) The general form of the conformal mapping function is as follows:

\[
z = \omega (\zeta) = \sum_{k=1}^{n} C_k \zeta^{-(k-2)},
\]  
where \( z = x + iy \) and \( \zeta = \rho e^{i\theta}. \) \( \rho \) and \( \theta \) represent polar coordinates in the plane \( \zeta. \) For a tunnel with a given cross section, \( n \) and \( C_k \) are known constants which can be obtained by many methods [25–30]. Using the above conformal mapping function, the tunnel boundary is mapped onto the unit circle.

For the generalized plane strain problem, the characteristic equation for orthotropic rock mass can be written as given by Chen [11]:

\[
\beta_{11} \mu^2 + (2\beta_{12} + \beta_{66})\mu^2 + \beta_{22} = 0,
\]
where the equivalent elastic coefficients $\beta_{ij} = a_{ij} - a_{j3}a_{ji}/a_{33}$ $(i, j = 1, 2, 6)$ and the compliance coefficients $a_{ij}$ are generally expressed with engineering constants.

The roots of (2) are as follows:

$$
\begin{align*}
\mu_1 &= \alpha_1 + i\beta_1,
\mu_2 &= \alpha_2 + i\beta_2,
\mu_3 &= \alpha_1 - i\beta_1,
\mu_4 &= \alpha_2 - i\beta_2,
\end{align*}
$$

(3)

where $\alpha_1, \beta_1, \alpha_2,$ and $\beta_2$ are real constants and $\beta_1 > 0$ and $\beta_2 > 0$.

On the tunnel edge, $\rho = 1$, $\zeta = \sigma = e^{i\theta}$. Substituting $\sigma^k = \cosh(k\theta) + i\sinh(k\theta)$ into (1) yields the following equation:

$$
\begin{align*}
z_1 &= x + \mu_1 y = Y_1 \sum_{k=1}^{n} C_k \zeta^{-(k-2)} + \delta_1 \sum_{k=1}^{n} C_k \zeta^{(k-2)} z_2 = x + \mu_2 y = Y_2 \sum_{k=1}^{n} C_k \zeta^{-(k-2)} + \delta_2 \sum_{k=1}^{n} C_k \zeta^{(k-2)} \Bigg),
\end{align*}
$$

(5)

where $Y_1, Y_2, \delta_1,$ and $\delta_2$ are complex coefficients introduced for simple expression.

$$
\begin{align*}
Y_1 &= \frac{(1 - i\mu_1)}{2}, \\
\delta_1 &= \frac{(1 - i\mu_1)}{2}, \\
Y_2 &= \frac{(1 - i\mu_2)}{2}, \\
\delta_2 &= \frac{(1 - i\mu_2)}{2}.
\end{align*}
$$

(6)

2.2. Stress Functions. The two stress functions $\phi(z_1)$ and $\psi(z_2)$ can be written as follows:

$$
\begin{align*}
\phi(z_1) &= B_1 z_1 + \phi_0(z_1), \\
\psi(z_2) &= (B_2 + iC_2) z_2 + \psi_0(z_2),
\end{align*}
$$

(7)

where real constants $B_1, B_2,$ and $C_2$ are determined from the far-field stresses $\sigma_x^{\infty}$ and $\sigma_y^{\infty}$

$$
\begin{align*}
B_1 &= \frac{\sigma_x^{\infty} + (a_2^2 + \beta_2^2)\sigma_y^{\infty}}{2(a_2 - a_1) + (\beta_2 - \beta_1)}, \\
B_2 &= \frac{a_2^2 - \beta_2^2 - 2a_1a_2\sigma_y^{\infty} - \sigma_x^{\infty}}{2(a_2 - a_1)^2 + (\beta_2 - \beta_1)^2}, \\
C_2 &= \frac{(a_1 - a_2)\sigma_x^{\infty} + [a_1(a_2 - \beta_2^2) - a_1(a_2 - \beta_2^2)]\sigma_y^{\infty}}{2\beta_2^2(a_2 - a_1)^2 + (\beta_2 - \beta_1)^2}.
\end{align*}
$$

The negative stress boundary conditions $f_1^0$ and $f_2^0$ on the tunnel boundary can be written as follows [17, 19]:

$$
\begin{align*}
z &= x + iy \\
&= \sum_{k=1}^{n} C_k \sigma^{-(k-2)}, \\
x &= \frac{1}{2} \left[ c_1 (\sigma + 1) + \sum_{k=2}^{n} C_k \left( \sigma^{k-2} + \frac{1}{\sigma^{k-2}} \right) \right],
\end{align*}
$$

(4)

$$
\begin{align*}
y &= \frac{1}{2} \left[ c_1 (\sigma - 1) - \sum_{k=2}^{n} C_k \left( \sigma^{k-2} - \frac{1}{\sigma^{k-2}} \right) \right].
\end{align*}
$$

(5)

Then, the two affine transformation functions $z_1 = \omega_1(\zeta)$ and $z_2 = \omega_2(\zeta)$ are represented by the same variable $\zeta$ as the conformal mapping function [11, 17–19]:

$$
\begin{align*}
f_1^0 &= -2 \Re \left[ B_1 z_1 + (B_2 + iC_2) z_2 \right], \\
f_2^0 &= -2 \Re \left[ B_1 z_1 + \mu_2 (B_2 + iC_2) z_2 \right]
\end{align*}
$$

(9)

where $"\Re\left[\cdot\right]"$ denotes the real part of what it encloses.

Substituting (5) into (9) yields the following equation:

$$
\begin{align*}
f_1^0 &= \left[ L_1 + iL_3 \right] \sum_{k=1}^{n} C_k \zeta^{-(k-2)} + \left( L_1 + L_2 \right) \sum_{k=1}^{n} C_k \zeta^{(k-2)} \Bigg], \\
f_2^0 &= \left[ L_3 + iL_4 \right] \sum_{k=1}^{n} C_k \zeta^{-(k-2)} + \left( L_3 + L_4 \right) \sum_{k=1}^{n} C_k \zeta^{(k-2)} \Bigg],
\end{align*}
$$

(10)

where $L_1, L_2, L_3,$ and $L_4$ are complex coefficients introduced for simple expression and upper bars $\overline{\cdot}$ denote complex conjugates.

$$
\begin{align*}
L_1 &= \mu_1 B_1 \gamma_1 + (B_2 + iC_2) \gamma_2, \\
L_2 &= \mu_1 \delta_1 + (B_2 + iC_2) \delta_1, \\
L_3 &= \mu_1 B_1 \gamma_1 + \mu_2 (B_2 + iC_2) \gamma_2, \\
L_4 &= \mu_1 B_1 \delta_1 + \mu_2 (B_2 + iC_2) \delta_2.
\end{align*}
$$

(11)

The stress functions $\phi_0(z_1)$ and $\psi_0(z_2)$ can be obtained by the following integrals [17, 19]:

$$
\begin{align*}
\phi_0(\zeta) &= \frac{i}{4\pi(\mu_1 - \mu_2)} \int \left[ (\mu_2 f_1^0 - f_2^0) \frac{\sigma + \zeta}{\sigma - \zeta} \right] d\sigma, \\
\psi_0(\zeta) &= \frac{-i}{4\pi(\mu_1 - \mu_2)} \int \left[ (\mu_2 f_1^0 - f_2^0) \frac{\sigma + \zeta}{\sigma - \zeta} \right] d\sigma.
\end{align*}
$$

(12)

Substituting (10) into (12) and calculating Cauchy integrals yields
\[
\phi_0(\zeta) = \frac{1}{\mu_1 - \mu_2} \left\{ \frac{1}{\zeta} \left[ \mu_2 (L_2 + L_1) - (L_4 + L_3) \right] C_1 + \left[ \mu_1 (L_1 + L_2) - (L_3 + L_0) \right] \sum_{k=3}^{n} C_k \zeta^{-(k-2)} \right\} \]
\[
\psi_0(\zeta) = \frac{-1}{\mu_1 - \mu_2} \left\{ \frac{1}{\zeta} \left[ \mu_1 (L_2 + L_1) - (L_4 + L_3) \right] C_1 + \left[ \mu_1 (L_1 + L_2) - (L_3 + L_0) \right] \sum_{k=3}^{n} C_k \zeta^{-(k-2)} \right\} \]

2.3. Stresses and Displacements. The stress components \(\sigma_x\), \(\sigma_y\), and \(\tau_{xy}\) in the Cartesian coordinates can be written as follows:

\[
\sigma_x = \sigma_x^{\infty} + 2\Re \left[ \mu_1 \phi_0'(z_1) + \mu_2 \psi_0'(z_2) \right]
\]
\[
\sigma_y = \sigma_y^{\infty} + 2\Re \left[ \phi_0'(z_1) + \psi_0'(z_2) \right]
\]
\[
\tau_{xy} = \tau_{xy}^{\infty} + 2\Re \left[ \mu_1 \phi_0'(z_1) + \mu_2 \psi_0'(z_2) \right]
\]

where \(\phi_0'(z_1) = d\phi_0(\zeta)/d\zeta/dz_1\) and \(\psi_0'(z_2) = d\psi_0(\zeta)/d\zeta/dz_2\), and they can be obtained from Equations (5), (8), and (13).

The displacements caused by tunnel excavation in the Cartesian coordinates can be written as follows:

\[
u = 2\Re \left[ p_1 \phi_0(z_1) + p_2 \psi_0(z_2) \right],
\]

where \(p_1, p_2, q_1,\) and \(q_2\) are complex coefficients related to material constants.

\[
p_1 = \beta_1 \mu_1^2 + \beta_2 \mu_2^2, \quad p_2 = \beta_1 \mu_2^2 + \beta_1 \mu_2
\]
\[
q_1 = \left( \beta_1 \mu_1 + \beta_2 \mu_2 \right), \quad q_2 = \left( \beta_1 \mu_1 + \beta_2 \mu_2 \right)
\]

3. Numerical Results and Discussions

In this section, taking a horseshoe-shaped tunnel as an example, the analytical and numerical distributions of stress and displacement around tunnels with a noncircular cross section in orthotropic rock mass are given to verify the correctness of the above analytical solutions.

The conformal mapping function in (1) is obtained by Wang [30], which is as follows:

\[
z = \omega(\zeta) = 2.3095 + 6.7771 \zeta - 0.9785 \zeta^{-1} + 0.3119 \zeta^{-2} - 0.1391 \zeta^{-3}
\]
\[
+ 0.0364 \zeta^{-4} - 0.0331 \zeta^{-5} + 0.0374 \zeta^{-6} + 0.0181 \zeta^{-7} - 0.0017 \zeta^{-8}
\]

The transformed tunnel shape is used for analytical and numerical computations. A two-dimensional plane strain condition is used in the finite element software ANSYS. To simulate an infinite body, the orthotropic rock mass size is taken 160 m \times 160 m. The far-field stresses are imposed on the boundaries of the domain. The numerical results are obtained by the following two timesteps: (1) the displacements in orthotropic rock mass without tunnels; (2) the stresses and displacements in orthotropic rock mass with tunnels. The displacement and stress caused by tunnel excavation are the displacement difference between the two timesteps and the stress at the second timestep, respectively. Figure 2(a) shows the whole model grid of the second timestep. Because of the large model and the fine discretization, it is difficult to clearly display the whole elements, so the grid around the tunnel of the second timestep is presented in Figure 2(b).

The engineering constants of orthotropic rock mass are assumed as follows: Young’s modulus, \(E_x = 20\) GPa, \(E_y = 10\) GPa, and \(E_z = 16\) GPa, shear modulus, \(G_{xy} = 6\) GPa, \(G_{xz} = 4\) GPa, and \(G_{yz} = 8\) GPa. Poisson’s ratios \(\nu_{xy} = 0.2, \nu_{xz} = 0.25,\) and \(\nu_{yz} = 0.1\). They satisfy all the limit conditions of orthotropic materials, such as \(1 - \nu_{xy} \nu_{xz} > 0, \nu_{xy} \nu_{yz} \nu_{xz} < 0.5,\) \(|\nu_{xy}| < \sqrt{E_x/E_y}\) [31]. Far-field stresses are \(\sigma_x^{\infty} = 3\) MPa and \(\sigma_y^{\infty} = 2\) MPa.

3.1. Comparison of Analytical and Numerical Solutions. The comparison of the stress \(\sigma_x\) contours around the tunnel predicted by the analytical solution and ANSYS software is shown in Figure 3. Some differences between the two solutions can be seen.

In order to display clearly the variation, the stress and displacement components along the tunnel edge and the positive direction of the \(x\)-axis and the \(y\)-axis are illustrated in Figures 4–9. The angle \(\alpha\) is \(0^\circ\) to \(180^\circ\) measured counter-clockwise from the positive \(x\)-axis (Figure 1). The numerical results are in excellent agreement with analytical ones along the tunnel edge (Figures 4 and 5). The stress \(\tau_{xy}\) and displacement \(v\) along the \(x\)-axis are equal to zero (Figures 6 and 7). These results indicate that the boundary condition of the tunnel edge and the symmetry condition are both satisfied. From Figures 6–9, it may be seen that the two predictions along the \(x\)-axis and \(y\)-axis basically agree with each other, and only abrupt changes of analytical stress distributions occur in some regions near the tunnel (Figures 6 and 8). With the increase of the distance from the tunnel edge, the displacement caused by excavation gradually decreases from the maximum to zero (Figures 7 and 9). Through calculation, it is found that abrupt changes are caused by the functions \(dz_1/d\zeta\) and \(dz_2/d\zeta\).

3.2. Analytical Contours of Stress and Displacement around the Tunnel. The contours of the stresses \(\sigma_x\) and \(\tau_{xy}\) and the displacements \(u\) and \(v\) around the tunnel predicted by the analytical solution are shown in Figures 10–13. From Figures 3 and 10–13, it can be seen that the stresses \(\sigma_x\) and
and the displacement $u$ are all symmetric with respect to the $x$-axis, while the shear stress $\tau_{xy}$ and the displacement $v$ are antisymmetric with respect to the $x$-axis. There are obvious stress concentrations near the tunnel edge, and their areal extent is limited. At about 5 times the tunnel span from the tunnel edge, the stresses $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ tend to be the applied far-field stresses 3 MPa, 2 MPa, and 0. The displacements without abrupt changes like the stresses drop steadily from maximum to zero. These results indicate that the boundary conditions at infinity are also satisfied [32]. The difference between orthotropic and isotropic infinite rock mass can be seen. When the stress boundary conditions at the tunnel edge and infinity are both satisfied, the solution for stress and displacement is accurate for any point in isotropic mass rock [6, 30]. Although abrupt changes occur in stress distributions near the tunnel in orthotropic rock mass, the stresses and displacements along the tunnel edge are the most important in practical engineering, which are completely correct, showing that these two affine transformation

\[ \begin{align*}
\sigma_x & = \text{Stress in } x \text{-direction} \\
\sigma_y & = \text{Stress in } y \text{-direction} \\
\tau_{xy} & = \text{Shear stress in xy} \\
\end{align*} \]

\[ \begin{align*}
\alpha (\degree) & \\
\end{align*} \]
functions represented by the same variable are available and simple enough.

3.3. Influence of Rock Mass Parameters. In order to find out the influence degree of rock mass parameters on stress and displacement, the results of the present paper are compared with those of Wang [30]. The tunnel shape and loading are the same, and the only difference is that rock mass in Wang [30] is isotropic with elastic modulus $E = 1$ GPa and Poisson’s ratio $\nu = 0.4$. The relationship between the stress components $\sigma_\theta$ and $\sigma_\rho$ in the curvilinear coordinates and $\sigma_x$ and $\sigma_y$ in the Cartesian coordinates is $\sigma_\theta + \sigma_\rho = \sigma_x + \sigma_y$. At the tunnel edge, $\sigma_\rho = 0$, then $\sigma_\theta = \sigma_x + \sigma_y$ [32]. Figure 14 presents the stress $\sigma_\theta$ of isotropic rock mass and orthotropic rock mass along the tunnel edge, which is predicted by the analytical methods by Wang [30] and this paper, respectively. An interesting observed phenomenon is that although there are obvious differences in rock mass parameters, the stress...
distributions between isotropic and orthotropic rock mass change little. Because the solving process is simple and the results are accurate enough, isotropic rock mass may replace orthotropic rock mass if only stresses are considered. Figure 15 shows displacements $u$ and $v$ of isotropic rock mass and orthotropic rock mass along the tunnel edge, which is predicted by the analytical methods by Wang [30] and this paper, respectively. The displacement distribution trends in isotropic rock mass and orthotropic rock mass are almost the same, but the values at the same point are quite different, indicating that rock mass parameters have significant effect on the displacement. For orthotropic rock mass, when displacements are controlling factors in engineering, parameters
should be selected according to actual conditions to obtain reliable results.

4. Conclusions

(1) The conformal mapping function and two affine transformation functions were represented by the same variable. The analytical solutions for two stress functions satisfying boundary conditions through the integral method were derived. Then, the solutions for the stress and displacement around a deeply buried tunnel with noncircular cross sections in elastic orthotropic rock mass were obtained.

(2) The normal stresses and the vertical displacement are all symmetric with respect to the vertical axis, while the shear stress and the horizontal displacement are antisymmetric with respect to the vertical axis.

(3) There are obvious stress concentrations near the tunnel edge, and their areal extent is limited. At about 5 times the tunnel span from the tunnel edge, the stresses tend to be the applied far-field stresses, respectively. However, abrupt changes in stress distributions occur in some regions near the tunnel. The displacements without abrupt changes like the stresses drop steadily from maximum to zero.

(4) Although abrupt changes occur in stress distributions near the tunnel in orthotropic rock mass, the stresses and displacements along the tunnel edge are completely correct and the most important in practical engineering, showing that these two affine transformation functions represented by the same variable are available and simple enough.

(5) The influence of rock mass parameters on displacements is more obvious than that on stresses. The stress distribution in orthotropic rock mass is consistent with that in an isotropic one, and the values are not much different from each other. If only stresses are concerned, orthotropic rock mass may be replaced by isotropic rock mass for simplicity. When displacements are controlling factors in engineering, parameters should be selected according to actual conditions to obtain reliable results.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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