Analysis of Stress and Deformation Law of Tunnel Crossing Sliding Body Based on Pasternak Two Parameter Foundation Assumption

Jiqiang Guo*, Ming Xu, Xiaoting Zhang, Shang Xiao, and Riyan Lan

***Abstract*—Because the landslide has an important influence on the internal force and deformation of the existing tunnel, and the research on the stress and deformation of the tunnel in the landslide area tends to field engineering monitoring, the corresponding theoretical analysis is relatively small, and there are some defects. First, Pasternak two parameter foundation model is introduced to establish the elastic foundation beam model of tunnel landslide interaction, which solves the soil discontinuity of Winkler foundation in the previous theory, and the transfer matrix method is used to derive the transfer matrix formula. Then, Matrix Laboratory (MATLAB) is used to compile the corresponding calculation program to analyze the distribution characteristics of internal force and deformation of the tunnel. Finally, the influence of relevant parameters such as the elastic coefficient of foundation inside and outside the landslide deformation area, the magnitude and distribution of landslide thrust, and the foundation shear stiffness inside and outside the landslide area are analyzed.**

***Index Terms*—Tunnel landslide interaction, Pasternak elastic foundation beam, transfer matrix, theoretical analysis**

I. Introduction

Although the construction of the tunnel should avoid the landslide deformation area as much as possible, due to the complexity and limitation of the mountainous terrain conditions, the route selection of some tunnels inevitably passes through the slope deformation area [1]. Others are due to human disturbance and geological evolution in the late stage, which caused large deformation of the originally stable and not obvious deformation slope, thus causing varying degrees of damage to the tunnel structure, even interrupting the operation of the tunnel [2].

At present, domestic and foreign scholars have studied landslide deformation [3–5] and tunnel excavation influence [6–8] separately, and the study on interaction between landslide and tunnel together is relatively few. Moreover, the research on the interaction between the two is more about numerical simulation methods [9, 10], geomechanics model simulation experiments [11, 12] and on-site engineering monitoring [13, 14], and relatively less about theoretical calculation and analysis. At present, the research on the interaction between landslide and tunnel mainly focuses on the interaction mechanism between tunnel and landslide mass, the deformation characteristics of tunnel in landslide area and the control and protection technology of tunnel landslide mass [15, 16]. Moreover, the research on the internal force and displacement of the whole tunnel in the landslide deformation area under the interaction between tunnel and landslide is relatively few, and the stress of cross section structure is usually taken as the main basis in the design process of tunnel. Therefore, it is necessary to analyze the stress and displacement of the longitudinal structure of the tunnel under the potential landslide.

For the theoretical analysis of the influence of landslide on the deformation of the longitudinal structure of the existing tunnel, it is a common calculation model to simplify the tunnel into an elastic foundation beam in the soil. Both Yin *et al.* [17] and Zhang *et al.* [18] use the calculation model based on Winkler elastic foundation beam assumption, so as to conduct theoretical calculation and analysis. Although the elastic foundation beam method of Winkler model is clearer in concept, simpler in calculation and more practical than the finite element method, Winkler model is established on the premise of ignoring tangential friction resistance, which can’t faithfully reflect the continuity of soil mass structure. Therefore, it is necessary to introduce double parameters to solve the soil mass discontinuity of Winkler foundation model. In this paper, the Pasternak two parameter elastic foundation beam model is used for the corresponding theoretical calculation and analysis. Pasternak foundation uses two parameters to reflect the soil structure characteristics. Assuming that the soil spring element is connected to a layer of vertical elements that can only produce shear deformation but not compression, the force transfer between soil springs is considered, which reflects the continuity of soil deformation and is more in line with the mechanical deformation characteristics of soil. Therefore, Pasternak foundation assumption has been more widely used. The Pasternak two parameter elastic foundation beam model adopted in this paper is more reasonable and more realistic.

In this paper, the calculation assumption based on Pasternak double parameter elastic foundation beam model is adopted. And the tunnel crossing the landslide deformation area is regarded as an elastic foundation beam, the corresponding Pasternak elastic foundation beam model is established, and the transfer matrix is used to calculate and deduce it. Then MATLAB is used for theoretical calculation to obtain the internal force and displacement of the tunnel longitudinal structure. Finally, the influence of the relevant parameters such as the foundation coefficient inside and outside the landslide deformation area, the size and distribution of the landslide thrust, and the shear stiffness of the foundation inside and outside the landslide area on the stress deformation of the tunnel is analyzed, so as to obtain the deformation law of the longitudinal structure of the tunnel crossing the landslide deformation area and the influence of the relevant factors.

Manuscript received November 14, 2022; revised December 20, 2022; accepted February 10, 2023.

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DOI: 10.7763/IJET.2023.V15.1218

II. Theoretical Calculation of Tunnel Longitudinal Structure in Landslide Deformation Area

Yin *et al.* and Zhang *et al.* [17, 18] found that when the tunnel axis direction is perpendicular to or intersects with the landslide sliding direction at a certain angle, the longitudinal structure of the tunnel is most stressed. Therefore, based on the Pasternak foundation model, this paper assumes that the stress and deformation of the longitudinal structure of the tunnel crossing the landslide deformation area where the tunnel axis direction is vertical to the landslide sliding direction are theoretically calculated. The tunnel structure is simplified as an elastic foundation beam. The location relationship between the tunnel and the landslide is shown in Fig. 1.

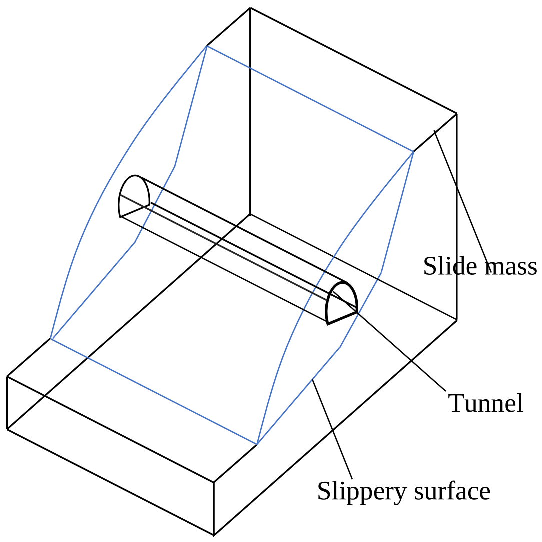


Fig. 1. Location relationship between tunnel and landslide.

A. Mechanical Model of Tunnel under Landslide

The tunnel in the landslide body is deformed due to the influence of landslide thrust. Its mechanical model can be simplified as the elastic foundation beam model under Pasternak foundation, as shown in Fig. 2. Based on the difference between the foundation elastic coefficient and the foundation shear coefficient inside and outside the landslide, it can be divided into OA and AB calculation sections.

Based on Pasternak elastic foundation beam assumption, the theoretical calculation and analysis of this paper analyzes the stress and deformation law of the tunnel in the landslide area. In order to simplify the mechanical calculation model of the tunnel, the following assumptions are made. Firstly, soil properties, tunnel deformation and stress are symmetrical about the central axis. Secondly, in Fig. 2, q(x) is the landslide thrust, which is evenly distributed along the elastic beam of the surrounding rock tunnel structure. Thirdly, the landslide thrust is the main force to deform the tunnel, so the influence of the gravity of the tunnel and lining can be ignored. Finally, the coupling effect of longitudinal tension and transverse bending is not considered.

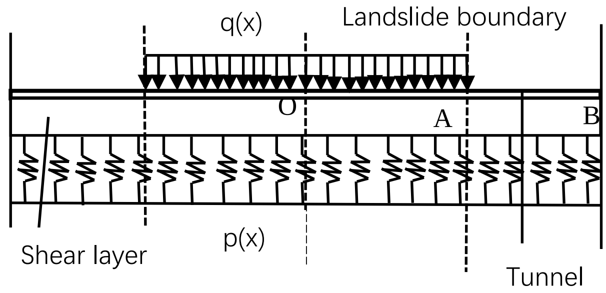


Fig. 2. Calculation model under Pasternak foundation assumption.

B. Establishment of Transfer Matrix

According to the specific conditions of the tunnel and landslide, the tunnel is divided into several micro segments, and several micro segments are defined as transfer units. Take the ith transfer unit in the longitudinal direction of the tunnel for stress analysis. The stress of the ith transfer unit is shown in Fig. 3.

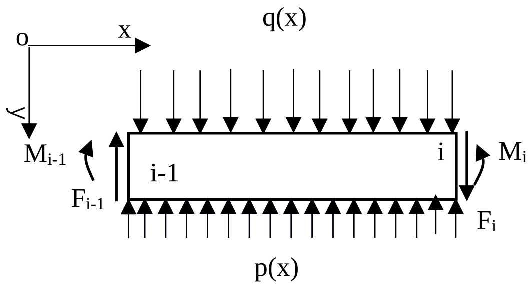


Fig. 3. Stress diagram of the ith transfer unit.

According to the differential equation of the deflection curve of the beam and the assumption of Pasternak foundation, the differential control equation of the deflection curve of the transfer element can be obtained as shown in Eq. (1).

$$EIy^{IV} - GDy'' + kDy = q \tag{1}$$

Including: $y^{IV} = \dfrac{d^4y}{dx^4}$, $y'' = \dfrac{d^2y}{dx^2}$

D: outer diameter of equivalent circle of transfer unit(m);
G: foundation shear stiffness of transfer element(N/m);
k: foundation elastic coefficient of transfer element(N/m^3);
EI: bending stiffness of transfer element(N·m^2);
q: landslide thrust on transfer unit(N/m);

Note: Because the influence of the tunnel cross-section shape on the stress of its longitudinal structure is not considered, the tunnel cross-section can be regarded as equivalent to a circular cross-section. When the tunnel is located in the main sliding area of the landslide, it can be considered that the lower soil mass has lost its supporting effect on the tunnel. In this case, the elastic foundation coefficient and shear stiffness coefficient of the soil mass in the landslide mass in the calculation program can be set to zero. When *G*=0, Eq. (1) is equivalent to the deflection curve differential control equation of elastic foundation beam under the assumption of Winkler foundation. Define the relevant parameters for easy calculation.

$$\alpha = \sqrt[4]{\frac{kD}{4EI}} \quad (2)$$

$$\gamma = \sqrt{\frac{k}{G}} \quad (3)$$

α: Eigenvalues of Wikler foundation model
β: Eigenvalues of Pasternak foundation model

$$\rho = (a/\gamma)^2 \quad (4)$$

Substitute the above three redefined parameters into Eq. (1) to obtain the non-homogeneous linear equation:

$$y^{IV} - 4\alpha^2 \rho y'' + 4\alpha^4 y = q/EI \quad (5)$$

According to the transitivity between adjacent transfer units divided, it can be seen that the boundary condition relationship at the left end of the ith transfer unit in Figure 3 is Eq. (6).

$$\left.\begin{array}{l} y(0) = y_{i-1} \\ y'(0) = \varphi_{i-1} \\ -EIy''(0) = M_{i-1} \\ -EIy'''(0) = Q_{i-1} \end{array}\right\} \quad (6)$$

In Eq. (6) φ_{i-1}, M_{i-1}, Q_{i-1} and y_{i-1} is the corner, bending moment, shear force and deflection of the right end boundary of the *i*-1 transfer unit. The shear force is positive when it rotates clockwise and negative when it rotates counterclockwise; The bending moment is positive if the transfer unit is bent downward and negative if it is bent upward; The deflection is positive according to the direction of landslide thrust, and negative on the contrary.

The transfer matrix of the transfer element can be obtained by combining the boundary condition relationship Eq. (6) and the deflection differential control Eq. (1).

$$(Q_i \quad M_i \quad \varphi_i \quad y_i \quad 1)^{\mathrm{T}} = \boldsymbol{D}_i^{\mathrm{T}} (Q_{i-1} \quad M_{i-1} \quad \varphi_{i-1} \quad y_{i-1} \quad 1)^T \quad (7)$$

In Eq. (7), D_i is defined as the transfer matrix of ith transfer unit. The transfer matrix of the transfer element can be obtained by using MATLAB to write the corresponding calculation program.

Since it has been assumed that the stress and deformation of the tunnel are symmetrical about the central axis, the right half of the tunnel which is the OB segment shown in Fig. 1 can be used for research. Because of the difference of landslide thrust, foundation coefficient and tunnel design parameters, OB section must be divided into enough transfer units to ensure the accuracy of the results. As shown in Eq. (8), the total transfer matrix *D* can be obtained according to the transmissibility of each transfer unit.

$$D = D_1 D_2 D_3 \cdots D_{i-1} D_i D_{i+1} \cdots D_{n-1} D_n \quad (8)$$

Since the relevant parameters of the tunnel inside and outside the landslide are different, it is necessary to divide them into transmission units. Since the tunnel outside the landslide is not affected by the landslide thrust, q(x) can be set as 0 in the calculation. The equation group can be listed according to the total transmission matrix and boundary conditions.

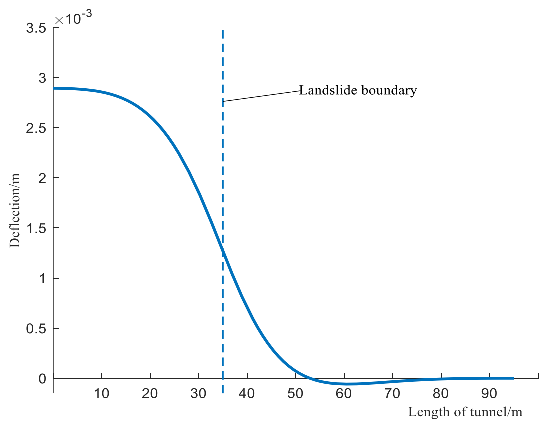
$$\left.\begin{array}{c} \{Q_B,\ M_B,\ \varphi_B,\ y_B,\ 1\} = D\{Q_O,\ M_O,\ \varphi_O,\ y_O,\ 1\} \\ \{Q_O \quad \varphi_O\}^{\mathrm{T}} = \{0 \quad 0\}^{\mathrm{T}} \\ \{y_B \quad \varphi_B\}^{\mathrm{T}} = \{0 \quad 0\}^{\mathrm{T}} \end{array}\right\} (9)$$

According to Eq. (9), there are eight unknowns. From the boundary conditions, we can know that there are exactly eight equations for the four equations of section B boundary and section *O* boundary and the four equations obtained by using the transfer matrix. Therefore, the shear force, bending moment, rotation angle and deflection of sections at both ends of *O* and *B* can be obtained by solving the equation set of Eq. (9). From this, it can be concluded that the internal force and deformation of the whole longitudinal structure of the tunnel are large.

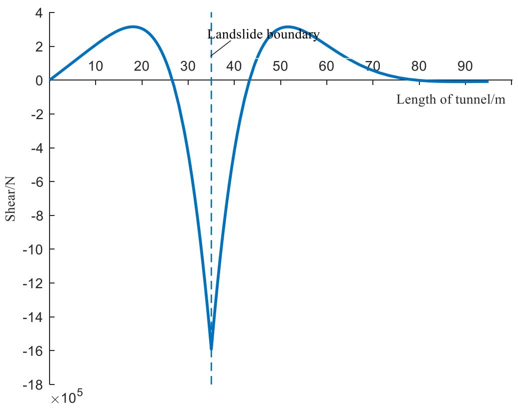
III. Example Analysis

In order to further explain the establishment of the above transfer matrix, this paper must be combined with the corresponding examples for analysis. The parameter values of this example are landslide thrust uniformly distributed q=800KN/m, elastic coefficient of soil foundation in contact between sliding body and tunnel $k_1=2.963\times10^7$N/m^3, foundation shear stiffness $G_1=1.951\times10^7$N/m, elastic coefficient of soil foundation in contact with tunnel in sliding bed $k_2=4.216\times10^7$N/m^3, foundation shear stiffness $G_2=1.617\times10^7$N/m, the span of the tunnel in the sliding body l= 70m, the length of the tunnel in the sliding bed on both sides l_1=60m, the outer diameter of the tunnel D=6.68m, the wall thickness δ= 0.48m and equivalent bending stiffness of tunnel $EI=7.67\times10^{11}$ N/m.

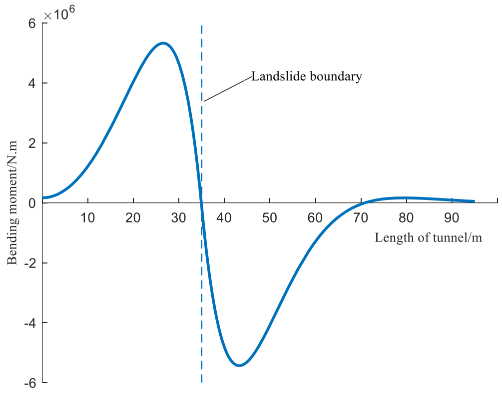
First, the tunnel is divided into 190 parts, and each meter is a transfer unit. Then the force and deformation of the boundary section are calculated according to the above transfer matrix and the provided calculation parameters. Finally, the stress and deformation of the longitudinal structure of the whole tunnel are obtained, and the distribution characteristics of its internal force and displacement are shown in Fig. 3.



(a) Tunnel deflection diagram



(b) Tunnel Shear Diagram



(c) Tunnel bending moment diagram
Fig. 3. Stress and deformation diagram of tunnel.

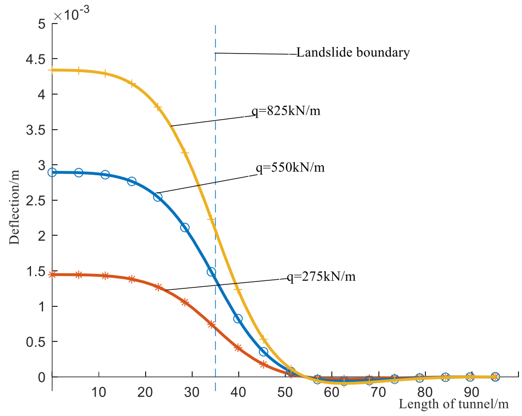
Fig. 3 (a) shows the tunnel shear force diagram under the landslide thrust. It can be seen from the figure that the tunnel deflection is the largest near the tunnel center point. There is a displacement in the direction of the landslide thrust at the landslide boundary. The tunnel displacement changes from positive to negative near x=55m. The longitudinal structure of the tunnel inside the landslide mass mainly displays as an overall displacement. Fig. 3 (b) shows the tunnel shear force diagram under the action of landslide. It can be seen from the figure that the shear force at the landslide boundary has a sudden change, and the shear force at the landslide boundary is the largest, so damage is easy to occur near the landslide boundary. The shear force distribution on the left and right sides of the landslide boundary is similar. Fig. 3 (c) is the bending moment diagram of the tunnel under the action of landslide. It can be seen from the diagram that the bending moment is the largest near x=25. The bending moment at the landslide boundary changes from positive to negative, and the maximum positive and negative bending moments are reached around the tunnel boundary.

IV. Analysis of Influence Parameters

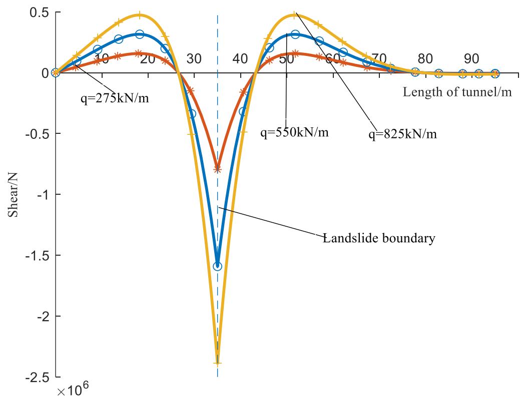
The basic parameters for calculation are as follows: landslide thrust uniformly distributed q=800KN/m, elastic coefficient of soil foundation in contact between sliding body and tunnel $k_1=2.963\times10^7$N/m^3, foundation shear stiffness $G_1=1.951\times10^7$N/m, elastic coefficient of soil foundation in contact with tunnel in sliding bed $k_2=4.216\times10^7$N/m^3, shear stiffness coefficient of foundation $G_2=1.617\times10^7$N/m, the span of the tunnel in the sliding body l=70m, the length of the tunnel in the sliding bed on both sides l_1=60m on both sides, the outer diameter of the tunnel D=6.68m, the wall thickness δ= 0.48m and equivalent bending stiffness of tunnel EI=7.67 $\times 10^{11}$ N/m.

A. Influence of Landslide Thrust on Tunnel Stress and Deformation

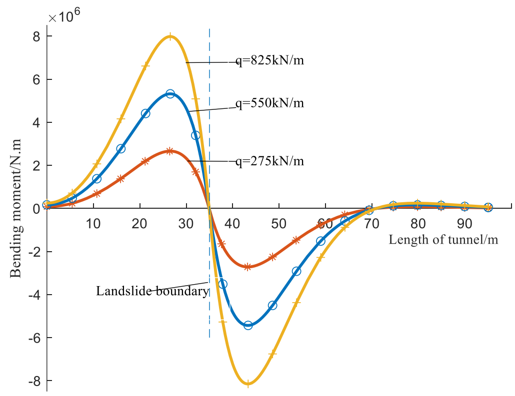
When the landslide thrust is 275, 550 and 825kN/m respectively, the stress and deformation characteristics of the tunnel are shown in Fig. 4.



(a)Tunnel deflection diagram under different landslide thrust



(b) Shear diagram of tunnel under different landslide thrust

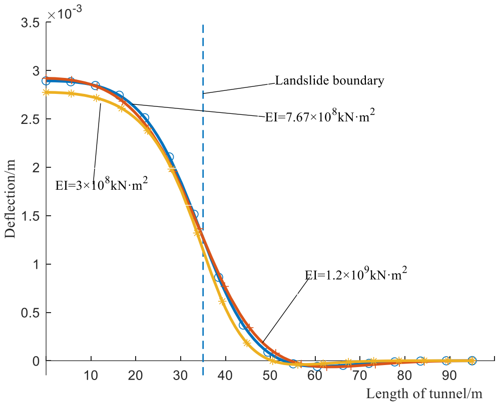


(c) Bending moment diagram of tunnel under different landslide thrust
Fig. 4. Tunnel internal force and deformation curve under different landslide thrust.

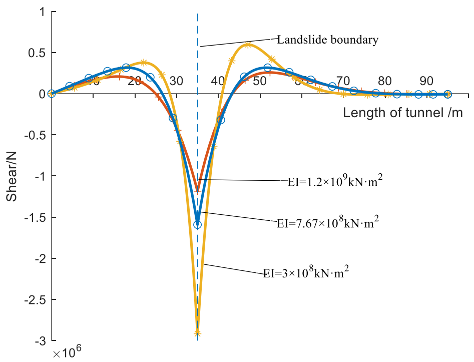
As shown in Fig. 4, the tunnel deflection, shear force and bending moment will change significantly under different landslide thrust. First of all, it can be seen from Fig. 4 that with the increase of landslide thrust, the location of the maximum values of tunnel displacement, shear force and bending moment does not change significantly, but their maximum values increase significantly with the increase of landslide thrust. Secondly, the deflection and shear of landslide boundary also increase with the increase of landslide thrust. Finally, although displacement, shear force and bending moment will change with the change of landslide thrust, the overall trend is roughly the same.

B. Influence of Bending Stiffness of Tunnel on Stress and Deformation of Tunnel

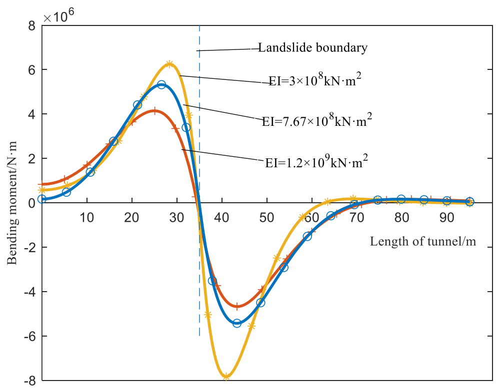
When the bending stiffness of the tunnel is taken as 3×10^{11}N·m^2, 7.67×10^{11}N·m^2 and 1.2×10^{12}N·m^2, the internal force and deformation curve of the tunnel is shown in Fig. 5.



(a) Tunnel deflection diagram under different tunnel bending stiffness



(b) Tunnel Shear Diagram under Different Tunnel Bending Stiffness



(c) Tunnel bending moment diagram under different tunnel bending stiffness

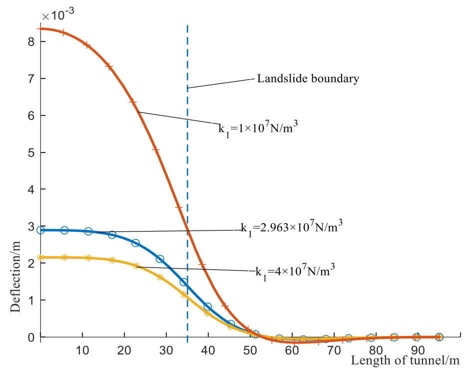
Fig. 5. Tunnel internal force and deformation curve under different tunnel bending stiffness.

According to the change of tunnel internal force and deformation curve under different tunnel equivalent bending stiffness shown in Fig. 5. First of all, it can be seen from Fig. 5 (a) that the deflection of the tunnel is the largest in the middle of the tunnel, and the overall change trend is similar. It can be seen from Fig. 4 (b) and (c) that the maximum negative shear of the tunnel is still located at the landslide boundary, but with the increase of the bending stiffness of the tunnel, the maximum shear force decreases, and the maximum positive shear force and bending moment on both sides of the landslide boundary are farther away from the landslide boundary. In a word, the increase of the bending stiffness of the tunnel mainly plays a greater role in reducing the shear force and bending moment.

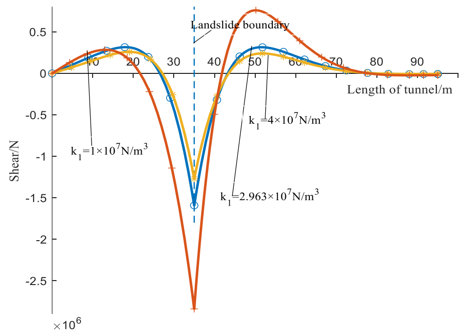
C. Influence of Elastic Coefficient of Foundation in Sliding Body on Internal Force and Deformation of Tunnel

When the elastic coefficient of the foundation in the sliding body is taken as 1×10^7N/m^3, 2.963×10^7N/m^3 and 4×10^7N/m^3, so the internal force and deformation curve of the tunnel is obtained as Fig. 6.

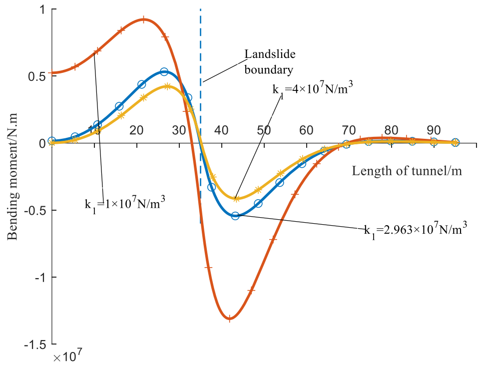
It can be seen from Fig. 6 that the internal force and displacement of the tunnel have obvious changes under different foundation elastic coefficients of the sliding body. First, it can be seen from Fig. 6 (a) that the tunnel deflection decreases with the increase of the foundation elastic coefficient in the landslide body. It can be seen from Fig. 6 (b) that the maximum value of tunnel shear force is still at the landslide boundary, but its maximum value decreases with the increase of foundation elastic coefficient in the landslide body. It can be seen from Fig. 6 (c) that the bending moment at the tunnel center and the landslide boundary will increase with the decrease of the foundation elastic coefficient of the sliding body.



(a) Tunnel deflection diagram under elastic foundation coefficient of different sliding bodies

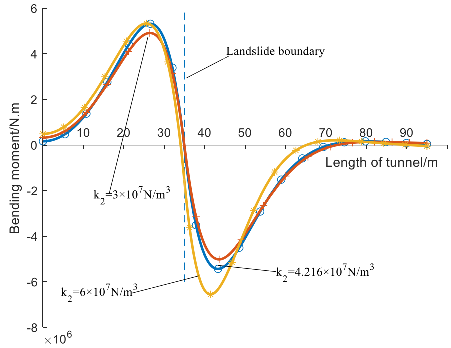


(b) Tunnel shear diagram under elastic foundation coefficient of different sliding bodies



(c) Tunnel bending moment diagram under different foundation elastic coefficients of sliding mass

Fig. 6. Tunnel internal force and deformation curves under different elastic coefficients of foundation in sliding bodies.



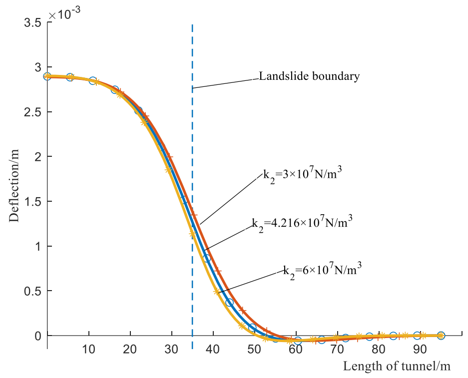
(c) Tunnel bending moment diagram under different foundation elastic coefficients in sliding bed

Fig. 7. Tunnel internal force and deformation curve under different elastic coefficient of foundation in sliding bed.

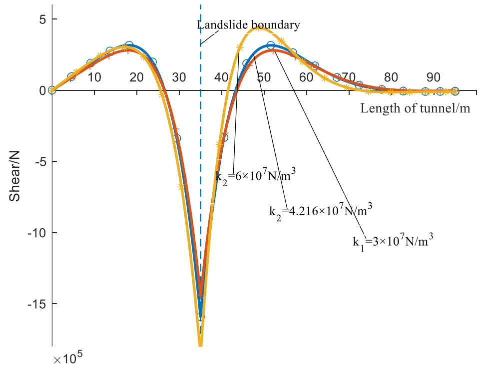
D. Influence of Elastic Coefficient of Foundation in Sliding Bed on Stress and Deformation of Tunnel

When the elastic coefficients of the foundation in the sliding bed are respectively taken as 3×10^7N/m^3, 4.216×10^7 N/m^3 and 6×10^7N/m^3, the internal force and displacement curve of the tunnel at this time is obtained as shown in Fig. 7.

It can be seen from Fig. 7 that the internal force and displacement at the center point of the tunnel are less affected by the elastic coefficient of the foundation in the sliding bed. In contrast, the internal force at the landslide boundary will increase with the increase of the elastic coefficient of the foundation in the sliding bed, and the tunnel bending moment and shear force are more inclined to the landslide boundary.



(a) Tunnel deflection diagram under different foundation elastic coefficients in sliding bed

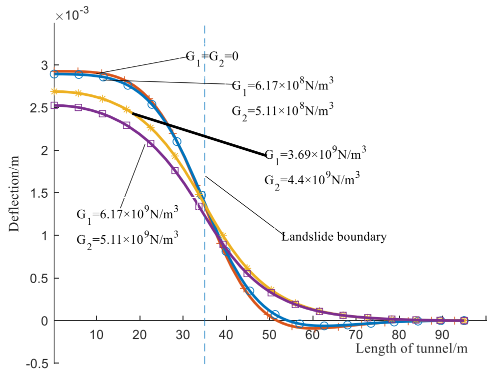


(b) Tunnel shear diagram under different elastic coefficients of foundation in sliding bed

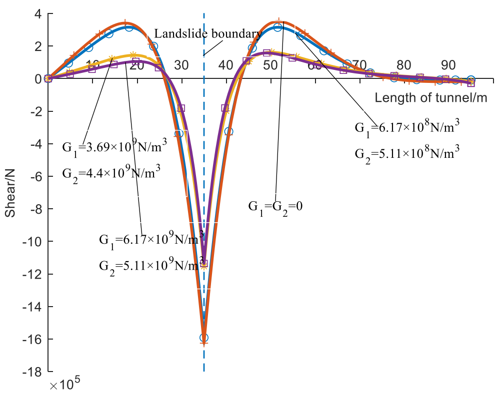
E. Influence of Foundation Shear Stiffness on Tunnel Internal Force and Deformation

When the shear stiffness of foundation soil is different, the tunnel internal force and deformation curve is as shown in Fig. 8.

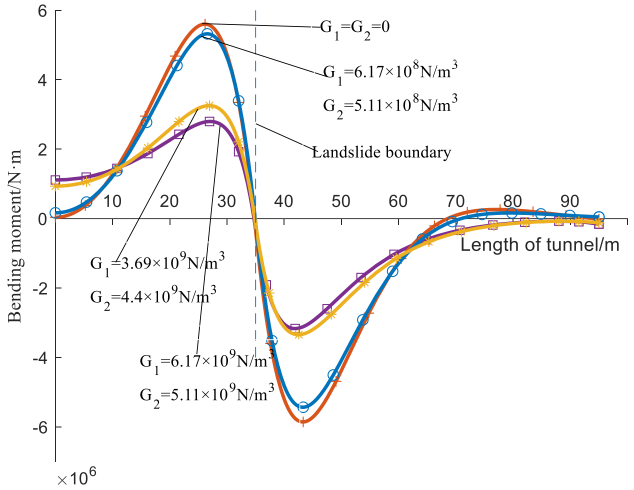
It can be seen from Fig. 8 that the internal force and deformation of the tunnel are obviously affected under different shear stiffness. First of all, the maximum deflection of the tunnel is located in the center of the tunnel, but the maximum deflection of the tunnel decreases with the increase of the shear stiffness, on the contrary, the deflection of the tunnel boundary is not greatly affected by the shear stiffness. The maximum bending moment and shear of the tunnel decrease with the increase of the foundation shear stiffness, and the maximum is far away from the tunnel boundary. In a word, with the increase of the shear stiffness of the foundation, the internal force and deformation of the tunnel will decrease.



(a) Tunnel deflection diagram under different foundation shear stiffness



(b) Tunnel shear diagram under different foundation shear stiffness



(c) Tunnel deflection diagram under different foundation shear stiffness

Fig. 8. Tunnel internal force and deformation curve under different foundation shear stiffness.

V. Conclusion

(1) Based on Pasternak's foundation assumption, the analysis of the laws of the stress and deformation of the tunnel crossing the landslide body makes up for the inherent defects of the Wikler foundation model to some extent, reflects the continuity of the soil, and more accurately calculates the results of the tunnel internal force and displacement.

(2) Based on Pasternak assumption, this paper analyzes the internal force and displacement of the tunnel structure crossing the landslide, in which the tunnel is assumed to be an elastic beam, and the internal force and displacement solution of the tunnel longitudinal structure is obtained by using the transfer matrix method. From the internal force and deformation curve in Figure 3, we can see that the displacement mainly occurs in the tunnel in the sliding body. From the tunnel deflection curve, it can be seen that the longitudinal structure of the tunnel affected by the landslide is dominated by overall displacement and deformation. The shear force at the boundary of the tunnel is the largest and sudden change occurs, where it is easy to be staggered. The bending moment in the landslide is relatively large.

(3) By analyzing the influence of different parameters on the stress and deformation of the tunnel, it is known that the internal force and displacement of the tunnel increase with the increase of the landslide thrust. The internal force of the tunnel will decrease with the increase of the bending stiffness of the tunnel, and the deflection will increase with the increase of the bending stiffness of the tunnel. The internal force and displacement of the tunnel will decrease with the increase of the elastic coefficient of the foundation in the sliding bed. The elastic coefficient of the foundation in the sliding bed has little influence on the internal force and displacement of the tunnel; The increase of the shear stiffness of the foundation will reduce the internal force and deformation of the tunnel.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors conducted the research. Riyan Lan and Xiaoting Zhang found information; Xiaoting Zhang and Ming Xu analyzed the data; Jiqiang Guo wrote the paper; all authors had approved the final version.

Funding

This work was supported by the National Natural Science Foundation of China (52279094, 51478065) and the Key Research and Development Program of Guangxi (AB20238036).

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