WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2026.158618

ARCHIVES OF CIVIL ENGINEERING

Vol. LXXII ISSUE 2 2026

pp. 419 –432

Research paper

Research on the mechanical model and control standards for ground loss rate of shield tunnels underpassing high speed rail tunnels

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Abstract: The analytical models for calculating the longitudinal deformation of existing high-speed railway tunnels when a shield tunnel passes beneath them mostly consider the underlying soil as a homogeneous foundation and neglect the variability of the strata. Taking into account the inherent spatial variability of the strata parameters, this study constructs a new mechanical model for the shield tunnel passing beneath existing high-speed railway tunnels, considering the influence of spatial variability in foundation stiffness, and derives the corresponding finite element solution. Through engineering case studies, the reliability of the established mechanical model for the shield tunnel passing beneath existing high-speed railway tunnels is verified. A stochastic analysis method is used to analyze the longitudinal deformation and internal forces of existing high-speed railway tunnels caused by the shield tunnel passing construction. The research results indicate: (1) For single-line shield tunnel construction, once the stratum loss rate exceeds 0.36%, the probability of exceeding the standards rapidly increases. When the loss rate reaches 0.96%, the probability of high-speed railway tunnel deformation exceeding the standards is already at 97.5%. For double-line shield tunnel construction, once the stratum loss rate exceeds 0.18%, the probability of high-speed railway tunnel performance exceeding the standards rapidly increases, and the risk of shield tunnel passing construction sharply rises. (2) The stratum loss rate during single-line shield tunnel passing beneath high-speed railway tunnels should be kept within 0.36%, while for double-line shield tunnel passing, the loss rate should be controlled within 0.18%.

Keywords: high-speed railway tunnel, shield tunnel passing beneath, stochastic analysis, stratum loss rate, safety control standards

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1. Introduction

Regarding the disturbance caused by the construction of new shield tunnels to adjacent existing tunnels, scholars at home and abroad have conducted extensive research using theoretical calculations [1–4], numerical simulations [5–8], model experiments [9–11], and on-site measurements [12], and have achieved rich research results. Among them, due to the advantages of clear concepts and simple and convenient calculations, the theoretical analysis method has been widely applied in solving such problems.

Starting from the mechanism of mechanical action, the response of adjacent tunnels caused by the construction of new tunnels is essentially a problem of rock structure interaction between existing tunnels under the additional load generated by the construction of new tunnels. Therefore, the existing theoretical analysis methods generally adopt the "two-stage method" for the analytical solution of this problem. In the first stage, the existence of the existing tunnel is ignored to obtain the additional load (force load or displacement load) caused by the construction of the new tunnel. Then, in the second stage, this free field load is applied to the rock structure interaction model of the existing tunnel to obtain the additional response (deformation and internal force) of the existing tunnel. At present, the differences in different theoretical analysis methods are mainly reflected in the structural mechanics analysis model of the existing tunnel constructed in the second stage. Liang et al. [13] analyzed the longitudinal deformation of existing shield tunnels caused by the underpass and double span construction of new shield tunnels using the Winkler foundation EB beam (Euler Bernoulli beam) model and the Winkler foundation T-beam (Timoshenko beam) model, respectively; Gan et al. [14] studied the impact of double line shield tunnel underpass on existing shield tunnels based on the Pasternak foundation EB beam model. Liu et al. [15] and Zhang et al. [16] regarded the existing shield tunnel segments as a series of elastic foundation short beams connected by tension springs, compression springs, and shear springs on the Pasternak foundation, and established a method for calculating the longitudinal deformation of subway shield tunnels passing through existing lines at close range.

A survey of existing research shows that in the current research on the additional response of existing tunnels caused by the construction of new tunnels using theoretical analysis methods, the research objects generally focus on shield tunnels, and there is less attention paid to special situations such as new tunnels passing through high-speed rail tunnels. This is mainly due to the special nature of high-speed rail tunnels, and in general, new tunnel routes will try to avoid high-speed rail tunnels as much as possible. However, the current solution method established for the problem of new tunnels penetrating existing shield tunnels still has certain applicability for the construction of high-speed rail tunnels adjacent to new tunnels. Therefore, the basic idea can be used as a reference to establish a mechanical model of the characteristics of the new tunnel passing under the existing high-speed railway tunnel project.

It is worth pointing out that in existing theoretical analysis models, the underlying foundation of the existing tunnel is generally regarded as a homogeneous foundation, that is, the parameters of the foundation model are treated as constant values, ignoring the inherent spatial variability of the foundation parameters. For shield tunnels with ultra long linear structures, it is inevitable to cross multiple geological layers along the longitudinal direction; Even in nominally homogeneous formations, due to the complex historical sedimentary processes involved in the formation of rock and soil masses, various physical and mechanical parameters will inevitably exhibit a certain degree of spatial variability [17]. Research has shown that the spatial variability of geotechnical parameters has a significant impact on the mechanical properties of geotechnical structures [18]. The deterministic analysis method based on fixed parameters may not reflect the failure mechanism of existing tunnels under the disturbance of new tunnel construction, thus overestimating the disaster bearing capacity of existing tunnel structures and causing significant construction risks. Especially for engineering structures such as high-speed railway tunnels with extremely high safety and importance levels, the reliability requirements for engineering risk assessment are higher. Therefore, it is extremely necessary to establish a risk assessment method that takes into account the variability of foundation parameters for the disturbance caused by the construction of high-speed rail tunnels under new tunnels.

Therefore, based on existing research, in order to address the special problem of new shield tunnels penetrating existing high-speed railway tunnels, considering the inherent spatial variability of foundation parameters, a corresponding analytical model is constructed, and combined with the random field model of foundation parameters, a random analysis method for the additional response of existing high-speed railway tunnels caused by the construction of new shield tunnels is established. Based on the probability risk perspective, a risk assessment of the construction of new shield tunnels penetrating underground is carried out.

2. Mechanical model of a new shield tunnel passing through an existing high-speed railway tunnel

2.1. Basic assumptions

Considering the construction process of shield tunnels and the structural characteristics of existing high-speed railway tunnels, a mechanical model of a newly constructed shield tunnel penetrating through an existing high- speed railway tunnel is established as shown in Fig. 1. In the figure, $q(x)$ represents the additional load caused by the construction of the new tunnel at the axis of the existing high-speed railway tunnel. To simplify the research and highlight the key points, the following basic assumptions are made:

1. Consider the transverse shear effect of the existing high-speed railway tunnel lining and simplify it as a homogeneous Timoshenko beam with free ends;
2. Using the Pasternak dual parameter foundation model to describe the interaction between the tunnel and soil, and further considering the inherent variability of foundation parameters using a variable stiffness foundation model;

3. The existing high-speed railway tunnel is coordinated with soil deformation, without considering the time-varying effects of the strata, such as consolidation and creep.

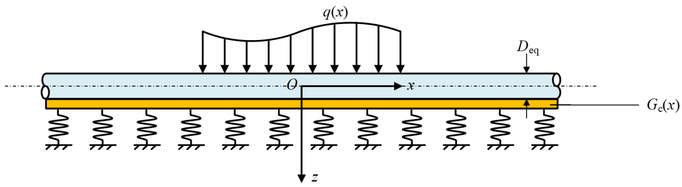


Fig. 1. Mechanical model of a newly constructed shield tunnel passing through an existing high-speed railway tunnel

2.2. Control equation of analytical model

For the Pasternak foundation model, the relationship between the pressure (or foundation reaction) at any point on the foundation and the deformation at that point is:

$$p(x) = kw(x) - G_c \frac{d^2 w(x)}{dx^2} \tag{2.1}$$

Where p is the foundation reaction force; k and G_c are the compression modulus and shear modulus of the elastic foundation, respectively; w is the vertical deformation of the foundation calculation point. Since it is assumed that the deformation of the tunnel is coordinated with the deformation of the foundation, w also represents the vertical deformation of the existing tunnel.

According to Timoshenko's beam theory, there exists a differential relationship between beam deformation and internal forces as follows:

$$M = -D\chi \tag{2.2}$$

$$Q = C\gamma \tag{2.3}$$

$$\chi = \frac{\mathrm{d}\varphi}{\mathrm{d}x} \tag{2.4}$$

$$\gamma = \frac{\mathrm{d}w}{\mathrm{d}x} - \varphi \tag{2.5}$$

Where M and Q are the bending moment and shear force of the beam section, respectively; $D = EI$ represents the bending stiffness of the beam section, which is the longitudinal equivalent bending stiffness $(EI)_{\mathrm{eq}}$ of the high-speed railway tunnel lining, where E is the elastic modulus of the beam and I is the moment of inertia of the beam section; $C = \kappa GA$ represents the shear stiffness of the beam section. Here is the equivalent shear stiffness of the existing high-speed railway tunnel $(\kappa GA)_{\mathrm{eq}}$, where κ is the correction factor for the shear stiffness of the section, and G and A are the shear modulus and cross-sectional area of the beam, respectively; φ represents the angle of rotation of the beam section; γ is the cross-sectional shear angle; χ is the curvature of the cross-section.

Perform force analysis on the micro segment of the beam with a length of dx in Fig. 1, as shown in Fig. 2. Establish the equilibrium equation for the micro segment of the beam:

$$Q + \mathrm{d}Q + qD_{\mathrm{eq}}\mathrm{d}x = Q + pD_{\mathrm{eq}}\mathrm{d}x \tag{2.6}$$

$$M + Q\mathrm{d}x + pD_{\mathrm{eq}}\frac{(\mathrm{d}x)^2}{2} = M + dM + qD_{\mathrm{eq}}\frac{(\mathrm{d}x)^2}{2} \tag{2.7}$$

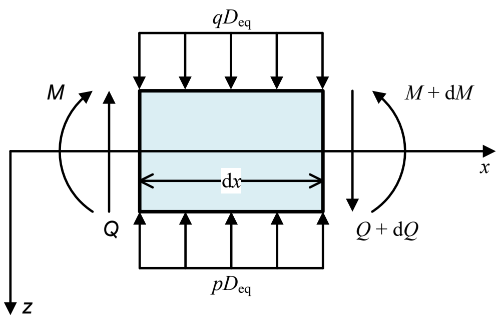


Fig. 2. Schematic diagram of stress on micro segments of beams

By combining Equations (2.6) to (2.7) and omitting higher-order trace elements, let $K = kD_{\mathrm{eq}}$ and $T = G_c D_{\mathrm{eq}}$ to obtain the equilibrium differential equations for the Timoshenko beam rotation angle φ and deflection w on the Pasternak foundation under the additional load $q(x)$:

$$\frac{\mathrm{d}}{\mathrm{d}x}\left[C\left(\frac{\mathrm{d}w}{\mathrm{d}x} - \varphi\right)\right] = Kw(x) - T\frac{\mathrm{d}^2 w}{dx^2} - qD_{\mathrm{eq}} \tag{2.8}$$

$$-D\frac{\mathrm{d}^2\varphi}{\mathrm{d}x^2} = C\left(\frac{\mathrm{d}w}{\mathrm{d}x} - \varphi\right) \tag{2.9}$$

Decoupling equations (2.8) and (2.9) yields the governing differential equation for the longitudinal deformation of an existing high-speed railway tunnel under the additional load generated by the newly constructed shield tunnel:

$$\frac{\mathrm{d}^4 w}{\mathrm{d}x^4} - \frac{TC + KD}{D(C+T)}\frac{\mathrm{d}^2 w}{\mathrm{d}x^2} + \frac{KC}{D(C+T)}w = \frac{CD_{\mathrm{eq}}}{D(C+T)}q - \frac{D_{\mathrm{eq}}}{C+T}\frac{\mathrm{d}^2 q}{\mathrm{d}x^2} \tag{2.10}$$

2.3. Solving the Control Equations of the Analytical Model

The analytical model control equation (2.10) is a fourth-order non- homogeneous differential equation, and it is difficult to obtain its exact analytical solution. Meanwhile, in order to further consider the variability of foundation parameters along the longitudinal direction of the tunnel, this paper uses the finite element method to solve the analytical model.

Due to the use of the Pasternak foundation model in this article to describe the interaction between the tunnel and soil, the vertical additional load $q(x)$ acting on the existing high-speed railway tunnel can be determined by the following equation after obtaining the free field displacement of the strata caused by the construction of the new shield tunnel:

$$q(x) = kU_z(x) - G_c \frac{\mathrm{d}^2 U_z(x)}{\mathrm{d}x^2} \tag{2.11}$$

In the formula, $U_z(x)$ represents the vertical displacement of the strata at the axis of the existing high-speed railway tunnel caused by the construction of a new shield tunnel.

The key parameters k and G_c of the Pasternak foundation model can generally be calculated according to the following formula:

$$\begin{cases} k = \dfrac{1.3E_s}{D_t\left(1-\mu_s^2\right)}\sqrt{\dfrac{E_s D_t^4}{EI}} \\ G_c = \dfrac{E_s h_t}{6\left(1+\mu_s\right)} \end{cases} \tag{2.12}$$

In the formula, E_s and μ_s are the elastic modulus and Poisson's ratio of the foundation, respectively; EI is the bending stiffness of the foundation beam, which refers to the bending stiffness of the existing high-speed railway tunnel; D_t is the width of the foundation beam, which is the outer diameter of the existing tunnel; h_t is the thickness of the foundation shear layer, generally taken as $h_t = 2.5D_t$ [19].

$U_z(x)$ can be calculated using the semi analytical calculation method proposed by Loganathan et al. [20] for the vertical displacement of surrounding free soil caused by shield tunneling.

$$U_z(x) = \frac{1}{4}D_N^2\varepsilon_0\left\{-\frac{2H_0B}{A^2} + (3-4v)\frac{a}{A} - \frac{b}{x^2+b^2}\right\} \cdot e^{\left(-\left[\frac{1.38x^2}{(H_N+0.5D_N)^2} + \frac{0.69H_0^2}{H_N^2}\right]\right)} \tag{2.13}$$

Among them: $a = H_0 + H_N$; $b = H_0 - H_N$; $A = x^2 + a^2$; $B = x^2 - a^2$; ε_0 is the average formation loss ratio (loss rate); x is the horizontal distance from the centerline of the tunnel; H_0 is the burial depth of the existing tunnel axis; H_N is the burial depth of the newly built tunnel; D_N is the outer diameter of the newly constructed tunnel.

3. Random analysis method for longitudinal mechanical response of existing high-speed railway tunnels

To quantitatively evaluate the influence of spatial variability of the underlying foundation parameters of existing high-speed railway tunnels on their longitudinal mechanical performance, a random analysis method for the longitudinal mechanical response of existing high-speed railway tunnels under the influence of new shield tunnel construction is established based on the longitudinal mechanical model of existing high-speed railway tunnels considering the spatial variability of foundation stiffness, the theory of soil random field, and the Monte Carlo simulation strategy. Probability risk analysis is carried out for the construction of new shield tunnels under existing high-speed railway tunnels.

The spatial variability of foundation parameters can be described by random field theory, and its variability characteristics are characterized by the mean, coefficient of variation, and fluctuation range (also known as autocorrelation distance) of the target parameters. Among them, the fluctuation range reflects the strength of the spatial variation characteristics of the target parameter, and its value can be determined by the autocorrelation function. This article uses the widely used exponential autocorrelation function to calculate the autocorrelation coefficient between any two points along the longitudinal direction of the tunnel. For one-dimensional problems, the exponential autocorrelation function can be expressed as:

$$\rho\left(x_i, x_j\right) = \exp\left(-\frac{2\left|x_i - x_j\right|}{l_x}\right) \tag{3.1}$$

In the formula, $\rho\left(x_i, x_j\right)$ is the correlation coefficient between any two points x_i and x_j at the axis of the existing tunnel $\left|x_i - x_j\right|$ represents the relative distance between two points; l_x is the horizontal autocorrelation distance of the target parameter.

In the mechanical model of the newly constructed shield tunnel passing through an existing high-speed railway tunnel, the inherent spatial variability of the underlying foundation parameters of the tunnel was considered by introducing a variable stiffness Pasternak foundation model. As shown in equation (3.1), the key parameters of the Pasternak foundation model (k and G_c) are mainly determined by the elastic modulus and Poisson's ratio of the foundation soil. However, relevant studies have shown that the variability of Poisson's ratio is relatively small, while the variability of elastic modulus is relatively large. Therefore, this paper establishes a random field model of the elastic modulus of the foundation to achieve spatial variability of the parameters of the underlying foundation of the existing tunnel along the longitudinal direction of the tunnel.

Due to the fact that the elastic modulus of the foundation soil cannot be negative, the elastic modulus of the foundation at any point along the longitudinal direction of the tunnel is considered as a random variable that follows a lognormal distribution. The logarithmic normal random field $H_E(x)$ of the elastic modulus of the foundation with a mean of μ_E and a standard deviation of σ_E can be expressed as:

$$H_E(x) = \exp\left[\mu_{\ln E} + \sigma_{\ln E} \cdot H_E^D(x)\right] \tag{3.2}$$

In the formula, $H_E^D(x)$ is the standard Gaussian random field of the elastic modulus E_s of the foundation; The mean and standard deviation of the normal random variable $\ln E_s$ are represented by $\mu_{\ln E}$ and $\sigma_{\ln E}$, respectively. They can be obtained by transforming the mean and standard deviation of the lognormal random variable E_s into:

$$\begin{cases} \sigma^2_{\ln E} = \ln\left(1 + \dfrac{\mu^2_E}{\sigma^2_E}\right) = \ln\left(1 + cov^2_E\right) \\ \mu_{\ln E} = \ln \mu_E - \dfrac{1}{2}\sigma^2_{\ln E} \end{cases} \tag{3.3}$$

In the formula, cov_E is the coefficient of variation of the lognormal random variable E_s.

To combine the random field model of foundation stiffness with the established mechanical analytical model of the new shield tunnel penetrating through an existing high-speed railway tunnel, it is necessary to discretize the random field. Due to the simple calculation process and ease of programming implementation of the center point method, this paper adopts the Cholesky center point method to discretize the logarithmic normal random field model of the foundation stiffness. The autocorrelation matrix **K** generated by the autocorrelation function is positive definite and can be decomposed into the product of the upper triangular matrix $\mathbf{S}^T$ and the lower triangular matrix **S** using Cholesky decomposition technique:

$$\mathbf{K} = \mathbf{S}^T\mathbf{S} \tag{3.4}$$

For a given finite element mesh and correlation distance, the value of matrix **K** is determined, and therefore the value of the upper triangular matrix $\mathbf{S}^T$T is also determined. At this time, the standard Gaussian random field of the soil elastic modulus E_s can be expressed as:

$$H^D_E(x) = \mathbf{S}^T\mathbf{X} \tag{3.5}$$

In the formula, **X** is a vector composed of a set of random variables that follow a standard normal distribution.

Thus, by combining equations (3.1) to (3.5), a logarithmic normal random field of the elastic modulus of the foundation soil along the longitudinal direction of the tunnel can be generated. Based on equation (2.12), the foundation reaction coefficient $k(x)$ and shear parameter $G_c(x)$ that vary along the longitudinal direction of the tunnel can be obtained.

4. Engineering case analysis

4.1. Case overview

The shield tunnel between Xianglong Station and Xingsha Station on Changsha Metro Line 3 passes under the Liuyanghe Tunnel on the Beijing Guangzhou high-speed railway at DK34+856. The position relationship between the shield tunnel on Line 3 and the existing high-speed railway tunnel is shown in Fig. 3. The current situation of the underpass section of the interval shield tunnel is that the Liuyang River Tunnel is an entrance open cut tunnel section. The newly built shield tunnel axis in the underpass section has a burial depth of 32.61 m, a vertical clearance distance of 12.48 m from the existing tunnel lining, and a center distance of 15.0 m between the left and right tunnel lines.

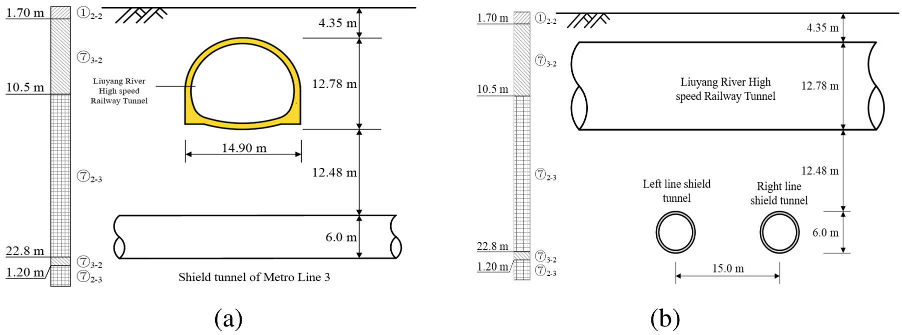


Fig. 3. Relative Position Relationship between Newly Built Shield Tunnel and Liuyang River High speed Railway Tunnel: (a) Vertical section, (b) Cross section

As shown in Fig. 3, the strata of the underpass section of the subway line 3 tunnel are mainly composed of ①$_{2-2}$ plain fill, ⑦$_{3-2}$ strongly weathered conglomerate, and ⑦$_{2-2}$ weathered mudstone sandstone. The main strata in the Liuyang River high-speed railway tunnel section are strongly weathered conglomerate and moderately weathered mudstone sandstone. The newly built shield tunnels for the left and right lines of Metro Line 3 are mainly excavated in the moderately weathered mudstone sandstone strata.

4.2. Basic parameters and safety control standards for formation loss rate

As shown in Fig. 3a, the existing Liuyang River high-speed railway tunnel has a horseshoe shaped section. For ease of calculation, its section is equivalent to a circular section based on its cross-sectional area. The inner contour area of the horseshoe shaped section is about 120 m^2, so the equivalent section diameter is taken as 12.36 m, and the lining thickness is calculated based on the thickness of the arch crown, which is taken as 0.8 m. The tunnel lining adopts C35 reinforced concrete segments, so the elastic modulus is taken as 3.15×10^4 MPa, and the Poisson's ratio is taken as 0.2. Considering the influence of lining construction quality and segment structural joints, the stiffness of the lining is reduced to a certain extent during actual calculation. The reduction factor in this article is considered as 0.8, and the longitudinal equivalent bending stiffness and shear stiffness of the existing high-speed railway tunnel are finally obtained as 1.23×10^{10} kN·m^2 and 1.62×10^8 kN/m, respectively.

According to the geological survey data, the basic physical and mechanical parameters of the main strata within the calculated cross-section of the underpass section are shown in Table 1. When calculating, the geological parameters are calculated based on the weighted average of the thickness ratio of the geological layer within the calculation section. The rock and soil calculation parameters used are: elastic modulus of 900 MPa, Poisson's ratio of 0.25, weight of 22.9 kN/m^3, and internal friction angle of 31°. Due to the lack of detailed geological mechanics statistical parameters, it is assumed that the coefficient of variation of the stiffness of the underlying foundation of the existing tunnel is 0.3 during the calculation. Phoon et al. [21] found that the horizontal fluctuation distance of natural soil is generally 10–80 m. Therefore, when using random analysis method, the horizontal fluctuation distance of foundation stiffness is taken as 5D (D is the outer diameter of the newly built shield tunnel) as the basic working condition for research.

Table 1. Physical and Mechanical Parameters of Strata

Stratum number	**Formation name**	**Unit weight (kN/m^3)**	**Internal friction angle (°)**	**Elastic modulus (MPa)**	**Poisson's ratio**
12-2	Plain fill soil	19.7	15.6	13	0.3
73-2	Strongly weathered conglomerate	22.9	30.0	150	0.25
72-2	Moderately weathered mudstone sandstone	23.1	32.0	1300	0.22

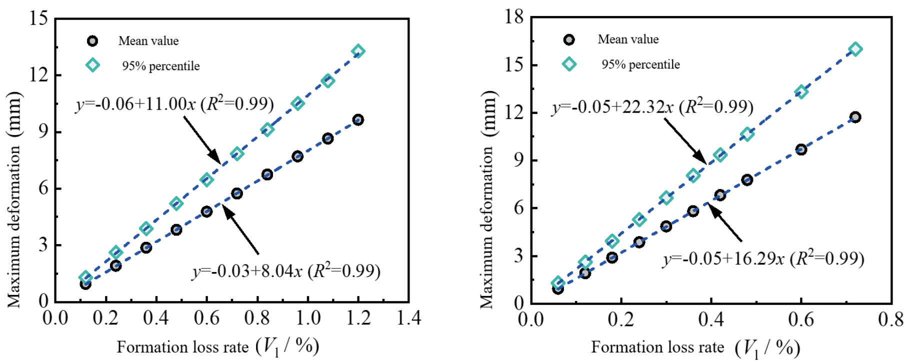
According to the on-site construction plan, the tunnel between Xianglong Station and Xingsha Station on Metro Line 3 will be constructed using two earth pressure balance shield machines. The excavation diameter of the shield machine is 6.25 m, the length of the shield body is about 8.0 m, and the cutterhead is constructed with 4 main beams and 4 panels, with an opening rate of 37%. The construction parameters for the shield tunneling under the Liuyang River Tunnel of the Beijing Guangzhou high-speed railway determined based on the excavation construction of the experimental section are shown in Table 2, and the average of each parameter is taken for calculation.

Table 2. Construction parameters of shield tunneling through Liuyanghe Tunnel of Beijing Guangzhou High speed Railway

Parameter	**Value**	**Parameter**	**Value**
Soil storage pressure (bar)	0.8–1.2	Synchronous grouting volume (m3)	6.9–7.1
Total thrust (MN)	11.5–12.5	Synchronous grouting pressure (MPa)	0.24–0.28
Knife disk torque (MN·m)	2.6–2.9	Excavated quantity (m3)	60–62
Cutterhead speed (rpm)	1.4–1.6	Secondary grouting pressure (MPa)	0.3–0.5
Excavation speed (mm/min)	20–25	Secondary grouting volume (m3)	1.0–1.4

The formation loss rate is a key control parameter during shield tunneling construction, and its magnitude directly affects the disturbance control effect of shield tunneling on the surrounding environment. According to the inversion results of surface displacement monitoring data caused by the experimental section and formal underpass process of this project (using Peck formula to fit the surface deformation data), the soil loss rate is basically controlled at around 0.12% during actual construction.

Figure 4 shows the variation of the maximum deformation statistics of high- speed rail tunnels with respect to the formation loss rate under the conditions of single line and double line shield tunneling. As shown in the figure, whether it is single line shield tunneling or double line shield tunneling, the maximum deformation mean and 95% percentile of high-speed rail tunnels increase linearly with the increase of formation loss rate. The fitting results show that the correlation coefficient between the two is 0.99. It is worth noting that the growth rate of the 95% percentile of the maximum deformation of high-speed railway tunnels with respect to the formation loss rate (slope of the fitting curve) is significantly greater than the growth rate of its mean, indicating that as the formation loss rate increases, the skewed distribution characteristics of the longitudinal maximum deformation of high-speed railway tunnels obtained by random analysis become more apparent.



(a) (b)

Fig. 4. Statistical value of maximum longitudinal deformation of existing high-speed railway tunnels as a function of the angle between the tunnel axis

As shown in Fig. 5, the probability of exceeding the maximum longitudinal deformation limit of high-speed rail tunnels varies with the formation loss rate. As can be seen from the figure, the probability of deformation exceeding the standard in high-speed railway tunnels changes in an "S-shape" with the increase of ground loss rate during shield tunneling construction. For single line shield tunneling construction, when the ground loss rate exceeds 0.36%, the probability of exceeding the standard increases rapidly. When the ground loss rate reaches 0.96%, the probability of high-speed rail tunnel deformation exceeding the standard has reached 97.5%. For the construction of double line shield tunneling, when the ground loss rate exceeds 0.18%, the probability of exceeding the standard performance of high-speed rail tunnels will rapidly increase, and the risk of shield tunneling construction will sharply increase. For this engineering case, under current conditions, the formation loss rate during single line shield tunneling should be controlled within 0.36% (corresponding to a deformation exceedance probability of 0.1% for high-speed rail tunnels), while during double line shield tunneling, the formation loss rate should be controlled within 0.18% (corresponding to a deformation exceedance probability of 0.1% for high-speed rail tunnels). From this, it can be seen that in order to ensure the safety of high-speed railway tunnels, the ground loss rate during shield tunneling must be strictly controlled, and its value should be much smaller than the ground loss rate control value during shield tunneling (about 1/2 of the ground loss rate during single line tunneling).

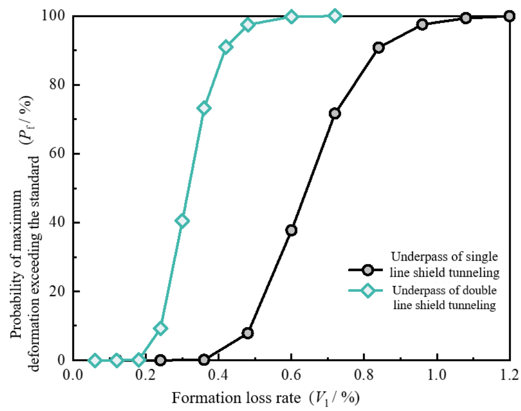


Fig. 5. Relationship between the probability of longitudinal deformation exceeding the standard and the formation loss rate in existing high-speed railway tunnels

5. Conclusions

A mechanical model for the underpass of a newly constructed shield tunnel through an existing high-speed railway tunnel was developed based on the two-stage method, accounting for spatial variability in foundation stiffness. Coupling a random field model with finite element analysis, a random analysis method for evaluating the longitudinal response of railway tunnels to shield tunneling was proposed. The model's reliability was confirmed through comparison with numerical simulations, and its application was demonstrated on the Changsha Metro Line 3, where variability in foundation stiffness was assessed for construction risk. The main conclusions are as follows:

1. The high-speed railway tunnel was modelled as a Timoshenko beam on a heterogeneous Pasternak foundation, incorporating spatial variability in foundation stiffness. Using Monte Carlo simulations, the model assessed longitudinal deformation risks.

2. In the case study, a 0.12% ground loss rate posed a minimal risk, while a 0.24% rate raised a significant safety risk in double-line tunneling, with exceedance probability at 9.3%, escalating to 73.3% at a 0.36% rate.
3. The probability of deformation exceedance rises in an "S-curve" with increasing ground loss, with critical thresholds identified at 0.36% for single-line and 0.18% for double-line shield tunneling.

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Received: 2024-11-09, Revised: 2025-01-03