

Article

Research on Key Deviation Sources of Floating Slab Track and Deviation Transmission Law of Foundation Construction Under Track

Xianfeng Duan ^{1,2,*} and Jianxi Wang ¹ 

¹ School of Traffic and Transportation, Shijiazhuang Tiedao University, Shijiazhuang 050043, China; qianxi-2008@163.com

² China Railway Xiong'an Investment & Development Co., Ltd., Xiong'an New Area, Baoding 071700, China

* Correspondence: 220180207@student.stdu.edu

Abstract

In the process of subway construction, the control of construction quality and accuracy is the core link. Deviation in the construction of a steel spring floating slab foundation under the rail can easily cause problems such as abnormal rail installation, insufficient adaptability of vibration isolators, and decreased vibration reduction performance, seriously threatening the safety of train operation and increasing maintenance difficulty. In view of this, this article addresses the issue of excessive deviation in the construction of a subway steel spring floating slab track, and systematically identifies the main types of spatial geometric deviations in each process. Based on on-site measured data, the distribution pattern and statistical characteristics of construction deviations in each process were revealed through data statistical methods, and the causes of deviations were analyzed. Based on the quantitative analysis of structural characteristics and deviation sources, a mathematical model of the underground foundation space was constructed using the spatial geometric transformation method. Combined with the process sequence relationship, a deviation transmission model for floating slab track construction was established, clarifying the deviation analysis process and providing theoretical support for subsequent research on construction correction.

Keywords: steel spring floating plate track; quantification of construction deviation; deviation mathematical model; deviation analysis steps



Academic Editor: Tiago Filipe da Silva Miranda

Received: 18 June 2026

Revised: 13 July 2026

Accepted: 15 July 2026

Published: 21 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Urban rail transit has become the mainstay of urban public transportation [1–5], and the vibration and noise problems caused by large-scale operation are becoming increasingly prominent. The steel spring floating plate track has excellent vibration reduction effect and is suitable for environmental control needs in sensitive urban areas. It is widely used in subways. However, deviations in construction foundations can easily cause defects in component installation, attenuation of vibration reduction performance, and residual operational hazards. At present, a large amount of research has been conducted both domestically and internationally on monitoring and controlling deviations in tunnel construction.

At present, scholars at home and abroad have carried out systematic research on tunnel construction deviation monitoring and control technology. Fang et al. [6] relied on the secondary development technology of CAD, and compared the measured point cloud section with the designed section to achieve the accurate calculation of tunnel overbreak

and underbreak. Xu et al. [7] introduced the vatti clipping algorithm to efficiently calculate the statistics of tunnel overbreak and underbreak areas. Wang et al. [8] used the point cloud slice to fit the tunnel section parameters, and evaluated the tunnel construction quality based on the difference between the measured and designed sections. Wilson et al. [9] took the lead in taking the floating slab track as the core vibration reduction scheme of the subway, and built a dual vibration reduction system by optimizing the structure and vehicle supporting design, which provided a theoretical basis for the development of related technologies. Li et al. [10] optimized the drainage and stray current control supporting technology, summarized the design experience and proposed improvement strategies, and improved the track design system, aiming at the construction problems of the prefabricated steel spring floating plate turnout area. In addition, Watanabe et al. [11] verified the significant vibration reduction advantages of the floating slab track compared with the traditional track through measured data.

Previous studies have confirmed that the construction deviation of the foundation under the track significantly affects the long-term service performance of the track. The mechanical performance of the floating slab track is related to its vibration reduction efficiency and structural stability, and academia has systematically carried out relevant research. Gu et al. [12] used ANSYS v11.0 to build a three-dimensional numerical model to explore the vibration transmission characteristics of the track system under harmonic load, quantify the impact of frequency on tunnel and ground vibration, and provide support for the evaluation of the vibration reduction effect. Li et al. [13] used the double model system and dynamic flexibility method to analyze the force transfer law of a floating plate under asymmetric wheel load, verify its high-frequency vibration isolation advantage, and put forward an optimization method to eliminate the interference of load phase difference. Castellani et al. [14] used frequency wave domain numerical simulation to analyze the law of vehicle rail soil coupling vibration, explore the impact of geological conditions on the vibration reduction effect of the track, and provide reference for the track's adaptability design. M.F.M. Hussein et al. [15–17] compared various floating plate structures, explored the parametric excitation characteristics of a discrete floating plate, and clarified the influence of plate length on structural resonance and ground vibration propagation. Yao et al. [18], based on the vehicle rail coupling model, confirmed that optimizing the parameters of the floating plate and support can effectively improve the vibration isolation effect, and its vibration reduction performance is better than that of the conventional monolithic track bed. Nishimural [19] clarified the influence of micro-defects on the fatigue performance of steel springs through fatigue testing, providing a test basis for spring quality control. Ling et al. [20] combined theoretical tests and numerical simulation to reveal the fatigue fracture mechanism of fasteners and provide support for fastener operation and maintenance selection. Wu et al. [21] confirmed that the actual impact of construction error on structural performance is small by combining actual measurements and simulation. Lu et al. [22] clarified the deterioration effect of weld and concrete defects on bridge bearing capacity.

The construction accuracy of the steel spring floating slab track directly determines its vibration reduction effect and service safety. At present, systematic research on the transmission of construction deviation and the coupling control of the whole process is still lacking. Therefore, this paper delineates the main types of spatial geometric deviation in the construction of a subway floating slab track foundation and quantitatively analyzes the distribution characteristics and change rules of construction deviation. Furthermore, with the help of the spatial geometric transformation method, the spatial mathematical models of the tunnel segment, base and floating slab track are established; the construction deviation transfer model is constructed, combined with process time sequence logic; and

the deviation analysis steps are established, which can provide theoretical support for the subsequent precision control and deviation correction of track construction.

2. Design Concept of the Floating Slab Track

2.1. Composition of the Floating Slab Track Structure

The steel spring floating slab track is arranged in a layered structure from top to bottom. The core components, in turn, are the steel rail and supporting fasteners, horizontal limit device, sealing strip, shear hinge, steel spring vibration isolator, and floating slab track bed. All components cooperate to achieve a high-efficiency track vibration isolation effect. The track system relies on the support of steel spring vibration isolators to construct the floating plate in the suspended layout state as a whole. The load and vibration of the whole section of the track structure are conducted by the vibration isolators. When the train passes through the rail section, the vibration generated by wheel rail contact is first transmitted to the floating plate, and then attenuated step by step by steel spring vibration isolation components, greatly reducing the vibration amplitude transmitted to the lower foundation structure, weakening the impact of ambient vibration caused by train operation from the source, and achieving the goal of vibration reduction and noise reduction along the rail transit.

The stiffness of the track vibration isolation system is mainly provided by the built-in spiral steel spring, and the damping is realized by the supporting viscous damper. The two components work together to dissipate and block the vibration energy. During the operation of the train, the wheel rail force is transmitted to the floating slab track bed step by step through the rails and fasteners. Due to the low natural frequency of the floating slab itself, the high-frequency vibration generated by wheel rail contact is difficult to be directly transmitted to the lower subgrade, and only a small part of the low-frequency vibration corresponding to the natural frequency of the floating slab will be transmitted to the subgrade with a resonance effect. When the residual vibration energy passes through the steel spring isolator, it will be further absorbed and weakened by the vibration isolation components, continuously reducing the vibration transmission strength and maximizing the transmission path of vibration to the foundation and surrounding environment.

2.1.1. Track Bed

For the cast-in-place steel spring floating slab track, the length of its standard plate is set at 25 m, and the plate thickness range is controlled between 300 mm and 400 mm. The specific size needs to be reasonably determined based on the working conditions of the actual line. The ballast bed structure is usually bound with HRB400 grade reinforcement to form a reinforcement cage, and then poured with C40 concrete to complete the molding operation at the same time. With this construction method, the ballast bed has good structural stability.

2.1.2. Structure of the Vibration Isolator

The overall structure of the isolator can be divided into four parts: the outer sleeve, the inner sleeve, the leveling steel plate and the locking system. See Figures 1–3 for the specific structure. The outer sleeve of the vibration isolator is installed at the gap between the two sleepers and embedded in the concrete of the floating slab. Its main function is to transfer the upper load to the inner sleeve. As the core functional component of the vibration isolator, the stiffness of the inner sleeve is achieved by the spiral steel spring, and the damping is provided by the viscous damper. The leveling steel plate is used in conjunction with the locking system, which is mainly used to adjust the height of the floating plate to ensure that the rail elevation meets the design requirements.

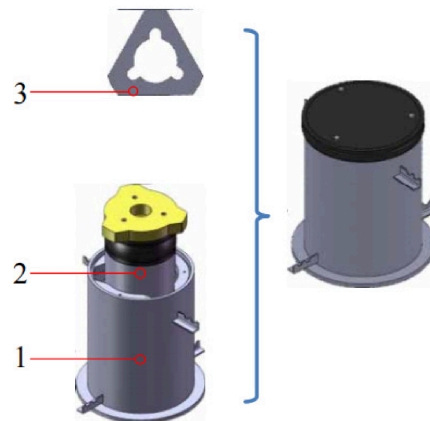


Figure 1. Composition of the vibration isolator: 1-Outer sleeve; 2-Inner sleeve; 3-Leveling steel plate.



Figure 2. Observation tube.



Figure 3. Shear hinge.

2.2. Vibration and Noise Reduction Mechanism of the Floating Slab Track

According to vibration isolation theory, when the wheel rail excitation frequency f is greater than $\sqrt{2}$ times the natural frequency f_0 of the floating plate system (i.e., $f > f_0$), the vibration will be effectively isolated. The calculation formula of the natural frequency of the system is:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{K_t}{M_t}} \quad (1)$$

where f_0 is the natural frequency of the floating plate system; K_t is the total vertical stiffness of the steel spring isolator; and M_t is the total mass of the floating plate system.

When the subway train is running, the wheel rail excitation frequency is mainly 10~80 Hz (the main frequency is 20~50 Hz). By designing the mass of the floating plate and the stiffness of the steel spring, the natural frequency f_0 of the system is controlled to be

2~5 Hz to meet $f > \sqrt{2}f_0$ (i.e., $f > 2.8\sim 7.1$ Hz), thereby achieving vibration isolation. The calculation formula of vibration reduction (insertion loss) is:

$$I_L = 20\lg\left(\frac{A_0}{A_1}\right) = 20\lg\left(\frac{\sqrt{1 + (2\zeta r)^2}}{\sqrt{(r^2 - 1)^2 + (2\zeta r)^2}}\right) \quad (2)$$

where I_L is the damping capacity; A_0 is the foundation vibration acceleration without vibration isolation measures; A_1 is the foundation vibration acceleration after setting the floating plate; ζ is the damping ratio of the system, and ζ of the steel spring floating plate system is usually 0.05~0.15; and r is the frequency ratio, $r = f/f_0$.

The vibration reduction function of the steel spring floating plate is realized based on the coupling mechanism of “inertia mass elastic support energy dissipation”. Its core principle is to block the vibration transmission path and absorb vibration energy through structural design, and finally achieve the goal of vibration reduction and noise reduction. The steel spring isolator, as the core damping component, adopts the composite structure of “spiral steel spring + viscous damper” to form a three-dimensional elastic support system.

Elastic buffer of spiral steel spring: the steel spring provides vertical, horizontal and longitudinal elastic support. When the floating plate is subjected to vibration load, the spring absorbs the vibration kinetic energy through compression and rebound, and converts the vibration into elastic potential energy to realize the initial attenuation of vibration amplitude. Its elastic stiffness is precisely designed to filter the main vibration frequency band of 15~100 Hz generated by subway train operation, so that the vibration frequency can avoid the structural resonance frequency and vibration amplification.

Energy dissipation of viscous damper: the damper is arranged in parallel with the steel spring. During the deformation and resetting of the spring, the elastic potential energy is converted into heat energy through the viscous friction of the internal medium, which can effectively inhibit vibration rebound and shorten the vibration attenuation time. Especially for high-frequency vibration (above 50 Hz), the damper can quickly dissipate energy and greatly reduce the vibration transmission efficiency.

2.3. Key Design Parameters and Deviation Standards for the Floating Slab Track

According to the relevant provisions of “technical specification for floating slab track CJJ/T 191-2012” [23], the key design parameters of the cast-in-place steel spring floating slab mainly include the length and thickness of the floating slab and the height of the track structure. Among them, the length is usually controlled at about 25 m, and the plate thickness range is 300~500 mm. Under different laying scenarios, the height of the track structure varies: 800~900 mm in horseshoe and arch tunnels, 750~840 mm in rectangular tunnels, and not less than 650 mm when laid on viaducts.

The length specifications of prefabricated steel spring floating plates are mainly 6 m, 4.8 m, and 3.6 m, and the thickness of the floating plates is 300~500 mm. The layout of the steel spring floating plate isolators needs to distinguish between straight and curved sections. In the transition section of the track, the isolators are connected to the front and rear track structures by a densified layout. See Figures 4 and 5 for the specific layout.



In the actual construction process, it is found that the tunnel centerline and the track centerline may deviate due to the influence of its own mechanical performance, running posture and other factors when the shield machine carries out the tunneling operation. This offset problem will directly cause the height of the track structure to fail to meet the design

standard. Therefore, the floating slab in such sections needs to adopt a special design scheme, and some vibration isolators need to be adjusted to be arranged directly below the rail. See Figure 6 for the specific layout.

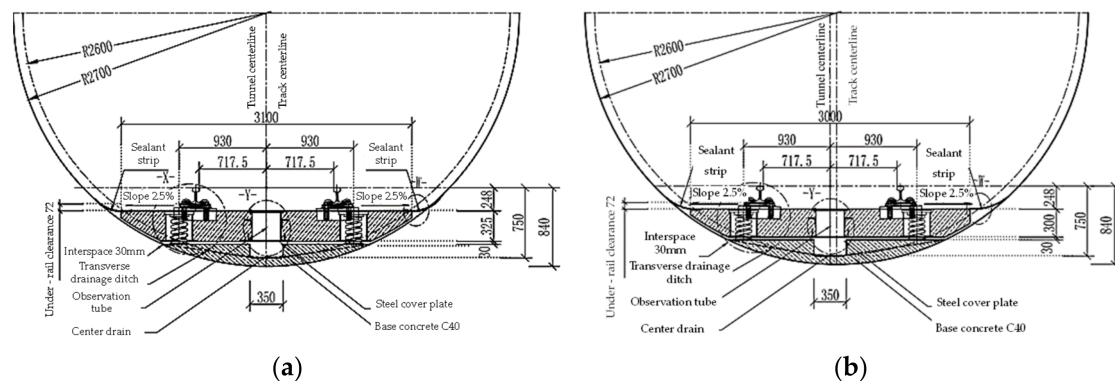


Figure 6. Cross-section of the tunnel floating slab: (a) No deviation of tunnel centerline; (b) deviation of tunnel centerline.

By examining and analyzing the entire process of shield tunnel construction, it is found that during shield tunneling, due to the mechanical structure characteristics, operational stability, and other factors, it is very easy to cause a serpentine lateral offset between the tunnel centerline and the track design centerline, which will have a negative impact on the construction quality and installation accuracy of the subsequent floating slab track.

In the construction process of the base cast in situ, due to technical reasons such as inadequate control of the construction process and nonstandard operating procedures, overall uneven deviation of the base cast-in-place thickness may occur, which will further affect the subsequent installation and construction of the floating slab track and is not conducive to controlling track installation quality. Referring to the relevant technical requirements in [23], it is clearly stipulated that the pouring thickness of the base shall not be less than 150 mm, the pouring thickness of the floating slab shall not be less than 250 mm, and the minimum control value of the clearance under the rail shall be 30 mm. Based on the minimum limit specified in the above specifications, combined with the research requirements of this paper and the actual situation of the site construction, it is determined that the maximum allowable deviation during the pouring construction of the base is 87 mm, the maximum allowable deviation during the pouring construction of the floating slab is 75 mm, and the maximum allowable deviation of the clearance under the rail is 42 mm.

When the base is cast in situ, the thickness of the left and right sides of the cross section is different, resulting in the deviation of the flatness of the base, which may affect the subsequent construction of the floating plate and the installation of the steel spring. During construction using the cast-in-place method, because the floating slab is cast in situ, there may be a deviation in thickness during casting, which may affect the overall elevation of the track structure.

Through the above analysis, and considering different construction methods and line positions, the construction of steel spring floating plates can be divided into cast-in-place straight-line segments, cast-in-place curve segments, prefabricated straight-line segments, and prefabricated curve segments. For the foundation deviation, four kinds of deviation forms are considered: the transverse deviation between the tunnel centerline and the track centerline caused by the tunnel construction, the thickness deviation of the base caused by the construction, the left and right thickness deviation caused by the base construction, and the thickness deviation of the floating plate caused by the construction.

3.2. Distribution Law of Construction Deviation of the Foundation Under the Rail

Based on the measured data of a subway line after tunneling, the distribution law of construction deviation of the tunnel lining along the route mileage direction is analyzed. Among them, the horizontal and vertical construction deviation of the tunnel centerline and the construction deviation of the tunnel bottom elevation are shown in Figures 7 and 8. Further, the mean value, standard deviation and extreme value of positive and negative deviation of each construction deviation are obtained through statistical analysis.

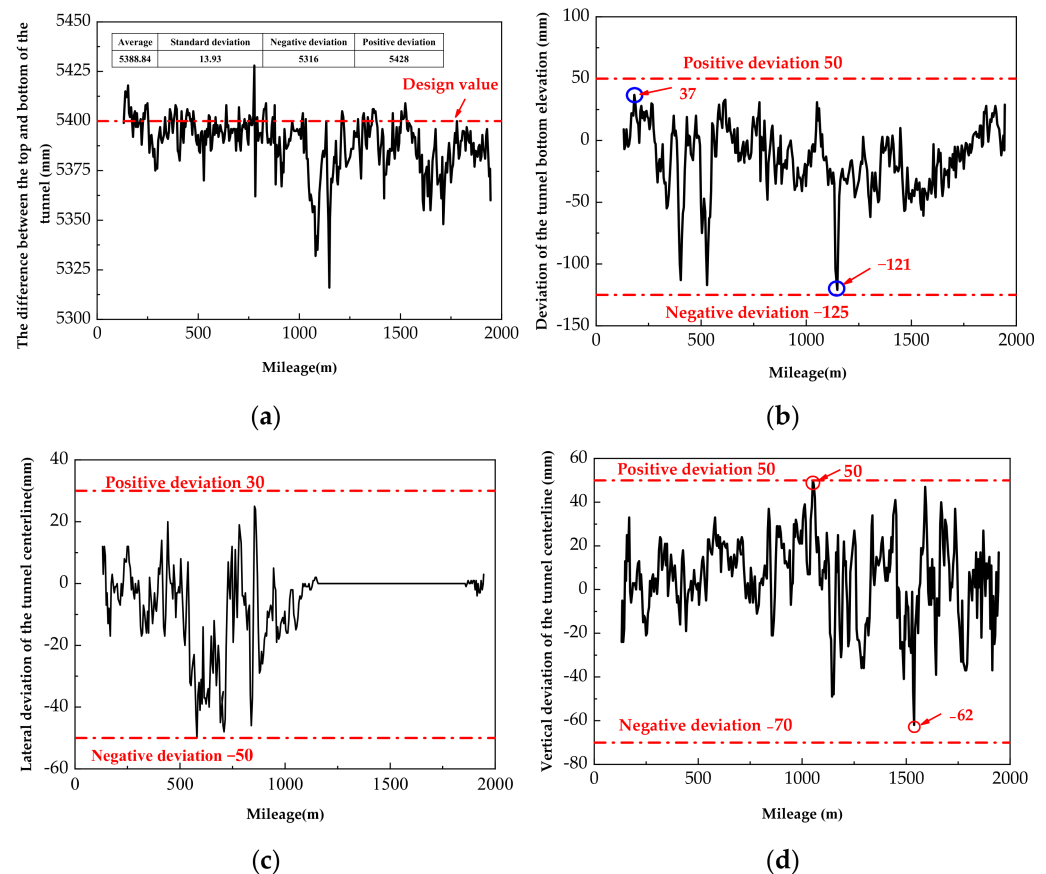


Figure 7. Longitudinal data analysis of tunnel construction deviation along the line: (a) Difference between tunnel top and bottom; (b) elevation deviation of tunnel bottom; (c) lateral deviation of tunnel centerline; and (d) vertical deviation of tunnel centerline.

It can be seen from Figure 7 that the construction deviation interval of tunnel diameter is $-80\sim 30$ mm, and the construction deviation interval of tunnel bottom elevation is $-125\sim 30$ mm. The deviation of tunnel diameter and tunnel bottom elevation is mainly negative, and the maximum relative error is only 2.31%. Therefore, the tunnel lining surface can be regarded as the ideal circumference calculation.

According to Figure 8, the horizontal deviation interval of the tunnel centerline is $-50\sim 30$ mm, and the vertical deviation interval of the tunnel centerline is $-70\sim 50$ mm. In addition, the randomness of tunnel construction deviation is high, and the data are highly discrete, so the longitudinal distribution of construction deviation data along the line needs to be considered when formulating the construction scheme. In order to keep the elevation of the track structure unchanged during construction, when the tunnel section is regarded as an ideal circumference, and when the transverse deviation of the tunnel centerline is large after construction, the floating plate steel spring will be placed under the rail, or even at the edge of the base. When the elevation deviation of the tunnel bottom is large, it may also lead to the above situation. The elevation of the rail surface can be

ensured by adjusting the thickness of the base or the thickness of the floating plate, but the change in size of the floating plate will inevitably lead to changes in the structural bearing capacity and vibration damping performance. Therefore, it is of great theoretical and engineering significance to design a reasonable construction scheme according to the construction deviation to ensure the smoothness of the line, the bearing capacity of the track slab and the vibration reduction performance.

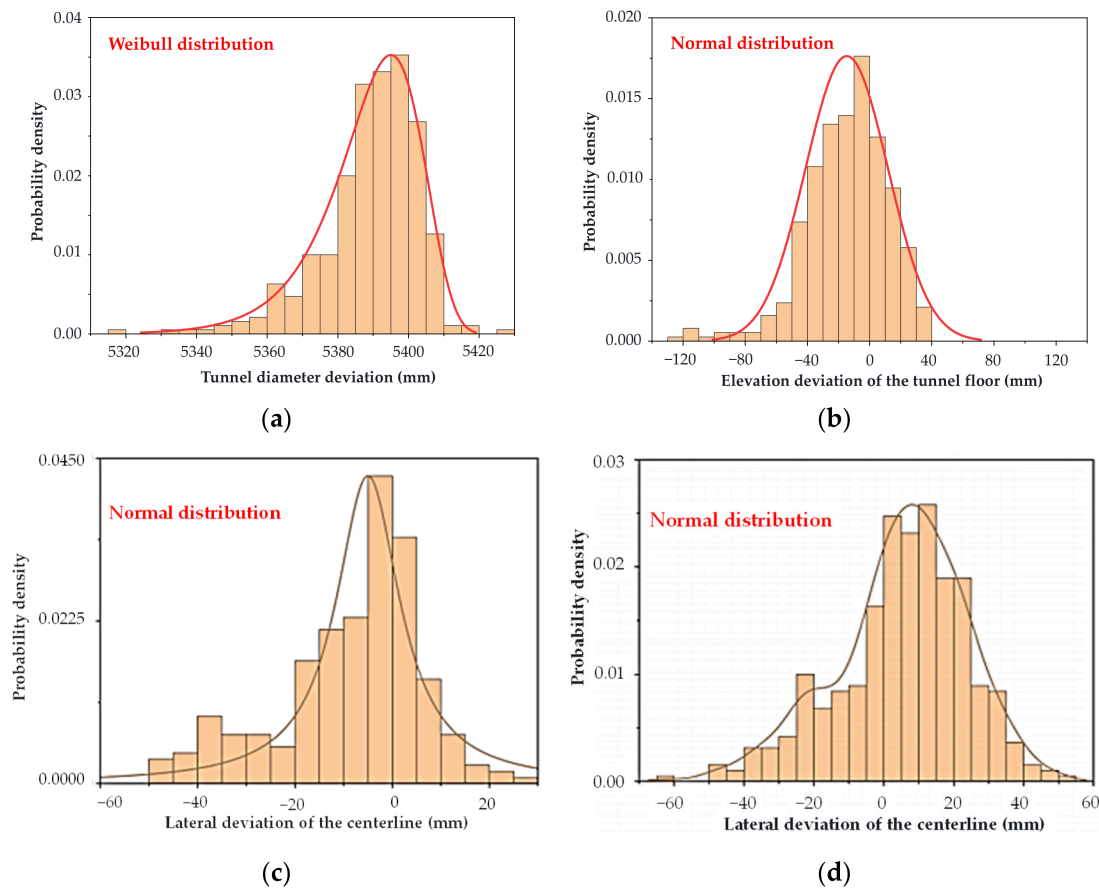


Figure 8. Distribution of actual measured samples and fitted distribution curve for tunnel construction deviation: (a) Difference between tunnel top and bottom; (b) elevation deviation of tunnel bottom; (c) lateral deviation of tunnel centerline; and (d) vertical deviation of tunnel centerline.

4. Transmission Law for the Construction Deviation of an Under-Rail Foundation

Combined with the measured data, the core deviation sources, such as the tunnel, basement, and floating slab, are selected to build the transfer model. Based on the structural characteristics and deviation analysis results, taking straight tunnels as the research object, this chapter uses the spatial geometry method to establish the global spatial model, constructs the deviation transmission system combined with the construction process, delimits the analysis process, and preliminarily formulates the deviation correction scheme for the cast-in-place and prefabricated floating slabs. The three-dimensional diagram of the prefabricated floating slab track of a metro line is displayed in Figure 9, which was drawn using SolidWorks 2024 software.

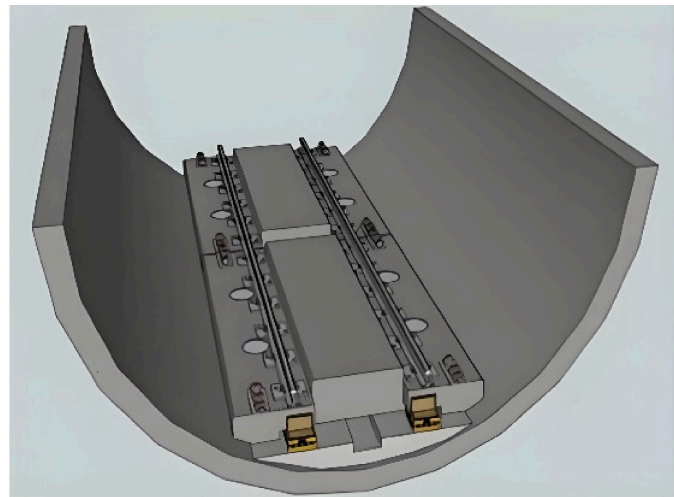


Figure 9. Three-dimensional diagram of a prefabricated floating slab for a subway.

4.1. Construction of a Parametric Mathematical Model for the Under-Track Foundation

4.1.1. Deviation Model of the Tunnel Centerline

In order to further consider the influence of the construction deviation of the floating slab track along the line direction, and to facilitate the establishment of the mathematical model of the construction deviation of the subway floating slab track, this paper first analyzes the spatial geometric relationship of each structure in the tunnel without construction deviation, regards the upper surface of the tunnel segment as an ideal cylindrical shell, and makes the following assumptions. The tunnel lining segment is assumed to be an ideal cylindrical shell; the floating slab track is assumed to be a rigid body when considering the installation attitude deviation of the track slab; the lateral deviation of the floating slab track sleeve along the line is ignored; and the gradient of the centerline vector is small within the range of a track slab.

As shown in Figure 10, the subway tunnel lining is assumed to be an ideal cylindrical shell, and the right-hand coordinate system $O\text{-}xyz$, as shown in the figure, is established. Among them, the x -axis is along the longitudinal direction of the line, with the direction of increasing mileage taken as positive; the y -axis is along the transverse direction of the line; and the z -axis is along the vertical direction of the line.

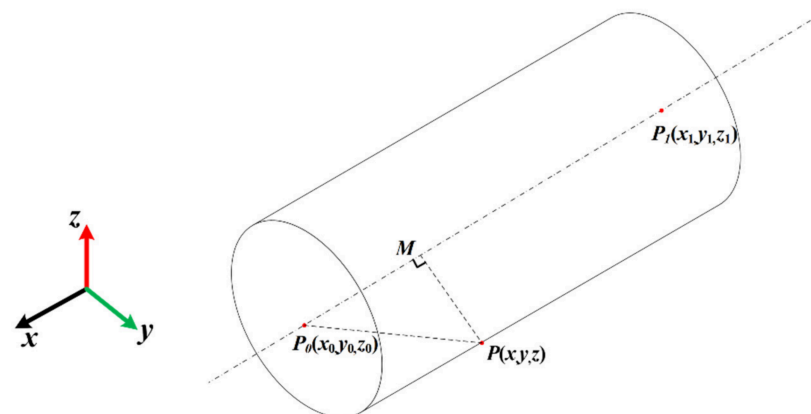


Figure 10. Mathematical model of the metro tunnel.

$P_0(x_0, y_0, z_0)$ is the coordinate of the center starting point of the floating slab track slab corresponding to the tunnel centerline, and (x, y, z) is any point on the tunnel centerline in

a floating slab. If the error between the tunnel centerline and the line centerline is known, the actual centerline q space equation can be expressed as:

$$q: \frac{x - x_0}{l} = \frac{y - y_0}{m} = \frac{z - z_0}{n} \quad (3)$$

where (l, m, n) is the tunnel centerline vector, which can be obtained from the coordinates of the tunnel centerline at the starting point and end point of the track slab.

Suppose that point $P(x, y, z)$ is any point on the tunnel segment, while points P_0 and M are on the tunnel centerline q . The distance from P to the straight line q is the tunnel radius r , which can be obtained from the Euclidean distance formula and the straight line symmetry equation:

$$\begin{cases} PP_0 = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2} \\ \vec{e}_{PP_0} = (x - x_0, y - y_0, z - z_0) \\ \vec{e}_{l_q} = (l, m, n) \end{cases} \quad (4)$$

where $\vec{e}$ is the direction vector of the line.

The included angle between the straight line PP_0 and the tunnel centerline is θ , which can be obtained from the vector expression for $\cos \theta$:

$$\cos \theta = \frac{\vec{a} \cdot \vec{b}}{|\vec{a}| \cdot |\vec{b}|} = \frac{\vec{e}_{PP_0} \cdot \vec{e}_l}{|\vec{e}_{PP_0}| \cdot |\vec{e}_l|} = \frac{l(x - x_0) + m(y - y_0) + n(z - z_0)}{\sqrt{l^2 + m^2 + n^2} \cdot \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}} \quad (5)$$

Meanwhile, based on the geometric relationship shown in Figure 10, $\cos \theta$ can be obtained using the following formula:

$$\cos \theta = \frac{\overline{MP_0}}{\overline{PP_0}} = \frac{\sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2} - r^2}{\sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}} \quad (6)$$

where $\overline{MP_0}$ and $\overline{PP_0}$ are the distances of straight lines mp_0 and pp_0 respectively, where:

$$\overline{MP_0} = \sqrt{PP_0^2 - r^2} = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 - r^2} \quad (7)$$

It can be seen from Equations (5) and (6) that:

$$\frac{l(x - x_0) + m(y - y_0) + n(z - z_0)}{\sqrt{l^2 + m^2 + n^2} \cdot \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}} = \frac{\sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2} - r^2}{\sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}} \quad (8)$$

The space equation of the ideal cylindrical surface of tunnel lining is obtained as follows:

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 - r^2 = \frac{[l(x - x_0) + m(y - y_0) + n(z - z_0)]^2}{l^2 + m^2 + n^2} \quad (9)$$

where (x, y, z) is any point on the tunnel segment; (x_0, y_0, z_0) is a point on the tunnel centerline; r is the actual tunnel radius; and (l, m, n) is the space vector of the tunnel centerline.

The spatial position relationship between any point within the scope of the subway tunnel and the tunnel segment can be further expressed as:

$$\begin{cases} (x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2 - r^2 = \frac{[l(x-x_0)+m(y-y_0)+n(z-z_0)]^2}{l^2+m^2+n^2}, & \text{on tunnel surface} \\ (x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2 - r^2 < \frac{[l(x-x_0)+m(y-y_0)+n(z-z_0)]^2}{l^2+m^2+n^2}, & \text{inside the tunnel surface} \\ (x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2 - r^2 > \frac{[l(x-x_0)+m(y-y_0)+n(z-z_0)]^2}{l^2+m^2+n^2}, & \text{outside the tunnel surface} \end{cases} \quad (10)$$

When the starting point is at the coordinate origin, the ideal cylindrical surface equation is:

$$\begin{cases} y^2 + z^2 - r^2 = 0, & \text{on tunnel surface} \\ y^2 + z^2 - r^2 < 0, & \text{inside the tunnel surface} \\ y^2 + z^2 - r^2 > 0, & \text{outside the tunnel surface} \end{cases} \quad (11)$$

It is worth noting that when the starting point and the end point of the tunnel centerline coincide, the above equation degenerates to a two-dimensional space, that is, the equation of a circle:

$$(y-y_0)^2 + (z-z_0)^2 = r^2 \quad (12)$$

where (y_0, z_0) are the central coordinates of the tunnel, and (y, z) is any point on the tunnel lining surface; r is the tunnel radius.

The length of a floating slab is set as the basic analysis unit to analyze the construction deviation of the tunnel centerline, as shown in Figure 11.

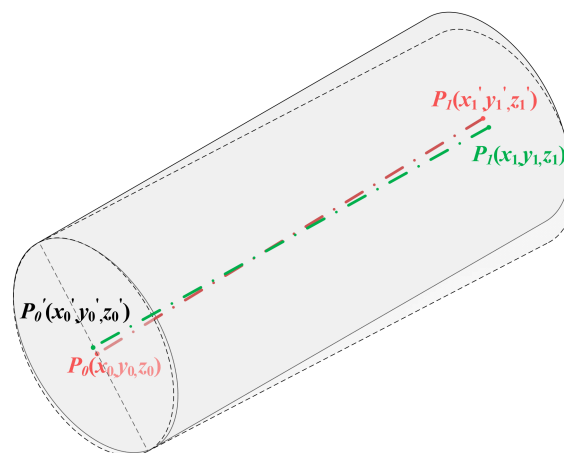


Figure 11. Diagram showing the deviation of the tunnel centerline.

The design value of the tunnel centerline follows the vector $\mathbf{P}_0\mathbf{P}_1$, and the actual tunnel centerline vector after construction is $\mathbf{P}'_0\mathbf{P}'_1$. The construction deviation at any point of the track slab, including horizontal and vertical deviations, can be expressed as:

$$\begin{cases} \Delta l x = x' - x \\ \Delta l y = y' - y \\ \Delta l z = z' - z \end{cases} \quad (13)$$

Further, ignoring the longitudinal error of the tunnel centerline, the deviation vector along the longitudinal tunnel centerline can be expressed as:

$$\mathbf{T}^{(i)} = \begin{bmatrix} \Delta l x_1 & \Delta l y_1 & \Delta l z_1 \\ \Delta l x_2 & \Delta l y_2 & \Delta l z_2 \\ \vdots & \vdots & \vdots \\ \Delta l x_{n-1} & \Delta l y_{n-1} & \Delta l z_{n-1} \\ \Delta l x_n & \Delta l y_n & \Delta l z_n \end{bmatrix} \quad (14)$$

If the coordinates and deviations of the tunnel centerline are known, the coordinates of any point on the tunnel segment under the ideal cylindrical surface can be calculated according to formula (13), which can then be used for the deviation calculation of the downstream process. The spatial position relationship between any point within the scope of the subway tunnel and the tunnel segment can be expressed as:

$$\begin{cases} (x-x_0)^2 + (y-y_0-\Delta ly)^2 + (z-z_0-\Delta lz)^2 - r^2 = \frac{[l(x-x_0)+m(y-y_0-\Delta ly)+n(z-z_0-\Delta lz)]^2}{l^2+m^2+n^2}, & \text{on tunnel surface} \\ (x-x_0)^2 + (y-y_0-\Delta ly)^2 + (z-z_0-\Delta lz)^2 - r^2 < \frac{[l(x-x_0)+m(y-y_0-\Delta ly)+n(z-z_0-\Delta lz)]^2}{l^2+m^2+n^2}, & \text{inside the tunnel surface} \\ (x-x_0)^2 + (y-y_0-\Delta ly)^2 + (z-z_0-\Delta lz)^2 - r^2 > \frac{[l(x-x_0)+m(y-y_0-\Delta ly)+n(z-z_0-\Delta lz)]^2}{l^2+m^2+n^2}, & \text{outside the tunnel surface} \end{cases} \quad (15)$$

4.1.2. Mathematical Model of Base Construction Deviation

The cross section of the floating slab track is shown in Figure 12. According to the analysis of the construction steps of the floating slab track, the deviation transmission of the base is mainly related to the thickness of the base at the installation position of the steel spring. Therefore, it is only necessary to express the error of the base thickness at the position of the steel spring.

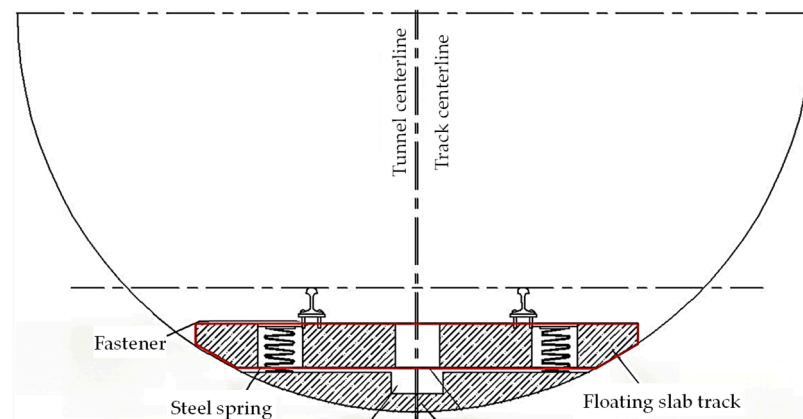


Figure 12. Schematic diagram of the cross section of a floating slab track.

As shown in Figure 13, the base is regarded as a rigid body. The top surface of the base at the left and right steel springs can be represented by a spatial straight line j , which describes the thickness of the top surface of the base, can be expressed as:

$$j: \frac{x_J - x_{J0}}{l_J} = \frac{y_J - y_{J0}}{m_J} = \frac{z_J - z_{J0}}{n_J} \quad (16)$$

where $J_0(x_{J0}, y_{J0}, z_{J0})$ and $J_1(x_{J1}, y_{J1}, z_{J1})$ are the points on the top of the base, respectively, and (l_J, m_J, n_J) is the vector of the straight line j .

After the base is poured, calculate the coordinates of any point on the tunnel segment. The points $J_0(x_{J0}, y_{J0}, z_{J0})$ and $J_1(x_{J1}, y_{J1}, z_{J1})$ on the top of the base can be obtained from the following formula:

$$\begin{cases} x_{J0} = x_J \\ y_{J0} = y_J \\ z_{J0} = z_J + h' \end{cases} \quad (17a)$$

$$\begin{cases} x_{J1} = x_J + l_J \\ y_{J1} = y_J \\ z_{J1} = z_J + h' \end{cases} \quad (17b)$$

where (x_j, y_j, z_j) is the point coordinate on the surface of the tunnel segment at the position of the steel spring; and l_j and h' are the length of the floating slab track and the base pouring thickness at the steel spring position, respectively.

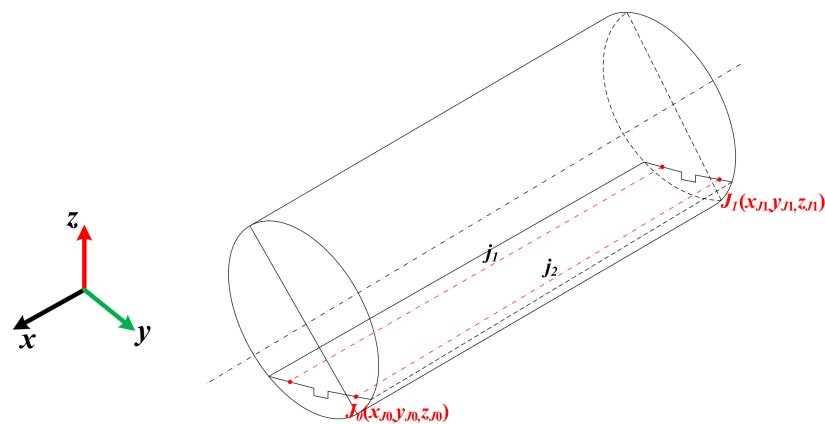


Figure 13. Mathematical model of the top surface of the substrate.

The spatial linear equation of the top surface of the base is determined by the top coordinates. Considering the irregular shape of the base, this paper uses the key control points to construct the thickness deviation vector of the floating plate. Taking the base thickness at the installation position of the steel spring as the control variable, the thickness deviation of the floating plate at the control points of the left and right steel springs can be expressed as:

$$\Delta h_j = h' - h \quad (18)$$

Further, the thickness deviation of the longitudinal floating plate along the line can be expressed as:

$$\mathbf{J}^{(i)} = \begin{bmatrix} 0 & 0 & \Delta h_{j1} \\ 0 & 0 & \Delta h_{j2} \\ \vdots & \vdots & \vdots \\ 0 & 0 & \Delta h_{jn-1} \\ 0 & 0 & \Delta h_{jn} \end{bmatrix} \quad (19)$$

4.1.3. Mathematical Model of Construction Deviations in the Floating Slab Track

It can be seen from the cross section of the floating slab track in Figure 12 and the analysis of its construction steps that the deviation transmission of the floating slab is mainly related to the thickness and installation posture of the floating slab. Therefore, the influence of the flexible deformation of the floating plate is ignored, and the floating plate is regarded as a rigid body. In the deviation analysis, the influence of the actual thickness of the floating plate and the installation attitude should be considered.

As shown in Figure 14, the floating slab track is regarded as a rigid body. The top surface of the floating slab track at the left and right rail positions can be represented by a spatial straight line, and the equation for the thickness of the straight line f of the top surface of the floating slab track can be expressed as:

$$f : \frac{x_F - x_{F0}}{l_F} = \frac{y_F - y_{F0}}{m_F} = \frac{z_F - z_{F0}}{n_F} \quad (20)$$

where $F_0(x_{F0}, y_{F0}, z_{F0})$ and $F_1(x_{F1}, y_{F1}, z_{F1})$ are the points on the top of the base, respectively, and (l_F, m_F, n_F) is the vector of the straight line f .

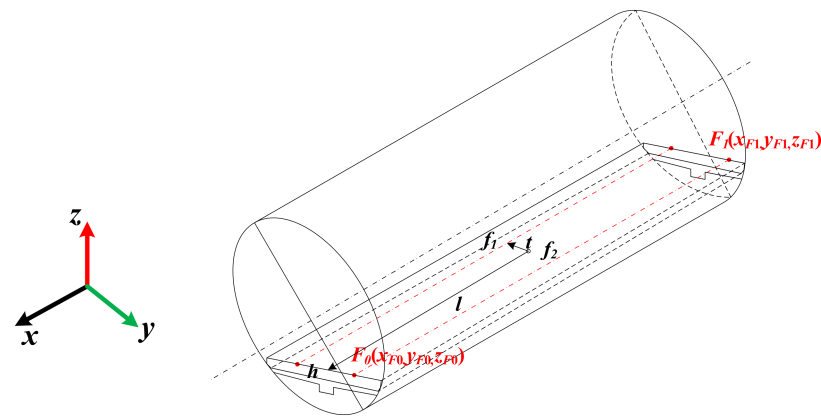


Figure 14. Mathematical model of the top surface of floating slab track.

The linear equation of the top surface of the floating slab track is determined by the coordinates at both ends of the top surface of the track slab. Considering that the shape of the floating slab is irregular, this paper also uses the key control points to construct the thickness deviation vector of the floating slab. The track deviation of the floating slab is shown in Figure 15. Assuming that the actual thickness of the floating slab after installation is h' , the angle deviation around the x axis is θ , the angle deviation around the y axis is ϕ , and the angle deviation around the z axis is ψ after installation.

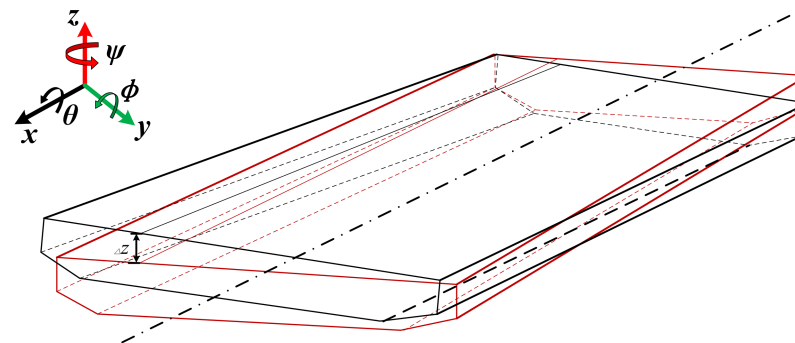


Figure 15. Deviation of the floating slab track.

Taking the thickness of the floating plate at the rail installation position as the control variable, the coordinates of the floating plate at the left and right rail control points can be expressed as:

$$\begin{cases} \Delta x_f = \mp \phi h / 2 \pm \psi t \\ \Delta y_f = \psi l - \phi t \\ \Delta z_f = \theta t - \phi l \end{cases} \quad (21)$$

where l and t are the transverse and longitudinal distances from the calculated deviation position to the center of the floating plate, respectively; and h' and h are the actual thickness and design thickness of the floating slab track, respectively.

After pouring the base, the coordinates of any point on the base can be calculated by Equation (21). The points $J_0(x_{J0}, y_{J0}, z_{J0})$ and $J_1(x_{J1}, y_{J1}, z_{J1})$ on the top of the base can be obtained by the following equation:

$$\begin{cases} x_{F0} = x_R + \Delta x_f \\ y_{F0} = y_R + \Delta y_f \\ z_{F0} = z_R + h' + \Delta z_f \end{cases} \quad (22a)$$

$$\begin{cases} x_{F1} = x_R + \Delta x_f \\ y_{F1} = y_R + \Delta y_f \\ z_{F1} = z_R + h' + \Delta z_f \end{cases} \quad (22b)$$

where (x_j, y_j, z_j) are the point coordinates on the surface of the tunnel segment at the position of the steel spring; and l_j and h' are the length of the floating slab track and the base pouring thickness at the steel spring position, respectively.

To sum up, after considering the thickness deviation and installation position deviation of the track slab, the deviation vector of the longitudinal floating slab along the line can be expressed as:

$$\mathbf{F}^{(i)} = \begin{bmatrix} \Delta x_{f1} & \Delta y_{f1} & \Delta z_{f1} \\ \Delta x_{f2} & \Delta y_{f2} & \Delta z_{f2} \\ \vdots & \vdots & \vdots \\ \Delta x_{fn-1} & \Delta y_{fn-1} & \Delta z_{fn-1} \\ \Delta x_{fn} & \Delta y_{fn} & \Delta z_{fn} \end{bmatrix} \quad (23)$$

4.2. Deviation Transmission Analysis Model of Foundation Construction Under Rail

The transmission of deviation is usually based on two transmission methods [24–29]: (1) transmission through geometric position deviation and (2) transfer by geometric deviation. After checking and analyzing the deviation of each link in the construction of the steel spring floating plate, it was found that the geometric position deviation in the construction process is mainly concentrated in three key aspects: first, the deviation of the tunnel centerline during tunnel excavation; second, the deviation for which the structural thickness does not meet the design standard in the process of base pouring construction, floating slab pouring and installation; and third, the problem of position deviation during the installation of the vibration isolator. When these geometric position deviations are transferred in the construction process, two different types of deviation flow will gradually form, namely continuous deviation flow and intermittent deviation flow, as shown in Figure 16.

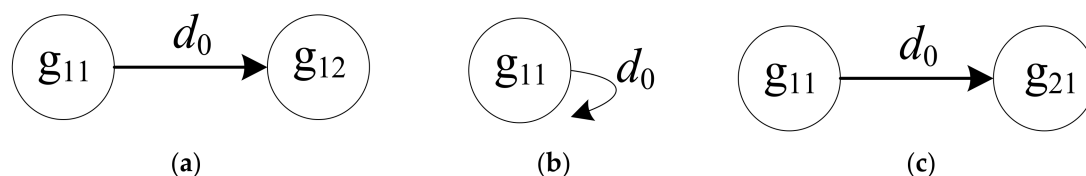


Figure 16. Digraphs of the first and second types of deviation sources: (a) Deviation flow I; (b) deviation flow II; and (c) deviation flow III.

As can be seen from the construction procedures of the floating slab, there are strict deviation control standards for tunnel excavation, base pouring, and floating slab pouring/precast floating slab installation. In addition, considering the construction deviation control from the perspective of a single process, it is more necessary to analyze the impact of upstream process deviations on downstream processes. Therefore, it can be found that in the actual construction process of the steel spring floating slab, the deviation transfer mode is consistent with the characteristics of type (a) deviation flow (continuous deviation flow) in Figure 16; that is, it is transferred through the set position deviation. Specifically, the deviation generated by each construction link does not exist in isolation, but will be gradually transmitted from the current construction link to the subsequent link, and the transmission process always follows the basic law of continuous transmission. For the specific transmission path, please refer to the detailed schematic in Figure 17. Among these, g_{ij} represents the process deviation node, indicating the geometric position deviation

generated by the j -th construction process in the i -th type of deviation flow. d_x represents the amount of deviation transferred between processes or transfer links, representing the effect of deviation conducted from the previous deviation node to the next node.

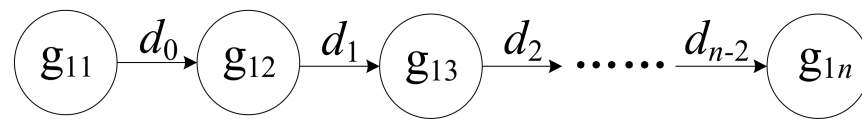


Figure 17. Deviation transmission process of the steel spring floating plate.

After constructing the spatial geometric model of the floating slab track, the deviation transfer model of the floating slab track can be established according to the construction process and the spatial position relationship of each component, so that how the deviation of each process is transferred to the downstream process, as well as the cumulative superposition mechanism of multiple process deviations in space (along the line direction and cross section direction), can be analyzed. Then, the construction process of the floating slab track under different construction processes is studied, the causes and characteristics of process deviation in each process are analyzed, and the rules and characteristics of deviation transmission under different processes are compared.

Considering that the construction deviation of the floating slab track is continuously transmitted to the downstream process, the cumulative construction deviation vector at the installation position of the floating slab rail can be obtained from the following formula:

$$\mathbf{H}^{(i)} = \mathbf{T}^{(i)} + \mathbf{J}^{(i)} + \mathbf{F}^{(i)} \quad (24)$$

where $\mathbf{T}^{(i)}$, $\mathbf{J}^{(i)}$, and $\mathbf{F}^{(i)}$ are the deviation vectors of the tunnel centerline, base elevation, and track slab top elevation, respectively, which can be obtained from the following matrix:

$$\begin{aligned} \mathbf{T}^{(i)} &= \begin{bmatrix} \Delta l x_1 & \Delta l y_1 & \Delta l z_1 \\ \Delta l x_2 & \Delta l y_2 & \Delta l z_2 \\ \vdots & \vdots & \vdots \\ \Delta l x_{n-1} & \Delta l y_{n-1} & \Delta l z_{n-1} \\ \Delta l x_n & \Delta l y_n & \Delta l z_n \end{bmatrix}; \\ \mathbf{J}^{(i)} &= \begin{bmatrix} 0 & 0 & \Delta h_{j1} \\ 0 & 0 & \Delta h_{j2} \\ \vdots & \vdots & \vdots \\ 0 & 0 & \Delta h_{jn-1} \\ 0 & 0 & \Delta h_{jn} \end{bmatrix}; \\ \mathbf{F}^{(i)} &= \begin{bmatrix} \Delta x_{f1} & \Delta y_{f1} & \Delta z_{f1} \\ \Delta x_{f2} & \Delta y_{f2} & \Delta z_{f2} \\ \vdots & \vdots & \vdots \\ \Delta x_{fn-1} & \Delta y_{fn-1} & \Delta z_{fn-1} \\ \Delta x_{fn} & \Delta y_{fn} & \Delta z_{fn} \end{bmatrix} \end{aligned} \quad (25)$$

where Δx , Δy , and Δz are the longitudinal, transverse, and vertical construction deviations of the tunnel centerline and floating slab, respectively; and Δh_{j1} is the construction deviation of the thickness of the floating plate at the installation position of the steel spring.

4.3. Analysis Steps for Construction Deviation Transmission of Foundation Under Rail

The schematic diagram of the deviation analysis model of the metro tunnel is shown in Figure 18. Considering that the construction deviation data is highly random and discrete

along the longitudinal direction of the line, the design and analysis steps of the deviation correction scheme for the floating slab track in a metro tunnel are as follows:

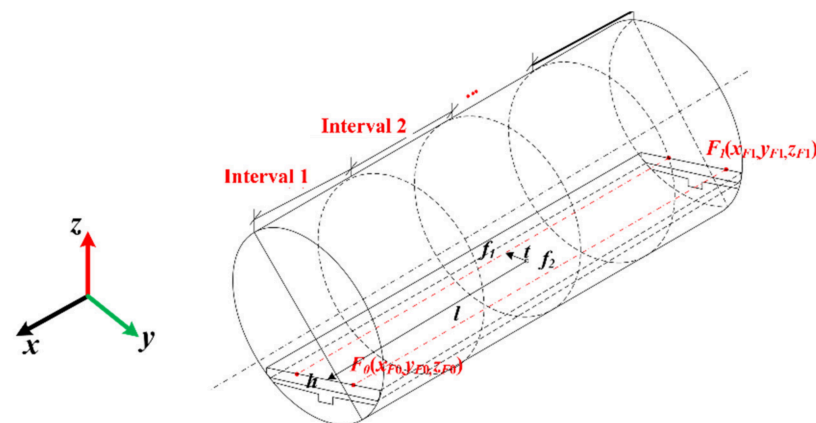


Figure 18. Schematic diagram of the tunnel deviation analysis model.

- (1) The construction deviation distribution histogram is drawn according to the central line measurement data after the completion of tunnel excavation, and the probability density function of construction deviation is calculated. Then, the construction deviation distribution function of the central line of the construction tunnel is fitted, and the characteristic parameters such as the construction deviation interval, mean value and variance are calculated to analyze the distribution law of construction deviation.
- (2) Calculate the construction deviation of the tunnel centerline. If the construction deviation gradient within the scope of a track slab changes a little, the centerline vector can be calculated according to the centerline coordinates corresponding to the start and end points of the track slab. If the construction deviation gradient within the scope of a track slab is large, the track slab can be divided into several sections to calculate the construction deviation as required, as shown in Figure 18.
- (3) According to the above calculation method, the ideal cylindrical surface equation of the tunnel surface, the linear equation of the installation position of the steel spring on the top surface of the base, and the equation of the rail laying position on the top surface of the track slab are constructed.
- (4) According to [23] and [29], the constraint conditions of the structural parameters of the floating slab track are determined. These also serve as the boundary conditions for the deviation mathematical model and the transfer analysis model established in this article.
- (5) Based on the comprehensive analysis of the specification requirements, the adjustable range of the thickness of each floating slab track is determined through the adjustable range of the pouring thickness of the base and the floating slab.
- (6) The Sobol sensitivity parameter analysis method is used to analyze the sensitivity of each construction process parameter, determine the key parameters of each construction process, and analyze the sensitivity of the cumulative impact of different process deviations and different deviation combinations on the final track spatial position (especially the track geometry: height, track direction, level, gauge, and distortion).
- (7) Considering the sensitivity of each construction process parameter, the deviation correction scheme of the downstream process is preliminarily determined.

5. Conclusions

This paper systematically identifies the types of spatial geometric deviation corresponding to each process of the floating slab track, and reveals the distribution law and

causes of construction deviation by statistical methods based on the measured data. At the same time, combined with the structural characteristics and deviation source analysis results, the mathematical model of the foundation space under the track is constructed, the construction deviation transfer analysis model is established based on the construction process logic, and the analysis steps of the deviation correction scheme are defined. The main conclusions are as follows.

- (1) Foundation construction deviation is classified into four typical forms: the lateral deviation between the tunnel and the track centerline, the overall thickness deviation of the foundation base, the left and right thickness deviation of the foundation base, and the thickness construction deviation of the floating slab.
- (2) The research shows that the diameter deviation of the tunnel follows a Weibull distribution, and the horizontal and vertical deviations of the tunnel bottom elevation and centerline follow a normal distribution. The deviation between the tunnel diameter and the bottom elevation is mainly negative, and the maximum relative error is only 2.31%. The tunnel lining surface can be calculated according to the ideal circumference. At the same time, the discreteness and randomness of the tunnel construction deviation are significant, and the longitudinal distribution law of the deviation along the line should be considered in the construction scheme design.
- (3) Based on the structural features of floating slab tracks and the analysis of construction deviation quantification sources, a spatial mathematical model for tunnel segments, the base, and floating slab tracks was established via the spatial geometric transformation method.
- (4) From the analysis of the construction deviation transfer model of steel spring floating slabs, construction geometric deviations mainly consist of three types: tunnel centerline offset, thickness deviations of the base and floating slab, and vibration isolator installation position offset. Deviations in each process are not independent but transfer continuously along the construction flow, presenting a chain transfer pattern.

Author Contributions: Conceptualization, X.D. and J.W.; methodology, X.D. and J.W.; validation, X.D. and J.W.; investigation, X.D.; data curation, J.W.; writing—original draft preparation, X.D.; writing—review and editing, X.D. and J.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: During the preparation of this manuscript, the authors used softwares such as SolidWorks 2024 and Origin 2018 for the purposes of drawing and analysis. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: Author Xianfeng Duan was employed by the company China Railway Xiong'an Investment & Development Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Wu, W.; Cao, M.; Wang, F.; Wang, R. Nonlinear influences of landscape configurations and walking access to transit services on travel satisfaction. *Transp. Res. Part A Policy Pract.* **2024**, *189*, 104232. [\[CrossRef\]](#)
- Huan, N.; Yao, E.; Zhang, J. Demand-responsive passenger flow control strategies for metro networks considering service fairness and passengers' behavioural responses. *Transp. Res. Part C Emerg. Technol.* **2021**, *131*, 103335. [\[CrossRef\]](#)
- Tan, Y.; Zhao, P.; Li, L. Subway expansion, residential relocation, and travel behavior: Causal evidence from China. *J. Transp. Geogr.* **2025**, *124*, 104166. [\[CrossRef\]](#)
- Wei, Y.; Yang, X.; Xiao, X.; Ma, Z.; Zhu, T.; Dou, F.; Gao, Z. Understanding the resilience of urban rail transit: Concepts, reviews, and trends. *Engineering* **2024**, *41*, 7–18. [\[CrossRef\]](#)
- Liu, Z.; Yin, J.; D'Ariano, A.; Yang, L.; Tang, T.; Chen, X. Balancing System Service Quality and Resilience for Urban Rail Networks: Preventive Train Timetabling with Disruptions. *Transp. Res. Rec.* **2026**, *2680*, 920–937.
- Fang, C. Study on Calculating Tunnel Overbreak and Underbreak Based on Secondary Development of CAD. *J. Geomat.* **2014**, *39*, 67–68. (In Chinese)
- Xu, L.; Wang, Z. Research on the Detection Method of Tunnel Under-over Break Using Point. *J. Railw. Eng. Soc.* **2016**, *33*, 77–81. (In Chinese)
- Wang, L.; Cheng, X.; Wang, C. Study on the 3D laser scanning technology for tunnel inspection. *Geotech. Investig. Surv.* **2013**, *41*, 53–57.
- Wilson, G.P.; Saurenman, H.J.; Nelson, J.T. Control of ground-borne noise and vibration. *J. Sound Vib.* **1983**, *87*, 339–350. [\[CrossRef\]](#)
- Li, J. Design and Application of New Track Technology in Shanghai Rail Transit Line 12. *Railw. Stand. Des.* **2017**, *61*, 5–8+18. (In Chinese)
- Watanabe, T.; Sogabe, M.; Yamazaki, T. A study of running safety and ride comfort of floating tracks for high-speed train. *J. Mech. Syst. Transp. Logist.* **2008**, *1*, 22–30. [\[CrossRef\]](#)
- Gu, A.; Zhang, H. Analyses of vibration isolation effect in different frequency band for steel-spring floating slab track. *Noise Vib. Control* **2009**, *29*, 39–42. (In Chinese)
- Li, Z.; Wu, T. 2-D Modelling of Floating Slab Track and Performance Analysis on Vibration Isolation. *J. China Railw. Soc.* **2011**, *33*, 93–98. (In Chinese)
- Castellani, A.; Kajon, G.; Panzeri, P.; Pezzoli, P. Elastomeric materials used for vibration isolation of railway lines. *J. Eng. Mech.* **1998**, *124*, 614–621. [\[CrossRef\]](#)
- Hussein, M.F.M.; Hunt, H.E.M. Modelling of floating-slab tracks with continuous slabs under oscillating moving loads. *J. Sound Vib.* **2006**, *297*, 37–54. [\[CrossRef\]](#)
- Hussein, M.F.M.; Hunt, H.E.M. Modelling of floating-slab track with discontinuous slab: Part 1: Response to oscillating moving loads. *J. Low Freq. Noise Vib. Act. Control* **2006**, *25*, 23–39. [\[CrossRef\]](#)
- Hussein, M.F.M.; Hunt, H.E.M. Modelling of floating-slab tracks discontinuous slab: Part 2: Response to moving trains. *J. Low Freq. Noise Vib. Act. Control* **2006**, *25*, 111–118. [\[CrossRef\]](#)
- Yao, J.; Yang, Y.; Wang, L. Analysis of vibration isolation effect of floating slab track structure. *J. Vib. Shock* **2005**, *6*, 108–110+113+143. (In Chinese)
- Nishimura, Y.; Endo, M.; Yanase, K.; Ikeda, Y.; Miyakawa, S.; Miyamoto, N. High cycle fatigue strength of spring steel with small scratches. In *Advances in Structural Integrity: Proceedings of SICE 2016*; Springer: Singapore, 2017; pp. 541–548.
- Ling, L.; Li, W.; Shang, H.; Xiao, X.; Wen, Z.; Jin, X. Experimental and numerical investigation of the effect of rail corrugation on the behaviour of rail fastenings. *Veh. Syst. Dyn.* **2014**, *52*, 1211–1231. [\[CrossRef\]](#)
- Wu, G.; Ren, W.X.; Zhu, Y.F.; Hussain, S.M. Static and dynamic evaluation of a butterfly-shaped concrete-filled steel tube arch bridge through numerical analysis and field tests. *Adv. Mech. Eng.* **2021**, *13*, 16878140211044671. [\[CrossRef\]](#)
- Lu, Z.; Guo, C. Effects of SWS strength and concrete air void composite defects on performance of CFST arch bridge rib. *Math. Probl. Eng.* **2020**, *2020*, 7202807. [\[CrossRef\]](#)
- CJJ/T 191-2012; Technical Specification for Floating Slab Track. China Architecture & Building Press: Beijing, China, 2010; Volume 46, pp. 14–21.
- Lou, H.; Chen, K.; Li, X.; Li, L.; Zhang, J.; Yu, H. Fluctuation diffusion network modeling and fluctuation source identification of multi-fluctuation-source and multi-process machining processes. *J. Xi'an Jiaotong Univ.* **2012**, *41*, 14–21. (In Chinese)
- Liu, D.; Jiang, P. Fluctuation Analysis of Process Flow Based on Error Propagation Network. *J. Mech. Eng.* **2021**, *55*, 73–83. (In Chinese)
- He, B.; Zhang, Z.; Dai, M.; Shi, J. Theory of Modeling Variation Propagation of Mechanical Assembly Processes. *J. Mech. Eng.* **2008**, *44*, 62–68. (In Chinese) [\[CrossRef\]](#)
- Zhu, P.; Yu, J.; Zheng, X.; Wang, Y.S.; Sun, X.W. Variation propagation network-based modeling and error tracing in mechanical assembling process. *J. Zhejiang Univ. (Eng. Sci.)* **2019**, *53*, 1582–1593. (In Chinese)

28. Liu, W.; Ning, R.; Liu, J.; Jiang, K. Mechanism Analysis of Deviation Sourcing and Propagation for Mechanical Assembly. *J. Mech. Eng.* **2012**, *48*, 156–168. (In Chinese) [[CrossRef](#)]
29. C/JJT/96-2018; Standard for Metro Gauges. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2018.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.