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Research Article

Fatigue Life Characteristics of Segmental Lining Structure for the Shallow Buried Metro Tunnel under the Dynamic Load of a High-Speed Railway

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Shallow buried shield metro tunnels constructed underneath subgrade project of high-speed railways are becoming increasingly common in China, but the lower metro tunnel bears the fatigue effect of dynamic load induced by the upper high-speed railway, so the long-term durability of segmental lining is a nonnegligible problem. The segmental lining structure of metro tunnel is in a state of static-dynamic loads for a long time, especially when a high-speed railway passes above the metro line, and the long-term durability of segmental lining needs further research. Based on theoretical analysis, the effect of different forms of loads on the fatigue life was analyzed, the change law of the static-dynamic loads on segmental lining was summarized, and the method was put forward to evaluate the fatigue life characteristics of segmental lining. The research results reveal that the additional dynamic load is the fundamental reason for the fatigue failure of the structure, and the existence of static load can cause and accelerate the occurrence of structural fatigue failure simultaneously. The results indicate that the fatigue life decreases gradually with the increase of static-dynamic load. Based on coupling analysis of static-dynamic loads of segmental lining, the fatigue life increases first and then decreases with the increase of buried depth of metro tunnel, and it remains unchanged when the depth exceeds a certain value. According to the actual metro tunnel engineering, by using ABAQUS software, a three-dimensional numerical simulation was carried out to analyze the characteristics of the fatigue life and evolution rules of segmental lining. Based on the modified fatigue life formula and metro service life, the optimization design of the buried depth was carried out to determine the most reasonable range of the buried depth. This study provides a valuable reference for safe operation and long-term durability of metro tunnels under high-speed railways.

1. Introduction

The metro segmental lining is a permanent supporting structure of shield tunnels. The stability and durability of segmental lining during the operation of tunnels directly influence the service life, durability, safety, and waterproof performance of the structure of metro tunnels [1]. During the normal service life of metro tunnels, the metro segmental lining must be in a state of static-dynamic loads for a long time. The static loads acting on metro segmental lining mainly include the formation pressure and additional pressure of buildings, and its value is constant during the operation for a given depth of metro tunnels [2, 3]. During the operation of tunnels, the metro segmental lining periodically bears the long-term metro train loads [4]. As for metro tunnels passing through a high-speed railway, the metro segmental lining inevitably bears cyclical dynamic loads transmitted by the dynamic stress of a high-speed railway subgrade [5]. Under the coupling of long-term periodic static-dynamic loads, there must be fatigue problems in the structure of metro segmental lining, which directly affects the durability of segmental lining. Therefore, fatigue characteristics of metro segmental lining deserve further investigation, especially the fatigue life of segmental lining, which directly determines the service life of metro tunnels.

Aimed at static-dynamic response and fatigue characteristics of tunnel support structures, relevant researches have been carried out both domestically and abroad. Caratelli [6] and Xue [7] studied the variation characteristics of segmental lining under static and dynamic loads, respectively, and analyzed differences between two types of loads from the crack development and structural displacement deformation. Based on safety assessments of tunnels constructed by shield driving method, under the long-term action of static-dynamic loads, there is a very different form of fatigue failure rather than general damage caused by short-term static loads, which causes rapid expansion and penetration of internal cracks, reduces the bearing capacity of structure, leads to excessive deformation, and directly affects the service life of tunnels [8, 9]. Yang [10] and Mussa [11] analyzed the dynamic response of lining structure under dynamic loads in the form of blasting by taking metro tunnels in the city as research objects, and it is shown that the vault and inverted arch of tunnel are more likely to be damaged. Mo [12] established a three-dimensional segmental model considering the joints of metro tunnels during operation and analyzed the rule of dynamic responses in different parts of segmental linings, and it was confirmed that the dynamic response value at the joint location of metro segmental linings was larger and the problem of fatigue failures occurred more likely at the joint. Luo [13] researched the initial stress field of metro segmental linings under the effect of surrounding medium and analyzed the influence of initial ground stress on dynamic responses under blasting loads. Huang [14] investigated fatigue characteristics of high-speed railway tunnels under the effect of train dynamic loads and introduced the double scalar of tension-compressive stress to predict the fatigue life of the tunnel, and the research indicated that the service life of inverted arch of the tunnel was determined by tensile characteristics of concrete materials. Li [15] studied the influence law of dynamic stress of heavy-load railway tunnel bases by means of numerical simulation and field measurement and investigated the lateral and vertical distribution laws of dynamic stress of the tunnel base. Liu [16, 17] summarized prediction methods for the fatigue life of inverted arch structures under the conditions of softening and voiding bedrock and studied the influence of different train loads on the fatigue life. Summarizing the above research focus, the current emphasis is mainly on analysis of dynamic responses and fatigue durability under the action of metro loads, heavy-load railway loads, or blasting loads, and there are no more reports on the study of metro tunnels passing through a high-speed railway. As for the analysis of dynamic responses and fatigue life under metro loads [4, 12, 16, 17], the metro tunnel can meet the requirements of both normal safety design and long-term durability. However, there is no relevant research result to prove whether metro tunnels meet the long-term durability requirement under the action of high-speed railway dynamic loads or not, and it remains to be further investigated. Therefore, it is necessary to study fatigue life characteristics and evolution rules of segmental lining under dynamic loads of high-speed railways.

As for the engineering project of shallow shield tunnels passing through high-speed railways, the metro segmental lining is subjected to cyclic high-speed dynamic loads transmitted from the upper strata for a long period. Whether the durability of segmental lining under the coupling of existing static loads and external dynamic loads is further reduced and whether its fatigue life satisfies the design of service life are the problems that need to be further investigated to ensure the safety operation and long-term durability of metro tunnels.

Based on above analysis, this paper studies and summarizes the fatigue life characteristics of segmental lining under the upper high-speed railway dynamic loads and proposes a suitable formula for the fatigue calculation of urban shallow buried metro tunnel combined with previous researches on concrete fatigue. Through the theoretical analysis of fatigue formula, the fatigue life characteristics of segmental lining are studied and the fatigue evolution of segmental lining under the coupling of static-dynamic loads is analyzed. Aimed at the high-gradient area in the fatigue life curve, fatigue safety coefficient is introduced to modify the fatigue curve to better reflect the actual physical state of the metro segmental lining. Concurrently, this paper analyzes the variation rule of stress state of segmental lining with the change of buried depth and concludes the evolution path of the fatigue life. Combining the example of Guangzhou Metro Line 9 passing through the Wuhan-Guangzhou High-Speed Railway and the numerical simulation of ABAQUS software, the fatigue life characteristics and its evolution rule of metro segmental lining are summarized. Based on the design service life of the metro tunnel, the optimization design of buried depth is carried out, and both of the critical depth without fatigue failure and the optimal depth are proposed. This research provides a valuable reference for safe operation and long-term durability of metro tunnels under high-speed railways.

2. Analysis of Fatigue Life Characteristics of Segmental Lining Structure

2.1. Optimal Selection of S-N Formula for the Fatigue Life of Segmental Lining. The segmental lining is a permanent structure of the shield metro tunnel, which is an integral ring structure mainly formed by assembling concrete material. The fatigue life characteristics of the concrete material determine the fatigue life of the entire segment structure. As is known to all, there is a great difference between tensile strength and compressive strength of concrete, and the tensile strength is only 1/10 to 1/20 of the compressive strength. A large number of scholars [11, 14, 17] verified the tensile characteristics of the concrete as an important factor in the evaluation of the structural safety through numerical simulation and laboratory tests, and the concrete structure was prone to tensile failure rather than compression failure in practical engineering. Thus, the tensile characteristics determined the service life of the tunnel to a certain extent.

For the research of tension fatigue of concrete, many researches have been investigated at home and abroad. Tepfers [18] conducted a splitting test on cubic lightweight concrete to analyze concrete fatigue sensitivity parameters

Table 1: The S-N formula of the concrete fatigue life with different types and stress conditions.

No.	Species	S − N formula	Condition	Author
1	C25	$\lg(N) = \dfrac{14.0(1-\sigma_{max}/f_t)}{(1-\sigma_{min}/\sigma_{max})}$	Splitting tensile	Tepfers
2	C25	$\lg(N) = 23.96 - \dfrac{24.27\sigma_{max}}{f_t}$	Uniaxial	Saito
3	C50	$\lg(N) = 14.91 - \dfrac{14.52\sigma_{max}}{f_t} + \dfrac{2.79\sigma_{min}}{f_t}$	Uniaxial, dry	Cornelissen
4	C50	$\lg(N) = 13.92 - \dfrac{14.52\sigma_{max}}{f_t} + \dfrac{2.79\sigma_{min}}{f_t}$	Uniaxial, humid	Cornelissen
5	C50	$\lg(N) = 17.87 - \dfrac{18.518\sigma_{max}}{f_t}$	Splitting tensile	Zhao
6	C50	$\lg(N) = 19.40 - \dfrac{20.0\sigma_{max}}{f_t}$	Axis tensile	Zhao
7	C50	$\lg(N) = 20.933 - \dfrac{22.222\sigma_{max}}{f_t},$	Bending tensile	Zhao
8	C25	$\lg(N) = 25.408 - \dfrac{28.169\sigma_{max}}{f_t}$	Splitting tensile	Zhao
9	C30	$\lg(N) = 18.968 - \dfrac{19.324\sigma_{min}}{f_t}$	Uniaxial	Song
10	C30	$\lg(N) = 16.67 - \dfrac{16.67\sigma_{max}}{f_t} + \dfrac{5.17\sigma_{min}}{f_t},$	Uniaxial	Song

Note. $\lg(N)$ is the fatigue life of the concrete, σ_{max} is the maximum stress of the specimen (MPa), σ_{min} is the minimum stress (MPa), and f_t is the tensile strength of the concrete (MPa).

and obtained the equations related to those of compressive stress. Saito [19] carried out the tensile fatigue test of gravel regular concrete under the condition of standard humidity and loading frequency of 5 Hz, and the ratio between the minimum tensile stress and the specimen tensile strength is the certain value, and the fatigue S-N formula based on the probability p=0.5 is obtained. Cornelissen [20] developed a large number of concrete tensile fatigue tests under both dry and humid conditions, simultaneously considered the influence of different minimum stress levels, and derived the fatigue S-N formula based on probability p=0.5 and confidence interval of 90%. Zhao [21] conducted fatigue tests on tensile, axial, and bending tensions of high-strength concrete under the condition of the minimum stress level of 0.1. The differences in fatigue life between high-strength concrete and ordinary concrete in different stress sections were compared and analyzed. Song [22] took concrete of grade C30 as a sample, studied the tensile fatigue tests under different stress levels separately, and the S-N formulas under different conditions were obtained. By comparing the concrete fatigue test of the above scholars, the fatigue formula was obtained at different concrete types and stress conditions, as shown in Table 1.

Comparing the formulas of Table 1, we can see that the fatigue life in different tests decreases with the increase of the maximum stress and increases with the increase of the minimum stress. Under the same stress level conditions, it can be found that the formula of number 4 has the smallest fatigue life and has a 90% confidence interval; that is, the S-N formula life of Cornelissen in uniaxial tests of C50 concrete under humid condition is minimal and highly reliable. Taking account of the environment and material composition of the metro tunnel, the formula $\lg(N) = 13.92 - 14.52\sigma_{max}/f_t + 2.79\sigma_{min}/f_t$ is selected as the basis for the subsequent fatigue life calculation.

2.2. Analysis of Fatigue Life Characteristics of Segments. By classifying and summarizing the fatigue formulas in Table 1, a general expression of the fatigue life can be obtained as formula (1).

$$\lg(N) = A - B \cdot \frac{\sigma_{max}}{f_t} + C \cdot \frac{\sigma_{min}}{f_t} \tag{1}$$

where A, B, and C are the parameters of the fatigue constant, and their values are 13.92, 14.52, and 2.79, respectively; $\sigma_{\max}$ is the maximum stress (MPa), and its value is the sum of the initial static and additional dynamic stress; $\sigma_{\min}$ is the minimum stress (MPa), and that is the initial static stress.

Considering the fatigue theory, the main formulas can be got as formula (2).

$$\begin{aligned} \sigma_m &= \frac{\sigma_{max} + \sigma_{min}}{2f_t} \\ \sigma_a &= \frac{\sigma_d}{2} = \frac{\sigma_{max} - \sigma_{min}}{2f_t} \\ R &= \frac{\sigma_{min}}{\sigma_{max}} \end{aligned} \tag{2}$$

where σ_m is the average stress (MPa), σ_a is the stress amplitude (MPa), σ_d is the stress range (MPa), and R is the stress ratio.

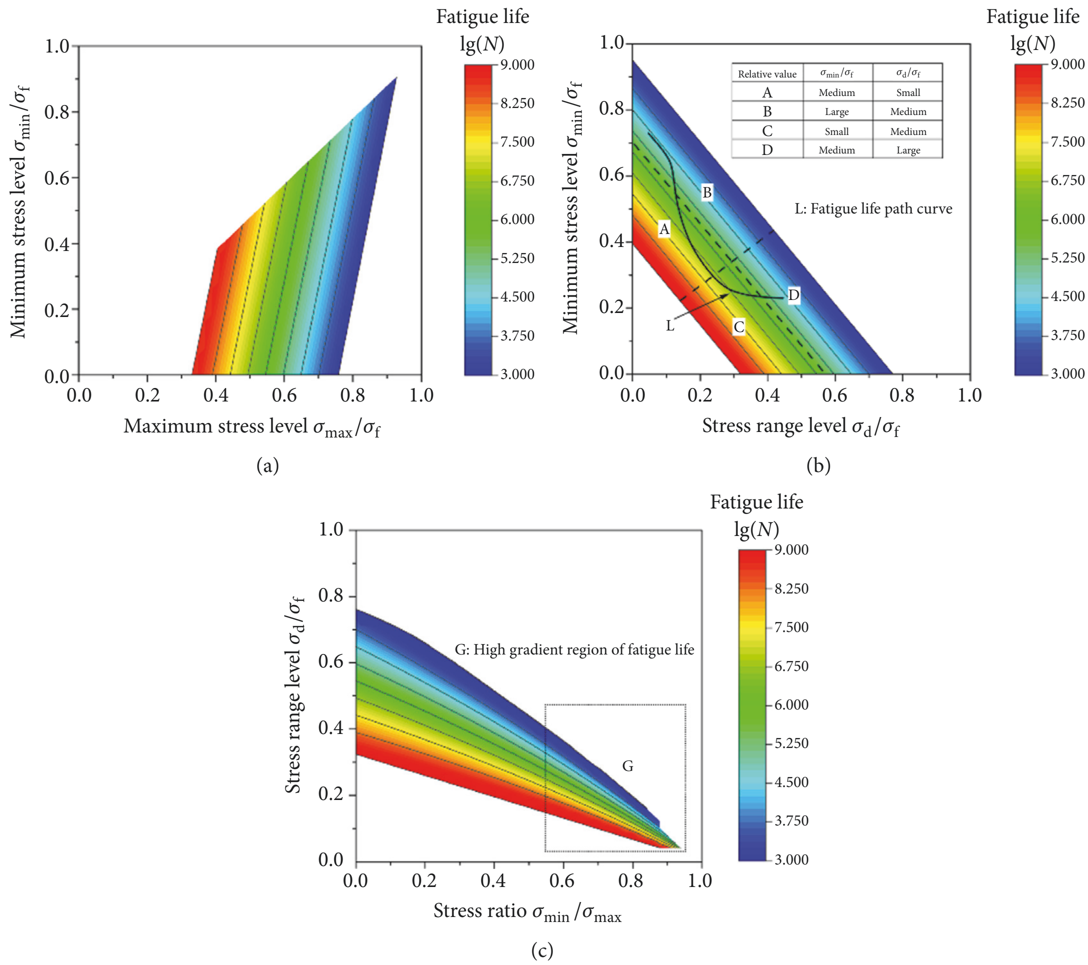


Figure 1: The evolution of fatigue life of segmental lining under the different load forms.

The transformation formula can be obtained based on the variables of σ_a and R, as shown in formula (4).

$$\sigma_{max} = \frac{2}{1-R}\sigma_a$$
$$\sigma_{min} = \frac{2R}{1-R}\sigma_a \qquad (3)$$
$$\sigma_m = 2\frac{1+R}{1-R}\sigma_a$$

Considering the actual service life of the metro tunnel segmental lining and the applicable range of the fatigue S-N formula, the following assumptions are made for the fatigue life of segmental lining.

(1) The upper limit of high-cycle fatigue: it is assumed that the segmental lining is under the normal train load, the amplitude of the dynamic stress is relatively small, and the frequency of dynamic load of the train exceeds 10E9 (the predicted years exceeds 1000 years), and there is no fatigue failure of segmental lining structure.

(2) The lower limit of high-cycle fatigue: it is presumed that the segmental lining is under special loads (such as earthquakes and train impact loads) and is in a relatively high stress of fatigue state; the local or total fatigue failure of segmental lining will occur when the frequency of special loads exceeds 10E3.

Based on the theoretical analysis of the fatigue formula (1), the evolution of the fatigue life of the metro segmental lining is the focus of research under the coupling of static-dynamic loads, as follows.

(1) Taking σ_{max} and σ_{min} as basic variables, the boundary condition can be expressed as formula (4).

$$3 < \lg(N) < 9,$$
$$0 < \sigma_{min} \le \sigma_{max} < f_t \qquad (4)$$

When the value of σ_{min} is equal to the value of σ_{max}, the fatigue of segmental lining cannot be considered and the fatigue formula is not suitable to discuss the fatigue life of segmental lining. The fatigue formula area is shown in Figure 1(a) (the horizontal and vertical coordinates are both unitized). It can be seen that the fatigue life of segmental lining gradually increases with the linear increase of the minimum stress, and the fatigue life of segmental lining gradually decreases with the maximum increase of the stress level. However, the absolute value of the increment of the maximum stress is greater than the minimum stress value, which indicates that the maximum stress has an important influence on the fatigue life of segmental lining than the minimum stress.

(2) Taking σ_{min} and σ_a as basic variables, the boundary condition can be expressed as formula (5).

$$\begin{aligned} &3 < \lg(N) < 9, \\ &0 < \sigma_{min} < f_t, \\ &0 < \sigma_a < f_t, \\ &2\sigma_a < f_t, \\ &\sigma_{min} + 2\sigma_a < f_t \end{aligned} \tag{5}$$

Formula (1) can be transformed as formula (6).

$$\lg(N) = A - 2B \cdot \frac{\sigma_a}{f_t} - (B - C) \cdot \frac{\sigma_{min}}{f_t} \tag{6}$$

In order to facilitate the analysis of its evolution, $\sigma_d = 2\sigma_a$ is used as the analysis variable, and its fatigue area is shown in Figure 1(b). It can be shown that the fatigue life of segmental lining gradually decreases with the increase of the stress range and the minimum stress, and the absolute increment of the stress range is greater than the minimum stress value. Based on theoretical analysis, it is proved that the additional dynamic stress σ_d of segmental lining is the fundamental reason for the structural fatigue failure, and the presence of the minimum tensile stress induces and accelerates the fatigue of the structure.

(3) Taking σ_a and R as basic variables, the boundary condition can be expressed as formula (7).

$$\begin{aligned} &3 < \lg(N) < 9, \\ &2\sigma_a < f_t, \\ &0 < R < 1 \end{aligned} \tag{7}$$

Formula (1) can be transformed as formula (8).

$$\lg(N) = A - \frac{(B - C \cdot R)}{(1 - R)} \cdot \frac{2\sigma_a}{f_t} \tag{8}$$

Similarly, $\sigma_d = 2\sigma_a$ is used as the analysis variable, and the fatigue area is shown in Figure 1(c). It can be illustrated that the fatigue life of segmental lining decreases with the increase of the stress ratio, and it shows a nonlinear decrease, so the existence of the average tensile stress has an important influence on the fatigue life of segmental lining. Meanwhile, the fatigue life of segmental lining gradually decreases as the stress range increases. While the stress range is small and the stress is relatively large, as shown in area G in Figure 1(c), the fatigue life of segmental lining changes very quickly within this range, so the fatigue life needs to be further corrected.

For example, when σ_{min} *and* σ_a are used as the analysis variables, a conclusion can be obtained from Figure 1 that the fatigue life of segmental lining can be clearly divided into four zones within its boundary conditions, namely, A, B, C, and D regions. As for the fatigue life design of segmental lining, the stress state of the structure should be distributed in A and C regions as much as possible. Therefore, there are two stress conditions of the structure to ensure the long-term safety and stability of segmental lining. One is that the minimum stress is small and the additional dynamic stress is relatively large, and the other one is that the minimum stress is relatively large and the additional dynamic stress is small.

2.3. Modification of Fatigue Life Based on Goodman Formula. Because of the tensile characteristics of concrete materials, there is no obvious yield strength. What is more, when the stress range is small and the stress ratio is relatively large, the fatigue life of segmental lining changes very quickly within this range, so it has a defect and hidden danger in the practical application process. Combined with the research on the fatigue characteristics of commonly used railway materials by China Academy of Railway Sciences [23], the fatigue safety factor of concrete is introduced in this research and the Goodman curve of concrete tension-tension fatigue is modified as formula (9).

$$\begin{aligned} &\frac{\sigma_a}{\sigma_{-1N}} + \frac{\sigma_m}{f_t} = 1 \quad \frac{\sigma_{0N}}{f_t} \le \frac{\sigma_m}{f_t} \le \frac{\sigma_g}{f_t} \\ &\frac{\sigma_a}{f_t} + \frac{\sigma_m}{f_t} = \frac{1}{n} \quad \frac{\sigma_g}{f_t} \le \frac{\sigma_m}{f_t} \le \frac{1}{n} \end{aligned} \tag{9}$$

where σ_g is $f_t(f_t - (N+1)\sigma_{0N})/n(f_t - 2\sigma_{0N})$, n is the fatigue safety factor, σ_{0N} is the stress amplitude when stress ratio $R = 0$, and σ_{-1N} is the stress amplitude when stress ratio $R = -1$.

From formula (9), the modified Goodman formula of concrete tension-tension fatigue is obtained and shown in Figure 2. As can be seen, the curve of FHK is the modified Goodman fatigue curve. Based on the judgment of the fatigue life, the lower part of the curve of FHK is the safe area and the upper part of the curve FHK curve is the nonsafe area.

In summary, the evolution of fatigue life of segmental lining under different stress conditions was studied from different perspectives, and the Goodman formula of concrete tension-tension fatigue was modified to better reflect the actual state. Therefore, all of the above conclusions provide a theoretical basis for subsequent study on the fatigue life characteristics of segmental lining.

3. Fatigue Loads Analysis of Segmental Lining Structure

With the rapid development of urban metros, the segmental lining structures are in different and complex stress states under the influence of three-dimensional cross traffic loads, which means the fatigue life of tunnel structures is different [24]. Based on this situation, the fatigue life characteristics of segmental linings under static-dynamic loads must be studied, and the variation rule of the fatigue life needs to be drawn to guide the design of complex project, so it can ensure that the actual project can meet the design life and the structure can achieve long-term safety, stability, and durability.

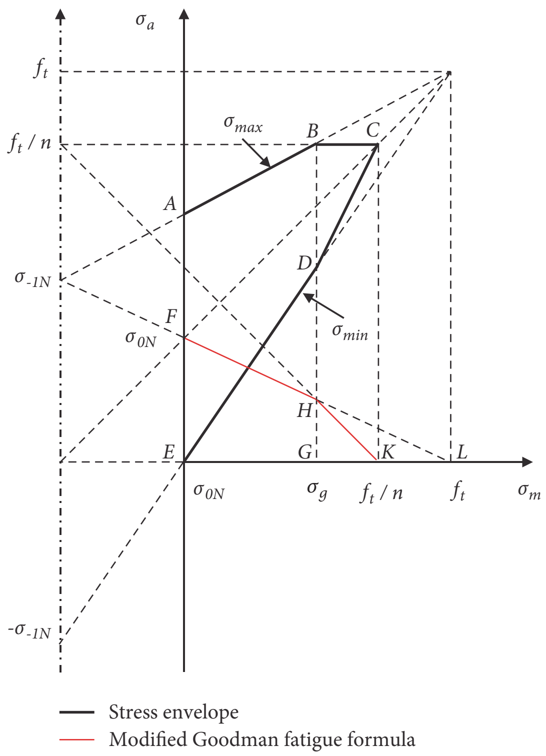


Figure 2: The modified Goodman formula of concrete tension-tension fatigue.

According to formula (1), the formula is substituted into the static and dynamic load of segments and transformed as formula (10).

$$\lg(N) = \left(A_d - B \cdot \frac{\sigma_d}{f_t}\right) + \left(A_i - D \cdot \frac{\sigma_i}{f_t}\right) \tag{10}$$

where σ_d is the additional dynamic stress of segments(MPa), σ_i is the initial static stress (MPa), A_d and A_i are constants related to the dynamic and static stress (A_d+A_i =A), and B and D are fatigue parameters (D=B-C and D>0).

It can be seen from (10) that the fatigue life of segmental linings is only related to the additional dynamic stress and initial static stress of segmental linings. Furthermore, there is a negative linear relationship between the fatigue life of segmental linings and the two kinds of loads, which means that the fatigue life decreases with the increase of initial static loads and additional dynamic loads. Therefore, in the process of design, construction, and operation of shield tunnels, it is necessary to investigate how to reduce the static and dynamic loads of segmental linings. By combining the research and analysis [4, 6, 9], the static loads of segmental linings are only related to the environment around. The dynamic loads of segmental linings, for the upper high-speed railway load, are only related to the depth of segmental linings, the axle loads, and the speed of the train. Therefore, according to the characteristics of loads, the factors affecting the fatigue life of segmental linings are discussed separately as shown in formulas (11) and (12), and the evolution of loads is analyzed separately to find out the fatigue life path curve in the fatigue life surface.

$$f_i(h) = A_i - D \cdot \frac{\sigma_i}{f_t} \tag{11}$$

$$f_d(v, h, m) = A_d - B \cdot \frac{\sigma_d}{f_t} \tag{12}$$

where $f_i(h)$ is a fatigue function related to static load, $f_d(v, h, m)$ is a fatigue function related to the dynamic load, and h, v, and m, respectively, represent the buried depth of the metro segmental lining, the train speed, and the axle load of the train.

3.1. Evolution Rule of Static Loads of Segmental Linings. The earth pressure acting on the metro segmental lining structure is actually the contact stress between the surrounding soil and segmental lining structure. Its size and distribution are not only related to the mechanical properties of the stratum and the stiffness of segmental lining, but also related to the construction method, the upper building, and the geometric parameters such as the depth, the straight diameter, and the shape of the tunnel. In order to facilitate the study of its evolution rule, it is considered that segmental lining load is mainly related to the depth of the metro tunnel, and the other factors are assumed to be consistent or unchanged in the calculation process. The Terzaghi's theory holds that the amplitude of the vertical loosening pressure of the surrounding rock tends to zero when the depth of the tunnel is increased to a certain limit, and the upper earth pressure is as shown in formula (13).

$$p_i = \begin{cases} \sum \gamma h, & h < 2.5D \\ \dfrac{\gamma}{f}\left(b + D \cdot \tan\left(45^\circ - \dfrac{\varphi}{2}\right)\right), & h \geq 2.5D \end{cases} \tag{13}$$

where p_i is the earth pressure, γ and φ are the unit weight and friction angle of the overlying soil, D is the diameter of segments, and b and f are the balance arch span and the sturdy coefficient.

Considering the existence of the ground water and the upper building, the effect of the water pressure and the additional load of the building on the initial static field of segmental lining should be analyzed [25, 26], and the p_i needs to be corrected. It can be seen from formula (13) that the stress of segmental lining increases with the increase of depth and then remains unchanged when the depth exceeds a certain value. According to formula (11) of the fatigue life of segmental linings, the fatigue life gradually decreases with the growth of the buried depth and then the fatigue life remains unchanged after a certain depth.

3.2. Evolution Rule of Dynamic Load of Segmental Lining. Many researchers had carried out a lot of research on the dynamic train loads from theory, simulation, and experiment and field measurement. Pan [27] and Jenkins [28] summarized a classical excitation force formula taking into consideration the train static load and track irregularity through the empirical analysis of a large amount of

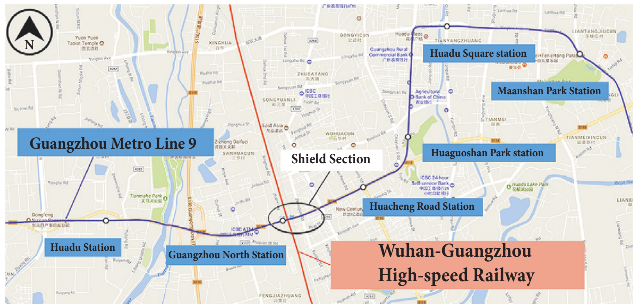


Figure 3: The location relation between the metro line and high-speed railway.

measured and experimental data. Song [29] investigated the distribution and transfer rule of the dynamic stress of the track and subgrade under different velocity moving loads. Simultaneously, the dynamic stress of the subgrade had an obvious linear relationship with the moving load speed at the range of 80km/h and 350km/h, and the dynamic stress remained unchanged when the speed was less than 80km/h or more than the 350km/h. Jiang [30] proved that the dynamic stress of the subgrade was linearly changed within the range of 150km/h and 300km/h through the laboratory experiment, and the dynamic stress in other ranges is independent of the speed of the train. Song [29] and Liu [31] had measured the dynamic stress of the subgrade of Beijing-Tianjin and Wuhan-Guangzhou High-Speed Railway, and its value ranged from 16.9kPa to 18.4kPa and the change rules conform to the results of the simulation software and the laboratory experiment. Based on the above analysis, the dynamic stress of the subgrade under different speed conditions is obtained as formulas (14) and (15).

$$p_d = \phi_d \cdot p_s \tag{14}$$

$$\phi_d = \begin{cases} \phi_d = d_0 & v \le 150km/\text{h} \\ \phi_d = \dfrac{(d_1 - d_0)(v - 150)}{150} + d_0 & 150km/\text{h} < v < 300km/\text{h} \\ \phi_d = d_1 & 300km/\text{h} \le v \end{cases} \tag{15}$$

where p_d is the dynamic stress of the subgrade under a certain speed condition, p_s is the static stress and its value is mainly related to the axle load of train and the type of track, ϕ_d is the dynamic stress amplification factor, and d_0 and d_1 are the coefficients related to the speed of the train.

The dynamic load of the train is equivalent to a stress area with rectangular distribution. According to the load transfer law, the dynamic load of the train gradually attenuates during the downward transfer process, so the dynamic response of segmental lining is gradually reduced. According to the fatigue formula (12), the fatigue life of segmental lining presents a nonlinear reduction state with the increase of buried depth.

3.3. Analysis of Fatigue Life Path of Segmental Lining under the Coupling of Static-Dynamic Loads. For the actual metro tunnel engineering, the segmental lining is in a certain depth and also subjected to the action of the upper high-speed railway load, and the stress of segmental lining is in a joint state of static-dynamic loads. The fatigue failure of segmental lining is a mechanical phenomenon under the coupling of static-dynamic loads. According to formulas (13) and (14), the trend of additional dynamic and initial static loads with depth can be obtained. Therefore, the total stress of segmental lining structure decreases first and then increases with the increase of the buried depth, and the total stress remains unchanged after reaching a certain depth. According to formulas (11) and (12), the evolution of the fatigue life with the change of buried depth can be obtained under the coupling effect of static-dynamic loads; that is, fatigue life path is the change trend of area D, area C, area A, and area B in order (shown in Figure 1(a)). Under the dynamic load of high-speed railway, the fatigue life of segmental lining structure appears to increase at first and then decrease with the increase of the buried depth, and the fatigue life of segmental lining remains unchanged after exceeding a certain depth. Therefore, in the actual metro design process, the impact of high-speed railway on the fatigue of segmental lining is further considered, and the settlement of the upper stratum or building caused by the metro construction does not exceed the limit value, so the depth of the metro proposed a relatively reasonable value.

4. A Case Study of Metro Tunnel and Optimization Design of Buried Depth of Segmental Lining

4.1. Project Overview. Guangzhou Metro Line 9 passes through the Wuhan-Guangzhou High-Speed Railway and the Beijing-Guangzhou Railway between Guangzhou North Railway Station and Huacheng Road Station. The tunnel is constructed by the shield method. The plane angle between the tunnel and the railway is approximately 72 degrees, and the tunnel depths range from 7m to 9m. It is the first metro line in the shallow section of China to pass through the high-speed railway subgrade, and its location is shown in Figure 3. Guangzhou North Railway Station is the halfway station of the Wuhan-Guangzhou High-Speed Railway. Most of the trains pass through the line at a speed of about 300 km/h. Therefore, the dynamic load of the high-speed railway will inevitably have an important impact on the long-term stability and durability of the metro segmental lining structure.

Table 2: Physical and mechanical parameter of different strata.

No.	Thickness /(m)	Density /(kg/m3)	Elasticity modulus /(MPa)	Poisson ratio	Friction angle /(°)	Cohesive force/(kPa)	Rayleigh damping α	Rayleigh damping β
1	2.0	1880	10.15	0.43	15	18	0.021	0.093
2	4.0	2000	57.15	0.26	18.1	17.5	0.026	0.094
3	6.2	2050	60.435	0.25	33	48	0.039	0.063
4	6.2	1910	57.15	0.32	18.1	23.5	0.054	0.045
5	4.6	2760	650	0.15	28	400	0.047	0.053

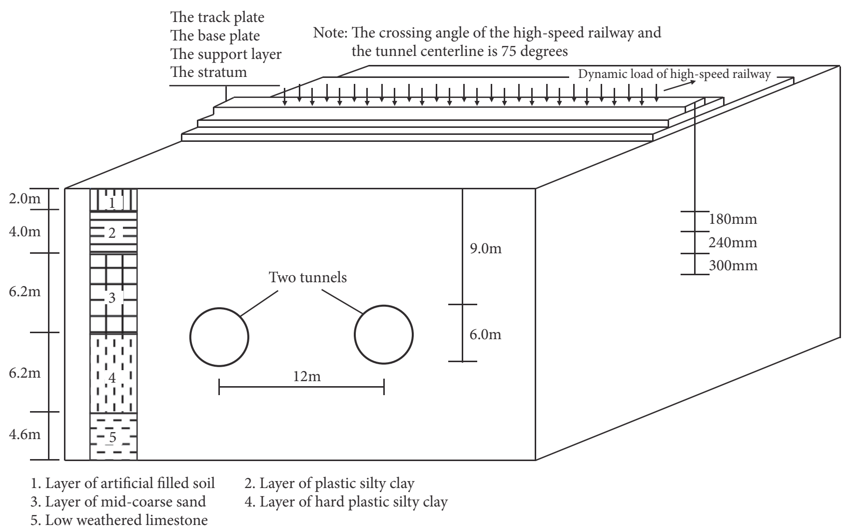


Figure 4: Geological conditions, tunnel conditions, and high-speed railway position.

4.2. Formation Conditions, Segment Conditions, and Train Conditions. According to the geological survey report of Guangzhou Metro Line 9, the distribution of strata is shown in Figure 4, and the physical parameters of each layer are shown in Table 2. In order to reduce the impact of shield construction on the high-speed railway subgrade, the horizontal jet-grouting technology was used to reinforce the stratum under the high-speed railway subgrade before the shield construction. The horizontal jet-grouting pile diameter is 2.0m, and the reinforcement angle is 160°. The strength of the solid after hardening in the sand layer is no less than 3.0MPa, it is no less than 1.0MPa after hardening in the clay layer, and the overlap thickness between the pile and the pile is no less than 300 mm to form an overall load-bearing structure.

The segmental lining of shield tunnel adopts a universal wedge-shaped lining ring. The diameter of segmental lining is 6.0m, the thickness is 0.3m, the width is 1.5m, and the lining loop is divided into six parts, that is, three standard segments (central angle of 67.5 degrees), two adjacent segments (central angle of 68 degrees), and one key segments (center angle of 21.5 degrees). The method of staggering of 22.5 degrees is assembled, two bolts of grade M30 are used between the two parts, and sixteen bolts of grade M30 are used to connect two rings. The lining ring structure is shown in Figure 5.

The specification and model of the train directly affect the dynamic stress acting on the subgrade. According to the design plan of Wuhan-Guangzhou High-Speed Railway, the model of the train is CRH380, the axle load is 15t, the length of the car is 24.175m, the distance between wheels is 17.375m, and the train formation is composed of eight groups. The operating speed of the train is 300 km/h. According to the previous research and investigation, the maximum measured value of dynamic stress of the subgrade is 19.8kPa. In this calculation, the maximum stress is chosen as 20kPa and the loading frequency is 3.3Hz.

4.3. Three-Dimensional Model and Numerical Assumption. In the process of numerical simulation, the dynamic calculation is performed by coupling finite element and infinite element. The geometric dimension of the model is 60m×40m×72m (X×Y×Z). The size of the segmental lining is based on Section 4.2, and the segmental lining uses homogeneous solid element in the model. The three-dimensional structure is adopted and the element type is CIN3D8.

The infinite element can serve as the function of absorbing the dynamic wave in the boundary generated by the finite element calculation and propagated to the far field, prevent the stress wave from propagating to the static artificial boundary, and reenter the finite element calculation model,

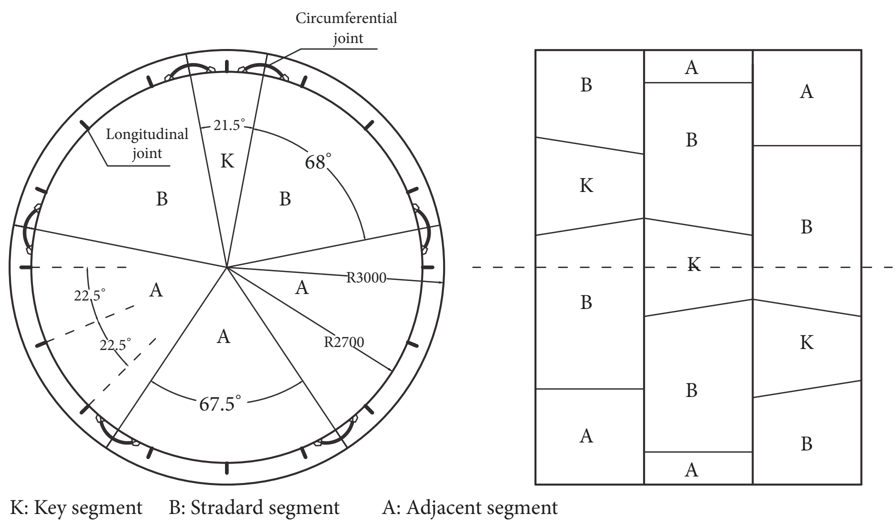
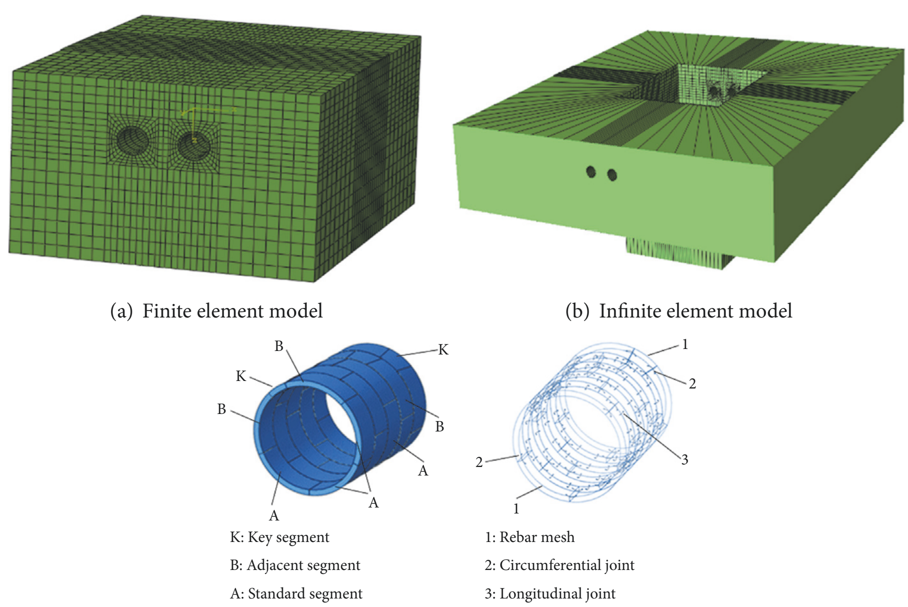


Figure 5: Segmental lining structure of shield tunnel.



(a) Finite element model (b) Infinite element model

(c) Sectional metro tunnel (d) Segment connection

Figure 6: Three-dimensional model.

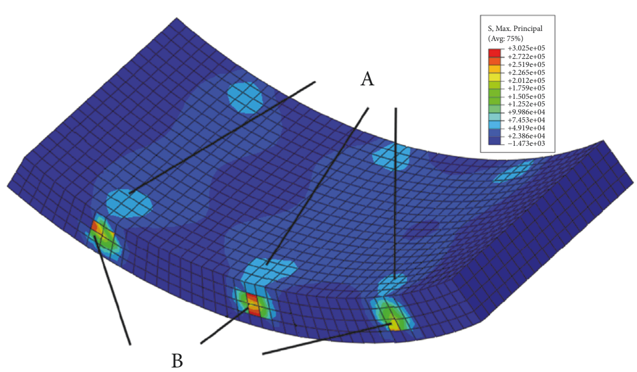
so it can reduce the interference of the reflected wave. Thus, the infinite element is built at the periphery and bottom of the finite element model as an infinite element boundary condition. Moreover, in order to simulate the actual segment, the model of the solid element is performed for segmental lining and bolt, and the contact between different parts and bolts is established, respectively. The three-dimensional model is shown in Figure 6.

The high-speed railway is mainly composed of the support layer, base plate, and track plate, and the dynamic load of high-speed railway acts directly on the track plate; the location of dynamic load is shown in Figure 4. The dynamic load of high-speed railway propagates downward, passes through the soil layers, then acts on the segmental lining, and finally passes into the infinite element at the periphery and bottom of the model.

Some assumptions are proposed in the process of numerical simulation. The Mohr-Coulomb model is used as the constitutive model of the soil layers, and the linear elastic model is selected as the constitutive model for the segmental lining, the support layer, the base plate, and the track plate. In the damping setting, the Rayleigh damping coefficient (containing α and β) is adopted and the damping ratio of analysis is 0.05. Its coefficient is taken by the reference frequency of the first two orders of the soil layer in the modal analysis, and the values of different soil layer are shown in Table 2.

Table 3: Fatigue life of segment at different buried depths.

Depth	The joint between the two rings			The end of the bolt		
	Minimum stress /(MPa)	Maximum stress /(MPa)	Fatigue life lg(N)	Minimum stress /(MPa)	Maximum stress /(MPa)	Fatigue life lg(N)
5m	0.7326	1.2955	7.658	0.7185	1.2104	8.108
7m	0.7911	1.2342	8.055	0.7867	1.1599	8.456
10m	0.8933	1.2192	8.135	0.8615	1.1321	8.687
13m	1.0944	1.3384	7.697	1.1554	1.2631	8.282
16m	1.2657	1.4218	7.532	1.1924	1.3198	8.011



A: The end of the bolt
B: The joint between two rings

Figure 7: The stress of the inverted arch of the tunnel segment.

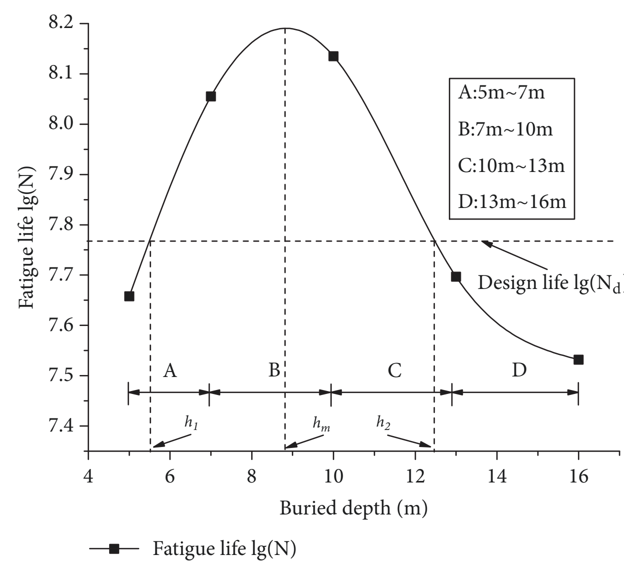


Figure 8: The change trends of segment fatigue life at different buried depths.

4.4. Fatigue Life Prediction of Different Buried Depths of Segmental Lining. By analyzing the force value in the position of the invert, it can be found that the tensile stress at the joint between two rings, as well as the end of the bolt, is relatively larger than other parts, as shown in Figure 7. Therefore, the position of the invert is the most dangerous position and further selected as the research object. Based on the fatigue formula (1), the fatigue life prediction of segmental lining is performed at different depths, as shown in Table 3.

From Table 3, the fatigue life at the invert of segmental lining is analyzed at different positions. The results show that the fatigue life at the end of the bolt is greater than the fatigue life at the joints of adjacent segments, and the fatigue failure occurs first at the joint of adjacent ring segment. Therefore, under the dynamic load of high-speed railway, the dislocation between adjacent segments is the main cause of the fatigue failure of the concrete, and this position causes fatigue failure before other parts in a long-term dynamic load.

When the metro segmental lining are at different depth, it can be seen from the calculation results that the minimum stress of segmental lining gradually increases with the increase of the depth, and the maximum stress of segmental lining decreases first and then increases with the increase of the depth. Taking the fatigue life of the joints as an example, as shown in Figure 8, the fatigue life of segmental lining is increasing from lg(N) = 7.658 to lg(N) = 8.055 when the depth of segmental lining ranges from 5m to 7m, and it decreased from lg(N) = 8.135 to lg(N) = 7.532 when the depth of segmental lining is from 10m to 16m, which means the fatigue life shows a tendency of increasing first and then decreasing with the increase of the depth. Therefore, this phenomenon is consistent with the conclusion of the fatigue life characteristics of segmental lining structure described above (see Section 3.3). Meanwhile, by observing the fatigue life curves at different depths, it can be seen that there is a reasonable buried depth in the interval between 7m and 10m, and the fatigue life of segmental lining reaches a maximum value in that depth. When the depth of segmental lining is larger than 16m, it can be seen that the fatigue life tends to be stable. The main reason is that the depth exceeds 2.5D (15m), the static stress remains stable, and the dynamic response value is very small.

When the buried depth of metro segment exceeds a certain value, the fatigue characteristic value of segmental lining is in the region of high-gradient variation, that is, the area G in Figure 1(c). Combined with the modified Goodman formula, the fatigue safety factor is taken as 2, so the corrected fatigue curve can be obtained as shown in Figure 9. It can be seen that, in addition to the depth of segmental lining of 16m, the fatigue characteristics of different depths are in the safe area. Through curve fitting and mathematical

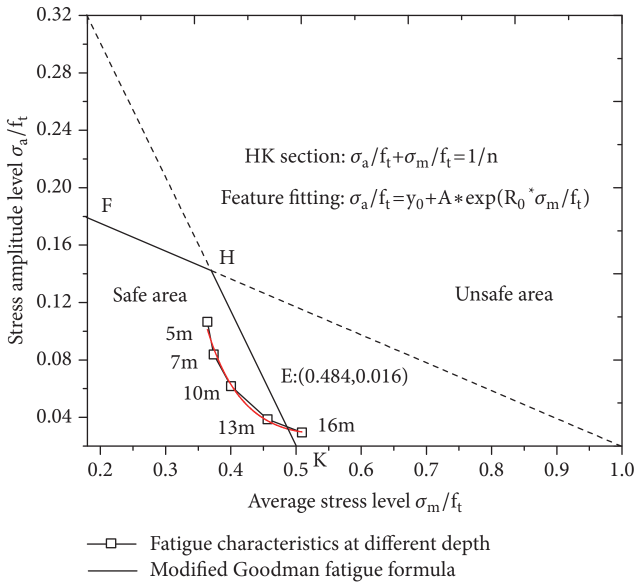


Figure 9: The modified Goodman formula and fatigue characteristic value at the different buried depths.

interpolation, the modified Goodman curve HK is $\sigma_a/f_t + \sigma_m/f_t = 1/2$, the fatigue characteristic curve with different depths is $\sigma_a/f_t = 0.029 + 526.31\exp(-24.33\sigma_m/f_t)$, and the determination coefficient is 0.982. It can be determined that the coordinates of the intersection point between the modified Goodman curve and the fatigue characteristic curves are (0.484, 0.016), so the depth of segmental lining is 14.417m. For the convenience of analysis, the depth is taken as 2.5D. Therefore, when the depth is greater than 2.5D, the fatigue formula (1) is not applicable to the evaluation of fatigue of segmental linings and the failure rule needs to be evaluated according to the normal serviceability state.

4.5. Optimization Design of Buried Depth with Consideration of Fatigue Life of Segmental Lining. Based on the evaluation of fatigue life of segmental lining, it is necessary to consider which depth can meet the design life, has the largest safety reserve life of the metro tunnel, and can ignore the effect of fatigue life. Therefore, it is necessary to optimize the design of segmental lining depth. It is assumed that the most unfavorable position of segmental lining structure is the same position in different buried depths, and it provides convenience for the optimization design and analysis of the buried depth of segmental lining.

Through the analysis of the additional stress and static load on segmental lining structure, the static-dynamic stress formula for different position of segmental lining can be obtained as formulas (16) and (17) taking into account the effect of strata reinforcement and the relationship between the subgrade dynamic load and depth.

$$\sigma_i(h) = \alpha_1\beta_1\gamma h P(\theta) \quad (16)$$

$$\sigma_d(v,h,m) = \alpha_2 p_d\left(a_1 + b_1\ln\left(h + d_1\right)\right)P(\theta) \quad (17)$$

where α_1 and α_2 are the influence parameters of the reinforcement layer above segmental lining, β_1 is the proportional parameter between the static load and depth, γ is the equivalent parameter of the upper soil layer, a_1, b_1, and d_1 are the fitting parameters of the dynamic load, and $P(\theta)$ is a function of position relative to segmental lining stress.

It is assumed that the fatigue failure of segmental lining occurs at the same position of different depths and $P(\theta)$ is a constant value. From the fatigue formula (1), the fatigue characteristic equation of segmental lining is obtained as formula (18).

$$\lg(N) = A - \frac{B\left(\alpha_1\beta_1\gamma h P(\theta)\right)}{f_t} - \frac{C\left(\alpha_2 p_d\left(a_1 + b_1\ln\left(h + d_1\right)\right)P(\theta)\right)}{f_t} \quad (18)$$

For a given metro designed service life N_d, it can be used as a judgment standard to meet the design life. When the calculation life is more than the design life at different depths, the segmental lining structure meets the fatigue life requirements in any case, so the segmental lining structure does not consider fatigue failure under static-dynamic loads. When the calculation life is less than the design life at different depths, the structural design of segmental lining does not meet the actual service life, so the segmental lining design needs to be corrected. When the calculated fatigue life includes the design service life, the depth interval that meets the normal design can be determined according to the designed service life (as shown in Figure 8); that is, $\lg(N) = \lg(N_d)$. Through the calculation of formula (18), a reasonable depth range can be determined to satisfy the design life of segmental lining.

For the depth range that satisfies the fatigue design life, it can be seen that there is an optimal depth in the interval and the fatigue life of segmental lining is the largest, so the metro has a longer safety reserve period. The derivative of $\lg(N)$ is equal to 0, and the optimal buried depth is shown in formula (19).

$$h_m = \frac{C\alpha_2 b_1 p_d}{B\alpha_1\beta_1\gamma} - d \quad (19)$$

where the parameter h_m is mainly affected by α_1, α_2, and p_d.

Based on the ABAQUS calculation results (see Table 3), taking the results of joints as an example, the datum is processed to fit the curves of the static-dynamic load. The static load curve is $y = 0.0486x + 0.4557$ *and* $R^2 = 0.9752$ and the dynamic load is $y = -0.334\ln(x) + 1.1024$ *and* $R^2 = 0.9899$. Based on formula (18), the calculation life can be obtained as $\lg(N) = 5.8338 + 1.837\ln(x) - 0.2158x$.

According to the current survey of the high-speed railway, 103 pairs of trains are arranged every day. For the 100 years of design life, the actual times of dynamic loading are $N_d = 100 \cdot 365 \cdot 103 \cdot 8 \cdot 2 = 60152000$ and $\lg(N_d) = 7.779$. Therefore, the depth interval is from $5.51m$ to $12.45m$. According to formula (19), the optimal buried depth is calculated as $\lg(N)' = (5.8338 + 1.837\ln(x) - 0.2158x)'=0$, and the depth is 8.51m. Combined with the modified Goodman fatigue formula, the depth of the metro within the range of 5.51m to 15m can guarantee the design service life of the metro tunnel under the action of a high-speed railway.

5. Conclusion

In this paper, we analyze and summarize fatigue life characteristics of metro tunnel structure based on fatigue life formula, in terms of static load, dynamic load, and fatigue life path. Taking the Guangzhou Metro Line 9 cross underneath the Wu-Guang High-Speed Railway as a case, the fatigue life of segmental lining under the action of high-speed railway is analyzed. The main results of the research are summarized below:

(1) There is a negative linear relationship between the fatigue life and the static-dynamic load, and the fatigue life gradually decreases with the increase of static-dynamic load, which can provide a feasible reference for the design of the metro tunnel.

(2) Based on the coupling analysis of the static-dynamic load of metro tunnels, the fatigue life of segmental lining increases at first and then decreases with the increase of the depth.

(3) There is a reasonable buried depth in the interval between 7m and 10m to maximize the fatigue life of segmental lining. What is more, it is concluded that the fatigue failure of segmental lining can be ignored when the depth is greater than 2.5D and the failure rule needs to be evaluated according to the normal serviceability state.

(4) According to the optimization design of the fatigue life, it is concluded that the buried depth in the range of 5.51m to 15m can meet the design service life of 100 years and the optimal depth in this interval is 8.51m.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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