Research Article

Study on the Influence of Train Dynamic Load on underneath Tunnel Cast-in-Situ Concrete in Early Age

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Received 25 October 2021; Accepted 17 February 2022; Published 28 March 2022

Academic Editor: Madalina Dumitriu

The cast-in-situ concrete lining is prone to structural damage, cracks, and other defects, due to the influence of dynamic load at an early age, which is necessary to study the dynamic response. In this study, the finite difference software FLAC3D is used to carry out the dynamic analysis. Firstly, the reliability of the numerical model is verified by the train vibration test on-site. On this basis, the control variable method is used to analyze the dynamic response of the dynamic train load in early-age concrete structures under the factors of tunnel buried depth, train speed, cross angle, and surrounding rock grade. Then, the safety of the structure is evaluated. The numerical simulation results show that the influence of buried depth and surrounding rock on the early age structure is more obvious. Peak acceleration decreases with the increase in tunnel buried depth and increases with the increase in surrounding rock grade and train speed. Peak acceleration changes a little in the range of 0°–67.5°, but when the cross angle is 90°, the dynamic response reaches the minimum value. Multiple factors fitted the dynamic tensile stress, and the dynamic tensile stress under adverse conditions was calculated, compared with the splitting tensile strength of early-age concrete. The results show that the splitting tensile failure does not occur when the concrete age is more than 0.5 days.

1. Introduction

With the advancement of traffic infrastructure construction, there are many tunnels underneath passing the existing railway [1–4]. At present, the mining method is always used in tunnel construction, which means the cast-in-situ concrete structure is indispensable. However, the key lines are generally not allowed to interrupt, which will cause early-age concrete to be affected by train vibration and may cause the adverse effect of structure and decrease in bearing capacity [5–7].

The influence of train vibration on surrounding soil and tunnel structure has attracted many scholars’ attention. In the numerical simulation, two commonly used calculation methods are the pipe-in-pipe model and the coupled periodic FE-BE model [8–14]. Ju and Lin [15, 16] found that the dominant frequency of train load is very important when the train passes through the free field such as the soil layer, and they proposed a field test to verify the vibration effect of the dominant frequency of trainload. Wang et al. [17] studied the initial stress state and dynamic response characteristics of tunnel lining by the three-dimensional finite element method and obtained the damage evolution characteristics of tunnel invert by the indoor fatigue test device. Based on the heavy haul railway tunnel underneath passing the high-speed tunnel project, Dong et al. [2] studied the dynamic response characteristics of the tunnel by the model test. The results show that the dynamic response of the existing tunnel and the surrounding rock has been changed under the trainload, the acceleration of the existing tunnel is enhanced, and the dynamic stress of the rock mass between the tunnels is reduced. D.P. Connolly et al. [18] obtained the vibration characteristics of the railway by testing and analyzing. Du et al. [19, 20]
arranged resistance strain gauges inside the invert and obtained the dynamic stress of the invert and the filler by in situ measurement. Then, they used numerical simulations to validate the in situ test. Wu et al. [21] studied the dynamic response of train vibration to an adjacent tunnel at different buried depths by the model test and the discrete element method. They found that buried depth is closely related to the structure’s response under dynamic trainload, displacement, velocity, and acceleration in the vertical direction, which are much larger than the horizontal direction. Xu et al. [22] compared the dynamic response of the heavy haul train to the tunnel lining structure under the two measures (cabinet grouting reinforcement and cement-soil compaction pile). The results showed that the curtain grouting is more effective in reducing the acceleration and displacement of the tunnel lining structure’s response under dynamic trainload, displacement, and velocity in the vertical direction, which are more than twice as large as in the horizontal direction. Yan et al. [23] studied the dynamic response of the heavy haul train to the tunnel lining structure under the different train speeds and structures. They found that the buried depth is closely related to the dynamic stress of the invert and the filler by in situ tests, and numerical simulations. The performance of early-age concrete also is a hot research topic in recent years. At present, there is still no exact definition of the concept of early age. However, researchers generally pay attention to the performance of the first 24 or 48 hours after casting [24]. The uniaxial compressive strength of C40 concrete is about 13 MPa in 12 hours, 24 hours is about 16 MPa [25], and the elastic modulus of C40 concrete is about 2 MPa in 24 hours [26]. It is prone to micro-crack in early age, and external load is one of the reasons for cracking. Corrosive substances such as chlorides, sulfates, and carbonates will cause steel corrosion and concrete carbonation after cracks occur. Further, it shortens the service life of concrete structures. Therefore, crack greatly impacts the bearing capacity of structures [27, 28]. Wang et al. [29] studied the influence of dynamic load on the mechanical properties of concrete at different ages through the impact compression test. The test results showed that under dynamic load, concrete’s strength and elastic modulus increased with age, and the failure forms were mainly tensile failures. Dao et al. [30] tested the tensile strength of early-age concrete and found tensile strength and Young’s modulus of early-age concrete increased slowly in the first 3 hours and then increased significantly in the next few hours. Zollinger et al. [31] found that early-age concrete is more brittle than 28-day concrete. Li et al. [32] compared the impact compression test of concrete under different ages and found that the impact of 50% critical incident energy is helpful to improve the strength and elastic modulus within seven days of age but will decrease after seven days. Hulshizer et al. [33] systematically tested blasting vibration on early-age and 28-day concrete. The results showed that the average shear strength of early-age concrete decreased by 4% and the average bond strength decreased by 3% after blasting vibration. Still, the compressive strength of concrete mainly increased. Ansell [34] and Wei [35] found that concrete damage is a process of damage accumulation.

It can be seen from above that scholars have conducted a lot of research studies about the influence of dynamic trainload on tunnel vibration from theoretical exploration, model tests, and numerical simulation. However, most studies focus on concrete after 28 days. The research on the influence of vibration in the early age of concrete mainly focuses on the impact compression test and the influence of blasting vibration. There are few studies about the influence of train vibration on early-age concrete. The strength of cast-in-situ concrete is relatively low in early age, which is still in the stage of rapid growth. Once early-age concrete bears a large load, it may cause damage to concrete and affect its strength and other mechanical properties. Therefore, this study will study the dynamic response of cast-in-situ concrete at early age under train dynamic load, based on an engineering of Chengdu Metro Line 1 underneath passing the Chengdu-Kunming freight outer winding, to provide a case or method for further exploring the influence law and performance evaluation of early-age concrete affected by the trainload.

2. Methodology of Dynamic Analysis

For the overlying tunnel, the first problem is load of train vibration, and the other is the dynamic effect of soil and structure. At present, the vehicle-track coupled dynamics has developed into a new discipline field, to establish the dynamic model to solve the problem of the vehicle-track system by the analytical method or finite element method. This study analyzes the trainload problem based on the theory of vehicle-track coupled dynamics. The dynamic model of train-track vibration system regards wheel-rail irregularity as the vibration excitation source, which transmits to the track through the hertz contact relationship between wheel and rail.

Referring to the dynamic model of vehicle-track coupled vibration [36, 37], the model consists of train, track, and wheel-rail coupled relationships. Sleeper, trackbed, and subgrade form double-layer mass-three-layer spring-damped system. Adjacent elements are connected by shear stiffness and shear damping, as shown in Figure 1.

In Figure 1, $M_c$ is the car body mass, $I_c$ is the mass moment of inertia of car body about $y$-axis, $Z$ is the vertical displacement, $\beta$ is the pitch angle, and $P$ is fastener reaction force. $k_{cc}$ and $C_{cc}$ are stiffness coefficient of secondary suspension along $z$-axis and damping coefficient of secondary suspension along $z$-axis, and $Z_0$, $Z_0'$, and $\varphi$ are vertical vibration, vertical displacement, and vertical motion, respectively.

The brief steps of wheel-rail coupling dynamic analysis are as follows: (1) generating mass matrix, damping matrix, stiffness matrix, and force vector; (2) generating motion equation; (3) solving velocity and acceleration; and (4) getting fastener reaction.

The equation of dynamic calculation is as follows:

$$[M][\ddot{u}] + [C][\dot{u}] + [K][u] = [F(t)].$$

(1)

The central difference method uses the displacement of the structure to represent approximately the velocity and acceleration of the structure by finite difference expression:
\[ \ddot{u} = \frac{1}{\Delta t^2} \left( \{u_{t-\Delta t}\} - 2\{u_t\} + \{u_{t+\Delta t}\} \right). \]  
\hfill (2)

\[ \ddot{u} = \frac{1}{2\Delta t} \left( \{-u_{t-\Delta t}\} + \{u_{t+\Delta t}\} \right). \]  
\hfill (3)

Equations (2) and (3) are substituted into (1):

\[ [M] \frac{1}{\Delta t} \left( \{u_{t-\Delta t}\} - 2\{u_t\} + \{u_{t+\Delta t}\} \right) + [C] \frac{1}{2\Delta t} \left( \{-u_{t-\Delta t}\} + \{u_{t+\Delta t}\} \right) + [K]\{u_t\} = \{f(t)\}. \]  
\hfill (4)

Initial conditions can be expressed as follows:

\[ \{u_{t-\Delta t}\} = \{\dot{u}_0\} - \Delta t\{\ddot{u}_0\} + \frac{\Delta t^2}{2} \{\dddot{u}_0\}. \]  
\hfill (5)

The calculation steps are divided into as follows:

1. Calculation of \([K]\), \([M]\), and \([C]\);
2. Calculation of \(\{\dot{u}_0\}\) and \(\{\ddot{u}_0\}\);
3. Selection of \(\Delta t\);
4. Calculation of \(\{u_{t-\Delta t}\} = \{u_0\} - \Delta t\{\dot{u}_0\} + \Delta t^2/2\{\ddot{u}_0\}\);
5. Recalculation of \(\{\ddot{u}_0\} = 1/\Delta t^2 [M] + 1/\Delta t^2 [C]\); and
6. Triangular decomposition of \([M] = L \ D L^T\),

where \([K]\) is stiffness matrix; \([M]\) is mass matrix; \([C]\) is damping matrix; \(\{u_0\}\) is displacement; \(\{\dot{u}_0\}\) is initial velocity; \(\{\ddot{u}_0\}\) is acceleration; and \(\Delta t\) is time step.

3. Three-Dimensional Dynamic Model

Firstly, the numerical analysis is used in studying the dynamic response of early-age concrete of the metro tunnel. Therefore, an 3D FEM dynamic model is created according to the engineering of Chengdu Metro Line 1 tunnels underground passing the Chengdu-Kunming freight outer winding.

3.1. Project Overview. The subject, Chengdu Metro Line 1 in this study, is in Chengdu City of Sichuan Province, China,
and underneath passing the Chengdu-Kunming freight outer winding. Figures 2 and 3 show the relations and relative positions between metro lines and railway lines. There are three metro tunnels, the upper tunnel at the middle location is the access line tunnel and the others at both sides are the running tunnels. The space between these three metro tunnels is very small, from which the minimum distance between the access line tunnel and the running tunnel is 8.0 m. The intersection angle between the metro line and the existing railway line is 67.5°. The buried depth of the access tunnel is 12.4 m, and the vertical net distance between the subgrade and the shield tunnel is 20 m. The running tunnels were constructed by the shield method firstly, and the access line tunnel is then constructed by the conventional method. As to the access line tunnel, the lining is constructed with cast-in-place concrete. The train vibration will influence the concrete performance in early age.

3.2. Three-Dimensional Finite Element Model. Liner formwork is simulated by structural unit, and track, roadbed, stratum, and support are simulated by solid unit. According to the Saint-Venant principle, the model range is 80 m in the x-direction, 80 m in the y-direction, and 50 m in the z-direction. The mesh of the numerical simulation is shown in Figure 4.

3.3. Calculation Parameters. The rock-soil adopts the elastic-plastic model and obeys the Mohr–Coulomb yield criterion. The lining structure and track adopt the linear elastic model. C30 shotcrete is used in the primary lining with a thickness of 0.35 m. In the secondary lining, C40 concrete with 0.50 m thickness is used. C50 concrete is used for shield segment. The track slab of shield tunnel is backfilled with C20 concrete. Due to the influence of the segment joint, the parameters of pipe segment are multiplied by the reduction factor of 0.8 [38]. The principal stratum, where the tunnel is located, is moderately weathered mudstone. Silty clay and moderately weathered sandstone are found near the tunnel. The tunnel structure and surrounding rock parameters are shown in Table 1. The physical parameters of concrete are determined by the “Code for Design of Railway Tunnel” (TB10003-2016), and the field geological parameters are obtained from geologic examination and design document.

3.4. Boundary Conditions and Mechanical Damping. The selection of boundary conditions is critical in finite difference dynamic analysis. It is necessary to select boundary conditions to suppress the reflection of boundary vibration waves and set damping to simulate the attenuation.

3.4.1. Boundary Condition. FLAC3D software provides two boundary types: viscous boundary and free-field boundary. In this study, the static boundary is used to suppress the reflection of the vibration wave on the boundary of the model; that is, the normal and tangential dampers are set to absorb the incident wave.

3.4.2. Mechanical Damping. Damping is one of the essential parameters of dynamic analysis. The Rayleigh damping is often used to represent the damping mechanism in dynamic analysis. The damping matrix is usually simplified as a linear combination of [M] and [K], and the damping matrix expression is as follows:

\[ [C] = [\alpha][M] + [\beta][K], \]

\[ \alpha = \frac{2\omega_i\omega_j}{\omega_i + \omega_j} \xi_i, \]

\[ \beta = \frac{2}{\omega_i + \omega_j} \xi_i, \]

where \( \alpha \) and \( \beta \) represent the constants related to the mass matrix and stiffness matrix, respectively, and \( \omega_i \) and \( \omega_j \) are inherent frequencies.

According to practical engineering experiences and related literature, the minimum critical damping ratio usually is 0.02–0.05 [40]. In this study, the critical damping ratio is 0.05 [41]. The center frequency adopts the natural vibration frequency of the system without damping. The natural vibration frequency of the system is 1.46 Hz by monitoring the internal characteristic points of the boundary surface of the model. Till then, two parameters of Rayleigh’s damping are determined.

3.5. Simulation of Train Vibration Loading. In this study, the vehicle-track vertical coupled model is used to determine the train dynamic load. The train adopts the P70 general shed at a speed of 40–80 km/h. The wheel-rail irregularity is regarded as the excitation source of vehicle vibration. The time-history curve and the spectrum characteristics are basically the same except for the difference in phase on the wave, while the train passes through different positions. The time-history curve of train vibration load based on train-track coupling theory is shown in Figure 5. The load-time curve is based on the vehicle-track vertical coupling theory, and the train, track, and wheel-rail parameters are input into the software independently developed by the State Key Laboratory of Traction Power, Southwest Jiaotong University. The track includes rail, sleeper, ballast, and subgrade, and rail is regarded as Euler’s beam with infinite discrete support.

There is a time difference in the wave of the fastener reaction time-history curve of the adjacent fastener position. The time difference is equal to the fastener spacing divided by train speed, so time-history reaction force at different fastener positions can be applied to simulate the train moving. Before the lining casting, the stress redistribution of surrounding stratum has been completed. Therefore, this study considers the effect of self-weight, train dynamic load, and template supporting, yet does not consider the influence of surrounding stratum pressure and other loads on the lining.
3.6. Calculation Model Checking. Field tests are conducted to verify the reliability of the calculation model. The test site is located in the Chengdu Metro Line 1 Guangzhou Road Station-Xinglong Station underneath passing the existing Chengdu-Kunming freight outer winding. In the early age of the second lining, it is not easy to detect the vibration response of the concrete; therefore, the response of the acceleration of the sleeper and the primary support is tested. The field test is conducted while the newly built tunnel of the lower bench is excavated to the left line cross section. The monitoring points are arranged in the sleeper, right hance, and sidewall of the right line cross section, as shown in Figure 6.

The acceleration of time-history curve of the train vibration is obtained by numerical simulation and field test. The vibration produced by train belongs to random signal, and the analysis should be carried out from power spectrum; that is, the distribution of average energy in a certain frequency band, vibration time domain of filed test, and numerical simulation are converted to one-third octave vibrations. The main frequency band and energy in the spectrum are compared, which are shown in Figure 7.

As can be seen from a comparative analysis of the two curves at sleeper, hance, and sidewall respective in Figure 7, the response of acceleration obtained by numerical simulation is consistent with the measured value in the one-third
frequency domain. It proves the reliability of the numerical model, which can be used for further research and analysis.

4. Study on the Dynamic Response Law of Early-Age Structure

4.1. Analysis of Working Conditions. The lining is constructed from north to south, and five analysis cases are set to determine the unfavorable position. 0 m is the intersection of the newly built tunnel and the existing freight line. The construction surface of the second lining is 10 m, 5 m, 0 m, -5 m, and -10 m, respectively, as shown in Figure 8. The lining length is constructed with 10 m per step, and the concrete at the same step is considered the same age. The lining from construction to form removal is three days every step, so the age interval of adjacent lining is reckoned as three days in the calculation. In the FLAC3D, the template is simulated by shell element. The calculation results are listed in Table 2. It is easy to find that the dynamic response decreases obviously when the second lining passes through the cross section. The peak values of acceleration and dynamic stress both reach a maximum when the construction face of the lining arch wall is 0 m, which is the relatively unfavorable position. Therefore, the construction of the lining arch wall at the intersection of the tunnel and the existing railway is selected as the research section.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Elastic modulus (GPa)</th>
<th>Poisson’s angle (°)</th>
<th>Friction angle (°)</th>
<th>Cohesion (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast</td>
<td>1800</td>
<td>0.5</td>
<td>0.3</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Sleeper</td>
<td>2500</td>
<td>25.0</td>
<td>0.2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Pipe segment (C50)</td>
<td>2500</td>
<td>27.6</td>
<td>0.2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Primary lining (C30)</td>
<td>2500</td>
<td>30.0</td>
<td>0.2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Secondary lining (C40)</td>
<td>2500</td>
<td>It depends on concrete age</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Backfill (C20)</td>
<td>2500</td>
<td>25.5</td>
<td>0.2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Embankment filling</td>
<td>2000</td>
<td>0.25</td>
<td>0.25</td>
<td>30</td>
<td>90</td>
</tr>
<tr>
<td>Silty clay</td>
<td>1950</td>
<td>0.30</td>
<td>0.23</td>
<td>35</td>
<td>100</td>
</tr>
<tr>
<td>Moderately weathered mudstone (upper layer)</td>
<td>2260</td>
<td>0.35</td>
<td>0.24</td>
<td>35</td>
<td>130</td>
</tr>
<tr>
<td>Moderately weathered sandstone</td>
<td>2370</td>
<td>0.40</td>
<td>0.24</td>
<td>42</td>
<td>150</td>
</tr>
<tr>
<td>Moderately weathered mudstone (sublayer)</td>
<td>2340</td>
<td>0.50</td>
<td>0.24</td>
<td>33</td>
<td>130</td>
</tr>
</tbody>
</table>

Figure 4: Mesh of the numerical model.
According to the existing research, concrete strength is generally tested from the age of 0.5 days, before which the concrete is in the plastic state, and it is difficult to obtain uniaxial compressive strength. The early-age concrete parameters reference Dr. Xu’s [37] research results, and the elastic modulus curve is shown in Figure 9.

There are numerous factors affecting the vibration characteristics. This study uses the control variable method to set working conditions, as shown in Table 3. Considering the most unfavorable situation, that is, two trains meet in the tunnel. Therefore, the trainload is applied simultaneously from both ends. The influence of buried depth, train speed, cross angle, and surrounding rock grade on the early-age concrete structure of the underneath tunnel is studied. The dynamic responses of the tunnel lining were assessed by acceleration, displacement, and dynamic stress. In a numerical model of dynamic analysis, the four monitoring points of the vault, hance, sidewall, and arch foot are established (as shown in Figure 6) to study the law of early-age structure’s dynamic response.

Condition 3 (surrounding rock grade V, train speed 80 km/h, crossing angle 67.5°, buried depth 6 m) was selected as the standard condition. The other conditions only need to change the parameters of the research factors. For example, when analyzing the dynamic response under the different surrounding rock grades, changing the mechanical

![Figure 5: Time history of fastener reaction (80 km/h).](image)

![Figure 6: Layout of the measuring points.](image)
parameters of surrounding rock and the other variables remains unchanged. In accordance with the “Code for Design of Railway Tunnel” (TB10003-2016), geotechnical material parameters of different rock levels are listed in Table 4.

4.2. Influence of Buried Depth on the Response of Cast-In-Situ Structure. The dynamic response of cast-in-situ lining structure under the early-age stage at buried depths of 3, 4.5, 6, 8, 10, 12, and 15 m is studied. As shown in Figure 10, the analysis can be concluded as follows:

(1) The acceleration response at the vault is the most obvious. The acceleration response decreases with the increase in buried depth, and the attenuation gradient decreases gradually. The peak acceleration of the vault, for example, attenuates from 0.26 m/s² to 0.061 m/s², while the buried depth of the tunnel is 3 to 6 m, the peak acceleration attenuation amplitude is 76.5%, and the attenuation gradient is 0.066 m/s²/m. When the buried depth of the tunnel is 6 to 10 m, the peak acceleration decreases from 0.061 m/s² to 0.024 m/s², the attenuation amplitude is 60.6%, and
(1) The attenuation gradient is 0.01 ms\(^{-2}\)/m, which is about 1/6 in the range of 3 to 6 m of buried depth.

(2) The position sequence of peak vertical displacement from large to small is vault, hance, sidewall, and arch foot, which is consistent with the acceleration response. With the increase in buried depth, the peak vertical displacement decreases obviously. When the buried depth reaches 15 m, the vertical displacement of each position tends to be consistent. The maximum vertical displacement at the vault position is 2.31 mm when the buried depth is 3 m.

(3) The position sequence of dynamic tensile stress response from large to small is arch foot, vault, hance, and sidewall. The position sequence of dynamic compressive stress is sidewall, hance, arch foot, and vault.

4.3. Influence of Cross Angle on Response of Cast-In-Situ Structure. The dynamic response of cast-in-situ lining structure under the early-age stage at cross angles of 0°, 22.5°, 45°, 67.5°, and 90° is studied. As shown in Figure 11, the analysis can be concluded as follows:

(1) The peak acceleration changes little in the range of 0° ~ 67.5°. When the cross angle changes from 67.5° to 90°, the peak acceleration decreases obviously.
reaching the minimum value, indicating that the orthogonality between the newly built tunnel and the existing tunnel is the most favorable for controlling acceleration response.

(2) When the cross angles are 0°, 22.5°, 45°, 67.5°, and 90°, the peak values of vertical displacement of the vault are -1.67mm, -1.60mm, -1.51mm, -1.37mm, and -1.32mm, respectively. It can be seen that the peak values of vertical displacement decrease with the increase in cross angle.

(3) The variation law of peak dynamic tensile stress at each position is the same. The places of the peak dynamic tensile stress are different. When the intersection angles are 0° and 22.5°, the peak value appears at the vault, and when the intersection angles are 45°, 67.5°, and 90°, the peak value appears at the arch foot.

(4) With the change in cross angle, the dynamic compressive stress changes obviously at the sidewall. The dynamic compressive stress at the vault increases slightly with the increase in the cross angle, and others decrease with the rise of the cross angle.

### 4.4. Influence of Train Speed on Response of Cast-In-Situ Structure

The dynamic response of cast-in-situ lining structure under the early-age stage at train speeds of 40, 60, and 80 km/h is studied. As shown in Figure 12, the analysis can be concluded as follows:

(1) The position sequence of peak vertical acceleration and peak displacement is vault, hance, sidewall, and arch foot. When the train speed is 40 km/h, 60 km/h, and 80 km/h, the acceleration peak of vault is 0.025m/s², 0.045m/s², and 0.061m/s², respectively, and the vertical displacement peak is -1.03mm, -1.15mm, and -1.37mm, respectively.

(2) The change in dynamic stress is consistent with the change in acceleration and displacement. Still, the change amplitude is smaller, indicating that the dynamic tensile stress and compressive stress are less sensitive to the train speed than the acceleration and displacement responses.

(3) When the train speed is higher, the dynamic response of the early-age lining structure is more potent, indicating that the appropriate speed limit can effectively reduce the influence of train vibration on the early-age lining structure.

### 4.5. Influence of Surrounding Rock Grade on Response of Cast-In-Situ Structure

The dynamic response of cast-in-situ lining structure under the early-age stage at surrounding rock grades of III, IV, and V is studied. As shown in Figure 13, the analysis can be concluded as follows:

(1) The peak displacement, dynamic tensile, and compressive stress show noticeable nonlinear changes with the change in surrounding rock grade. The vertical acceleration peaks of III and IV class...
surrounding rocks are 295.7% and 247.8% of V class surrounding rock. The vertical displacement peaks are 6.4% and 21.9% of V class surrounding rock, respectively.

(2) The better the surrounding rock, the stronger the acceleration response of the early-age structure, and the weaker the vertical displacement and dynamic stress response. Therefore, in terms of the dynamic stress, the surrounding rock could be improved by grouting reinforcement to reduce the influence of train vibration on the early-age structure.

5. Influence Evaluation of Train Vibration on Cast-In-Situ Structure

From the above analysis, it can be seen that the tunnel depth, train speed, cross angle, and surrounding rock grade impact the dynamic response of the cast-in-situ structure. According to the literature [33], a series of tests on C40 early-age concrete show that the splitting tensile strength of standard concrete cube is only 0.28 MPa, and the compressive strength is 2.2 MPa when concrete age is 0.5 days. This strength may be used as the basis for evaluation,
although those are static strength index. Therefore, the early-age stage is more vulnerable to tensile stress damage. In this study, the dynamic tensile stress is fitted by a multifactor function to determine whether it will affect the cast-in-situ structure.

5.1. Multifactor Function Fitting of Tensile Stress. The buried depth, cross angle, train speed, and surrounding rock grade studied in this study are independent. The standard working condition can be selected to fit the dynamic tensile stress of a single factor. After determining the influence coefficient, the multifactor fitting can be obtained by superposition of multiple factors. Condition 3 (surrounding rock grade V, train speed 80 km/h, crossing angle 67.5°, buried depth 6 m) is selected as the standard condition. The above calculation can obtain the dynamic tensile stress under different working conditions, as shown in Table 5.

The nonlinear fitting is used for inductive analysis. The burial depth, cross angle, and train speed are all fitted by an exponential function, and the fitting formula of dynamic tensile stress on burial depth is as follows:
The fitting formula of dynamic tensile stress on train speed is as follows:

$$\sigma_{(H=67.5°, \nu=80\text{km/h})} = \left( 3.0284e^{-\frac{H}{5.3595}} + 0.0152 \right) \sigma_{t}. \quad (7)$$

The fitting formula of dynamic tensile stress on cross angle is as follows:

$$\sigma_{(H=6\text{m}, H=67.5°, \nu)} = \left( 0.06255e^{-\frac{\nu}{44.2492}} + 6.1857 \right) \sigma_{t}. \quad (8)$$
Figure 13: Dynamic response of characteristic points of tunnel structure varying with train speed, (a) peak acceleration, (b) peak displacement, (c) peak dynamic tensile stress, and (d) peak dynamic compressive stress.

Table 5: Peak dynamic tensile stress under different working conditions.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.95</td>
<td>7</td>
<td>2.09</td>
<td>13</td>
<td>12.58</td>
</tr>
<tr>
<td>2</td>
<td>13.74</td>
<td>8</td>
<td>7.97</td>
<td>14</td>
<td>10.31</td>
</tr>
<tr>
<td>3</td>
<td>10.31</td>
<td>9</td>
<td>8.88</td>
<td>15</td>
<td>8.98</td>
</tr>
<tr>
<td>4</td>
<td>7.19</td>
<td>10</td>
<td>10.31</td>
<td>16</td>
<td>1.33</td>
</tr>
<tr>
<td>5</td>
<td>4.93</td>
<td>11</td>
<td>14.64</td>
<td>17</td>
<td>4.11</td>
</tr>
<tr>
<td>6</td>
<td>3.48</td>
<td>12</td>
<td>14.11</td>
<td>18</td>
<td>10.31</td>
</tr>
</tbody>
</table>
\[
\sigma_{\text{d}}(H=6m, \beta=0, V=80km/h) = \left( \frac{1}{-0.50959e^{117.1110 \theta} + 1.9522} \right) \sigma_t,
\]

where \(\sigma_t\) is dynamic tensile stress under standard conditions; \(H\) is burial depth; \(\theta\) is cross angle; \(V\) is train speed; and \(\lambda\) is surrounding rock grade.

\[
\sigma = \lambda_i \left( 3.0284e^{-\frac{H}{5.3595}} + 0.0152 \right) \left( 0.06255e^{\frac{V}{44.2492}} + 0.61857 \right) \left( \frac{1}{-0.50959e^{117.1110 \theta} + 1.9522} \right) \sigma_t, \quad (10)
\]

Here, \(i = 3, 4, \text{ and } 5\), indicating that the surrounding rock grades are III, IV, and V, and coefficients are 0.1290, 0.3986, and 1.0, respectively. \(\sigma_t\) is 10.31 kPa.

5.2. Evaluation of Safety. As mentioned above, the splitting tensile strength is 0.28 MPa when concrete age is 0.5 days. Among the 18 calculated working conditions, the dynamic tensile stress of working condition 1 (buried depth of 3 m, train speed of 80 km/h, cross angle of 67.5°, V class surrounding rock) is the largest, 6.4% of the splitting tensile strength. In this research background, when engineering is in the most unfavorable conditions (i.e., the buried depth is 1 m, the speed is 80 km/h, the cross angle is 0°, and the V class surrounding rock), the dynamic tensile stress value is 25.96 kPa, which is only 9.27% of the splitting tensile strength. Although this condition is rarely encountered, the dynamic tensile strength of the tunnel lining would much more likely exceed tensile strength with the development of the higher speed and heavy haul trains. As to this project, the dynamic tensile stress of tunnel lining is less than splitting tensile strength of concrete at age of 0.5 days. Also, it can be considered that when the concrete age is more than 0.5 days, it will not cause splitting tensile damage. It should be noted that stress monitoring should be carried out in the construction of the underpass project to ensure the safety of the structure. Mechanical and vibrating wire sensors can show favorable performance in this case [42].

6. Conclusions

Based on the Guangzhou Road Station-Xinglong Station of Chengdu Metro Line 1 underneath the existing Chengdu-Kunming freight project, the numerical simulation and field test are combined to study the dynamic response of the early-age structure. The following conclusions can be drawn:

1. The influence of tunnel depth and surrounding rock grade on the dynamic response of the early-age structure is significant. The dynamic response changes a little in the speed of 40 to 80 km/h and the cross angle of 0 to 67.5°, but when the cross angle is 90°, the dynamic response decreases obviously.

The above three single factor fitting formulas of buried depth, cross angle, and train speed have been obtained. Considering the surrounding rock coefficient, the fitting function formula of structural tensile stress under the influence of multiple factors is as follows:

(2) The position sequence of vertical acceleration peak and displacement peak from large to small is vault, hance, sidewall, and arch foot. The position sequence of dynamic tensile stress is arch foot, vault, hance, and sidewall.

(3) The dynamic tensile stress is fitted by multiple factors, and the dynamic tensile stress of the most unfavorable conditions is obtained. Then, compared with the splitting tensile strength of early-age concrete, the results show that the splitting tensile failure will not occur in this project, but may happen in special condition and future engineering with the development of the higher speed and heavy haul trains.

(4) Since the concrete has not formed cement stone when the age is less than 0.5 days, the dynamic response before 0.5 days is unknown. The surrounding rock could be improved by grouting reinforcement to reduce the influence of train vibration on the early-age structure.

Data Availability

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

Conflicts of Interest

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

Acknowledgments

This study was financially supported by the National Science Foundation of China (grants nos. 51678494 and 52078431).

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