

Numerical Simulation Study of the Vibrational Response of Continuous Arch Tunnels under the Action of Overlying Train Loads

Weihuan Shen

Central South University of Forestry and Technology, China

Abstract: With the rapid development of transportation infrastructure in China, continuous arch tunnels passing under existing operational railways are increasingly encountered. This paper primarily investigates the mechanical response patterns of the lining of continuous arch tunnels under the vibrational loads generated by trains traveling on railways. To this end, a three-dimensional finite element model of the dynamic response of continuous arch tunnels under train vibrational loads was constructed using Midas GTS/NX software. This model explores the patterns of acceleration, dynamic displacement, and dynamic strain responses of continuous arch tunnels under the action of moving train loads. The study reveals that under train vibrational loads, the vertical acceleration, vertical displacement, and strain time history curves at various monitoring points in the continuous arch tunnel exhibit vibrational characteristics. The acceleration, vertical displacement, and dynamic strain increase as the train enters, fluctuate within a certain range, and then decrease to zero as the train exits. Under high-speed train loads, the acceleration peak values at the arch feet and outer sidewalls of the left and right tunnels are larger, with a greater peak value difference. The vertical displacement peak values at the arch shoulders and crown are larger, whereas those at the middle partition wall and base slab are smaller. During the process from the train's entry to its exit, the dynamic strain exhibits a trend of initially increasing, then stabilizing, and finally decreasing to zero, all while displaying vibrational characteristics. The strain response on the tunnel side where the train enters is greater than that on the side where it exits.

Keywords: Continuous arch tunnel; train vibration; dynamic response; numerical simulation.

1. Introduction

As China's transportation construction progresses, the area used for transportation infrastructure continues to grow, and the issue of intersecting routes becomes increasingly prominent. To ensure the normal operation of various transportation routes, tunneling beneath other transportation lines has become a common approach in transportation planning. There are overlapping sections in space between the underpass tunnel and the existing lines, requiring designers to thoroughly consider the mutual influences between the tunnel and the existing lines during construction and subsequent operations.

With the acceleration of urbanization in China, the distance of cross-line engineering projects is decreasing, and the issues associated with train dynamic loads are becoming more noticeable. The generation of train loads is influenced by many factors, and scholars have conducted extensive research on the mechanisms of train load generation and load descriptions. D.V. Jones and others considered the ground as a semi-infinite space and used a dynamic stiffness matrix analysis method to theoretically study the propagation range of vibrations on the ground surface^[1]. J. Bitzenbauer and others proposed a novel method that combines a subgrade layered half-space model in the Fourier transform domain to explore the dynamic interaction between moving vehicles and infinite body structures. Using models of single axle and bogies on irregular tracks, the study elucidated its characteristic effects^[2]. Kaynia A.M. developed a numerical model interconnecting the track and embankment to quantify and predict the vibrations induced by high-speed trains on subgrades^[3]. Dieterman H.A. applied Fourier transforms to the spatial and temporal domains to determine the equivalent

stiffness of an elastic semi-infinite body, thereby calculating and deducing the phenomenon of potential resonance caused by critical speeds^[4].

Dawn and Stanworth explored various residual issues that could be triggered by ground vibration, vehicle, and track characteristics, including the propagation of vibrations and their potential impacts on nearby buildings. Their experimental studies highlighted key aspects of railway design, analyzing how the design and operation of railways influence ground vibrations as trains become heavier and faster, and how these vibrations affect the surrounding environment, especially buildings close to the tracks^[5]. Huijian Zhang and others, based on the new metro tunnel closely intersecting beneath Chengdu's existing Line 1, studied the dynamic response characteristics of the new subway tunnel during train passage through field experiments and numerical analysis^[6]. Sanqing Su examined the dynamic response of an ultra-shallow buried rectangular tunnel beneath Ankang's freight yard V during train dynamic loads and seismic events, using field measurements and numerical simulation. The study found that the dynamic stress response was most significant at the mid-span of the tunnel crown and the upper end of the sidewall directly beneath the rails, while the bottom slab had the least dynamic stress response^[7]. Wenbo Yang introduced experimental research on the impact of tunnel cross-sectional shape on the dynamic response of tunnels and their surrounding soil, testing three different cross-sectional shapes (circular, rectangular, and horseshoe) of 1/20 scale tunnel models under dynamic loading from train loads, and analyzed the dynamic response of the tunnels and soil in both time and frequency domains^[8].

Despite the wealth of research on the dynamic response of underpass tunnels, studies focusing on continuous arch

tunnels are relatively scarce. Thus, this paper aims to enrich the academic theories in the field of continuous arch tunnel underpasses and contribute positively to the refinement of underpass tunnel design theories.

2. Establishment of the Dynamic Model and Main Parameters

2.1. Basic Assumptions for Numerical Simulation

Considering the complexity of geotechnical media parameters, material properties of underground structures, the contact behavior between soil and underground structures, and the complexity of constitutive relationships, it is currently impossible to establish a numerical model that can accurately reflect the dynamic response of continuous arch tunnels to high-speed train vibrations. Therefore, to simplify the model and focus on core factors, the following assumptions were adopted in establishing the numerical model in this study:

1. The soil is assumed to be a homogeneous, continuous, and isotropic elastic medium, described using a simplified elastic model.

2. The assumption of tightly connected soil particles ensures that there is no separation or relative slippage between the surrounding rock soil and the tunnel structure under the action of high-speed train vibrations, ensuring coordinated deformation of nodes on the contact surface.

3. Ignoring the soil's initial stress assumes that the soil's response can be considered zero at locations far from the tunnel.

4. Regarding the influence of groundwater, considering that it would introduce changes in parameters such as the surrounding rock soil and tunnel lining at different cross-sections along the tunnel, the model chooses to ignore its

effect. This assumes that the parameters of the surrounding rock and tunnel structure remain consistent at different cross-sections along the tunnel.

Through these assumptions, the numerical model in this paper focuses on studying the main influencing factors of train vibrations on the dynamic response of continuous arch tunnels, aiming to simplify the model while retaining key physical processes and characteristics.

2.2. Design of Main Parameters

When conducting three-dimensional modeling and dynamic finite element analysis of underground structures using Midas GTS/NX, the selected size of the soil model plays a crucial role in the accuracy of the computational results. A smaller model size can increase computational speed, but it also makes the model more susceptible to boundary effects, which can significantly influence the propagation characteristics of vibrational waves between the tunnel structure and the surrounding rock soil. Particularly when vibrational waves encounter artificial boundaries, phenomena such as wave reflection, refraction, or blocking of propagation may occur, all of which can significantly affect the simulation results. Conversely, a larger model size can more effectively simulate the propagation of vibrational waves, reducing the interference of boundary effects, but it also significantly increases the computational load, necessitating higher computational resources and longer computation times. Based on this, and considering the characteristics of the tunnel structure in this study as well as the distance between the tunnel outer wall and the boundary, the size of the soil model was determined to be 116 meters (length) \times 80 meters (width) \times 55 meters (height). The relevant parameters for each material were selected based on standards and indoor model tests, as shown in Table 1.

Table 1. Model parameters

Material Name	Model Type	Elastic Modulus (MPa)	Poisson's Ratio	Unit Weight (kN/m ³)	Cohesion (kN/m ²)	Internal Friction Angle (°)
Rail	Elastic	200000	0.3	78	-	-
Rail Pad	Elastic	34500	0.2	25	-	-
CAM Layer	Elastic	100000	0.15	18	-	-
Base	Elastic	32500	0.2	25	-	-
Tunnel Lining	Elastic	31500	0.2	25	-	-
Subgrade	Mohr-Coulomb	90	0.3	17	30	18
Miscellaneous Fill	Mohr-Coulomb	20	0.42	19	15	8
Clayey Soil	Mohr-Coulomb	68	0.32	17.8	12	18.5
Gravel Soil	Mohr-Coulomb	114	0.19	21.8	0	40
Weathered Rock	Mohr-Coulomb	500	0.3	18	20	30

2.3. Model Establishment

(1) Establishment of Boundary Conditions

In the static analysis of three-dimensional finite element models, it's sufficient to apply normal constraints at the bottom and sides of the model. However, in dynamic analysis, due to the challenge of simulating the infinite extension characteristics of soil, it's common to introduce artificial boundaries to study finite domain problems. The challenge with this method is that the setup of artificial boundaries must minimize wave reflection and other boundary effects to avoid

adverse impacts on the model's computational results. In this study, viscous boundaries are employed in dynamic analysis. These boundaries are designed to simulate the infinite domain boundaries of soil, with the advantage of effectively reducing wave reflection, thus diminishing the impact of boundary effects on the analysis results. Utilizing viscous boundaries in dynamic finite element analysis allows for controlling errors within a reasonable range, ensuring the accuracy and reliability of the analysis outcomes. Therefore, this research opts for viscous boundaries to simulate the infinite soil boundaries, aiming to enhance the precision and effectiveness

of dynamic analysis.

(2) Arrangement of Train Loads

Train vibration is a periodic loading phenomenon, originating from the intermittent contact and collision between train wheels and the track. The periodic nature of vibration is closely related to the track spacing and train speed. The generation and propagation of train vibration are influenced by various factors, including the vehicle itself, track system, supporting structures, and subsurface structures, interacting to form a complex vibration propagation phenomenon. In the Midas GTS/NX software environment, the simulation of train vibration loads can be achieved by directly inputting train dynamic load tables or using a dynamic load data generator. The generated loads can be automatically applied to the analysis model based on train speed and the distance between model nodes. This paper adopts the method of inputting train dynamic load tables to simulate the vibration loads of high-speed trains, using the KTX-type train as the prototype for the train load study. The train loads are applied along a predetermined track path, with selected nodes on the track serving as load application points. Considering that train track designs usually accommodate bidirectional travel, and the force effects generated by trains traveling in opposite directions in continuous arch tunnels are exceedingly complex, operational time optimization is employed in practice to ensure trains do not meet in the same

continuous arch tunnel. To simplify the numerical simulation and model test comparison analysis, this study only considers the scenario of trains traveling in one direction, with a load speed set at 97 meters per second.

(3) Model Establishment

In the numerical model established in this paper, there are five layers of soil structures arranged from top to bottom: railway subgrade, miscellaneous fill, clayey soil, gravel soil, and weathered rock. The physical parameters of these soil layers were determined by referring to relevant standards and conducting indoor physical model tests, ensuring the scientific validity and applicability of the parameters. Based on the dimensions of the engineering prototype and considering the numerical modeling requirements of this study, especially the continuous arch tunnel structure and the distance between the outer wall of the continuous arch tunnel and the boundary, a full-scale model as shown in Figure 1(a) is established, with dimensions of 116 meters in length, 80 meters in width, and 55 meters in height. During the analysis, the location intersecting the tunnel and railway crossing is set as the monitoring section at $Z=0$, to monitor and analyze the impact of train loads on the tunnel at this position. Additionally, monitoring points are set at locations A1 to A16, as shown in Figure 1(b). This setup helps in detailed analysis of the dynamic response of the tunnel structure to train loads, providing valuable reference data.

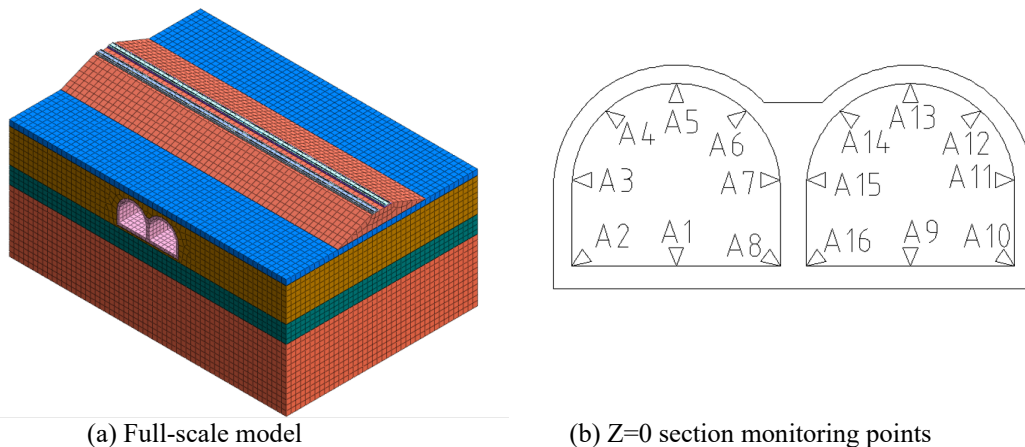


Figure 1. Three-dimensional finite element numerical model and $Z=0$ section monitoring point

3. Results Analysis

3.1. Acceleration Response Analysis

Figure 2 shows the time history curves of vertical acceleration at monitoring points A1 to A4 in the section at $Z=0$, passing through the tunnel. As the acceleration characteristics at other monitoring points are akin to those depicted in Figure 2, this paper focuses on analyzing points A1 to A4 as representative examples.

The analysis of Figure 2 reveals that the tunnel lining beneath the continuous arch experiences vibrational characteristics under the influence of dynamic loads from the high-speed train. This phenomenon primarily arises from the dynamic nature of the train loads and the intricate interplay between the soil and structure. The dynamic loads generated by the moving train, particularly due to the imperfect contact between the wheels and the track and the periodic loading between wheels, exhibit periodic variations, thereby inducing corresponding dynamic effects on the tunnel structure. The

vibrational loads during the train's passage encompass forces not only perpendicular to the track but also in horizontal (direction of train travel) and lateral (direction across the track width) directions. These forces generate dynamic strains within the tunnel lining. The interaction between the tunnel lining and the surrounding soil constitutes a complex dynamic system. When the train loads are applied to this system, vibration waves propagate through the soil and lining, eliciting strain responses in the lining. This response is intricately linked to the load characteristics, soil's dynamic properties, and the stiffness and mass of the tunnel lining, as well as their interactive dynamics. The vibration waves triggered by the train loads in the surrounding media not only directly impact the tunnel lining but also propagate, reflect, and refract through the soil and rock. These wave movements and interactions lead to varied dynamic strains across different locations and times on the tunnel lining, showcasing the vibrational nature.

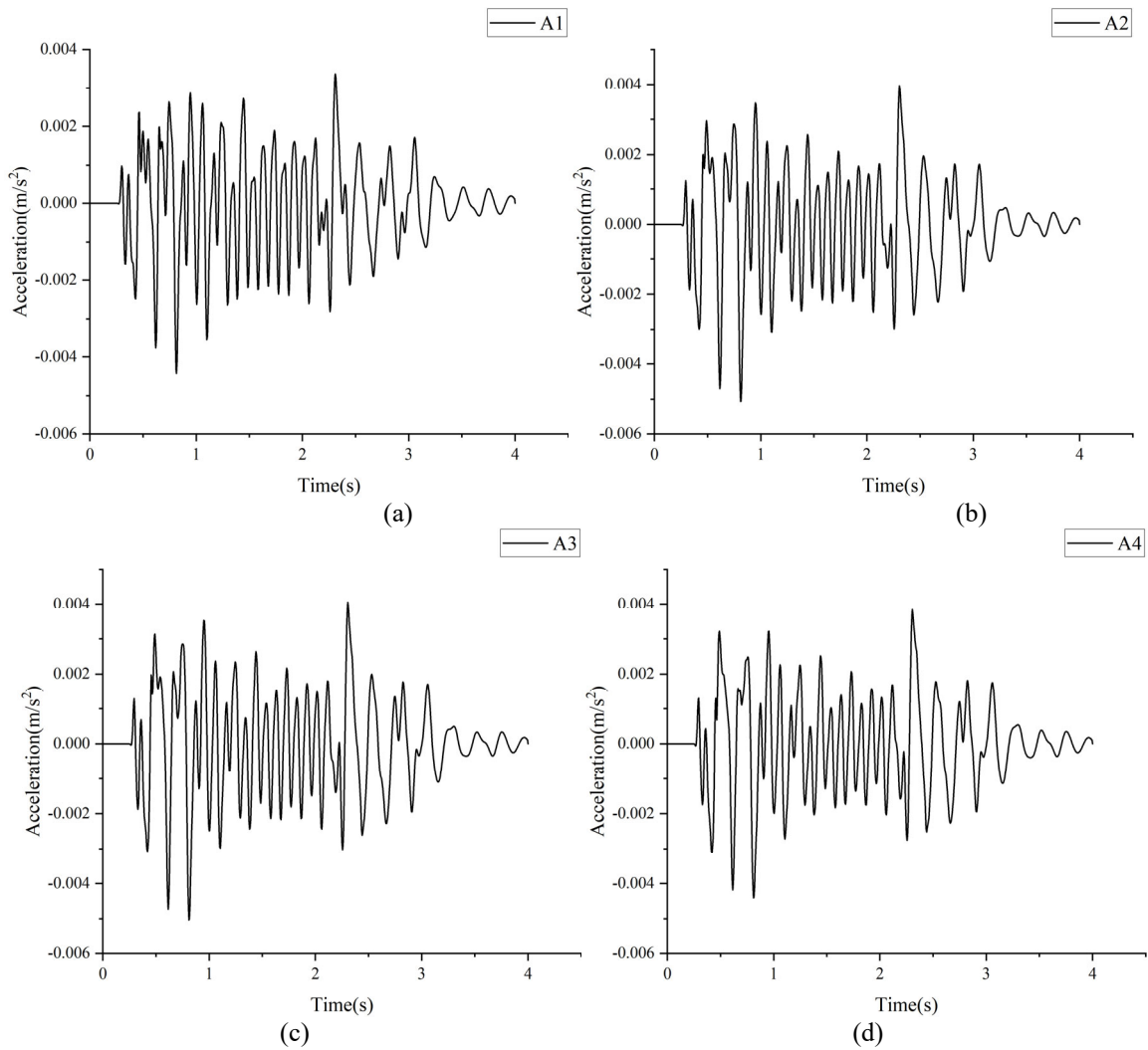


Figure 2. The vertical acceleration time history curve of the left hole A1-A4 measuring point

The acceleration time history curves at the various monitoring points on the $Z=0$ cross-section show a degree of similarity. As the high-speed train approaches, an increase in load leads to a significant acceleration increment, which gradually decreases and approaches zero after the train passes.

There's a discernible disparity in the specific values between the monitoring points on the right and left sides of the tunnel, attributed to the asymmetrical loading in the numerical simulation. However, the overall fluctuation trends and ranges are similar to those on the left side.

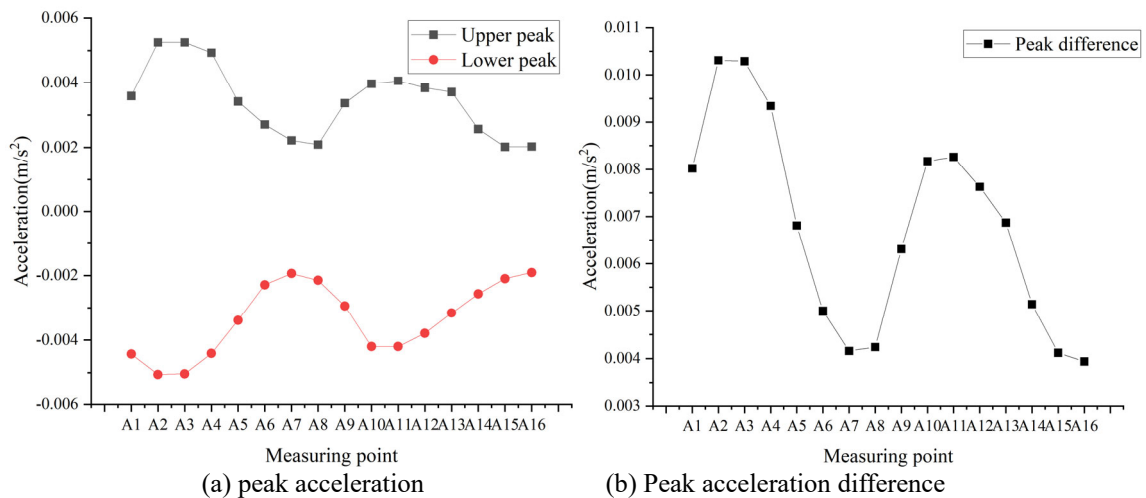


Figure 3. The vertical acceleration of each measuring point, the lower peak and the peak difference

Figure 3 illustrates the peak and trough values of acceleration and the difference between these peaks. It is observable that under the train load, the acceleration peak and

trough values at the arch feet and outer walls of both the left and right tunnels are significantly higher, with a greater peak difference. Specifically, the peak value is approximately

0.004 m/s², with a peak difference around 0.01 m/s². The acceleration peak and trough values and their differences are smaller at the mid-wall, with a peak value around 0.002 m/s² and a peak difference of about 0.004 m/s². This discrepancy likely stems from the train load being initially transmitted through the track structure to the tunnel, with the arch feet and side walls serving as primary pathways for load transfer, thereby experiencing stronger vibrations and acceleration responses. Conversely, the mid-wall, being relatively central,

encounters more dispersed and attenuated load transmission through various structural elements, resulting in a comparatively minor acceleration response.

3.2. Dynamic Displacement Response

Under the influence of high-speed railway train loads, the time history curves of vertical displacement at monitoring points A1 to A4 in the left tunnel of the cross-section at Z=0, passing beneath the tunnel, are depicted in Figure 4.

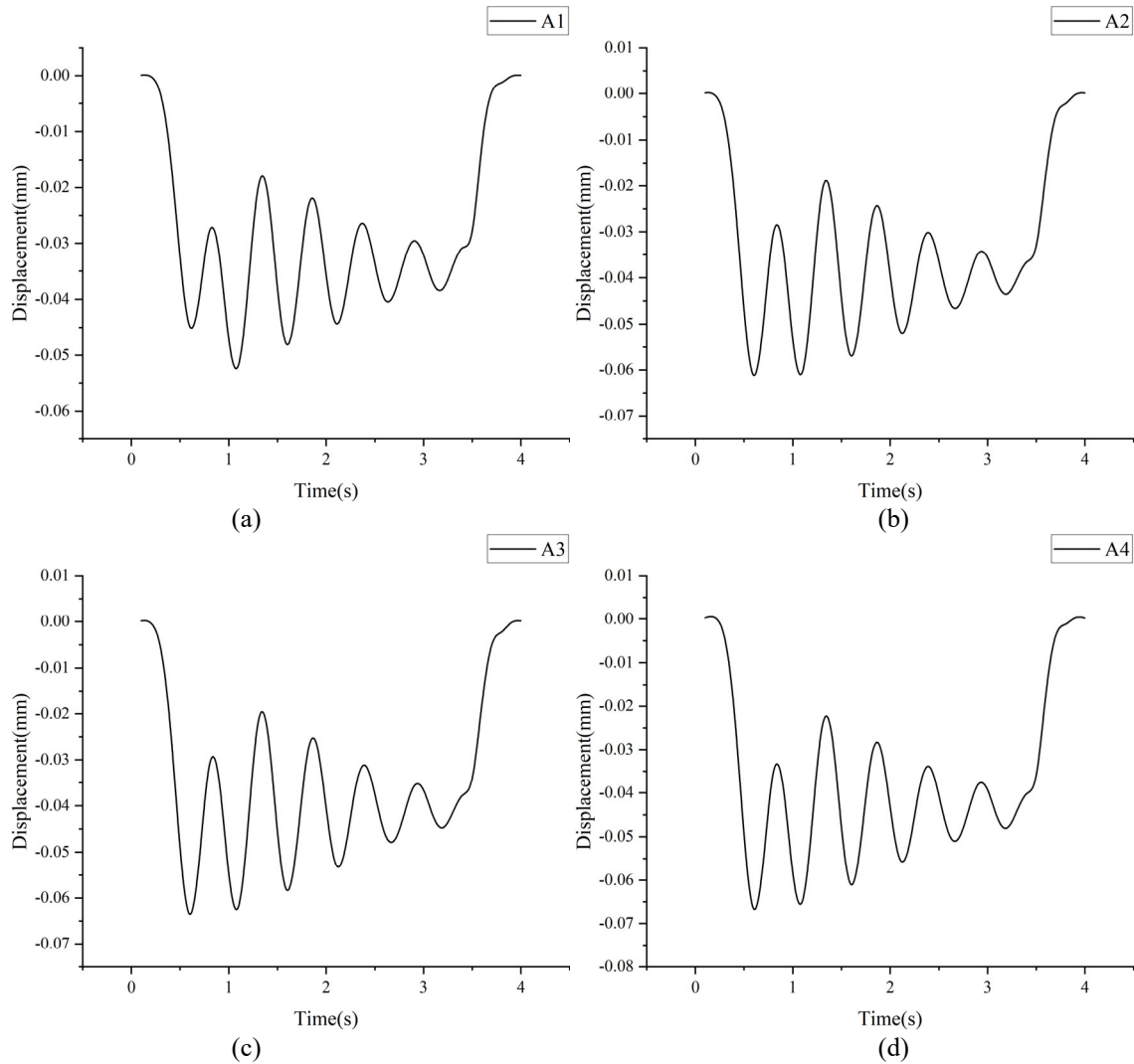


Figure 1. The vertical displacement time history curve of the left hole A1-A4 measuring point

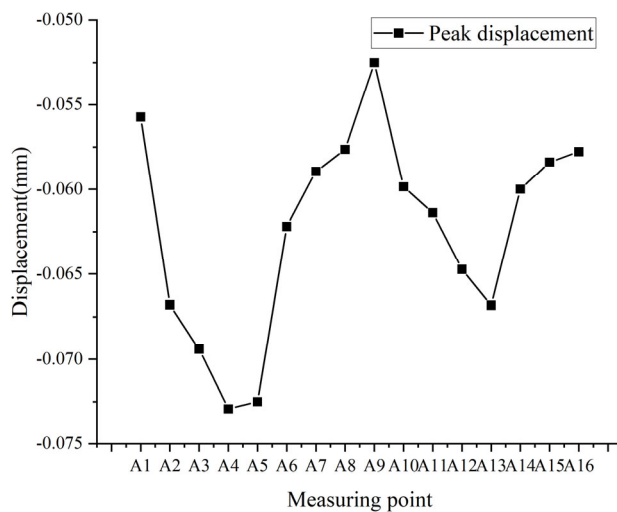


Figure 2. Peak displacement diagram of each monitoring point

Analysis of Figure 4 reveals that the monitoring points in the continuous arch tunnel exhibit vibratory characteristics under the influence of the vibrational loads from the overlying high-speed train. The vibrational response patterns at each monitoring point are similar, showing a gradual increase in vertical displacement as the train load begins to affect the tunnel, and then a gradual return to zero after the train passes. The dynamic displacement properties at the other monitoring points are similar to those observed at A1 to A4.

Figure 5 illustrates the peak vertical displacement curves at various monitoring points in the continuous arch tunnel. It is evident from the figure that the peak vertical displacements at the arch shoulders and crown are relatively large, while those at the mid-wall and the invert are smaller. Specifically, the vertical displacement at the arch shoulder of the left tunnel reached 0.0729 mm, and the vertical displacement at the invert of the right tunnel was 0.0525 mm.

The reason for this phenomenon is that the arch crown and shoulders of the continuous arch tunnel directly bear the pressure from the overlying soil layers and the impact of the

train loads. When the train passes over the tunnel, the load is directly transmitted through the soil layer to the upper part of the tunnel, especially at the arch crown and shoulders. As these parts are closer to the point of load application, they experience a greater impact of vertical displacement. Due to their structural shape and load-bearing characteristics, the tunnel arch crown and shoulders are relatively more flexible in the vertical direction and more susceptible to displacement. In contrast, the invert and mid-wall are more constrained by the surrounding soil, especially the invert, which is supported by the foundation, leading to relatively smaller vertical displacements. The train load is transmitted to the tunnel through the track and subgrade, resulting in an uneven distribution of load within the tunnel structure. The arch crown and shoulders directly bear the vertical pressure from the train load and the overlying soil, while the invert and mid-wall are further from the point of load application, thus experiencing less direct impact.

3.3. Dynamic Strain Response

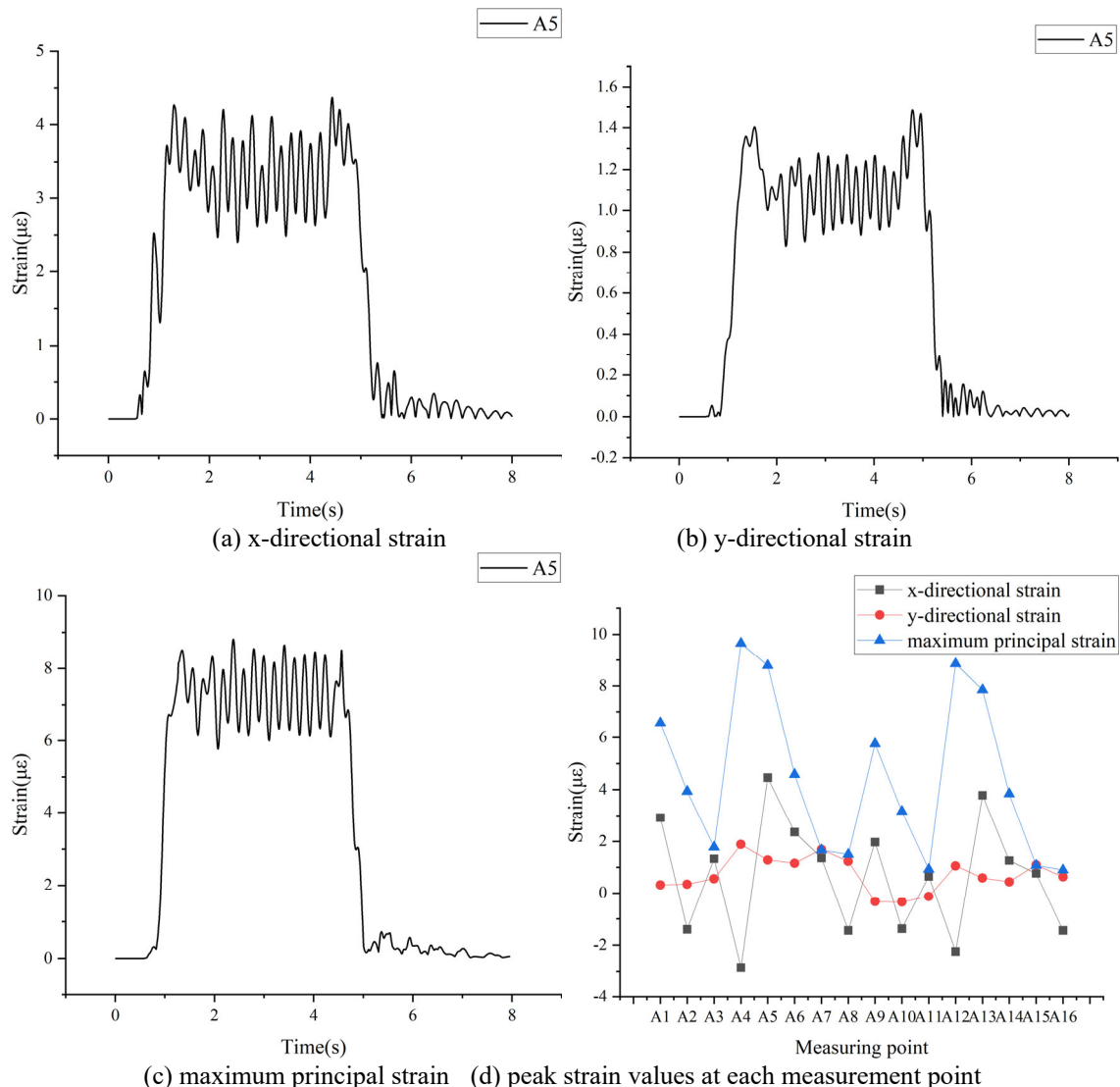


Figure 3. The strain time history curve of A5 measuring point and the strain peak value of each measuring point

In the analysis of strain in this paper, the tangential direction on the tunnel cross-section is defined as the x-direction, and the radial direction of the tunnel is defined as the y-direction. The strain responses in the x-direction, y-

direction, and the principal strain at various monitoring points in the underpass of the continuous arch tunnel exhibit similar patterns of behavior, although the fluctuation ranges differ. This paper uses monitoring point A5 in the left tunnel as an

example, as shown in Figures 6(a) to 6(c). The strain in each direction at point A5 displays vibratory characteristics, with the strain value increasing as the train enters, fluctuating within a certain range, and then decreasing back to zero as the train load moves away. Figure 6(d) shows the peak values of strain in the x-direction, y-direction, and principal strain at each monitoring point. It can be observed that the strains in the x-direction at most points are generally larger than those in the y-direction, although the x-direction strain is not always the principal strain. The difference in strain peak values between the left and right tunnels is not significant, but the strain is generally larger in the left tunnel. This phenomenon may be due to the dynamic interaction between the train and the tunnel being more pronounced on the side where the train enters the tunnel, causing the tunnel strain to peak when the train first arrives. Additionally, the damping characteristics of the tunnel materials and structure affect the strain response under dynamic loads. When the train leaves the tunnel, the internal strain of the tunnel can gradually decrease due to damping effects, resulting in smaller strain on the exiting side.

4. Main Conclusions

1. The lining of the continuous arch tunnel exhibits fluctuating characteristics in acceleration, dynamic displacement, and dynamic strain under the influence of vibrational loads generated by the train's movement. This phenomenon can be attributed to several interrelated factors. Firstly, the periodic nature of the train load leads to repeated dynamic actions on the tunnel lining, triggering fluctuating responses. Secondly, the transmission and dispersion of dynamic loads in the tunnel and its surrounding medium result in varying degrees of dynamic responses at different locations of the tunnel lining. Lastly, the interaction between the tunnel lining and the surrounding soil further complicates the response patterns, especially when considering the soil's heterogeneity and nonlinear behavior. Combining these factors, it's evident that the dynamic response of the tunnel lining under the high-speed train load is significantly fluctuating, reflecting the dynamic characteristics of the tunnel structure under complex loading conditions.

2. In the continuous arch tunnel, the arch crown and shoulders directly bear the load from the overlying soil layers and the trains passing above the tunnel. This direct action causes these areas to experience larger vertical displacements when the train passes through, with the response being particularly pronounced due to their proximity to the point of load application. Conversely, the invert and the mid-wall are located farther from the load application point, hence experiencing less direct load impact. In numerical simulations, the maximum vertical displacement observed at the arch shoulder of the left tunnel reached 0.0729 mm, while the maximum vertical displacement at the invert of the right tunnel was recorded at 0.0525 mm. These results further validate the differential response of various tunnel structure

parts under load, illustrating the dynamic behavioral characteristics of the continuous arch tunnel under complex loading conditions.

3. In the strain monitoring of the underpassing continuous arch tunnel, the strain responses in the x-direction and y-direction, as well as the principal strain at various monitoring points, exhibited a degree of similarity, despite differences in fluctuation ranges. As the train entered the tunnel, the strain values at the monitoring points increased, fluctuated within a certain range, and eventually decreased to zero as the train load moved away. Throughout this process, the strain in the x-direction at the majority of the monitoring points was significantly greater than that in the y-direction, although the x-direction strain was not always the principal strain. Moreover, comparing the peak strain values between the left and right tunnels, although the difference is not significant, the peak strain values are generally higher in the left tunnel. These observations reveal the complex strain response behavior of the continuous arch tunnel under train load, reflecting the tunnel's strain distribution characteristics in different directions and its sensitivity to the dynamic impact of train loads.

References

- [1] Jones, D. V. , & Petyt, M. . (1993). Ground vibration in the vicinity of a strip load: an elastic layer on an elastic half-space. *Journal of Sound & Vibration*, 161(1), 1-18.
- [2] J., Bitzenbauer, J., & Dinkel. (2002). Dynamic interaction between a moving vehicle. *Archive of Applied Mechanics*.
- [3] Kaynia, A. M. . (2000). Ground vibration from high-speed trains: prediction and countermeasure. *Journal of Geotechnical & Geoenvironmental Engineering*, 126(126), 531-537.
- [4] Dieterman, H. A. , & Metrikine, A. . (1996). The equivalent stiffness of a half-space interaction with a beam. critical velocities of a moving load along the beam. *European Journal of Mechanics - A/Solids*, 15(1), 67-90.
- [5] Dawn, T. M. , & Stanworth, C. G. . (1979). Ground vibration from passing trains. *Journal of Sound and Vibration*, 66(3), 355-362.
- [6] Zhang Huijian, Liu Gongning, Liu Qiuyang, Chen Zekun, Wang Zhengzheng & Niu Xiaoyu. (2023). Vehicle-induced dynamic response characteristics of a new subway tunnel closely undercrossing the existing subway. *Soil Dynamics and Earthquake Engineering*
- [7] Su Sanqing, Yin Tao, Cao Zhen, Lei Bin, Liu Zhao, Lin Wenxu & Kuang Anyuan. (2022). Dynamic Response Analysis of Super Shallow-Buried Rectangular Tunnel. *Advances in Civil Engineering*
- [8] Wenbo Yang, Chengping Zhang, Dexiong Liu, Jiulin Tu, Qixiang Yan, Yong Fang & Chuan He. (2019). The effect of cross-sectional shape on the dynamic response of tunnels under train induced vibration loads. *Tunnelling and Underground Space Technology incorporating Trenchless Technology Research* 231-238.