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Research Article

DLSM Simulation Analysis of the Influence of Blasting Construction on Adjacent Tunnels in Rock Mass with Discontinuities

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In order to study the influence of blasting construction of rock mass with discontinuities on adjacent tunnels, a feasible blasting scheme is formulated to ensure the safety of adjacent tunnels during construction. Based on the water resources allocation project in the Pearl River Delta, a tunnel construction model is established by using continuous-discontinuous medium mechanics calculation model, Distinct Lattice Spring Model (DLSM), to simulate the impact of blasting construction of the left tunnel on the right adjacent tunnel. According to the numerical simulation results, the stress wave transmission process of the left tunnel with blasting time $t = 18$ ms is analyzed. Furthermore, the effects of the positions of the discontinuity, the width of the discontinuity, and the angle between the discontinuity and the horizontal direction on the adjacent tunnel are studied. The modelling results show that the existence of discontinuities plays a certain role in improving the safety of adjacent tunnels in the blasting stage. The farther the distance between the discontinuity and the adjacent tunnel is, the smaller the impact of blasting on the adjacent tunnel is. In the process of blasting, the larger the width of discontinuity is, the more effective it is to block the influence of blasting stress wave on the adjacent tunnel. The smaller the angle between discontinuity and horizontal direction, the smaller the impact of blasting on adjacent tunnels.

1. Introduction

With the development of China's economy in recent years, the infrastructure construction has also developed with a fast speed. Major projects, such as the South-to-North Water Division Projects and West-to-East Gas Pipeline, have been implemented, indicating that the domestic tunneling projects are no longer limited to single-track tunnels. The double-track tunnel projects will bring higher economic benefits. With the increase of tunnel burial depth, the rock hardness and construction difficulties will increase, and the requirements of tunnel construction methods also are tending to be higher gradually. Among these construction methods, Drilling and Blasting method (D&B) is one of the most efficient and economic options [1].

During the D&B process, whether it is a double-track tunnel project or a single-track tunnel project, the surrounding rock mass of the tunnel will inevitably be affected during construction. Apart from that, when the site of D&B process is located near the buildings or existing tunnels, the impacts bringing to the building surroundings induced by blast stress wave also cannot be neglected [2], and it can even cause the instability of the surrounding buildings and structures. Although the technology is developing, new blasting technology [3] also has been continuously applied to tunnel excavation in rock stratum, and these technologies can effectively control the stress wave and disturbance zone. In most cases, it is limited by the efficiency and rock strength; the traditional blasting techniques are still widely used. Therefore, analyzing the impacts of tunnel brought by blasting has both practical significance and engineering values. The current general research method is to simulate the physical process of blasting by numerical simulation [4], so as to analyze the influence of blasting on tunnel surrounding rock, due to the limitation of monitoring means. Jia et al. [5] established the numerical model of the influence of blasting on lining vibration by using finite element method and provided the simulation methods of loading time and peak load and analyzed the impact of tunnel lining by blasting. Bi and Zhong [6] analyzed the impacts of existing tunnels by ANSYS according to different tunnel spacing and types of surrounding rock. Yu et al. [2] applied ANSYS/LS-DYNA to simulate the vibration response mechanism of the framework of adjacent buildings frame structure under tunneling blasting effects. And current analysis software types used in blasting simulations are FLAC3D, MIDAS/GTS, LY-dynamics and so on. These software types are mostly analyzed based on the finite element, ignoring the features like discontinuity and nonuniformity [7]. Apart from that, related numerical methods also include the discrete element [8], the boundary element [9], and discontinuous deformation [10]. Although these methods are successfully used in many blasting related analyses, the blasting belongs to a large deformation and the grasp of spread rules of stress waves is strictly controlled during the simulation processes. These analyzing methods still pose limitations on this aspect and continuous surface. Distinct Lattice Spring Model (DLSM) [11] is a continuous-discontinuous numerical calculation method, which can show the reality of continuity of layered rock mass and discontinuity between joints, with good optimization according to the spread law of stress waves, and can show the process of stress wave spreading again. As pointed out and investigated by Zhao [12], DLSM is very efficient in wave propagation problems. It could simulate the wave propagation problems with good accuracy and good agreements with experimental results. It is known that wave propagation is one of the key features of explosion problems; thus DLSM might have special potential on modelling of blasting wave propagation problems. Similar work based on DLSM can be found in [13, 14] for the cases of zonal disintegration and cavity on tunnel stability. Field work analysis for tunnel stability also can be referred to soil-water inrush case study by Huang et al. [15] and tunnel lining study by Lei et al. [16].

In this paper, in order to analyze the effect of blasting process of one side to another side of tunnel during the construction process of double-line tunnel, the numerical analysis model DLSM is used to analyze the actual tunnel engineering case in the Pearl River Delta water resources allocation project. Firstly, the general situation of specific projects is briefly introduced. Then the related principles of DLSM software are introduced, and the models and related methods constructed in this paper are introduced. Finally, through numerical simulation, the influence of the position of discontinuity, the width of discontinuity, and the angle between discontinuity and horizontal direction on adjacent tunnels are studied.

2. Project Overview

Located in the south central of Guangdong province, Pearl River Delta water resources allocation project is a crucial water resources allocation project put forward in "Comprehensive planning for the Pearl River Basin (2012–2030)" and it is also one of the 172 major water conservancy projects to save and supply water in China. The total length of the main water delivery line is about 90.3 km, starting from Liyuzhou, the mainstream of Xijiang River. After being pressurized by the pumping station, the water will be delivered to the newly built Gaoxinsha Reservoir at the intersection of Nansha New District by a double-line shield tunnel, with a line length of about 41.0 km. After being pressurized by Gaoxinsha Pumping Station, the water is delivered to Shaxi high-level pool on the south side of Shaxi Reservoir in Dongguan by single-line shield tunnel and then delivered to Luotian Reservoir in Shenzhen by single-line mountain tunnel, with the line length of about 49.3 km, of which the single-line shield tunnel is about 30.7 km long and the mountain tunnel is 18.1 km long.

The proposed water pipeline of the project is located in the plain area of the Pearl River Delta, among which the Liyuzhou-Gaoxinsha pipeline is located in Foshan area and Guangzhou area, respectively. In this area, the surface water system is developed, the river network is dense, and the groundwater level is shallow. The underground structure is mainly composed of Quaternary strata silt, silty sand layer, medium-coarse sand layer, cohesive soil layer, muddy siltstone layer, etc., among which the sand gravel layer has strong water permeability. Therefore, most of the water resources allocation projects along the Pearl River Delta pass through the areas along the route in the form of tunnels, in which TBM or drilling and blasting method is used for construction in some areas with rock strata underground. The main stratum introduction is shown in Table 1 and Figure 1.

Apart from that, the local soil layers are mingled with strongly weathered siltstone, totally weathered argillaceous siltstone, wear weathered granite, conglomerate, and siltstone containing conglomerate, among which the strongly weathered and fully weathered argillaceous siltstone are relatively soft, and weakly weathered granite, conglomerate, and siltstone containing conglomerate are hard.

3. DLSM Introduction and Model Overview

DLSM is a rock dynamics calculation model developed by Professor Zhao Gaofeng in Tianjin University based on continuum-discontinuous medium mechanics. Through DLSM, the material is dispersed into particles of different sizes, which are similar to the particles in PFC calculation software. These particles are the basic units of the material model-spherical units. At the same time, the ball units are connected with each other, and finally a material body with certain strength [8] is formed.

In DLSM calculation, when the gap between two particles is less than a given threshold, two particles will be connected together by a bond through the center point, which is composed of a normal spring and a shear spring, and the normal spring and the shear spring have certain strength. If the gap between two particles is greater than a given threshold distance, the spring will be broken, and local damage will occur. Therefore, the threshold will affect the

Table 1: Stratum conditions.

Main strata	Features
Silty soil	Light grey, dark grey, saturated, plastic flow to soft plastic condition, contains minor organic matter and humus layer, multisandwich thin layer of fine. The luster reaction is smooth with no shaking reactions. High dry strength and high toughness.
Silt	Grey, slightly dense to medium dense, the main composition id Quartz sand silt, with minor clay.
Medium to coarse sand	Grey, grey colour, saturated, slight to medium dense. Main composition are Quartz sand and it contains minor clay.
Cohesive soils	graphite, grey, light grey, grayish yellow, plastic to hard plastic, minor amount of slightly shiny shake reaction, medium dry strength, medium toughness.
Argillaceous siltstone	Dark grey, powder grain, layer structure, argillaceous cement fractures are developed and cores are in short columns.

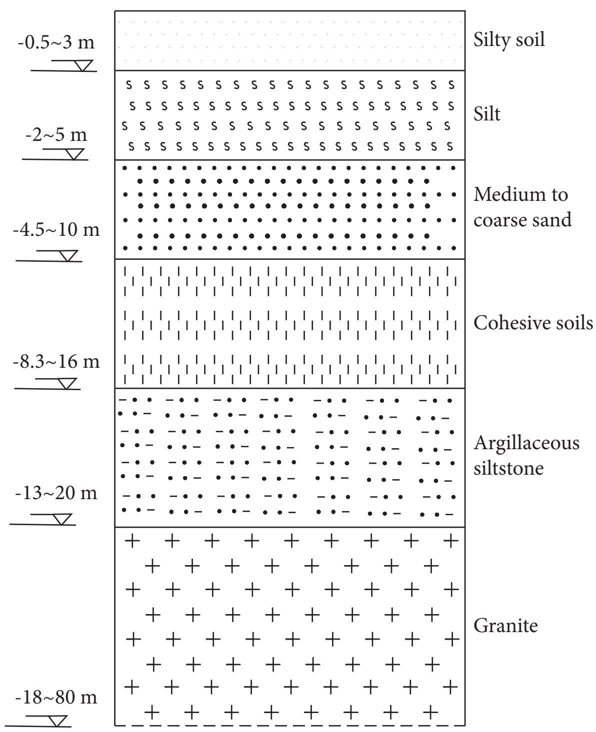


Figure 1: Stratum layout.

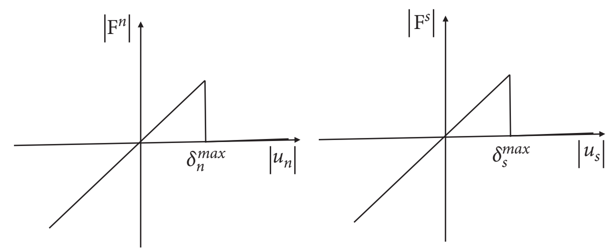


Figure 2: Constitutive model in DLSM.

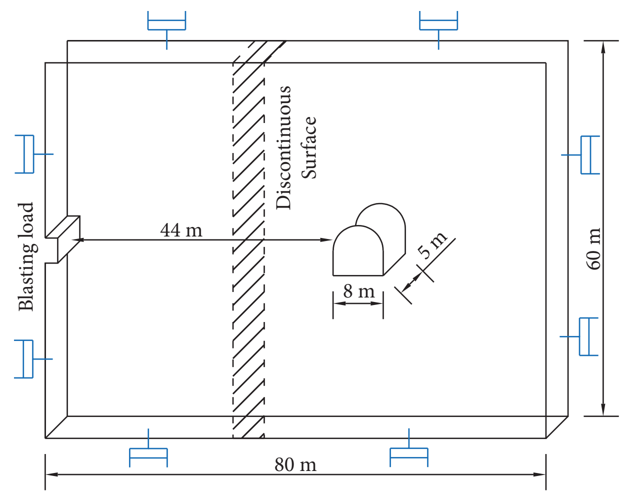


Figure 3: Calculation model diagram.

lattice structure of the model, and different thresholds will produce different lattice structures, which will have certain influence on the strength of the material system. Figure 2 is a schematic diagram of DLSM constitutive model. Because of the existence of normal spring and shear spring at the same time, when DLSM calculation software is used to analyze rock dynamic characteristics, only the elastic modulus and Poisson's ratio of rock mass can be input to calculate the strength of the spring, so that the continuity and local damage of rock mass can be fully considered. For the blasting simulation with discontinuities studied in this paper, DLSM software has unique advantages, which can well simulate the propagation of blasting stress wave in surrounding rock with discontinuities.

In this paper, the geotechnical calculation model DLSM is used to establish a 3D model. Because the newly built Gaoxinsha Reservoir from Liyuzhou to the intersection point of Nansha New District in the mainstream of Xijiang River uses a double-line shield tunnel to deliver water, the influence of the left tunnel blasting construction on the right adjacent tunnel is simulated here, and the calculation model is shown in Figure 3. The size of the model is 80 m × 60 m × 5 m, the explosion drilling is simplified to a rectangular box of 2 m × 4 m × 5 m, and the minimum distance of tunnel blasting is 44 m. In this study, only the responses of surrounding rock near the tunnel are studied. We separated the calculation region from the whole stratum. To eliminate the effects of those separated surfaces on dynamic response, nonreflection boundaries are applied on separated surfaces. The axial displacement of the front and rear faces of the tunnel is taken as the fixed boundary to simulate the plane strain problem, and the left, right, and bottom surfaces are set as no reflection boundaries.

In order to analyze the blasting impacts on each surface of the tunnel, the monitoring points are arranged at the arch foot, arch wall, and vault, respectively. In order to simplify the calculation, the loading stress diagram is simplified to triangular impulse load, which is the same as stated by literature [17], and relative curve is shown in Figure 4. The time of maximum stress is $t_e = 0.0005$ s, the blasting end time is $t_m = 0.0025$ s, and the total time is $t = 0.018$ s. At the same time, in order to simplify the model, let the blasting stress spread even to the defiled line of blast holes, which means that the delay time of explosion on different surfaces is ignored.

Only the adjacent tunnel is studied. Only one stratum is included inside the calculation region. Thus, only one set of material parameters is used. According to the actual situation of Liyuzhou-Gaoxinsha pipeline project, relevant parameters of tunnel surrounding rock are selected, as shown in Table 2.

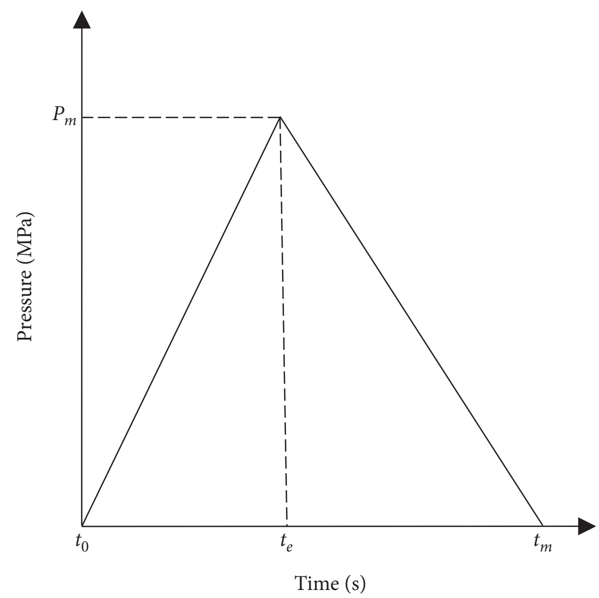


Figure 4: Loading curve.

Table 2: Geotechnical parameters used in calculation.

Density (kg/m^3)	Normal elastic modulus (GPa)	Elastic modulus of joint (GPa)	Poisson's ratio	Inner friction angle (°)	Cohesion (kPa)
2650	74	7.4	0.18	20	30

4. Results and Analysis

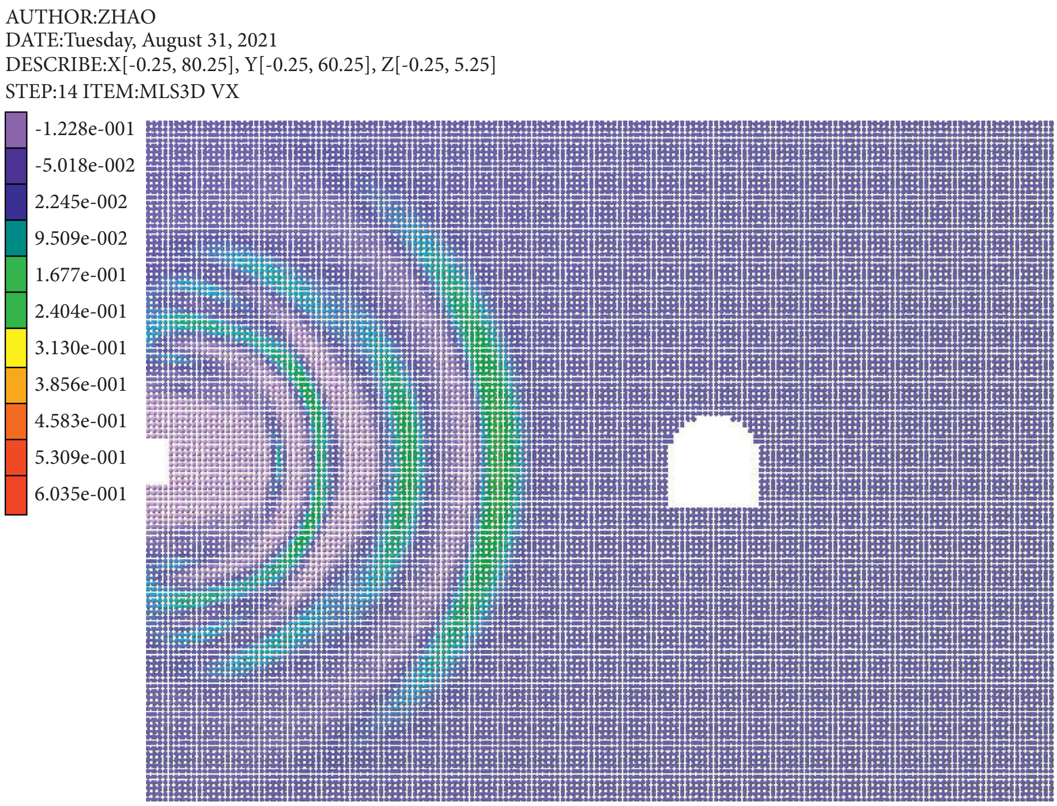
4.1. Stress Wave Transmission Process Analysis. Figure 4 shows the spread process of stress wave at $t = 6$ ms and $t = 8$ ms; Figure 5 shows the spread process of stress wave at $t = 9$ ms and $t = 11$ ms.

According to the stress wave transmission nephogram of $t = 6$ ms in Figure 5, it can be seen that, within 6 ms of blasting, the stress waves generated by blasting gradually spread around, including horizontal diffusion and vertical diffusion, mainly horizontal diffusion, and gradually spread to the vicinity of adjacent tunnels. According to the stress wave transmission nephogram of $t = 8$ ms in Figure 5, it can be seen that, after 8 ms of blasting, when the stress wave is transmitted to a position near the tunnel, the stress will be reflected and attenuated, which is the discontinuous surface near the tunnel. It can be seen that when the stress wave is transmitted to the discontinuous surface, some energy is absorbed by the discontinuous surface, and the discontinuous surface has a certain isolation effect on the stress wave. It can be seen that the existence of the discontinuous surface can weaken the blasting energy transferred to the adjacent tunnel.

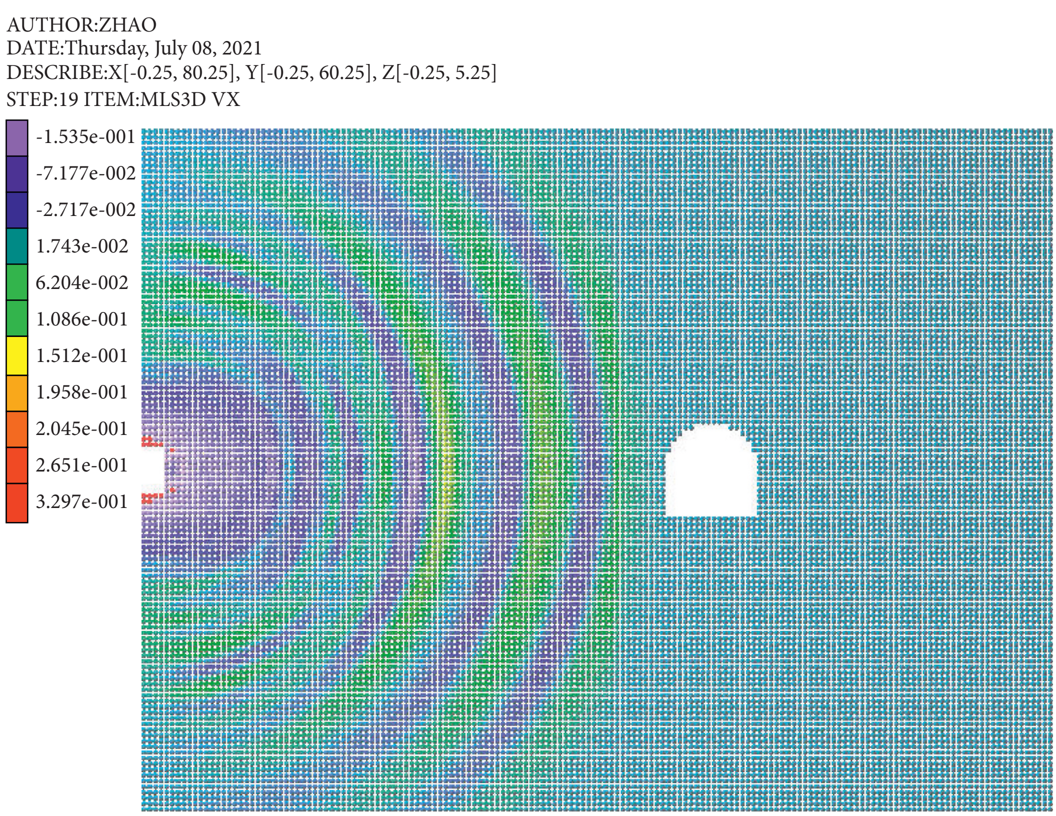
At the same time, according to the cloud image of spread of stress wave at $t = 9$ ms in Figure 6, the stress wave spreads to the left side surface of tunnel within 9 ms, and the reflection and incident superposition of vibration waves occur at the vertical wall, resulting in a certain tensile stress. According to the stress wave transmission nephogram at $t = 11$ ms in Figure 6, it can be seen that, under the influence of incidence, reflection, refraction, and other effects, the stress wave is repeatedly superimposed and its intensity is constantly decreasing, and the wave surface and shape are gradually becoming complex.

Figure 7 shows the vibration process curves of 6 monitoring locations which are left foot, right waist, vault, left waist, left foot, and bottom. It can be seen that the vibration speed is maximum at left waist location, which is close to 0.9 m/s, and then its left foot, which is slightly smaller than left waist with 0.78 m/s. And then its vault and bottom speed is 0.2 m/s. The measuring point with the smallest vibration velocity is the right waist, only 0.065 m/s. In Chinese standard GB-6722 (2014), the allowable maximum velocity for the hydraulic tunnel safety is 0.15 m/s. In our simulations, we could note that the maximum velocity in most part of the tunnel is far beyond this limit. Thus, the tunnel subjected to adjacent blasting is not safe. To control its response, supports should be implemented as quickly as possible to bring effective constrains on surrounding rocks and suppress the responses of surrounding rock mass. The vibration velocity on the left side of the tunnel reached the maximum value at about 11 ms and then gradually decreased due to the dissipation and superposition of blasting stress waves. It can be seen that the blasting vibration of the left waist and left foot of the tunnel is the most sensitive area of the surrounding rock of the whole tunnel, so it is necessary to strengthen monitoring and pay special attention for protection.

4.2. The Influence of the Distance between Discontinuities and Adjacent Tunnels. When analyzing the effects of discontinuous surface on the nearby tunnel, the width of discontinuities is uniformly set at 0.5 m, as shown in Figure 8. Figures 9 and 10, respectively, show the influence of blasting construction on adjacent tunnels when there is no discontinuity in the tunnel, with the discontinuity being 4 m and 12 m on the left side of the tunnel. The influence on the tunnel is mainly reflected by the horizontal wave velocity generated by the left arch foot, arch waist, and vault. These three positions are also the three positions where the



(a)



(b)

Figure 5: Cloud chart of stress wave transmission when (a) $t = 6$ ms and (b) $t = 8$ ms.

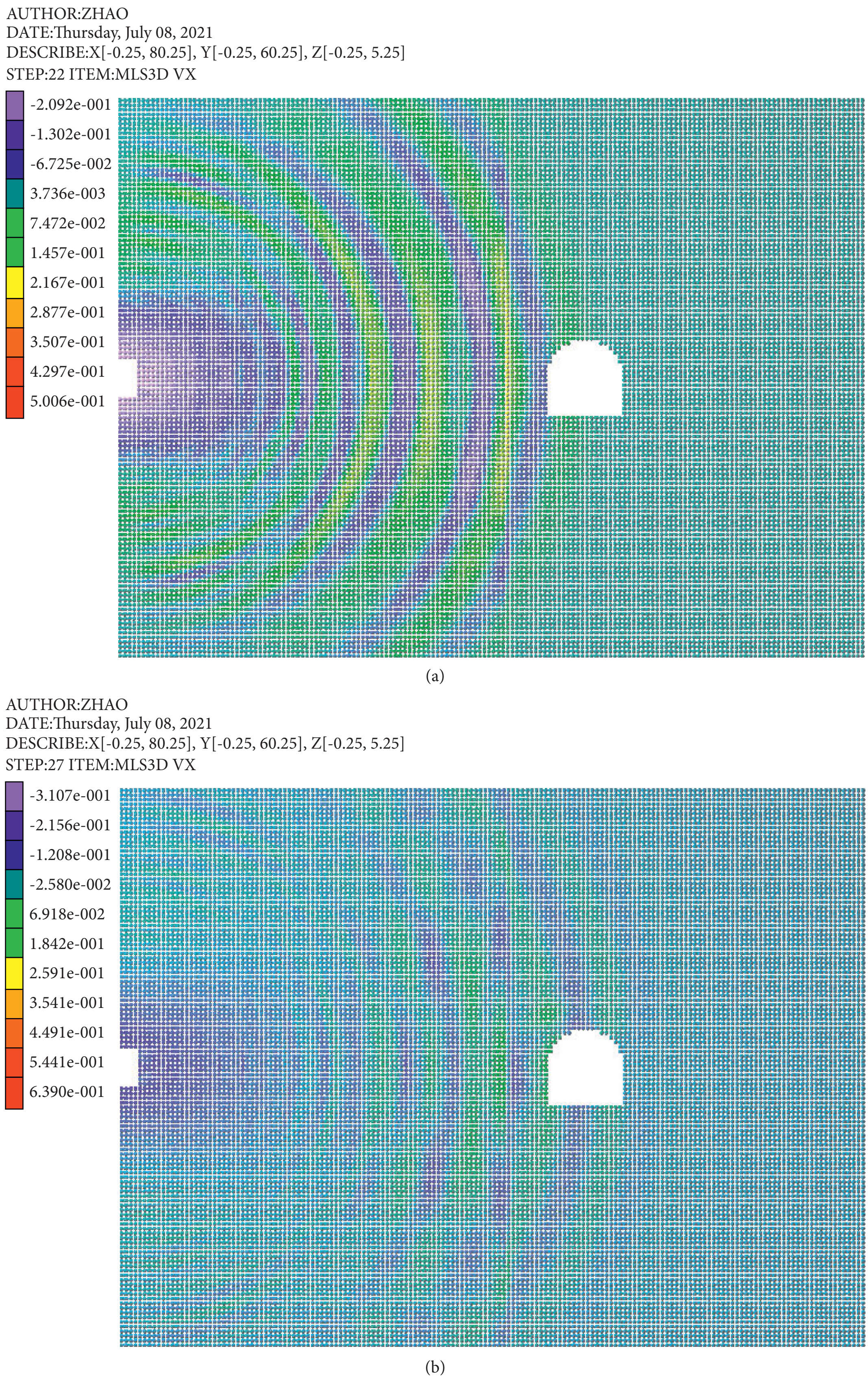


Figure 6: Cloud chart of stress wave transmission when (a) $t = 9$ ms and (b) $t = 11$ ms.

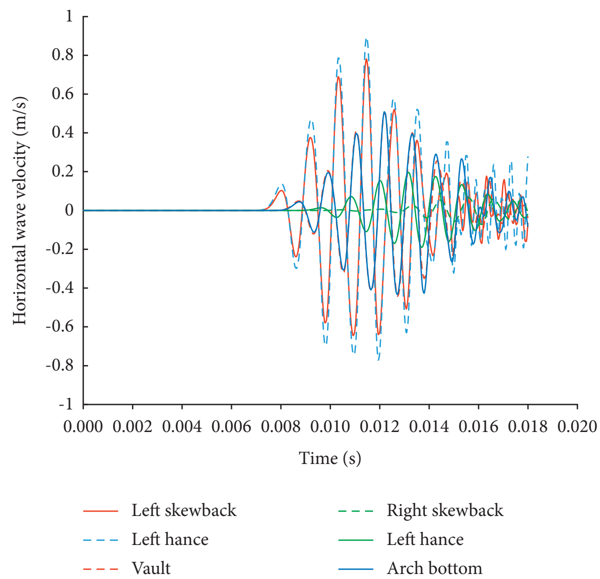


Figure 7: Time historic curve of wave velocity in different parts of tunnel.

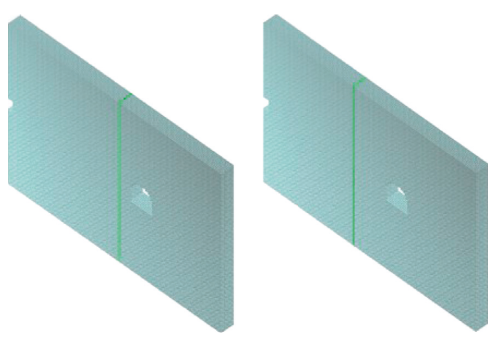


Figure 8: Schematic diagram of the model when the distance between the discontinuity and the adjacent tunnel is 4 m and 12 m, respectively.

surrounding rock of the tunnel is most likely to be damaged during blasting construction. Figure 9 is a schematic diagram of the model when the distance between discontinuity and adjacent tunnel is 4 m and 12 m.

It can be seen from Figure 9 that when there is no discontinuity in the rock mass, the maximum horizontal wave velocity of the left arch foot, arch waist, and vault of the tunnel is 0.7808 m/s, 0.8948 m/s, and 0.5035 m/s, respectively. According to Figure 9, when the discontinuity is 4 m on the left side of the tunnel, the maximum horizontal wave velocities of the arch foot, arch waist, and vault on the left side of the tunnel are 0.4296 m/s, 0.7202 m/s, and 0.3836 m/s, respectively. When the discontinuity is 12 m on the left side of the tunnel, the maximum horizontal wave velocities of the arch foot, arch waist, and vault on the left side of the tunnel are 0.4181 m/s, 0.7002 m/s, and 0.3837 m/s, respectively. It can be seen that the discontinuous surface can effectively block the impact of blasting stress wave on adjacent tunnels, and with the increase of the distance between the discontinuous surface and adjacent tunnels, the horizontal wave velocity of the left arch foot, arch waist, and vault gradually decreases, and the impact of blasting construction on adjacent tunnels is smaller, and the adjacent tunnels are much stable. Note that the response velocity of the tunnel, however, is greater than the safety control limit according to GB-6722 (2014) [18]. To ensure the safety during constructions, implementation of support should be applied to control the dynamic response.

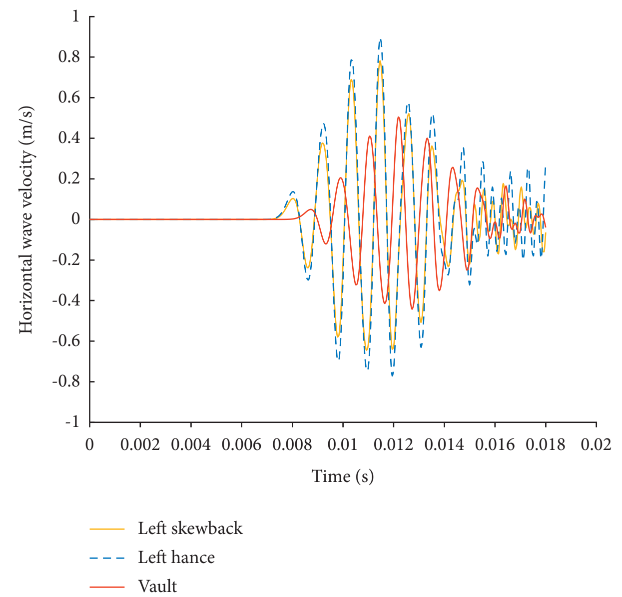


Figure 9: Horizontal wave velocity of each measuring point in tunnel without discontinuity.

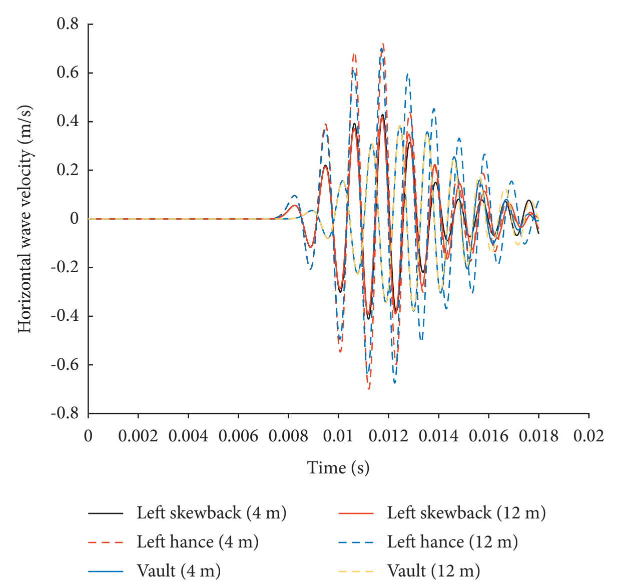


Figure 10: Horizontal wave velocity of each measuring point in tunnel when discontinuity is 4 m and 12 m on the left side of tunnel, respectively.

4.3. Analyses of Effects of Discontinuity Width on Tunnel. When studying the influence of discontinuity width, the distance between discontinuity and adjacent tunnel is set to

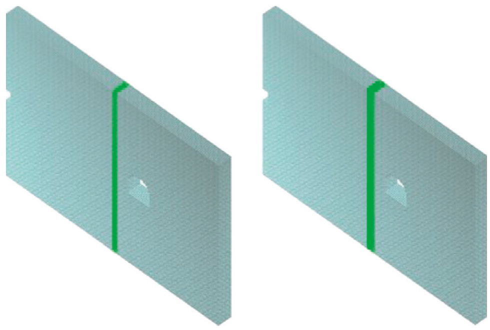


Figure 11: Schematic diagram of the model when the width of discontinuity is 2 m or 3 m, respectively.

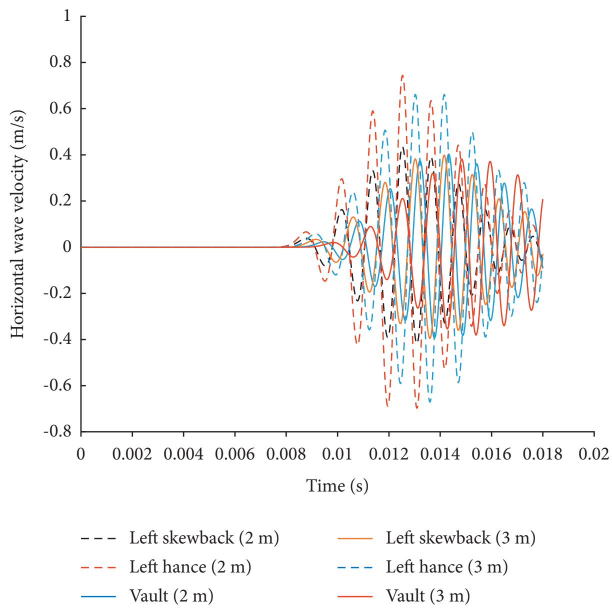


Figure 12: Horizontal wave velocity of each measuring point in tunnel when the width of discontinuity is 2 m and 3 m, respectively.

4 m. Figure 11 shows the impact of blasting construction on adjacent tunnels when the discontinuity width is 2 m and 3 m, respectively. The impact on the tunnel is mainly reflected by the maximum horizontal wave velocity generated by the left arch foot, arch waist, and vault. Figure 11 is the schematic diagram of the model when the width of discontinuities is 2 m and 3 m, respectively.

According to Figure 12, when the width of discontinuity is 2 m, the maximum wave speed from foot, waist, and vault is 0.4335 m/s, 0.7436 m/s, and 0.4026 m/s, respectively. When the width of discontinuity surface is 3 m, the maximum horizontal wave speed of the left arch foot, waist, and vault is 0.3983 m/s, 0.6612 m/s, and 0.3811 m/s, respectively. It demonstrates that, with the increase of the width of discontinuity, the maximum horizontal wave velocity of the left arch foot, arch waist, and vault of the tunnel gradually decreases, and the impact of blasting construction on adjacent tunnels becomes smaller. Based on cases mentioned above, the maximum responses of tunnel under various conditions still exceed the safety limit suggested by GB-6722 (2014) [18]. Thus, effective treatments should be used to prevent the tunnel from further destructions.

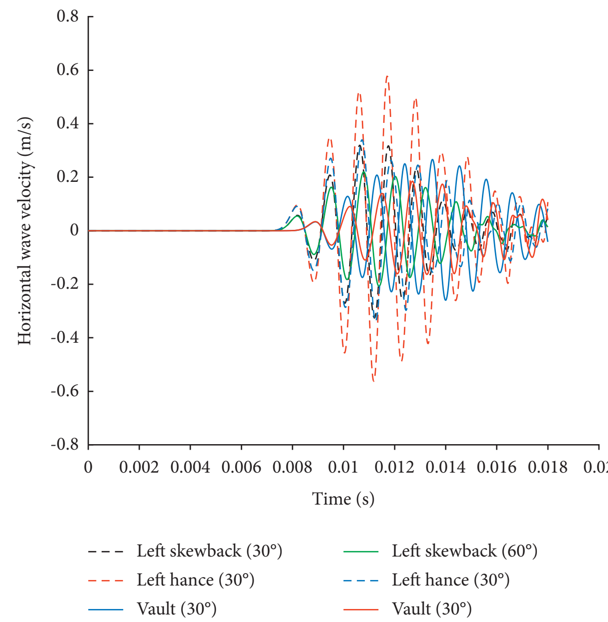


Figure 13: Horizontal wave velocity of each measuring point in tunnel when the angle of discontinuity is 30° and 60°, respectively.

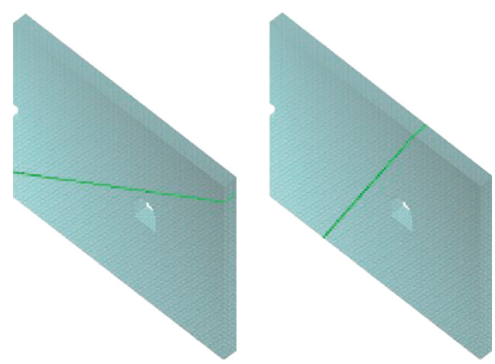


Figure 14: Schematic diagram of the model with 30° and 60° discontinuity angles.

4.4. Analysis of Impacts of Angle of Discontinuous Surface to the Tunnel. Figure 13 shows the influence of blasting construction on adjacent tunnels when the included angle between discontinuity and horizontal direction is 30° and 60°, respectively. The influence on the tunnel is mainly reflected by the maximum horizontal wave velocity generated by the left arch foot, arch waist, and vault for the tunnel subjected to stress wave. Figure 14 is a schematic diagram of the model when the angle of discontinuity is 30° and 60°, respectively.

It can be seen from Figure 14 that when the angle between the discontinuity and the horizontal direction is 30°, the maximum horizontal wave velocity of the arch foot, arch waist, and vault on the left side of the tunnel is 0.3185 m/s, 0.5769 m/s, and 0.2657 m/s, respectively; when the angle between the discontinuity and the horizontal direction is 60°, the maximum horizontal wave velocity of the left arch foot, arch waist, and vault of the tunnel is 0.2199 m/s, 0.3389 m/s, and 0.1851 m/s, respectively. Compared with the case where the included angle is 90°, when the included angle is 30 and the included angle is 60°, the maximum horizontal wave velocity of the left arch foot, arch waist, and vault of the tunnel significantly decreases, and the smaller the included angle is, the more the horizontal wave velocity decreases, and the smaller the impact of blasting construction on adjacent tunnels is. In Figure 13, all the maximum measured velocities exceed the limitation in GB-6722 (2014) [18], indicating tunnel under those conditions is not safe. For the stability analysis of tunnel lining subjected to dynamic loading, some dynamic model can be applied according to [13, 19].

5. Conclusion

In this paper, based on a practical engineering project, a well-developed geotechnical calculation model DLSM is applied to establish a three-dimensional model of the tunnel. The influence of blasting construction on one side of the tunnel on the other side of the tunnel during the double-track tunnel construction is simulated, and the influence of blasting construction and the stability of the tunnel are analyzed. According to the numerical simulation results, this paper analyzes the stress wave transmission process in the left tunnel blasting time $t = 18$ ms and studies the influence of the position of discontinuity, the width of discontinuity, and the angle between discontinuity and horizontal direction on the other tunnel. The conclusions are as follows:

(1) Different positions of discontinuities (different distances from the left side of the tunnel) have certain influence on the final horizontal wave velocity of the left arch foot, arch waist, and vault. With the distance between discontinuities and the left side of the tunnel gradually increasing, the horizontal wave velocity of adjacent tunnels affected by blasting gradually decreases.

(2) With the increase of the width of discontinuity, the horizontal wave velocity of the left arch foot, arch waist, and vault of the tunnel gradually decreases, and the impact of blasting construction on adjacent tunnels becomes smaller.

(3) The influence of the angle between the discontinuity and the horizontal direction on the final horizontal wave velocity of the left arch foot, arch waist, and vault is more significant than that of the position and width of the discontinuity. With the increase of the angle between the discontinuity and the horizontal direction, the horizontal wave velocity generated by the stress wave gradually increases.

(4) The numerical model DLSM can fully consider the discontinuous and uneven characteristics of rock and soil, and thus it can accurately analyze the impact of blasting construction and tunnel stability.

Data Availability

All data presented in this paper can be available by contacting the corresponding author (Junwei Guan).

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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