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Research Article

Numerical Analysis for Dynamic Response of In Situ Blasting Expansion of Large Cross-Section Tunnel with Small Net Distance

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Based on the Damaoshan Highway Tunnel Reconstruction and Expansion Project, the dynamic response of adjacent tunnels during the blasting excavation of existing tunnels is analyzed by using the LS_DYNA finite element software, and the blasting vibration response and lining stress change in the blasting process are studied. Taking the particle peak vibration speed as the criterion, the traffic safety of the adjacent operating tunnels is determined. Moreover, the stress changes of the adjacent tunnel lining caused by blasting excavation are studied through the maximum principal stress. The results show that the particle peak vibration speed on the front explosion side is significantly greater than that on the back explosion side, and the maximum particle peak vibration speed on the road surface is 13 cm/s, which is greater than the allowable safety standard. Besides, the maximum principal stress on the front explosion side is about 1.5 times of that on the back explosion side, showing a "quasi-bias" phenomenon. Therefore, it is recommended to control the operation of the tunnel during the blasting process and especially focus on monitoring the vibration responses and stress changes of the lining of the operating tunnel during the construction period.

1. Introduction

With the rapid economic development of China, the traffic volume of highway tunnels is gradually increasing. Due to the saturation of traffic volume in some economically developed areas, more and more expressway tunnels are expanded into two-way six-lane or even eight-lane road tunnels [1, 2]. The reasons of tunnel reconstruction mainly include structure of the tunnel constructed long time ago is too old or the tunnel structure is damaged by external forces. Moreover, due to the increase of traffic volume and disaster prevention limits, the requirements of the existing tunnels cannot be met [3, 4]. Although there are many tunnel reconstruction forms, the tunnel extension can only be carried out in situ by expanding the tunnel section and increasing the number of traffic lanes, in order to adapt to the growth of traffic volume. This is mainly due to the limitation of topography, geology, and construction conditions. The in situ extension of the tunnel has three commonly used forms: unilateral extension, bilateral extension, and peripheral extension [5, 6].

The span of the Damaoshan Highway Tunnel Reconstruction and Expansion Project is the largest in similar reconstruction projects of China. The characteristics of this project lie in the following: the tunnel section is large, the net distance between the new tunnel and the original tunnel is small, and the original tunnel will be kept in operation during the construction period [7, 8]. At present, Chinese researchers have carried out a series of studies on the reconstruction and expansion project of Damaoshan Tunnel. For example, Liu et al. [9] analyzed the cumulative damage effect of rock in the Damaoshan Tunnel Group based on the dynamic damage theory. Besides, Lin et al. [10–13] studied the vibration characteristics and regularities of the wall and middle rock of the existing operating tunnel through insite blasting tests. In addition, Sun et al. [14] studied characteristics of the deformation evolution of surrounding rock and the stress of supporting structure in the construction process of the new tunnel through the insite monitoring measurements. Moreover, Yang et al. [15] compared the deformation and mechanical properties of surrounding rock during the construction of new and expanded tunnels through numerical simulation. Furthermore, Chen et al. [16] proposed the maximum blasting charge insitu for the largest section of the Damoshan Tunnel by analyzing the influence of in situ blasting on the structural safety of adjacent operating tunnels. What is more, Li et al. [17] proposed an analytical algorithm for calculating the mechanical properties of surrounding rock during the in situ tunnel expansion, which was verified by the monitoring data of surrounding rock deformation during the expansion project in Damaoshan.

The LS-DYNA program is a fully functional geometric nonlinearity (large displacement, large rotation and large strain), material nonlinearity (more than 140 material dynamic models), and contact nonlinearity (more than 50) program. It is based on the Lagrange algorithm, combined with ALE and Euler algorithms, based on explicit solution, with implicit solution function, based on structural analysis, combined with thermal analysis and fluid-structure coupling function, and nonlinear dynamic analysis, mainly with static analysis functions (such as prestress calculation before dynamic analysis and springback calculation after sheet stamping and forming).

In the construction process of in situ tunnel expansion, the adjacent tunnels are planned to maintain normal traffic operation, so it is very important to ensure their operation and structural safety under the blasting load. In this study, the dynamic response of adjacent tunnels during the blasting excavation of existing tunnels is analyzed by using the LS_DYNA finite element software, which is based on the Fujian Quan-Xia Expressway Damoshan Tunnel Expansion Project, and the blasting vibration response and lining stress change in the blasting process are studied. According to these analyses, relevant suggestions are put forward to ensure the traffic safety of the operating tunnels, and it is expected to provide valuable references for similar tunnel reconstruction and expansion projects.

2. Project Overview

Damaoshan Tunnel is located in the Xiamen section of Quan-Xia Expressway which is called as the "First Road of Fujian" in Fujian Province of China. The original tunnel is a two-hole and four-lane separated tunnel with a total length of 600 m. The tunnel reconstruction and expansion project is to build a four-lane tunnel between the two original tunnels and expand the right tunnel into a four-lane tunnel in situ. The net distance between the original two-lane tunnel and the newly built four-lane tunnel is 5.89 m and that between the newly built and the expanded four-lane tunnel is 8.83 m, which is a typical tunnel with small net distance. After the completion of the expansion, the tunnel can meet the traffic requirements of a single hole with four lanes, a span of 22 m, and a cross section area of 255 m^2, of which the span is the largest in China. A rare tunnel group with large cross-section and small net distance is formed by the original tunnel, the newly built tunnel, and the expanded tunnel [18–33]. The cross-section layout of the tunnel group is shown in Figure 1.

According to the tunnel reconstruction and expansion plan, the tunnel group from left to right is two-lane tunnel (the original tunnel, which maintains traffic during construction and will be abandoned or used for other purposes after construction completed), newly built four-lane tunnel, and the in situ expanded four-lane tunnel (the expansion begins after the completion of the newly built four-lane tunnel). The illustration of the reconstruction and expansion of the tunnel is shown in Figure 2.

3. Numerical Calculation Scheme

3.1. Numerical Calculation Model. Large-scale dynamic finite element calculation software LS_DYNA is used to carry out the simulation of in situ blasting expansion. According to the construction plan of the in situ tunnel expansion, the original secondary lining is dismantled first; then, blasting excavation is carried out on the left guide pit, but this plan produces the most negative effect on adjacent operating tunnels. Therefore, in the numerical simulation, the typical section of IV class perimeter rock is selected, and the explosive is set in the left guide pit of the in situ expanding tunnel, while the equivalent TNT explosive is simplified into a cube loading. The model size of surrounding rock is $150\,m \times 100\,m$, and a single-layer mesh is taken for the tunnel axial. The partial diagram of the numerical model is shown in Figure 3.

The calculation algorithms of LS_DYNA mainly include the Lagrange algorithm, Euler algorithm, and ALE algorithm. In order to avoid calculation errors caused by grid distortion, the ALE algorithm is used for blasting simulation. The surrounding rock, primary support, and secondary lining are connected by common nodes, and Lagrange algorithm is used, while the ALE algorithm is also applied for explosives and air. The propagation of blast wave in the surrounding rock and its interaction with primary support and secondary lining are realized by the fluid-solid coupling method. In order to improve the calculation accuracy, regular quadrilateral SOLID164 element and hexahedral mapping grid are employed in the model, and the surrounding rock grid size is about 20 cm. The nonreflective boundary condition is adopted to avoid the reflection of shock wave around the surrounding rock.

3.2. Material Model and Parameter Settings. The explosive material is modeled by a high-energy explosive material defined in the numerical software (*Mat_high _Explosive_Burn), and it is described by the JWL state equation (*Eos_Jwl). The explosive detonates at the center of charge, with the explosive density of 1300 kg/m^3 and detonation velocity of 4000 m/s. The equation of explosive state is defined as

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V}, \quad (1)$$

where P is the pressure, V is the relative volume, E is the internal energy density, and A, B, R_1, R_2, and ω are the explosive constants. Wherein, $A = 214$ GPa, $B = 0.18$ GPa, $\omega = 0.15$, $R_1 = 4.2$, and $R_2 = 0.9$.

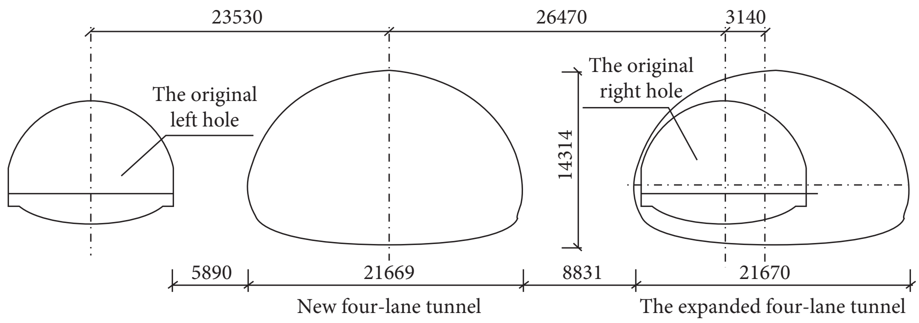

Figure 1: Layout of tunnel section (unit: mm).

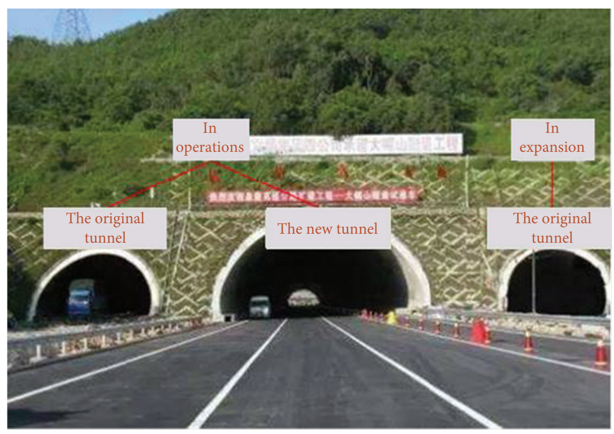

Figure 2: Illustration of reconstruction and expansion of tunnel.

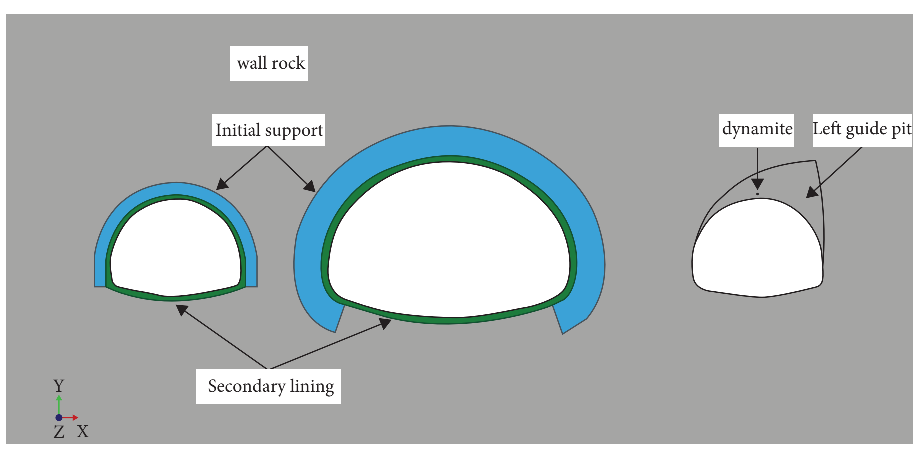

Figure 3: Partial diagram of the numerical calculation model.

Air is simplified as a nonviscous ideal gas, and the *Mat_Null material model is adopted for the air. The expansion process of the shock wave is assumed to be an isentropic adiabatic process, and the linearly polynomial state equation (*Eos_Linear_Polynomial) is used to describe this process. The state equation of air is defined as

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + \left(C_4 + C_5\mu + C_6\mu^2\right)E, \quad (2)$$

where C_0, C_1, C_2, C_3, C_4, C_5, and C_6 are the constants related to gas properties, $C_0 = C_1 = C_2 = C_3 = C_6 = 0$, and $C_4 = C_5 = \gamma - 1$; $\mu = \rho/\rho_0 - 1$; ρ_0, ρ, γ, and E are the initial density, density, adiabatic index, and internal energy density, respectively. Wherein, $\rho_0 = 1.293\,\mathrm{kg/m^3}$, $\gamma = 1.4$, and $E = 0.25\,\mathrm{MPa}$.

The ideal elastoplastic model is used for the surrounding rock and initial support (*Mat_Plastic_Kinematic). The parameters of initial support are represented by the increased surrounding rock properties, such as the 50% increased elastic modulus or yield stress. The secondary lining uses the J-H-C material model (*Mat_Johnson_Holmquist _Concrete). According to the geological survey report of the Damaoshan Tunnel and the reference of "the Road Tunnel

Design Specification," the physical and mechanical parameters of the surrounding rock, initial support, and secondary lining are determined and given in Table 1.

4. Calculation Results and Analysis

4.1. Vibration Control Analysis of Operating Tunnels

4.1.1. Blasting Vibration Velocity Control Threshold. Vibration caused by tunnel blasting has a negative effect on the surrounding rock and adjacent structures, and the in situ expansion blasting-induced vibration will affect the traffic safety of adjacent operating tunnels. Therefore, research studies on the vibration control of the tunnel in situ expansion blasting process should be conducted. The current promulgated "Blasting Safety Regulations" (GB6722-2014) of China regards the peak particle vibration velocity as the index of the allowable safety standard for blasting vibration, and the allowable safety standard is set at 10–20 cm/s for traffic tunnels.

By analyzing available literature, the blasting vibration velocity control thresholds of some tunnels with small net distance in China are summarized in Table 2. Through the combination of engineering practice and literature analysis, the maximum vibration speed of the surrounding rock and lining of existing tunnel is 15 cm/s due to the blasting construction of the new tunnel. Therefore, when the road vibration speed is less than 10 cm/s, no noticeable vibration will be aware when the car passes the tunnel in a quick speed. In the particular view of the Damaoshan Tunnel Reconstruction and Expansion Project, in order to ensure the traffic and structural safety of the adjacent operating tunnel, the secondary lining vibration threshold of the operating tunnel is set as 15 cm/s and the road vibration threshold is set as 10 cm/s.

4.1.2. Vibration Analysis of Adjacent Tunnels. During the numerical simulation process, monitoring points are set in the vaults, arch shoulders, arch waists, arch feet, and arch bottoms of the newly built four-lane operating tunnel to monitor the vibration effect of blasting expansion on the operation tunnel. The full section peak vibration velocity envelope of the original two-lane operating tunnel and the newly built four-lane operating tunnel is shown in Figures 4 and 5, respectively.

As can be seen from Figures 4 and 5, the peak vibration velocities at the arch shoulder and waist are the largest, followed by the vault and arch foot, and the arch bottom is the lowest. The peak vibration velocity of the side near the explosion is obviously higher than that of the side away from the explosion. Due to the long distance from the explosion point, the power response of the support structure of the original operating tunnel is smaller than that of the newly built operating tunnel. Therefore, when the construction of blasting expansion is carried out, the traffic and structural safety of the adjacent newly built four-lane operating tunnel should be paid more attention.

According to the simulation analysis of several blasting groups, the peak vibration velocity at the tunnel shoulder is about 1.5–4 times of that at the tunnel bottom, and the peak vibration velocity at the side near the explosion is about 5–10 times of that at the side away from the explosion. Therefore, the in situ expansion blasting has a great influence on the adjacent operating tunnel, and the shoulder and waist of the operating tunnel are the weak links during the blasting excavation. Thus, in the construction process, special attention should be paid to the blasting vibration response of the arch shoulder and waist at the side near the explosion in the adjacent operating tunnel.

Through numerical simulation, the maximum value of the mass point vibration speed of road is 13 cm/s, which is greater than the allowable safety value stipulated in "the Blast Safety Regulations." Therefore, during the construction of the expansion tunnel, temporary traffic control should be implemented in adjacent operating tunnels until the completion of the blasting and safety inspection. Thus, it is recommended that the blasting operations should be carried out at night or in the early morning with low traffic volumes, in order to avoid causing traffic jams. During the construction of tunnel expansion, the safety monitoring of the lining structure of adjacent operating tunnels should be strengthened, so as to provide timely and early warning.

4.2. Stress Analysis of Tunnel Lining in Operation. In order to analyze the influence of blasting expansion on the lining structure of adjacent operation tunnels, the monitoring points are set in the vaults, arch shoulders, arch waists, arch feet, and arch bottoms of the newly built four-lane operating tunnel, and the stress distribution of the lining structures is monitored, as shown in Figure 6.

It can be seen from Figure 6 that the stresses at the arch shoulder and waist of the lining structure are the largest, followed by the vault and arch foot, and the stress at the arch bottom is the smallest. The stress of the lining structure is asymmetrically distributed and that on the side near the explosion is obviously greater than that on the side away from the explosion. The maximum stress of the lining structure of the newly built four-lane operating tunnel is 1.76 MPa, which appears at the arch waist of the side near the explosion. The maximum principal stress of the arch waist of the side away from the explosion is 1.17 MPa; thus, the former is 1.5 times of the latter, showing a "quasi-bias" phenomenon.

The pressure distribution of the newly built four-lane operating tunnel is shown in Figure 7, and it is found that the surrounding rock pressure shows a side extrusion characteristic of "larger on both sides and smaller on vault" in the spatial distribution. The pressure of the side near the explosion of the surrounding rock is greater than the side away from the explosion, and the pressure distribution of the surrounding rock is in consistence with the stress distribution of the lining structure, which shows a "quasi-bias" phenomenon. Therefore, in the construction process of blasting expansion, the stress distribution of the explosion side lining structure adjacent to the operating tunnel should be paid more attention.

Table 1: Physical-mechanical parameters of materials.

Material	Density (kg·m^{-3})	Elastic modulus (GPa)	Poisson's ratio	Yield stress (MPa)
Surrounding rock	2300	3.0	0.35	10
Initial support	2400	4.5	0.30	15
Secondary lining	2700	30.0	0.20	20

Table 2: Control thresholds of the blasting vibration velocity for some tunnels with small net distance.

Project	Net distance (m)	Threshold of vibration velocity (cm·s^{-1})
Zhaobaoshan Highway Tunnel	0.95	10
Xiaoyangshan Tunnel	9.34	10
Bantao Tunnel	6.14	1.8
Wutong Mountain Tunnel	13.5	6
Sanfu Expressway Tunnel	5	10
Dongjiashan Tunnel	3.75	15
Shishi Tunnel	8.2	15

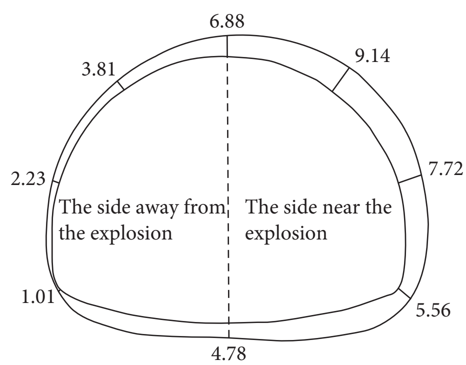

Figure 4: Envelope of full section peak vibration velocity of the original two-lane operating tunnel (unit: cm/s).

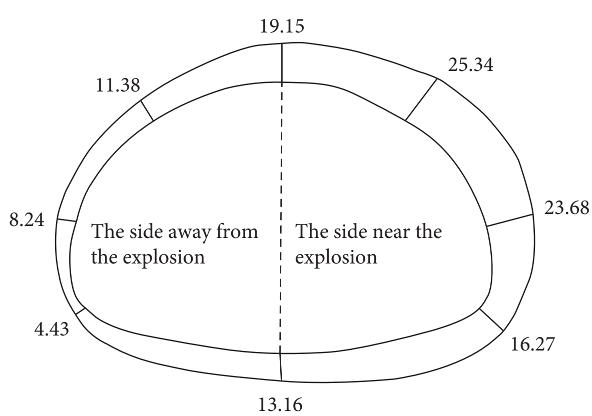

Figure 5: Envelope of full section peak vibration velocity of the new four-lane operating tunnel (unit: cm).

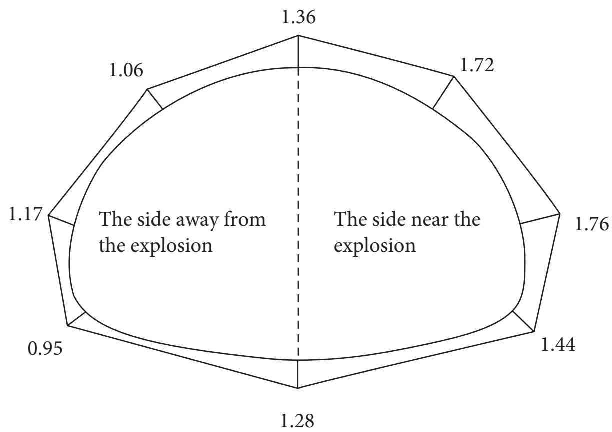

Figure 6: Stress distribution of the lining structure of the newly built four-lane operating tunnel (unit: MPa).

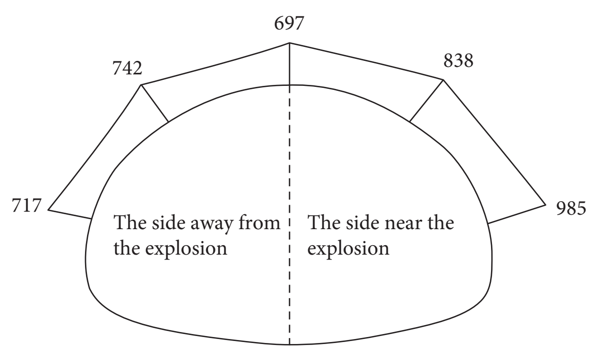

Figure 7: Pressure distribution of surrounding rock of the newly built four-lane operating tunnel (unit: kPa).

5. Conclusion

In this study, the numerical model for blasting expansion of the large section tunnel with small net distance in situ was established by LS_DYNA power finite element software; the vibration responses and lining stress changes of adjacent operating tunnels under blasting load of the Damaoshan Tunnel expansion project were simulated. The results of the present work can provide references and guidances for the construction problems of similar tunnel expansion projects. The main conclusions and recommendations are listed as follows.

(1) In situ expansion by blasting excavation has a great impact on adjacent operating tunnels, and the shoulder and waist of the operating tunnel are the weak links during the blasting excavation. The peak vibration velocity at the arch shoulder of the tunnel is about 1.5–4 times of the tunnel bottom and that on the side near the explosion is about 5–10 times of the side away from the explosion.

(2) Under the blasting loads during tunnel expansion, the peak particle vibration speed of the newly built four-lane operating tunnel reaches 13 cm/s, which exceeds the allowable safety value. Therefore, it is recommended that during the blasting construction of the expanded tunnel, traffic control should be implemented temporarily in the adjacent operating tunnels. It is also suggested that the blasting operations arranged at night or early morning during which the traffic volume is small.

(3) Under the blasting loads of the newly built four-lane operating tunnel, the stress of the lining of the near blast side arch waist is about 1.5 times of the side away from the blasting, showing a "bias-like" phenomenon, and the pressure distribution of surrounding rock presents similar trends.

(4) On the explosion side of the adjacent operating tunnel, the mass point vibration and stress distribution of the lining structure are in an unfavorable state. Dynamic monitoring should be carried out during the expansion process to ensure the traffic safety of the adjacent operating tunnels.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Min Zhang carried out the experiments, analyzed the results, conducted the theoretical explanations, and wrote the manuscript.

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