Hindawi
Advances in Civil Engineering
Volume 2023, Article ID 6021465, 12 pages
https://doi.org/10.1155/2023/6021465

Research Article

Numerical Investigation into the Effects of Controlled Tunnel Blast on Dynamic Responses of the Transmission Tower

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Received 9 February 2022; Revised 23 April 2022; Accepted 20 April 2023; Published 3 May 2023

Academic Editor: André Furtado

At present, the drill-and-blast method is still one of the main construction means in the road tunnel excavation process. When the tunnel penetrates underneath sensitive structures such as high-voltage transmission towers, the blasting and supporting parameters must be strictly controlled to ensure the stability and safety of the surface structures. In this paper, numerical simulations based on a large-section shallow buried tunnel project in Zhuhai are conducted to study the effect of controlled tunnel blast on the dynamic response of transmission towers. The numerical simulation results indicate that the blast vibration velocity of the rock generated by controlled blasting decreases rapidly along the tunnel excavation direction. The blast vibration velocity of the high-voltage transmission tower and its pile foundation gradually increases with the propagation of the blast waves, and the maximum vibration velocity is about 1.24 cm/s. The results indicate that the controlled blasting design of this project can effectively restrain the vibration velocity induced by the blasting load and could ensure the stability and safety of the transmission tower.

1. Introduction

With the rapid development of highways in China, large-section tunnels are widely used in highway construction because of their ability to significantly reduce road mileage and improve transport efficiency. The tunnels would sometimes inevitably penetrate beneath sensitive structures, such as transmission towers and other existing structures, which poses challenges for the design and construction of large-section tunnels.

At present, the drill-and-blast method is still one of the main construction methods in the road tunnel excavation process [1–3]. When the tunnel penetrates underneath sensitive structures such as high-voltage transmission towers, the blasting and support parameters need to be strictly controlled to ensure the stability and safety of the surface structures. To study the influence of vibration caused by controlled blasting on rock mass and sensitive structures, site test and numerical simulation methods are widely used by researchers [4–7]. The site test can objectively reflect the influence of blasting vibration on the rock mass structure. However, due to the nonhomogeneity and the defects of the internal structure in the rock mass, the experimental conditions are difficult to control. Compared with the site tests, the numerical calculation can simulate the dynamic response problem in the complicated geological conditions, thus the numerical simulation method is widely used to analyze the blasting vibration response. Some studies [8–10] evaluated the vibration damage to transmission towers based on the finite element method. Luo et al. [11] analyzed the dynamic characteristic of the tunnel for surface explosion of 100 and 300 kg TNT charge, respectively. Duan et al. [12] investigated the vibration characteristic of high-voltage tower under the influence of adjacent tunnel blasting excavation. Beside the study on the influence of vibration induced by controlled blasting on transmission tower, more research focuses on the dynamic responses of adjacent structures. Zhao et al. [13] used field monitoring experiments and numerical simulation to study the effect of blast-induced vibration from adjacent tunnel on existing tunnel. Jiang et al. [14] investigate the effect of excavation blasting vibration on adjacent buried gas pipeline in a metro tunnel. However, the dynamic responses of the transmission tower system remain one of the most challenging tasks in the civil engineering as a complex, continuous, and mechanical system.

Based on a large-section shallow buried tunnel project in Zhuhai, China, this paper studies the effects of controlled tunnel blasting on the dynamic responses of high-voltage transmission towers. Three-dimensional numerical analyses were conducted in the finite difference program FLAC3D, and the dynamic responses of the tunnel surrounding rock and high-voltage transmission towers under the blast loading were studied. The vibration velocity, deformation responses of surrounding rock and high-voltage transmission towers were predicted to provide scientific basis and reference for relevant construction optimization and decision-making.

2. Overview of the Project

The Black and White General Hill tunnel is a large-section shallow buried tunnel under construction in Zhuhai, China, which is built to enhance the transportation links between different districts in Zhuhai. The exit section of the tunnel penetrates directly underneath a high-voltage transmission tower. A schematic view of the locations of the tunnel and transmission tower is shown in Figure 1. The transmission tower is a 2F-SJ2 type tower with a total height of 41.5 m, supported by four piles with a diameter of 2.1 m and a length of 12 m. The vertical distance from the top of the tunnel to the pile toe is about 7.5 m, and the smallest horizontal distance from the tunnel to the transmission tower is about 1.9 m.

The surrounding rocks at the tunnel exit consisted of medium strongly weathered quartz amphibolite. The arches and sidewalls of the tunnel exit are of poor stability, which could lead to rock collapse and drops at drill-and-blast excavation. The uneven weathering of the surrounding rocks has an impact on the stability of the tunnel portal and the side slopes. These geological conditions would pose a threat to the stability of the transmission tower.

According to the geological survey, the soil stratum from top to bottom within the exploration depth is divided into clay, fully weathered, strongly weathered, medium weathered, and slightly weathered quartz amphibolite. Based on the results of the wave velocity test and other geotechnical tests, the physical properties of the soil and rock are shown in Table 1.

3. Numerical Investigation

3.1. Numerical Model. A 100 m range of tunnel exit (mileage YK4 + 820–YK4 + 920) is selected as the modelling area, with the tunnel and transmission tower included. The numerical model built in FLAC3D is shown in Figure 2. Considering the influence of tunnel depth and blasting, the total length and width of the model are selected as 100 m and 52 m, respectively, which could effectively reduce the boundary effect. The axis used in the numerical model is defined as follows: X axis is along the direction of tunnel excavation; Y axis is along the cross-section of the tunnel; and Z axis is along the gravity direction. The numerical model mainly consisted of the tunnel, surrounding rocks, transmission tower, and its file foundation. It is noted that the transmission tower and its pile foundation are modelled using the structure elements implanted in FLAC3D to reduce model complexity and increase calculation speed. The total number of zones in the 3D numerical model is 112,400, and the total number of nodes is 12033.

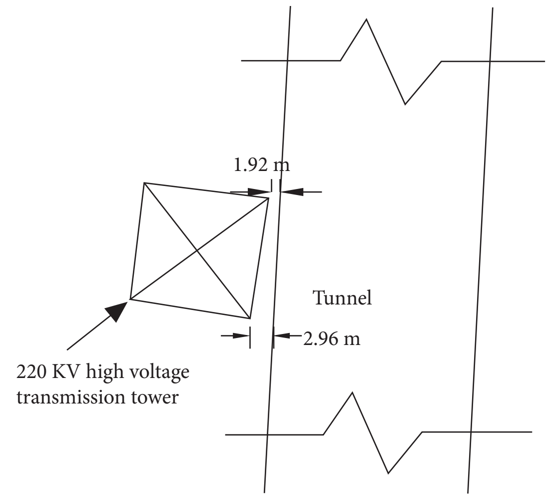

Figure 1: Schematic view of the locations of the tunnel and transmission tower.

The high-voltage transmission tower is built upon a hill which the tunnel penetrates through. The curved surface of the hill needs to be considered in the numerical model to obtain a correct initial stress condition in the surrounding rocks. The curved surface is generated in SketchUp by importing the contour lines of the hill. Then, the 3D hill surface is exported to FLAC3D, and it connects with the tunnel model built in FLAC3D to form the 3D numerical model. The process of model generation is shown in Figure 3. The soil layer distribution is generated based on the geological data using the curved surface import method.

3.2. Constitutive Model and Material Parameters. The Mohr–Coulomb model is selected as the constitutive model for the soil and rock in this project. The parameters of density, cohesion, and friction angle are adopted directly from the geological survey data, which is shown in Table 1. The transmission tower is modelled with the beam element implemented in FLAC3D, which is a two-noded, straight, finite element with six degrees of freedom per node. The beam element has three material parameters, density, elastic modulus, and Poisson's ratio, which are set to be 7850 kg/m^3, 200 GPa, and 0.3, respectively. The pile foundation of the transmission tower is modelled using the pile element, which could effectively simulate the normal-directed

Table 1: Property parameters of the soil.

Soil layer	Name	Density (kN/m^3)	Cohesion (kPa)	Friction angle (°)	Elastic modulus (MPa)	Poisson's ratio
1	Clay	19.8	25	20	20	0.38
2	Fully weathered quartz amphibolite	23.0	26	28	48	0.35
3	Strongly weathered quartz amphibolite	27.7	28	30	70	0.32
4	Medium weathered quartz amphibolite	28.9	5.5×10^3	41	4.0×10^4	0.30
5	Slightly weathered quartz amphibolite	30.0	7.0×10^3	42	6.5×10^4	0.23

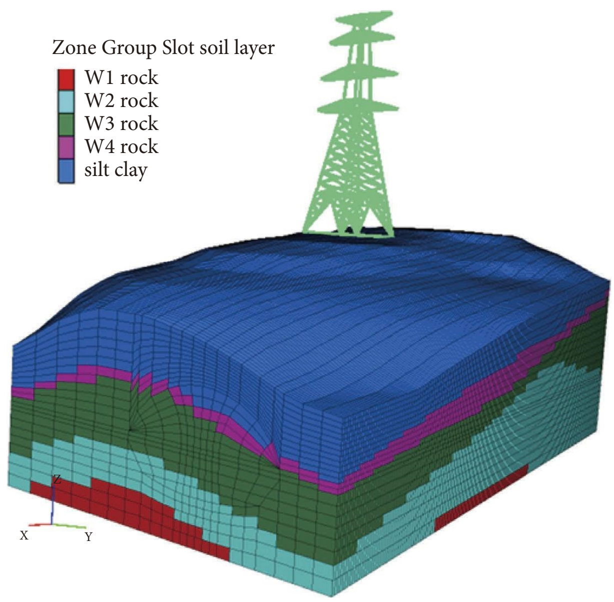

Figure 2: 3D numerical model.

(perpendicular to the pile axis) and shear-directed (parallel with the pile axis) frictional interaction between the pile and the soil. The soil-pile interaction is considered by the shear and normal coupling springs. The coupling springs are nonlinear, spring-slider connectors that transfer forces and motion between the pile and the grid at the pile nodes. The shear behavior of the pile-grid interface is cohesive and frictional in nature. The lining and anchors used as tunnel supporting are simulated with the liner element and cable element, respectively. The parameters of the structure element (pile, liner, and cable) adopted in this paper are shown in Tables 2–4.

3.3. Blasting Load. Due the short distance from the tunnel and the sensitivity of the transmission tower, the controlled blast and double-sided guide-pit method are adopted in the excavation and initial support of tunnel exit to ensure the stability of the transmission tower. The detailed blast-hole distribution and blasting sequences for the double-sided guide-pit method are shown in Figure 4. There are about 330 blast-holes in each blast section, distributed in a cross-sectional area of 305 m^2. The unit explosive consumption is about 0.9 kg/m^3 for the controlled blast design. In order to study the effect of controlled blast on the dynamic responses of the transmission tower and surrounding rock, the blast load generated by millisecond delay blasting needs to be applied at the tunnel.

In the process of blasting, the interaction of stress waves generated by blasting will make cracks spread along the connecting line of adjacent blastholes. With the growth of the blast induced crack and interpenetration throughout the rock, a new free surface will be created along the blasthole line, which is the designed blasting excavation boundary. Therefore, the blasting excavation boundary is taken as the inner boundary of the numerical model. Thus, the full scale blastholes are not included in this model, and the blasting pressure is applied equivalently to the excavation boundary, which avoids tremendous model meshing and computational work due to detonations of too many tiny blastholes.

In this paper, an equivalent pulse load of the multihole blasts is applied at the blasting excavation boundary of the tunnel. This simplified equivalent load method certainly causes some deviation in the immediate vicinity of blastholes. However, this study is to investigate the dynamic responses of the transmission tower and surrounding rocks outside the blasting boundary rather than the explosion-induced rock fracture and fragmentation process around blastholes. Therefore, this equivalent pulse load simplification is acceptable to a certain degree. Following the procedure used by Yang et al. [15, 16], the equivalent pulse load applied in this paper is shown in Figure 5.

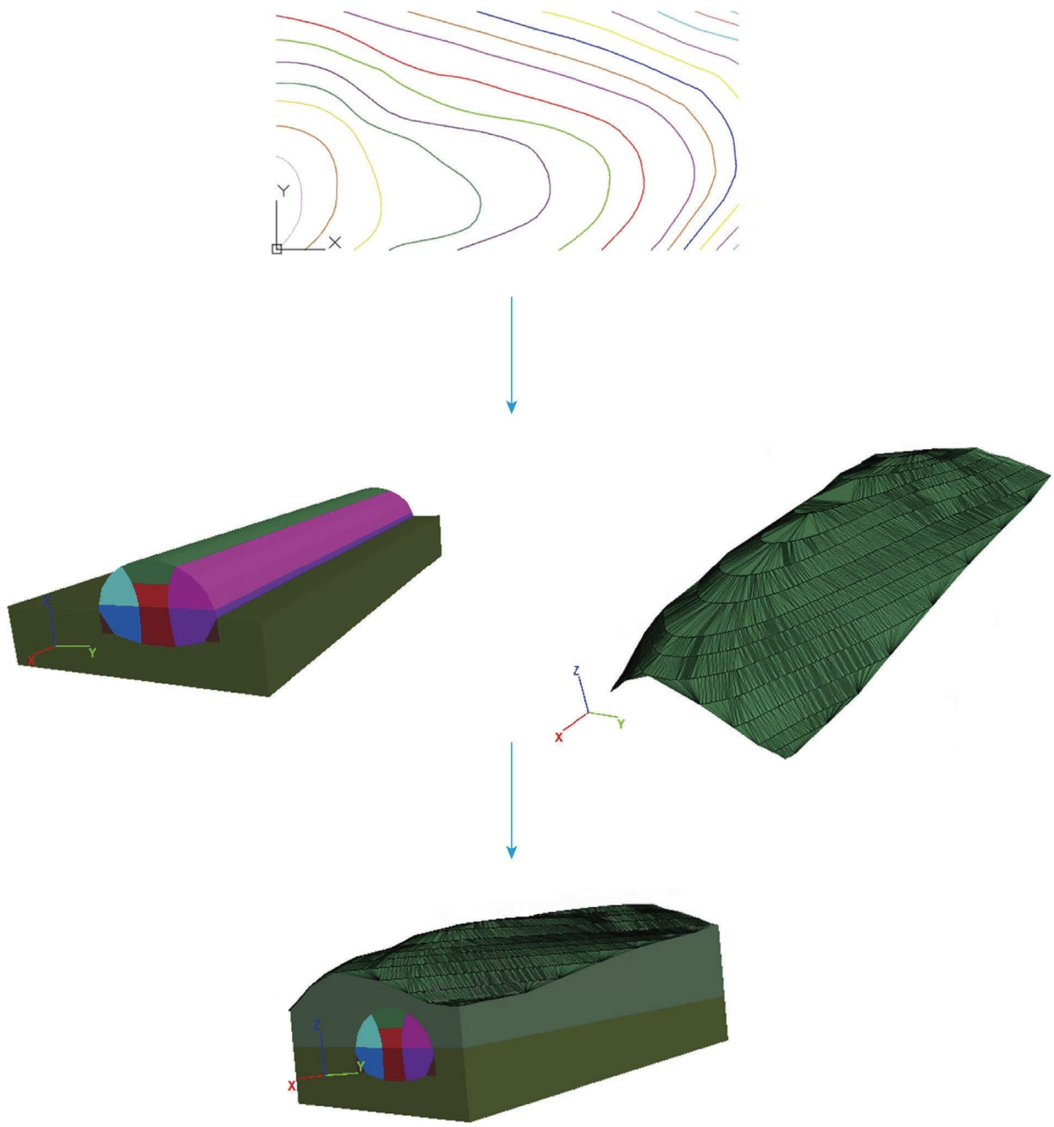

Figure 3: Process of 3D surface model generation.

3.4. Analysis Procedures and Boundary Condition. The focus of the research in this paper is to investigate the dynamic responses of the transmission tower under tunnel blasting to ensure the stability and functionality of the transmission tower. Therefore, the numerical study chooses the condition where the tunnel has been excavated directly underneath the transmission tower, and the initial support and cables have been installed in the excavated part of the tunnel, which is shown in Figure 6. The blast load generated by the first section of the tunnel (as shown in Figure 4) beneath the transmission tower is applied at the numerical model, when the influence of the blast on the transmission tower is the most obvious.

Before the blast loading is applied, the boundary of the numerical model is set to be fixed in their normal direction to calculate the initial stress condition. In static analysis, fixed boundaries applied here are realistic since the model size is large enough and the boundary is placed at some distance from the region of interest. However, such boundary conditions cause the reflection of outward propagating waves back into the model and do not allow the necessary energy radiation. Therefore, the fixed boundary condition is converted into a viscous boundary by using independent dashpots in the normal and shear directions at the model boundaries in the dynamic loading stage.

4. Results and Discussions

4.1. Responses of the Surrounding Rock. To ensure the stability of the transmission tower, the dynamic responses of the surrounding rock are analyzed first. Figure 7 shows the time histories of blast velocities measured at different distances from the blast surface. The maximum blast velocities along X, Y, and Z axis caused by controlled blasting of section 1 are about 9 cm/s, 0.58 cm/s, and 3 cm/s, respectively. It can be concluded that the control blasting of section 1 of the tunnel generates main vibration of surrounding rock in the tunnel excavation direction, while the Y and Z axis component is relatively small.

Table 2: Parameters of pile elements.

Type	Density (kg/m^3)	Elastic modulus (GPa)	Poisson's ratio	Cross-sectional area (m^2)	Coupling stiffness (GPa)	Coupling friction angle	Coupling cohesion (kPa)
Pile	2400	80	0.3	3.464	13	25	25

Table 3: Parameters of liner elements.

Type	Density (kg/m^3)	Thickness (m)	Elastic modulus (GPa)	Poisson's ratio	Normal coupling stiffness (GPa)	Shear coupling stiffness (GPa)
Liner	2000	1	30	0.25	9.77	9.77

Table 4: Parameters of cable elements.

Type	Density (kg/m^3)	Cross-sectional area (cm^2)	Elastic modulus (GPa)	Grout cohesion (kPa)	Grout friction angle
Cable	2000	5.9	100	50	35

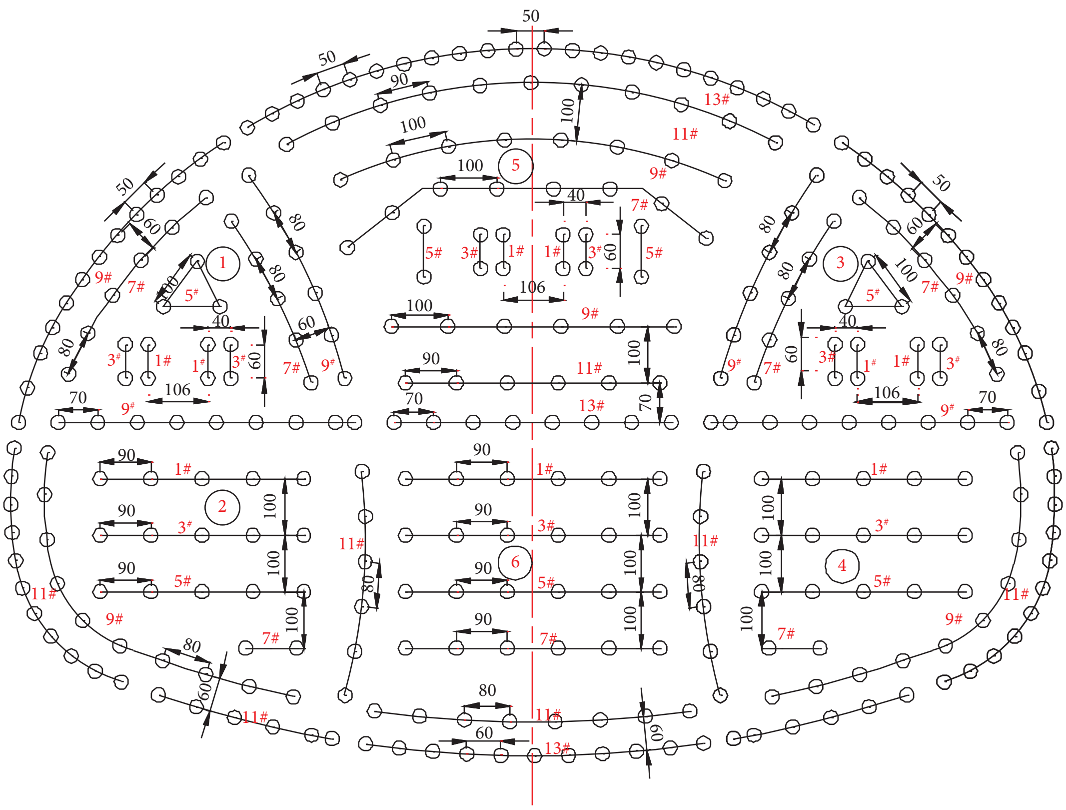

Figure 4: Blasting sequences of the double sidewall guide pit method.

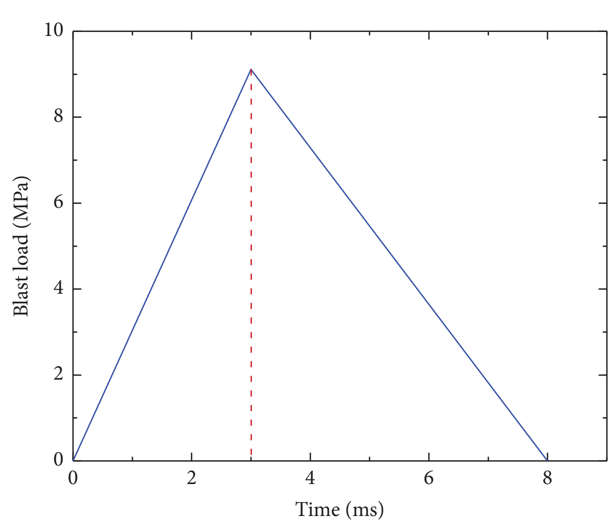

Figure 5: Time history of the equivalent pulse load.

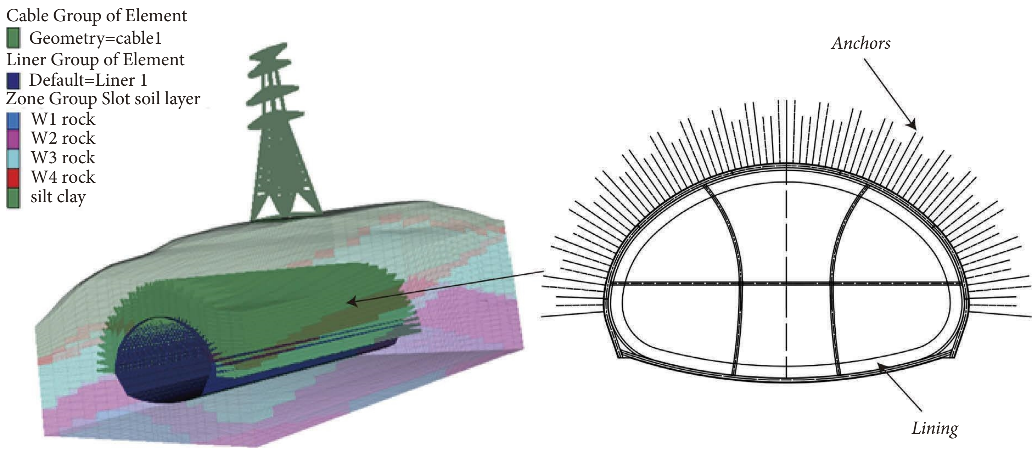

Figure 6: Initial support and cables of the tunnel.

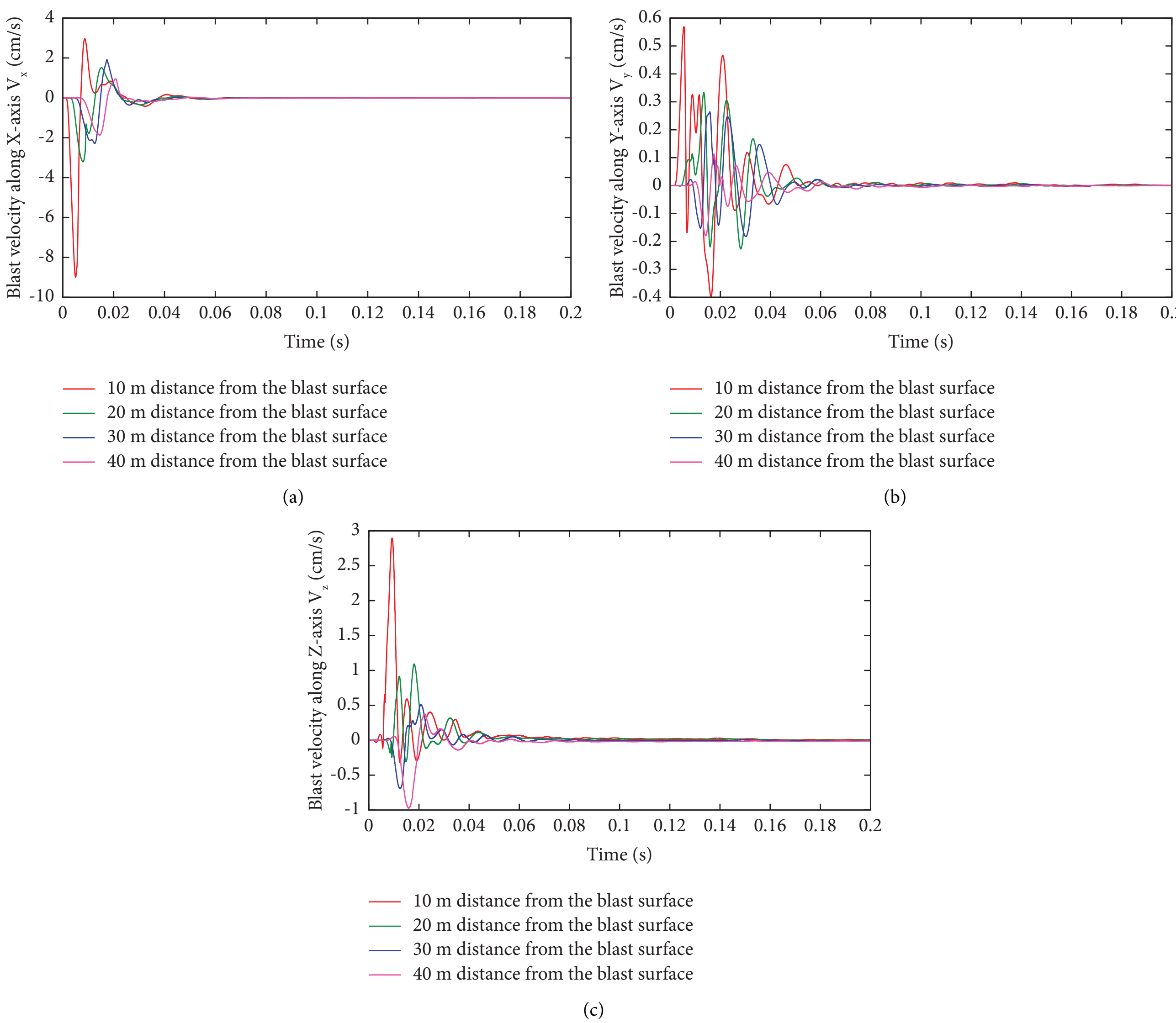

Figure 7: Time histories of blast velocities.

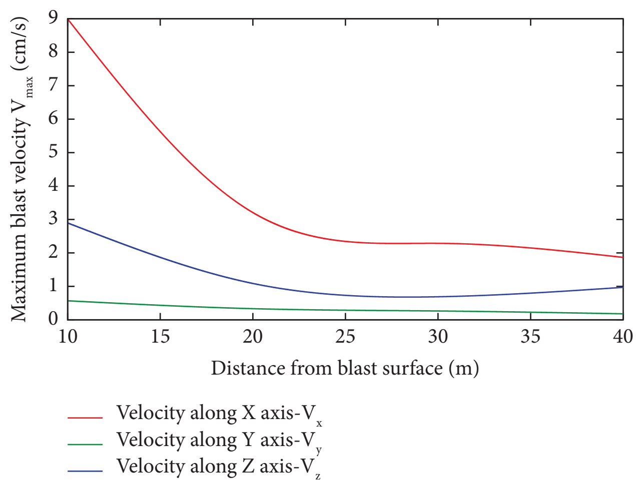

Figure 8: The maximum blast velocity distribution.

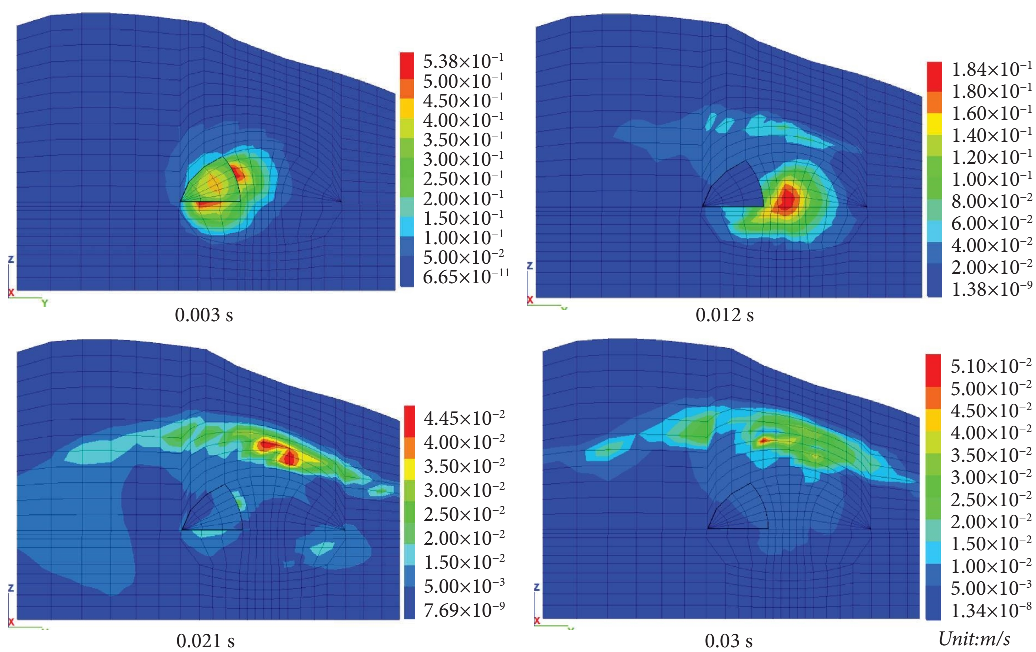

Figure 9: Blast velocity contour of the rock mass.

Figure 8 shows the decay curves of the maximum blast velocity along the tunnel excavation direction caused by controlled blasting in section 1, where the red, blue, and green curves are the velocity components in X, Y, and Z direction, respectively. As shown in the figure, the magnitude of blast velocity components in the three axes decreases rapidly in the range from 10 m to 20 m from the blast surface. Beyond that distance, the maximum blast velocity basically remains constant.

Figure 9 shows the blast velocity contour of the rock mass due to controlled blasting in section 1. The four contour graphs are captured at 0.003 s, 0.012 s, 0.021 s, and 0.03 s after blasting. It can be seen that at 0.003 s after blasting, the rock disturbance caused by controlled blasting of section 1 is basically concentrated within 4 m of the tunnel perimeter. With the increase of time, the range of rock disturbance gradually expands, but its peak size decreases rapidly. After 0.02 s from the start of blasting, the blast velocity around the tunnel has basically decayed to zero, while the vibration velocity above the tunnel is the largest part of the rock mass at this time. Therefore, the controlled blasting design of this project can effectively control the blasting vibration velocity of the rock around the tunnel, which meets the safety requirements of the specification and can effectively ensure the safety and stability of tunnel blasting.

Figure 10 shows the maximum dynamic stress induced by the controlled blast, which is measured at 3 ms. As shown in the figure, the maximum dynamic stress occurred at the surrounding rock located near the blast section, with a value about 10 MPa. The dynamic stress decreases dramatically with the increase of distance from the blast section, with an

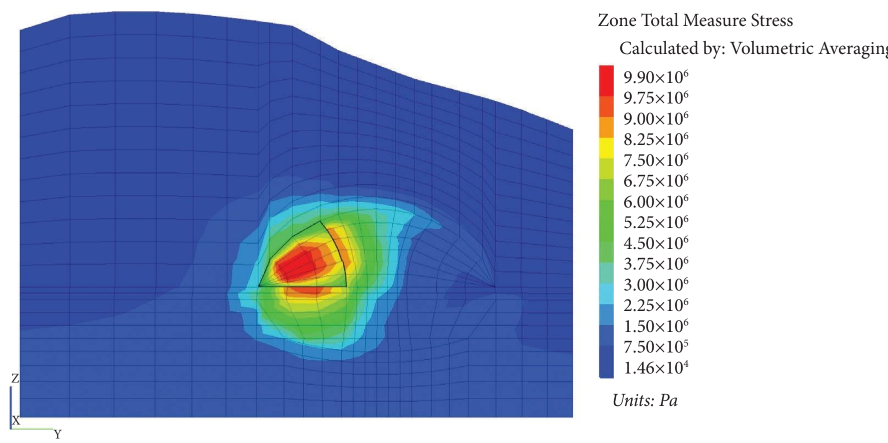

FIGURE 10: The maximum dynamic stress measured at the blasting surface.

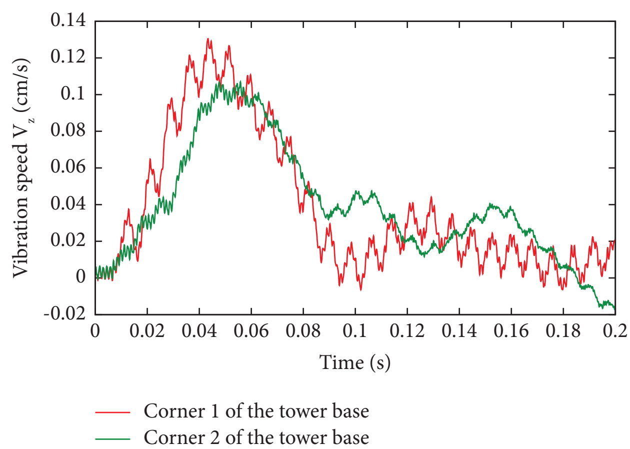

FIGURE 11: Vibration speed time histories at the tower base.

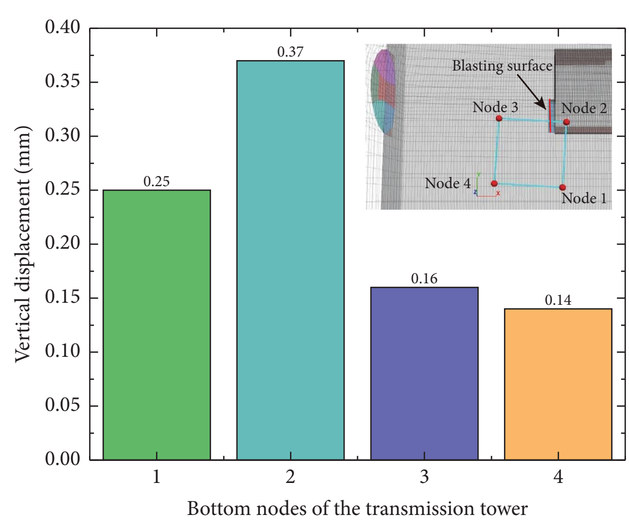

FIGURE 12: Vertical displacement measured at the tower base.

80% reduction in the peak value at the location with a distance of two times the largest dimension of the blast section from the blast center.

4.2. Responses of the Transmission Tower. Figure 11 shows the time histories of blasting velocity in Z direction at the corners of the base of the high-voltage tower. During the

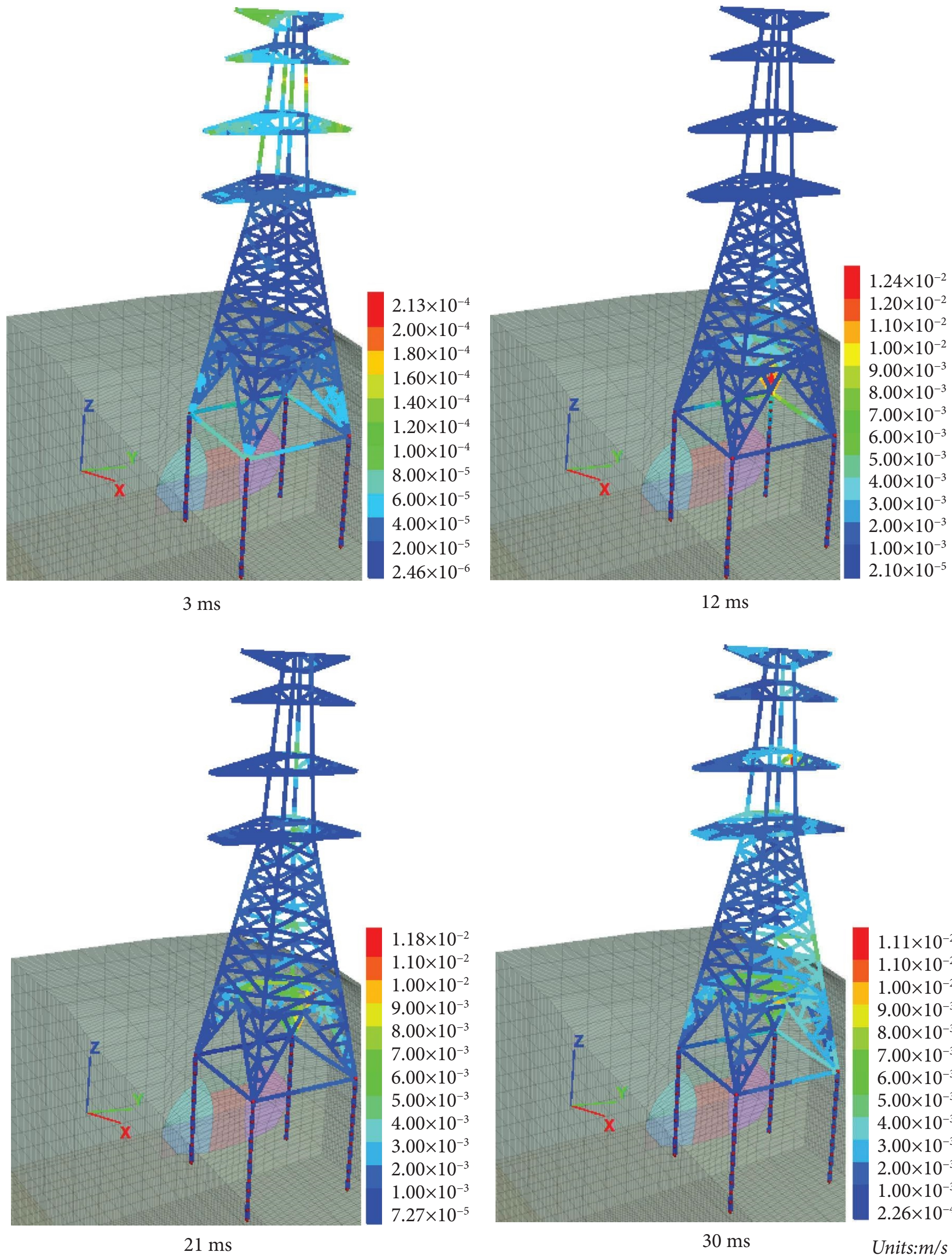

Figure 13: Vibration speed contour of the transmission tower.

controlled blasting of tunnel section 1, the blasting vibration in Z direction first increases and then decreases, with a peak value of about 0.12 cm/s. The blasting vibration velocity Vz in the Z-axis direction decreases to zero at about 0.2 s after the blasting. Therefore, the magnitude of velocity measured at the base of the transmission tower is relatively small and will not pose a threat to the stability of the transmission tower, which demonstrates the validity of the controlled blasting design.

The differential settlement of the transmission tower is a key factor to monitor in practice to ensure the stability of the transmission tower. Therefore, the vertical displacements of the tower base are measured at the end of blast loading. Figure 12 presents the vertical displacement at the four corner nodes of the tower base and their relative position to the blasting surface. The maximum and minimum vertical displacements of the tower base are about 0.37 and 0.14 mm, respectively, which would result in a differential settlement of 0.23 mm. It can be concluded that the differential settlement would only cause a neglectable tilt angle and would not threaten the stability of the transmission tower.

Figure 13 shows contour of vibration speed of the transmission tower generated by controlled blasting. As can be seen, the maximum vibration speed of the transmission

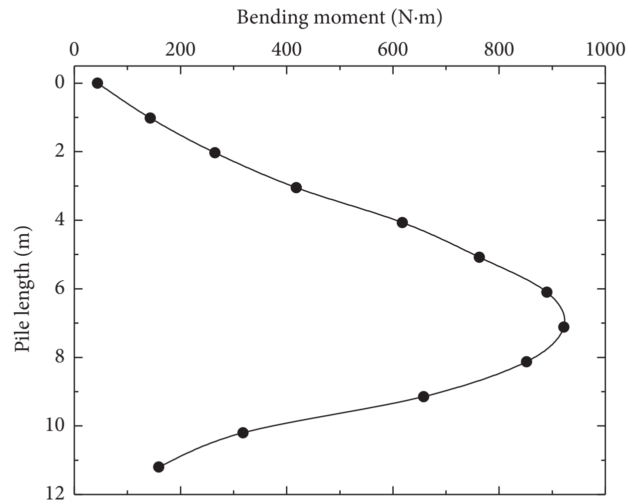

Figure 14: Maximum bending moment of the pile foundation.

tower and its pile foundation is about 0.02 cm/s at 0.003 s after the controlled blasting. As the blast wave in the rock propagates to the surface, the vibration speed of the transmission tower and its pile foundation gradually increases and its maximum vibration velocity is about 1.24 cm/s, which occurs at the location of the tower base 0.012 s after the blasting. Then, the vibration speed gradually decreases. It can be concluded that the design of controlled blasting of this project can ensure that the vibration speed of the transmission tower is below the safe vibration speed of 3.5 cm/s in the Chinese specification.

Due to the short distance between the pile foundation and the undercrossing tunnel, the dynamic responses of the pile foundation would also affect the stability of the transmission tower. Therefore, the maximum bending moment of the pile is measured during the controlled blasting, which is shown in Figure 14. The peak value of the bending moment developed in the pile is about 920 N·m, which is developed at 7 m below the pile top. Therefore, the blasting wave generated by controlled blast would not significantly affect the internal force in the pile. This result indicates that the pile foundation and the transmission tower remained stable during the blasting construction.

5. Conclusions

This paper investigates the dynamic effects of controlled tunnel blasting on surrounding rock and high transmission tower. A three-dimensional numerical analysis of a large section shallow buried tunnel under a transmission tower was conducted. The dynamic responses of the surrounding rock and the high transmission tower were analyzed in detail. The main conclusions can be drawn as follows:

(1) The vibration speed generated by controlled blasting decays rapidly along the tunnel excavation direction

(2) At 0.003 s after the start of blasting, the rock disturbance caused by controlled blasting of section 1 is basically concentrated within 4 m of the tunnel perimeter, and with the increase of time, the rock disturbance range gradually expands, but its peak size decays rapidly

(3) As the blast wave in the rock mass propagates to the ground surface, the vibration speed of the transmission tower and its pile foundation gradually increases with a maximum vibration velocity of about 1.24 cm/s

(4) The controlled blasting design of this project can effectively restrain the vibration velocity of the surrounding rock and the transmission tower, which could ensure the stability and safety of the transmission tower.

Data Availability

The data come partly from the project site and engineering survey and partly from numerical simulations. All 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 they have no conflicts of interest.

Acknowledgments

The research was supported by <Research on Key Technologies for Construction of Large-Section Shallow Buried Tunnels under Sensitive Structures in Jiangjunshan Tunnel>.

References

[1] B. Duan, W. Gong, G. Ta, X. Yang, and X. Zhang, "Influence of small, clear distance cross-tunnel blasting excavation on existing tunnel below," *Advances in Civil Engineering*, vol. 2019, Article ID 4970269, 16 pages, 2019.

[2] X. Xia, H. B. Li, J. C. Li, B. Liu, and C. Yu, "A case study on rock damage prediction and control method for underground tunnels subjected to adjacent excavation blasting," *Tunnelling and Underground Space Technology*, vol. 35, pp. 1–7, 2013.

[3] Q. Liang, J. Li, D. Li, and E. Ou, "Effect of blast-induced vibration from new railway tunnel on existing adjacent railway tunnel in Xinjiang, China," *Rock Mechanics and Rock Engineering*, vol. 46, no. 1, pp. 19–39, 2013.
[4] N. Jiang and C. Zhou, "Blasting vibration safety criterion for a tunnel liner structure," *Tunnelling and Underground Space Technology*, vol. 32, pp. 52–57, 2012.
[5] M. Mohamadnejad, R. Gholami, and M. Ataei, "Comparison of intelligence science techniques and empirical methods for prediction of blasting vibrations," *Tunnelling and Underground Space Technology*, vol. 28, pp. 238–244, 2012.
[6] J.-H. Shin, H.-G. Moon, and S.-E. Chae, "Effect of blast-induced vibration on existing tunnels in soft rocks," *Tunnelling and Underground Space Technology*, vol. 26, no. 1, pp. 51–61, 2011.
[7] M. Monjezi, M. Ghafurikalajahi, and A. Bahrami, "Prediction of blast-induced ground vibration using artificial neural networks," *Tunnelling and Underground Space Technology*, vol. 26, no. 1, pp. 46–50, 2011.
[8] L. Tian, H. Li, and G. Liu, "Seismic response of power transmission tower-line system subjected to spatially varying ground motions," *Mathematical Problems in Engineering*, vol. 2010, Article ID 587317, 20 pages, 2010.
[9] F. Wang, Z. Su, Q. Li, and J. Yang, "Response analysis of cathead transmission tower seismic performance based on Open Sees," in *Proceedings of the 2014 Fifth International Conference on Intelligent Systems Design and Engineering Applications*, pp. 893–896, IEEE, Hunan, China, June 2014.
[10] H.-N. Li, W.-L. Shi, G.-X. Wang, and L.-G. Jia, "Simplified models and experimental verification for coupled transmission tower–line system to seismic excitations," *Journal of Sound and Vibration*, vol. 286, no. 3, pp. 569–585, 2005.
[11] K. Luo, Y. Wang, Y. Zhang, and L. Huang, "Numerical simulation of section subway tunnel under surface explosion," *Journal of PLA University of Science and Technology (Natural Science Edition)*, vol. 6, 2007.
[12] L. Duan, W. Lin, J. Lai, P. Zhang, and Y. Luo, "Vibration characteristic of high-voltage tower influenced by adjacent tunnel blasting construction," *Shock and Vibration*, vol. 2019, Article ID 8520564, 16 pages, 2019.
[13] H. Zhao, Y. Long, X. Li, and L. Lu, "Experimental and numerical investigation of the effect of blast-induced vibration from adjacent tunnel on existing tunnel," *KSCE Journal of Civil Engineering*, vol. 20, no. 1, pp. 431–439, 2016.
[14] N. Jiang, T. Gao, C. Zhou, and X. Luo, "Effect of excavation blasting vibration on adjacent buried gas pipeline in a metro tunnel," *Tunnelling and Underground Space Technology*, vol. 81, pp. 590–601, 2018.
[15] C. Z. Yang, Z. J. Yu, and S. F. Wang, "Analysis of the dynamic influence of the input blasting load on the tunnel surrounding rock," *Materials Research Innovations*, vol. 19, no. 8, pp. S8-S923–S8-930, 2015.
[16] J. H. Yang, C. Yao, Q. H. Jiang, W. B. Lu, and S. H. Jiang, "2D numerical analysis of rock damage induced by dynamic in-situ stress redistribution and blast loading in underground blasting excavation," *Tunnelling and Underground Space Technology*, vol. 70, pp. 221–232, 2017.