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NUMERICAL ANALYSIS ABOUT BLASTING EFFECT OF DIGITAL DETONATOR AND MILLISECOND DETONATOR IN UPPER AND LOWER CROSS TUNNELS

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ABSTRACT

In order to study on the vibration effect of the blasting in the upper and lower cross tunnels, depress the impact of blasting vibration on existing adjacent tunnel and acquire the sound way of tunnel blasting construction, the finite element software LS-DYNA was adopted to calculate what vibration effect of existing tunnel would be generated by the different detonation modes (simultaneous initiation and hole-by-hole initiation) and the different cut modes (parallel cut and oblique cut). In general, the results of numerical simulation compared with the results measured in real, they are generally consistent. Results show that the vibration velocity of hole-by-hole initiation of digital electronic detonator is 40% lower than ordinary simultaneous initiation of millisecond detonator, and the vibration acceleration is reduced by 24%. As regards vibration displacement, the distinction between the two detonation modes is small. The rule of velocity decay with increasing distance from the initiating position is similar in this two cases. Meanwhile, the vibration velocity of oblique cut is lower than parallel cut. But, for the vibration acceleration, the oblique cut is 15% higher than parallel cut. For oblique cut, the seismic waves show a pronounced periodicity and the energy is relatively concentrated. The fact is quite opposite when the parallel cut applied. In the case of explosion of hard rock strata, the effect of oblique cut is better than parallel cut.

KEY WORDS

Tunnel engineering, Explosion vibration, Numerical simulation, LS-DYNA

INTRODUCTION

In recent years, with the rapid economic growth in China and the booming development of the national transport industry, the subway construction has become an essential development project in large and medium-sized cities. In that cities, such as Chongqing, Xiamen and Qingdao, the drilling and blasting method usually used to subway construction in hard rock strata. In addition, due to the outward expansion of the city and the characteristics of the original terrain, a lot of “mountain city” appeared. As a result, many mountain hard rock tunnels have emerged in the construction of municipal roads and subway traffic. So, the surrounding buildings, especially cultural building relics, will be impacted by blasting construction in central urban area. How to choose a reasonable tunnel blasting method to reduce the impact of blasting vibration on the surrounding buildings is a considerable issue.

As the science and computer technology progressed, the method of numerical simulation of blasting vibration effect and evaluating structural safety is widely used. Singh P K (2002) delved into the destruction problems of underground tunnels in the effect of adjacent tunnel blasting[1]. There are research results indicate that blasting vibrations induced by a new tunnel excavation might cause spalling, fissures, or even collapse of existing tunnel linings[2]. Yao et al. (2004) conducted numerical simulations on the blasting construction process of the road tunnels with small spacing under different support conditions[3]. Zhao et al. (2007) studied the response of blasting vibration of neighbourhood cross tunnel by numerical simulation and determined the influence range of blasting vibration[4]. Wen (2008) established the 3D model by MIDAS/GTS software to simulate the situation that the existing tunnel was impacted by the burst of adjacent tunnel. Under the different tunnel spacing and different surrounding rock grades, the vibration velocity, stress and strain of the lining and surrounding rock of adjacent tunnel during blasting were evaluated[5]. Li[6] (2010), Yang[7] (2011) and Zhang[8] (2011) used the finite element program ANSYS/LS-DYNA to implement the numerical simulations of tunnel blasting excavation in many different situations. The dynamic effect of the adjacent tunnel lining caused by blasting seismic wave was explored from two aspects -- the spatial distribution and time history of the particle vibration velocity and the spatial distribution and time history of the element strain. Sambuelli[9] and Liang[10] et al. have been studied some empirical or theoretical methods to calculate the blasting vibration velocity maximum based on in situ monitoring data. Zou (2011) simulated the tunnel blasting by using ANSYS/LS-DYNA and got the peak values of blasting vibration at different measuring points, and verified the feasibility of numerical simulation method for predicting the blasting vibration peak velocity[11]. Utilizing the empirical formula of the predecessor, Liang et al. (2012) calculated the blasting load and simplified it into 8 triangular-shaped impulsive loads and adopted numerical simulation to explain the impact of the newly built railway tunnel blasting on the existing railway tunnel. Observed results surfaced that the additional stress and the total stress peak appeared at the tunnel cross-section of the vault and wall feet[12]. Meng et al. (2015) inquired into the dynamic response of tridimensional cross tunnel blasting construction under many circumstances[13]. Yu et al. (2014) adopted numerical simulation to analyse the construction of Zoumagang diversion tunnel intersection. Based on the simulation results, the safety control area and corresponding construction scheme of the intersection were obtained[14]. Cai et al. (2015) availed of ANSYS/LS-DYNA software to simulate the construction that the Dawangshan tunnel built on the existing Shawan supply tunnel, and indicated the stress and particle vibration velocity of the supply tunnel below[15].

Currently, on the part of numerical simulation, there are mainly three methods for calculating tunnel blasting . Firstly, blasting vibration load in the form of uniform triangular pressure load acting on the tunnel wall along the normal direction. Secondly, blasting vibration load is applied in the form of equivalent load on the plane defined by the concentric line of the same row of blast holes and the axis of the blast hole. The range of pressure effect is equal to the length of the charge section in the blast-hole. Thirdly, there will do a dynamic solution, when the blast-hole wall is applied the blasting vibration load which varies with the time history. Among the three methods, the third method can simulate the blasting process of blast-hole during tunnel excavation. In this paper, this method will be used to clarify the blasting process of the tunnel provided with a certain number of cutholes.

METHODS

Project profile

From FSDK11+ 205 to FSDK11+ 684, the excavation mileage of Shijingshan tunnel in Fengsha railway rebuilding project is 479 meters. The concealed excavation is located in the city center area. The depth of the tunnel is 4~32m. At the FSDK11 + 460 mileage, the new tunnel is built below the civil air defence tunnel (It is 2.17m from the civil air defence tunnel. The size of the civil air defence tunnel is 2m wide and 2.4m high.). The plane position of the new tunnel is approximately orthogonal to the civil air defence tunnel, as Figure 1 shows below. For the concealed excavation of new tunnel, the design surrounding rock grade is V. With the drilling and blasting method adopted, the three steps of excavation is applied in the new tunnel construction. The excavation footage is 0.8m, the number of cut holes on the top level is 6. The blast-hole depth is 1m. The single hole charge amount is 0.45kg. The engineering geology is mainly tufa at weak weathered and moderate weathered , uniaxial compression strength reach 109MPa.To ensure the safety of civil air defence tunnel during the construction of tunnel blasting, blasting vibration monitoring is conducted on the civil air defence tunnel.

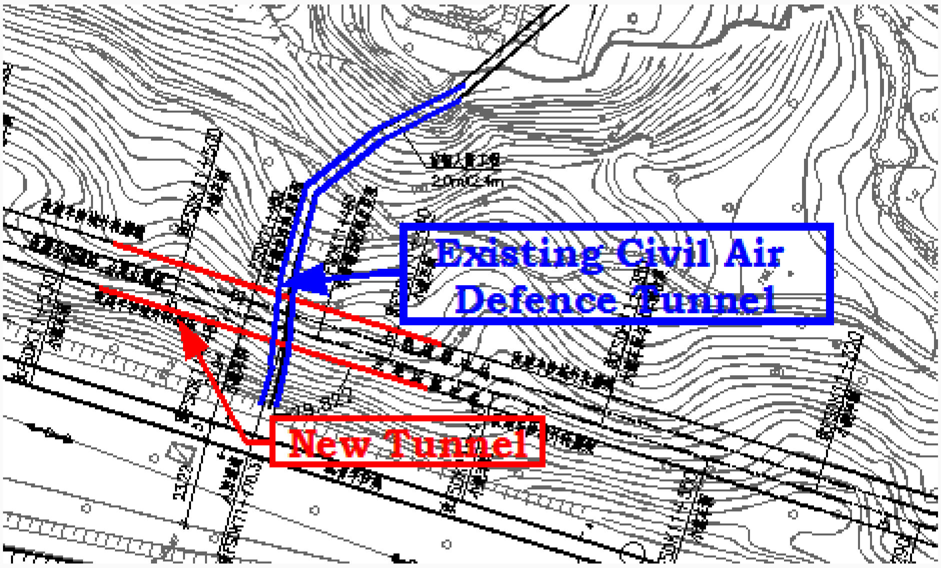


Fig.1 – Location relationship between new tunnel and civil air defence tunnel

Numerical simulation and analysis

Now, the major control blasting technique adopted by the drilling and blasting construction in the mountain tunnel is smooth blasting. The sectional blasting of initiation of millisecond detonator is the core content of smooth blasting. The cutholes are detonated at the same time in the sectional blasting. The charge weight per delay interval is large, so the greater impact will be generated on the surrounding structure. The time interval between holes can be precisely controlled in the hole-by-hole initiating of digital detonator. This blasting method exploits the effect of the seismic wave among holes superimposed destructive interference to significantly reduce the vibration influence. Moreover, different cut modes also have different vibration effects on adjacent structures. Under normal circumstances, due to the large charge amount of cutholes and cutholes grasped by the rock mass, so the vibration velocity of neighbouring structures caused by cuthole blasting seismic wave is larger than the satellite hole and periphery hole. Therefore, this paper aims to reduce the vibration velocity of neighbouring structures caused by cuthole. And LS-DYNA will be adopted to study the detonation modes and cut modes of cutholes.

Element and arithmetic

Surrounding rock, explosives and air will employ solid-164 element. The rock uses constant stress solid element. This element uses pure Lagrange algorithm. When the structural deformation is huge, it is possible to cause severe distortion of the finite element mesh, which causes problems in numerical calculation, so the algorithm is not suitable for air and explosives. The coupling between explosives and air uses the ALE (Arbitrary Lagrangian-Eulerian) algorithm. The ALE algorithm can handle similar grid distortions arose from large deformations, such as explosives and air. The interaction among the air, rock and explosives will be considered by fluid-solid coupling method. There are usually two methods for fluid-structure interaction, one is common node and the other is by *CONSTRAINED_LAGRANGE_IN_SOLID. The first numerical simulation method is used in this paper. The air and explosives material are bound in an element algorithm with the keyword of *ALE_MULTI_MATERIAL_GROUP. Set the detonation point coordinates and detonation time by keyword of *INITIAL_DETONATION. Then, the termination time of blast set to 0.03s by keyword of *CONTROL_TERNITION.

Material parameters and equation of state

Air is defined by the *MAT_NULL material model and the *EOS_LINEAR_POLYNOMIAL linear polynomial equation of state. The equation expression is as follows.

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \tag{1}$$

Where: $\mu = \rho/\rho_0 - 1$, ρ and ρ_0 are the mass density and the reference mass density, respectively. E is the material internal energy per unit volume. C_0, C_1, C_2, C_3, C_4, C_5, and C_6 are all real constants. The parameters are valued according to the ideal gas state equation (Table 1). V_0 represents the initial relative volume.

Tab. 1 - Material parameters of air[16]

ρ (kg/m^3)	C_0	C_1	C_2	C_3	C_4	C_5	C_6	E (J/m^3)	V_0
1.290	0	0	0	0	0.4	0.4	0	2.5×10^5	1.0

With *MAT_PLASTIC_KINEMATIC model adopted, surrounding rock is considered as the ideal elastic-plastic material. Yield condition:

$$\phi = \frac{1}{2}\xi_{ij}^{2} - \frac{\sigma_y^2}{3} = 0 \qquad (2)$$

Where: stress deviator tensor $\xi_{ij} = s_{ij} - a_{ij}$, yield stress $\sigma_y = [1 + (\frac{\dot{\varepsilon}}{C})^{\frac{1}{P}}](\sigma_0 + \beta E_P \varepsilon_{eff}^{p})$, among left equation, s_{ij} is Cauchy ' s stress tensor, P and C are constants input. σ_0 and β are the initial yield stress and hardening parameters respectively. $\dot{\varepsilon}$ is the strain rate, $\dot{\varepsilon} = \sqrt{\dot{\varepsilon}_{ii}\dot{\varepsilon}_{ij}}$; E_P is the plastic hardening modulus, $E_P = \frac{E_t E}{E - E_t}$. E and E_t is the elasticity modulus and tangent modulus respectively. ε_{eff}^{p} is the finite plastic strain. Core samples were drilled from the surrounding rock. The mechanical parameters of the rock were obtained from a triaxial compression test of the field laboratory. The parameters of rock are shown in the Table 2.

Tab. 2 - Parameters of rock mechanics

Density (g/cm^3)	Elasticity modulus (10^3MPa)	Shear modulus (GPa)	Poisson's ratio	Yield stress (MPa)	Cohesion (MPa)	angle of internal friction (º)
2.3	2	0.06	0.34	70	0.3	50

In the LS-DYNA program, *MAT_HIGH_EXPLOSIVE_BURN is adopted to represent the explosive material model and describe the relationship between gas pressure and volume. It is to calculate the detonation pressure that the JWL (Jones-Wilkens-Lee) equation of state is employed. JWL equation of state as follows:

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega N}{V} \qquad (3)$$

Where: *P* — detonation pressure, *N* — internal energy of explosive detonates products, *V* — relative volume of explosive detonates products, *A*, *B*, R_1, R_2, ω — the constants of explosives nature. The parameters of explosive materials and the equation of state should generally be obtained from cylinder tests[17-19]. The related parameters valued refer to the previous research as a result of low experimental conditions (Table 3).

Tab. 3- Materials of explosive & parameters of state equation[20]

Density (kg/m^3)	Detonation velocity (m/s)	Detonation pressure (GPa)	*A* (GPa)	*B* (GPa)	R_1	R_2	ω	*E* (GPa)
1100	3500	4	214	0.182	4.15	0.95	0.3	4.192

Calculation model

This paper calculates and analyses the impact of tunnel blasting on the civil air defence tunnel under the three conditions of parallel cut (simultaneous initiation), parallel cut (hole-by-hole initiation) and oblique cut (hole-by-hole initiation). The specific calculation model size is 30m (width)×22m (height)×13.2m (length). The blasting holes of parallel cut perpendicular to the rock surface. The angle between the blasting holes of oblique cut and the rock surface is 120°. So, the model of oblique cut is more difficult to build. In order to improve the calculation accuracy, the meshes in the lateral and longitudinal ranges of the oblique blasting holes are refined. The local grid size of blasting holes and explosives is 0.005m. The basic grid size of other parts is 0.2m. The parallel cut model contains 1095636 elements, 1171446 nodes. The oblique cut model contains 1157923 elements, 1386325 nodes. Reverse uncoupled charge is adopted in the blasting process. The borehole diameter, explosives diameter, blast hole depth, the charge weight per delay interval and the time interval between holes are 42mm, 30mm, 0.8m, 0.45kg and 5ms respectively. The calculation models are shown in the Figure 2 and Figure 7.

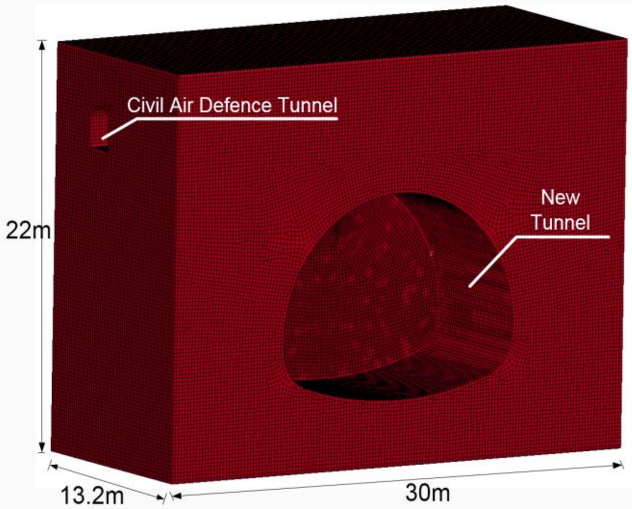


Fig.2 – The diagram of calculation model parallel cut

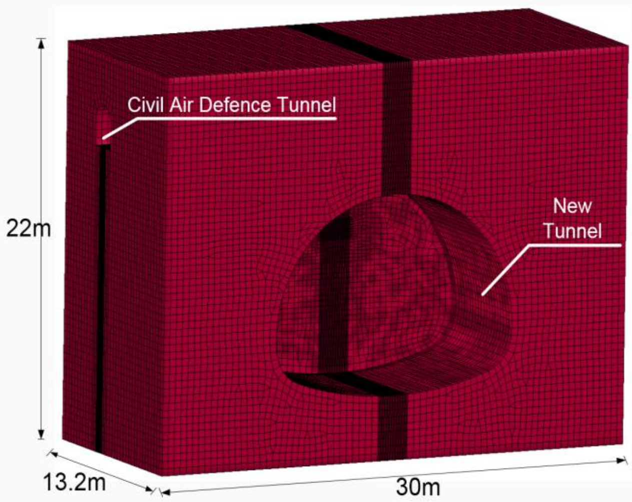
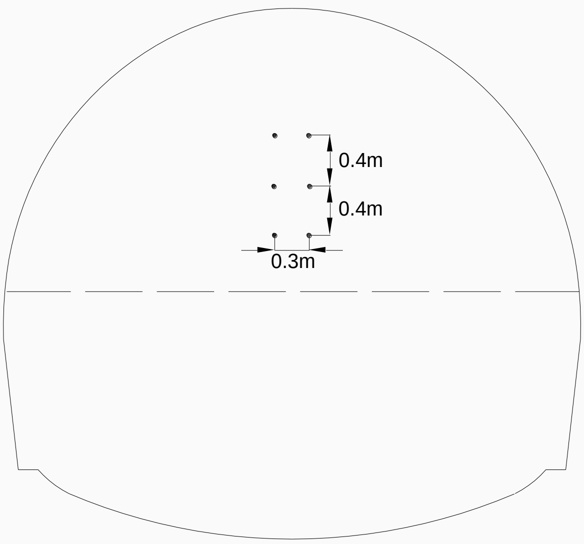


Fig.3 – The diagram of calculation model oblique cut



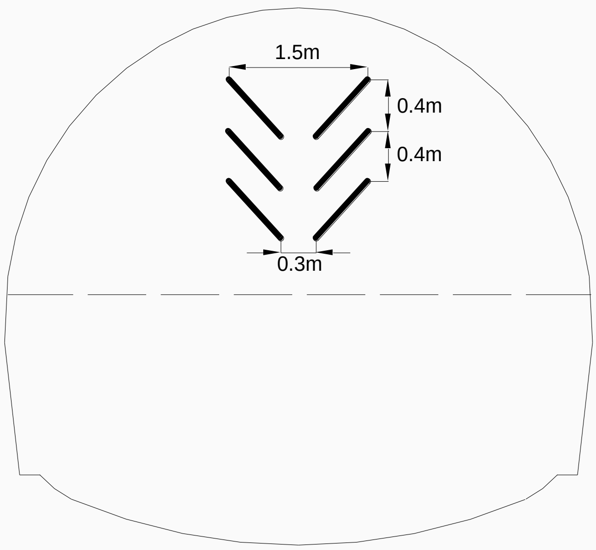


Fig.4 – Distribution of parallel cut

Fig.5 – Distribution of oblique cut

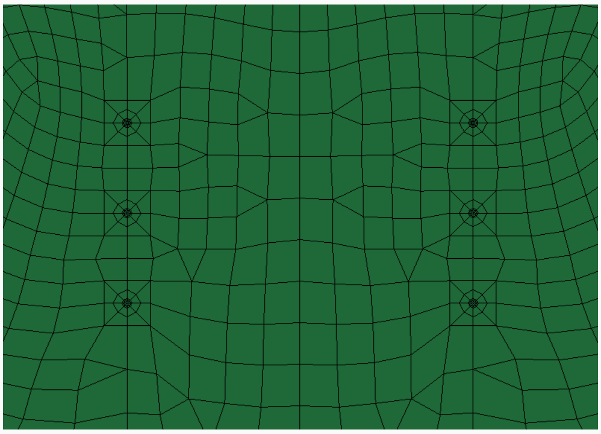


Fig.6 – Blasting holes of parallel cut

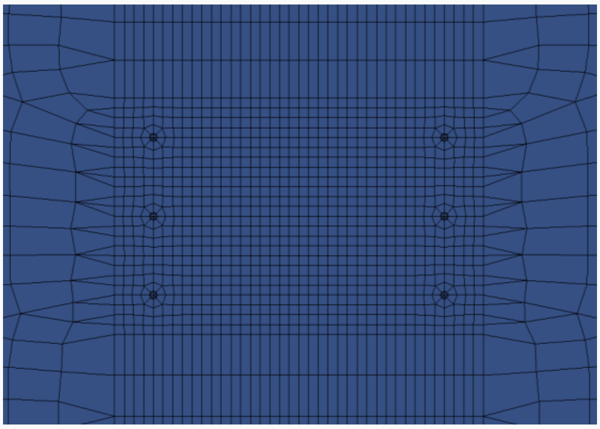


Fig.7 – Blasting holes of oblique cut

RESULTS

Experimental verification

Blasting vibration data are acquired by Chengdu ZKCK TC-4850N (Figure10) blasting seismometer acquisition. The instrument vibration monitoring frequency range is 5 to 500 Hz. And the resolution, sampling rate, and reading accuracy are 0.01, 100, and 0.1, respectively. The oblique wedge cut and hole-by-hole initiation of digital detonator are applied to site construction. With the new tunnel axis as the center line, the left and right sides of the tunnel should be equipped with a three-phase acceleration sensor at every 5m. There are 5 instruments in total. The specific figure of distribution and field test figure are shown at the Figure 8. The numerical calculation results and field test results of the vertical vibration velocity of the floor (monitoring point 3) of the civil air defense tunnel right above the new tunnel center-line are selected to make a comparative analysis. This is because the monitoring point 3 is closest to the newly built tunnel and the velocity in the vertical direction is the largest. Typical working conditions can more clearly reflect the physical laws implied by the data. The results are shown in the Figure 9.

Fig.8a – Layout of monitoring points in civil

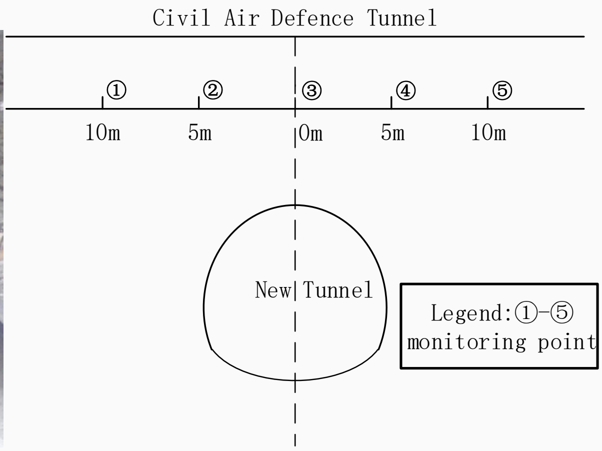


Fig.8b – Diagram of field test air defence tunnel

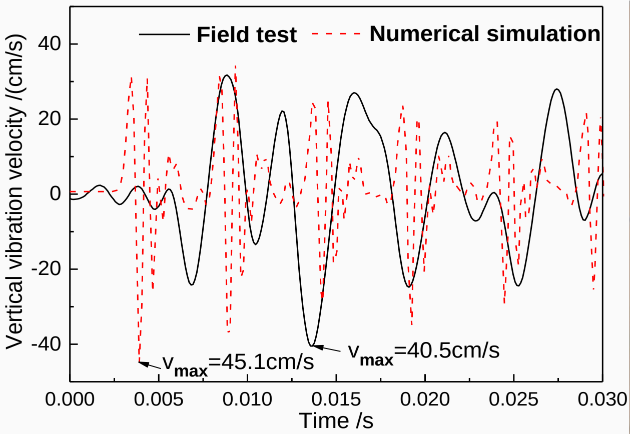


Fig.9 – Comparative analysis of test data

Fig.10 – Picture of TC-4850

It can be seen from Figure 9 that the maximum of vibration velocity measured at the monitoring point 3 is 0.405 m/s and the seismic wave period of each hole is between 3 and 4 ms. The hump phenomenon of vibration waveform appealed after the seismic waves of adjacent holes superimposed. The maximum vertical vibration velocity of numerical calculation is 0.451m/s, 11% higher than the measured results, the hole blasting seismic wave period between 2 ~ 3ms. The each hole blasting seismic waves have no superposition phenomenon. The amplitudes of the vibration-velocity curves of field-measured and numerical simulation both decrease with time. Overall, the numerical results are in good agreement with the results of field test, and the calculation method is reliable.

Analysis of detonation mode

The vibration effects of simultaneous initiation (millisecond detonator) and hole-by-hole initiation (digital detonator) on adjacent civil air defence tunnel are studied through the numerical simulation. The advantage of numerical simulation is that it can monitor the vibration at any point. This section selects the data of the four monitoring points (located at the left wall, the right wall, the crown and the floor) of the civil air defence to make a comparative analysis. The specific layout of the tunnel cross-section monitoring point is shown in Figure 11. The vibration velocity of X, Y and Z directions of the four monitoring points are listed in Table 4.

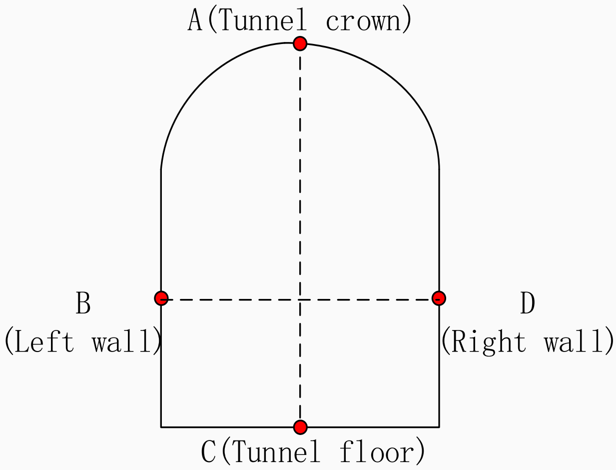


Fig.11 – Layout of monitoring points

Tab. 4- Vibration velocity in three directions (m/s)

Parameters	Parts	X (Tunnel longitudinal)	Y (Vertical direction)	Z (Tunnel transverse)	Comment
Velocity	Tunnel floor	-0.405	0.754	0.0124	simultaneous initiation
		0.238	-0.451	0.0983	hole-by-hole initiation
	Left wall	-0.214	-0.447	-0.00348	simultaneous initiation
		-0.114	-0.215	-0.0283	hole-by-hole initiation
	Right wall	-0.148	-0.246	0.00642	simultaneous initiation
		-0.0602	-0.105	-0.026	hole-by-hole initiation
	Tunnel crown	-0.0415	0.0592	0.00215	simultaneous initiation
		0.0209	0.0323	-0.00725	hole-by-hole initiation

As the Table 4 shows, the vibration velocity in the X and Y direction of hole-by-hole initiation are about 50% of simultaneous initiation. And the vibration velocity in the vertical direction under both conditions is faster than the other two directions. The vibration velocity in the Z direction caused by hole-by-hole initiation is larger than simultaneous initiation. However, the vibration velocity in the Z direction is small on the whole and does not have a large impact on the structural safety, so it is not the key point of research. Therefore, the vertical direction of the data is selected as the focus of comparative study in what follows in this passage. The Y-direction vibration (vertical direction) velocity of four monitoring points in the civil air defence tunnel shown in Figure 12.

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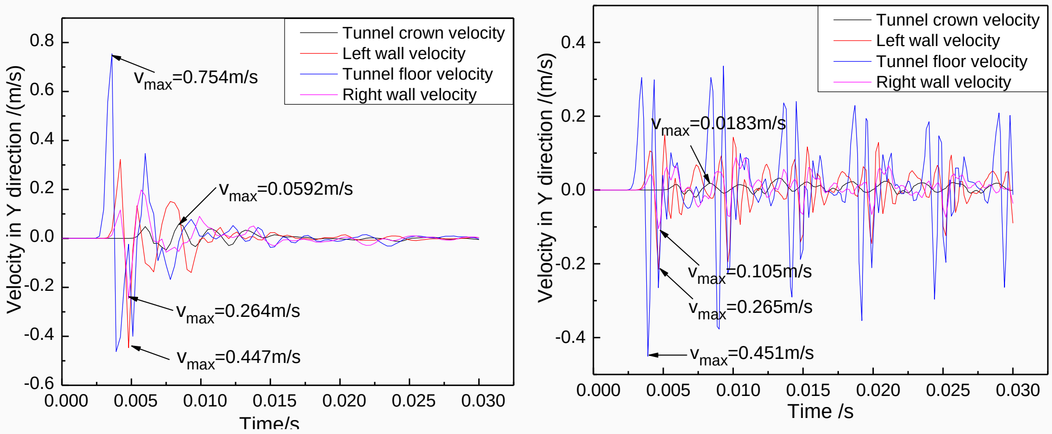

(a) Simultaneous initiation (millisecond detonator)

(b) Hole-by-hole initiation (digital electronic detonator)

Fig.12 – Vibration velocity in vertical direction

Comparing Figure 12(a) and Figure 12(b) shows that the maximum vibration velocity(0.754m/s) of simultaneous initiation is much larger than the maximum vibration velocity(0.451m/s) of hole-by-hole initiation. Digital detonators can reduce the maximum velocity by 40%. The moment of the peak of vibration velocity appears in the first three peaks, because the first wave of different detonation modes has no phenomenon of superimposition and cancellation between peak and trough. The vibration velocity caused by simultaneous initiation is almost attenuated to 0 after 0.015 s. The vibration velocity caused by hole-by-hole initiation is not linearly attenuated due to the mutual interference of different seismic waves, but the vibration velocity assignment decreases with time. The descending order of the vibration velocity of the four monitoring points of the civil air defence tunnel is the floor, left wall, right wall and crown. This is because the blast center distance of floor is nearest, and it has the maximum vibration velocity, the blast center distance of crown is farthest, and it has the minimum vibration velocity. The right wall is located in the upside of the tunnel excavated. Due to the existence of the free face (Fig 2 and 3), the vibration velocity of right wall is less than the velocity of left wall. And the vibration velocity of right wall is close to half of the left wall.

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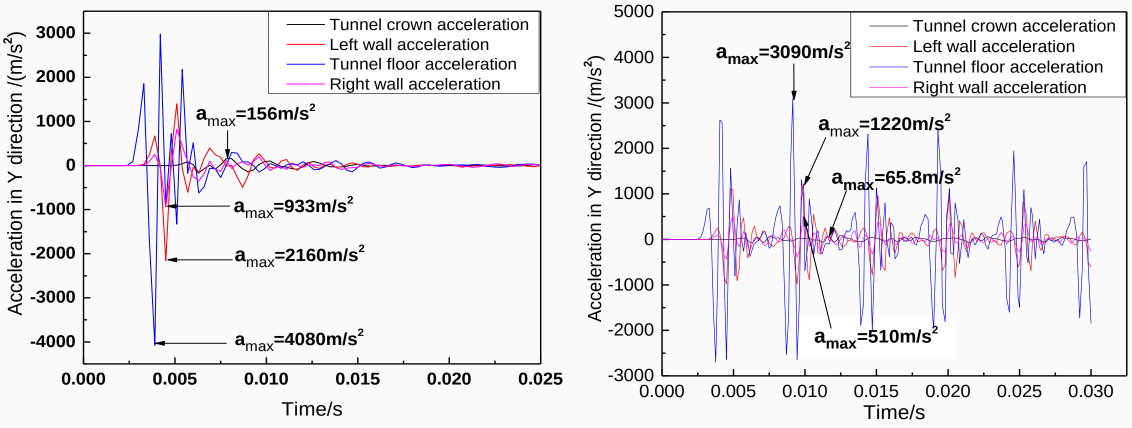
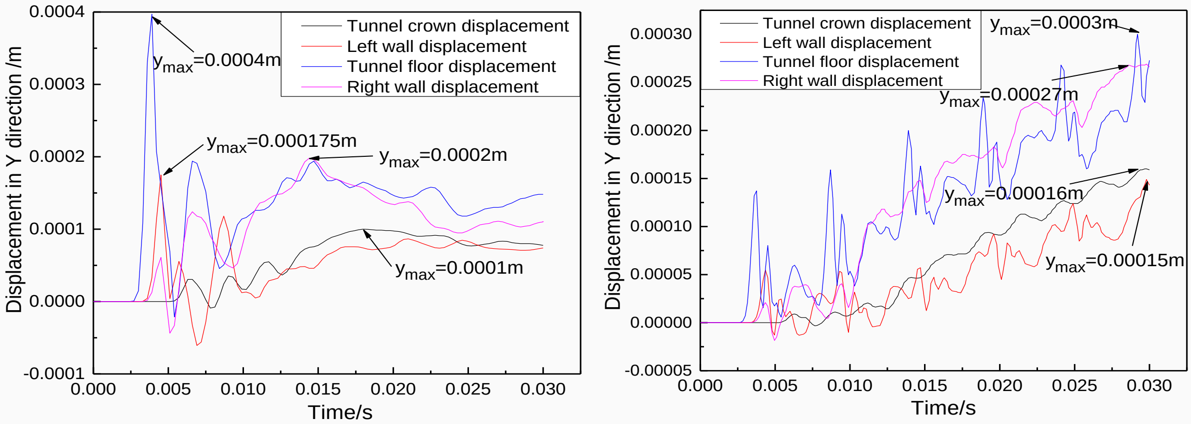


(a) Simultaneous initiation *(b) Hole-by-hole initiation*

(millisecond detonator) *(digital electronic detonator)*

Fig.13 – Vibration acceleration in vertical direction

Comparing Figure 13(a) and Figure 13(b), it can be seen that under both conditions, the peak acceleration of the floor is far greater than other parts. The peak acceleration of vibration (4080m/s^2) of simultaneous initiation is far greater than the peak acceleration of vibration (3090m/s^2) of hole-by-hole initiation. Digital detonators can lower the peak vibration acceleration by 24%. In the same time, the descending order of the vibration acceleration of the four monitoring points of the civil air defence tunnel is also the floor, left wall, right wall and crown. The law of acceleration is similar to the law of velocity change, which indicates that in blasting construction, increasing the free surface helps to reduce the adverse effects caused by blasting. It can be also found that the energy is relatively concentrated at the simultaneous initiation, and the spectrum shows a single peak phenomenon. After 0.015s, the acceleration of each part is almost attenuated to 0. The energy of hole-by-hole initiation is relatively dispersed, the spectrum shows multi-peak phenomenon. The vibration velocity of hole-by-hole initiation coincides with the vibration period of acceleration, which is about 9 ms. The curve of simultaneous initiation does not show significant periodicity. Most of the energy of simultaneous initiation is released at the beginning of the explosion, and the force generated is large, while hole-by-hole initiation has a process of energy release for a certain period of time.

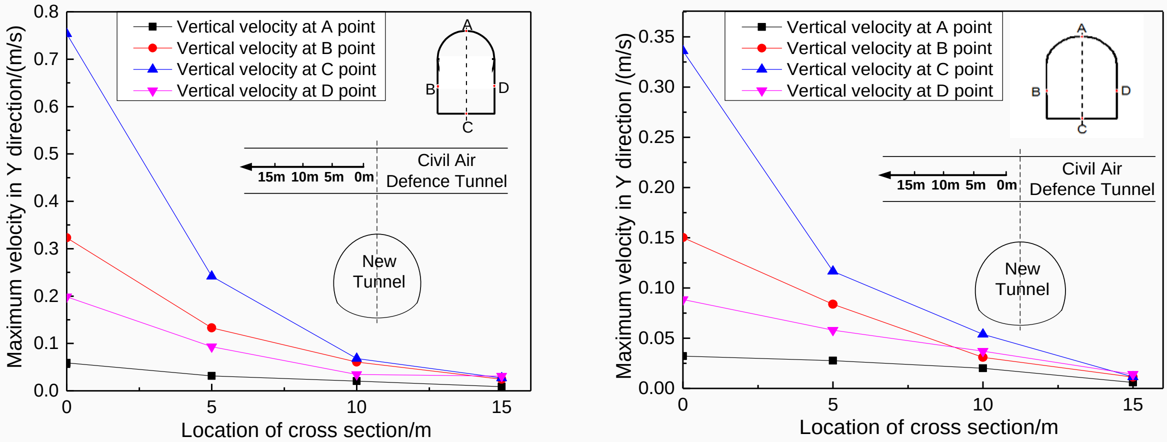


(a) Simultaneous initiation *(b) Hole-by-hole initiation*

(millisecond detonator) *(digital electronic detonator)*

Fig.14 – Displacements in vertical direction

Comparing Figure 14(a) and Figure 14(b), it can be seen that under both conditions, the vibration displacement in the vertical direction is small. The maximum vibration displacement of the floor of simultaneous initiation and hole-by-hole initiation are 0.4mm and 0.3mm respectively. The reason is that the blasting time is extremely brief, and different detonation modes have less influence on the vibration displacement, and there is no significant divergence in the displacement extreme value. Hence, the vibration displacement should not be used as the evaluation criterion of vibration impact.



(a) Simultaneous initiation *(b) Hole-by-hole initiation*

(millisecond detonator) *(digital electronic detonator)*

Fig.15 – Vibration velocity in different positions

As Figure 15 shows, under the two conditions of simultaneous initiation and hole-by-hole initiation, the vibration velocity at different monitoring points decays with the distance from the initiation position increases in a similar law. Because the vibration velocity of the tunnel floor (C point) is the largest, it is the research object. Under the condition of simultaneous initiation, from monitoring point 3(0.754m/s) to monitoring point 4(0.240m/s), the maximum vibration velocity is reduced by 68%. Under the condition of hole-by-hole initiation, from monitoring point 3 (0.3336m/s) to monitoring point 4(0.120m/s), the maximum vibration velocity is reduced by 64%. Further analysis shows that the vibration velocity of C point decreases exponentially with distance increases. The blasting distance of C point is the smallest, although the vibration velocity is the largest, the attenuation is faster than other parts (A, B, D). Moreover, the vibration velocity of the civil air defence tunnel other than 15 m is close to, which indicate that the blasting vibration influence range is roughly 30m directly above the detonation point. This range of influence can provide a reference for the safety monitoring of civil air defence tunnel.

Analysis of cut modes

The quality of cut-holes has a direct influence on the dig velocity of hard-rock tunnel and the efficacy of smooth blasting. At present, the main cut modes are parallel cut and oblique cut. In this section, numerical simulation is used to explain the influence of parallel cut and oblique cut on blasting vibration. Figure 16, Figure 17 and Figure 18 show the time history of vertical vibration velocity, displacement and acceleration of civil air defence tunnel floor under two kinds of cut modes.

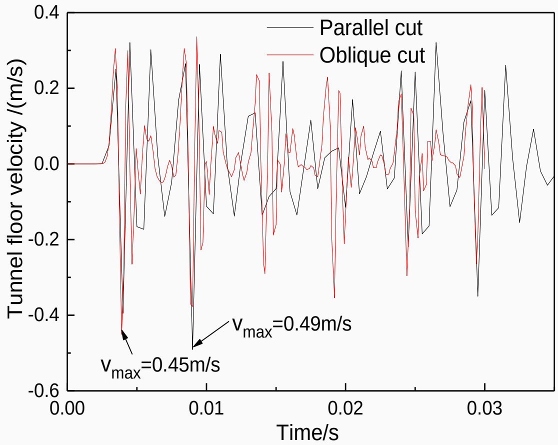


Fig.16 – Vibration velocity in vertical direction

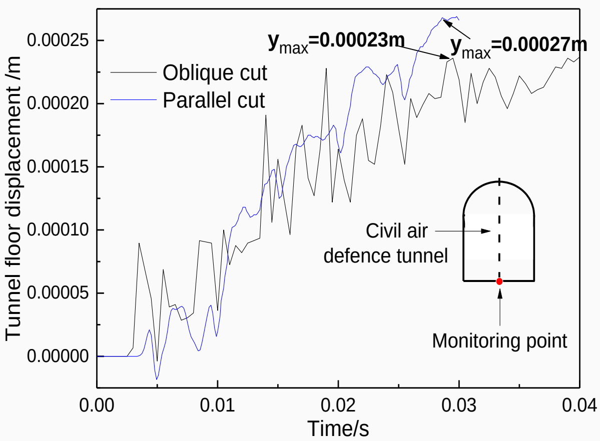


Fig.17 – Time history curve of vertical displacement

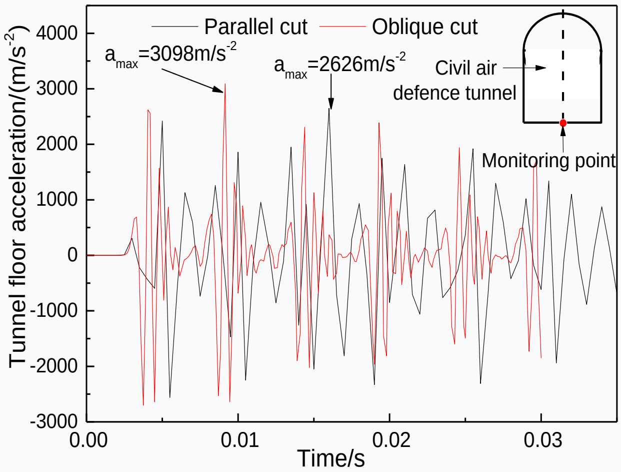


Fig.18 – Vibration acceleration in vertical direction

Knowing from Figure 16, the maximal vibration velocity of parallel cut is slightly larger than the maximum of oblique cut. Oblique cut shows a clear periodicity. The vibration period is approximately 5ms, and the energy is relatively concentrated, while the parallel cut does not have obvious periodicity, the energy is relatively dispersed. Therefore, in the condition of hard-rock, the rock-breaking effect of oblique cut is better than parallel cut, and the oblique cut has a slighter impact on the adjacent structure than parallel cut.

Observed results from Figure 17 generate that the vibration displacement maximum (0.27mm) of the parallel cut is slightly larger than that of the oblique cut (0.23mm), and the vibration displacement of the adjacent structure under both conditions is small. After the start of blasting, due to the vibration of the seismic wave, the displacement of the tunnel floor under the condition of two types of cut, but generally increased with time. However, the vibration displacement of the parallel cut tends to be stable after 0.03 s, and the vibration of the oblique cut continues to 0.04 s, which indicates that the oblique cut has a stronger vibration effect in hard rock blasting.

It can be seen from Figure 18, the maximum value (3098m/s^2) of the oblique cut vibration acceleration is 15% greater than the maximum value (2626m/s^2) of the parallel cut vibration acceleration, and the acceleration of oblique cut appears 9 ms earlier than parallel cut. The energy released after blast starting of the oblique cut is concentrated in the early stage of the blasting process. And in the later stage, the vibration acceleration of the oblique cut shows a more regular periodicity, and the attenuation velocity is slower. The results indicates that, compared with parallel cut, the oblique cut's the surrounding rock stress is greater. Through the above analysis, it can be materialized that the rock-breaking effect of oblique cut is better.

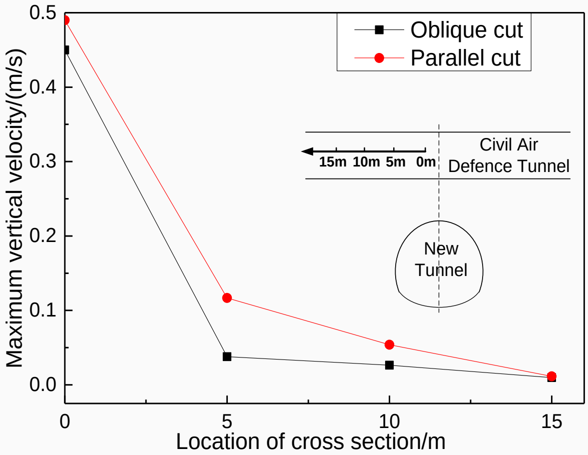


Fig.19 – Relationship between vibration velocity & distance

Obtained curves form Figure 19 shows that, under different positions, the vibration velocity of parallel cut is greater than that of oblique cut, and the change trend of the velocity with distance is similar under the two conditions. Further studies reveal that the trend shows an exponential decay. In the range of 0 to 5 m, the vibration velocity generated by the oblique cut is rapidly attenuated. In the range of 5 to 15 m, the vibration velocity is close to 0. Therefore, the oblique cut is more advantageous for the protection of the civil air defence tunnel.

CONCLUSION

In this paper, the reliability of the finite element method is verified by comparing the measured data with the results of LS-DYNA finite element program. Then, numerical simulation is used to illustrate the influence of different detonation modes and different cut modes on the vibration effect of adjacent structures. The main conclusions in this paper are as follows:

(1) As mentioned earlier, single-hole coupled blasting vibration analysis is carried out by using ALE algorithm. And the calculation results can accurately reflect the vibration characteristics of seismic waves of holes. The calculation parameters and methods are basically reasonable.

(2) The vibration velocity of hole-by-hole initiation (digital electronic detonator) is 40% lower than simultaneous initiation (millisecond detonator), and the vibration acceleration is reduced by 24%. The vibration velocity at different monitoring points decays with the distance from the initiation position increases in an exponential rule. The digital detonator is more suitable for the vibration damping control blasting of the tunnel under complex condition in the central urban area, but its cost is 6 to 8 times higher than that of an ordinary millisecond detonator.

(3) The vibration velocity of parallel cut on surrounding structure is larger than the oblique cut a bit. However, the vibration acceleration of oblique cut is 15% larger than the parallel cut, and has a better effect for rock-breaking. Consequently, the oblique cut is more fitting for hard rock tunnel blasting.

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