EXPERIMENTAL STUDY ON THE STABILITY OF SURROUNDING ROCK IN TUNNEL BLASTING CONSTRUCTION

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ABSTRACT

In this study, criteria and blasting technologies are introduced in order to control the stability of surrounding rock of tunnel built using drill-and-blast safety. The paper is composed of three parts, namely, a blast vibration propagation law in roof surrounding rock in close proximity to tunnel face, two formulae to calculate particle critical vibration velocity of shotcrete and key structural element at the roof of tunnel, and innovative technologies of tunnel blasting. The blast vibration propagation law is the base to control the stability of surrounding rock during tunnel blasting. Based on Morhr-Coulomb criterion and the dynamic analysis, two formulae to calculate the critical particle vibration velocity are proposed. Based on a series of trial blasts using electronic detonators, two innovative blasting technologies are derived. One is the blast holes detonated one by one by using electronic detonator, and another is the blast holes detonated by combining initiation system of electronic detonators and nonel detonators. The use of electronic detonators in tunnel blasting not only leads to a smaller blast vibration but also to a smaller extent of the EDZ (excavation damaged zone).

KEY WORDS

Tunnel Engineering, Blasting, Attenuation Law of Blast Vibration, Stability

INTRODUCTION

Drill-and-blast is a cost-effective method for excavating tunnels in rock mass, the blast vibration often affects the stability of surrounding rock of tunnel and may result in collapse of tunnel, threatening the safety of workmen and the buildings.

The stability of surrounding rock of tunnel in construction using drill-and-blast has been studied by many scholars [1-3]. The influences of blasting vibration on stability of existing adjacent tunnel have been studied [4-5]. Shotcrete is one of initial supports of tunnel in construction in order to ensure the stability of surrounding rock, and widely used in China. The stability of the shotcrete of tunnel has been studied [6-7]. Blasting vibration law is base to control the stability of surrounding rock. The laws have been proposed or studied [8-9], but they were gained from far-field vibration

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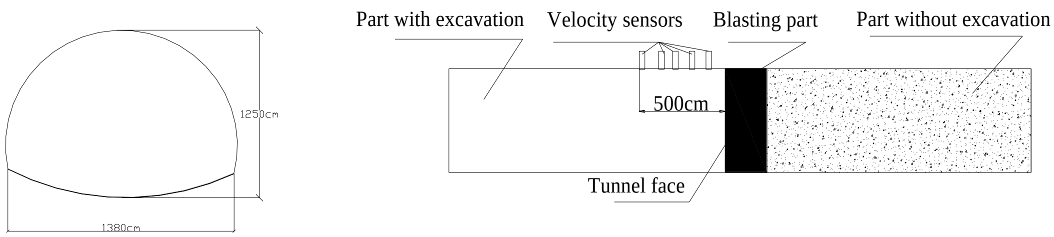
data and do not favor to control blast vibration in close proximity behind tunnel face [10-11]. The rock damage and ground vibration in the closed proximity of blasting source were measured [12]. The near-field damage in blasting construction of tunnel was assessed [13]. In order to control the stability of surrounding rock of tunnel, electronic detonator has been widely used in tunnel blasting [14-15].

This study is structured as follows. First, a blasting vibration law in near-field of tunnel blasting was put forward. Then, the stability of surrounding rock of tunnel were described and analyzed. Finally, innovative blasting technologies to decrease blasting vibration were introduced.

BLAST VIBRATION PROPAGATION LAW IN NEAR-FIELD OF TUNNEL BLASTING

The effect of blast vibration on the stability of surrounding rock is a common concern for geotechnical engineer. The blast vibration measurements in the roof surrounding rock within the range of 5m behind tunnel face were carried out in Qipanshan railway tunnel, which is located in the city of Hezhou in Guangxi province, China. It has a total length of 2378m, and an overburden of 50 to 200m, mainly composed of moderately limestone with density of 2400kg/m3, P-wave velocity of 4000m/s. Emulsion explosive is used, the density of the explosive is 1.0 g/cm3, the explosive strength is more than 260 ml, while the detonation velocity is 3200m/s. Nonel detonator is used, which is resistant to stray current, static electricity, thunder and lighting, radio frequency, water and spark, as well as being safe and easy to operate.

The velocity sensors were assembled in the bottom of the shallow holes with 30cm length and 40mm diameter, and filled with the mixture of gypsum and water. These shallow holes were drilled upward in the range of 5m behind funnel face. A typical cross-section of the tunnel and arrangement of the sensors are shown in Figure1. The distance between the sensors is from 50cm to 100cm.



(a) (b)

Fig. 1 - (a) Tunnel cross-section (b) Distribution of measurement points in the roof of surrounding rock.

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(c)

Fig. 1 - (c) Photo of velocity sensors in the roof of surrounding rock.

Three trail blasts were carried out. The arrangements of blastholes were shown in Figure 2, blasting design parameters were shown in Table1.

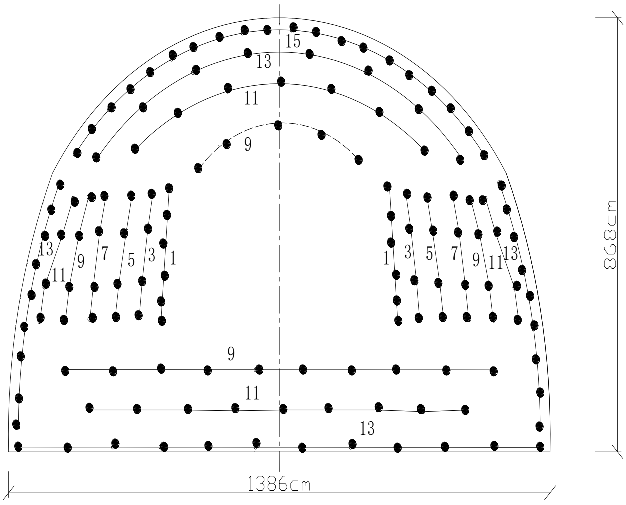

Fig. – 2 Blastholes pattern of using nonel detonators (the number indicate delay number of nonel detonator)

Tab. 1 - Summary of blasting properties

Blasting hole type	Number of holes	Hole length/m	Charge weight per hole /kg	delay	Explosive weight per delay /kg
Cut holes	12	5	3.0	1	36.0
Easer hole 1	8	5	2.8	3	22.4
Easer hole 2	8	5	2.6	5	20.8
Easer hole 3	8	4	2.2	7	17.6
Easer hole 4	8	4	2.0	9	16.0
Easer hole 5	8	4	2.0	11	16.0
periphery hole	18	4	0.8	13	14.4
Above easer hole 1	4	4	1.6	9	6.4
Above easer hole 2	7	4	1.6	11	11.2
Above easer hole 3	8	4	1.6	13	12.8
Roof hole	20	4	0.4	15	8
Bottom hole3	10	4	2	9	20
Bottom hole 2	11	4	2	11	22
Bottom hole	12	4	2	13	24
Sum	142				247.6

The UBOX-5016 Data Collection System and its PS-10K3 velocity sensors with the maximum measurement of 250cm/s are used to measure the blasting vibration. The measured data are analyzed by the BM View software; the results are listed in Table 2.

Tab. 2 - Monitoring data of blast vibration

Distance between monitoring point and the tunnel face (m)	Charge weight per delay (kg)	Scaled distance m/kg1/3	Measured vertical PPV (cm/s)
0.5	51.2	0.135	116
0.5	49.2	0.136	111
0.5	8	0.250	84
0.7	51.2	0.189	51
0.7	8	0.350	36
0.9	51.2	0.242	29
0.9	49.2	0.246	44
0.9	8	0.450	17
1.3	8	0.650	37
1.3	51.2	0.350	35
1.3	49.2	0.355	32
1.5	51.2	0.404	35
1.5	49.2	0.409	29
1.5	42.4	0.430	29
1.9	51.2	0.512	27
1.9	49.2	0.519	20
1.9	8	0.950	18
2.1	51.2	0.566	29
2.1	49.2	0.573	25
2.8	22.4	0.993	28
2.8	8	1.400	15
2.8	51.2	0.754	18
2.8	49.2	0.764	12
4	22.4	1.419	21
4	49.2	1.092	20
4	51.2	1.077	19
4	8	2.000	14
5	51.2	1.347	22
5	22.4	1.774	21
5	8	2.500	13
5	49.2	1.366	12

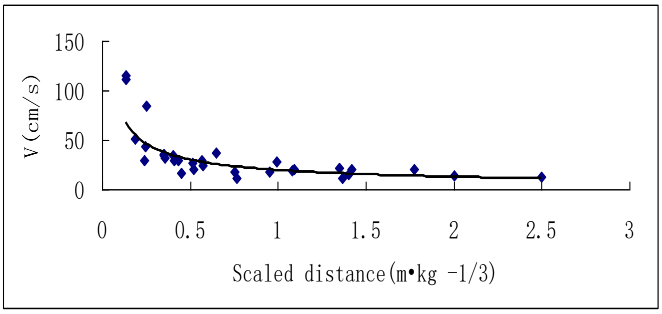

Fig. 3 - Relationship between vibration velocity and scaled distance

According to the Sadaovsk formula, the statistical relationship of scaled distance and vertical Peak Particle Velocity (PPV) is shown in Figure 3, the blast vibration propagation law in roof surrounding rock in close proximity to tunnel face is written as:

$$V = 19.58\left(\frac{\sqrt[3]{Q}}{R}\right)^{0.62} \tag{1}$$

Where V the PPV, (cm/s) is, Q is the charge per delay, (kg), R is the distance between the monitoring point and the tunnel face, rather than the distance between the monitoring point and the explosion source, (m). The correlation coefficient is 0.84.

The constants of the blast vibration propagation law are 19.58 and 0.62, much less than those of the Sadaovsk formula, which are the range of 50-350 and the range of 1.3-2.0[16], in GB6722-2014[16] respectively. The blast vibration propagation law is perfect for calculating blast vibration in the far-field to tunnel blasting [17] (Rao 2010).

SAFETY CRITERION FOR TUNNEL BLASTING

Due to the complexity of tunnel blasting as well as properties of the rock mass, the safety criterion for tunnel blasting is often set empirically. In order to investigate the influences of blasting vibration on surrounding rock and shotcrete, blasting vibration velocities and dynamic stresses of them were analyzed and studied.

Safety criterion for shotcrete

Initial support is usually required when surrounding rock mass of tunnel is fractured and weathered. Shotcrete (sprayed concrete) is one of initial supports widely used in tunnel construction in China. The function of shotcrete is to prevent fallout of rock blocks thereby securing the arch-shape of tunnel profile. During tunnel blasting, the interaction between shotcrete and rock is influenced by stress wave propagation. Stress waves induced from blasting propagate through the rock, reflect and transmit at the shotcrete-rock interface and free surface. When the stress waves reflect at a free surface of shotcrete, the particle velocities are doubled and the corresponding stress are zero over the free surface. This means that a compressive wave reflects backs as a tensile wave, which may result in debonding at the shotcrete-rock interface. As a result, the shotcrete may lose the function of support. Figure 4 shows the shotcrete under blasting stress waves.

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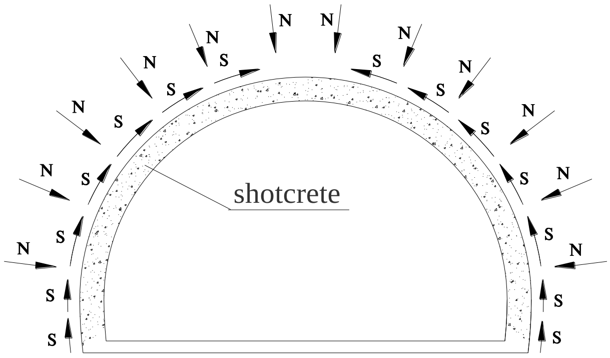

Fig. 4 - Stress state of shotcrete (after [18] Guan, 2009) (N representing normal stress, S representing shear stress)

The adhesion strength between the shotcrete and the rock mass is less than the tensile strength of Shotcrete. The adhesion strength is less in normal than in shear ([7] Ahmed et al. 2012), and determines the function of shotcrete.

The stresses σ corresponding to particle vibration velocities V in elastic materials can be written as ([7] Ahmed et al. 2012)

$$\sigma = \rho C_p V \tag{2}$$

Where ρ is the density, C_p is P-wave velocity.

Based on the elastic stress wave theory, the critical particle vibration velocity V_{scrit} of the shotcrete can be written as:

$$V_{scrit} = \frac{\sigma_{dsr}}{\rho_s C_{sp}} \qquad \sigma_{dsr} = k\sigma_{ssr} \tag{3}$$

Where σ_{dsr} is the dynamic adhesion strength in normal between the shotcrete and the mass rock, ρ_s is the density of the shotcrete, C_{sp} is P- wave velocity propagating in the shotcrete, σ_{ssr} is the static adhesion strength in normal between the shotcrete and the mass rock , k is the dynamic increasing coefficient, $k = 3-4$ [19].

The adhesion strength σ_{ssr} is about 1.8 MPa [19], the density of the shotcrete and the P-wave velocity of shotcrete are 2100kg/m3 and 4140m/s, respectively [7]. V_{scrit} is then can be calculated according equation (3) to be about 82.8cm/s, which agrees with the Sweden tests[6].

Safety criterion for tunnel without initial support

For tunnels in intact rock mass, initial supports are usually not used during construction. The surrounding rock is often cut by discontinuities into various structural elements.

The stability of tunnel often depends on the stability of one key structural element, which is often located at the roof of tunnel. The key structural element may fall due to the impact of stress waves from blasting, which may result in collapse of tunnel. The stability of symmetric roof wedge of a circular tunnel in nonhydrostatic natural stress field was studied [20]. The behavior of shotcrete supported roof wedge subjected to blast-induced vibrations was studied [21] using the single-degree-of-freedom (SDOF) model. The reliability of roof wedges was analyzed [22] using the reliability index with the first-order reliability method (FORM) and second-order reliability method(SORM). These interesting works contribute to explicate the mechanism of stability of the key structural element. However, these works have shortcomings due to difficulty in determining related parameters of discontinuity such as shear and normal stiffness.

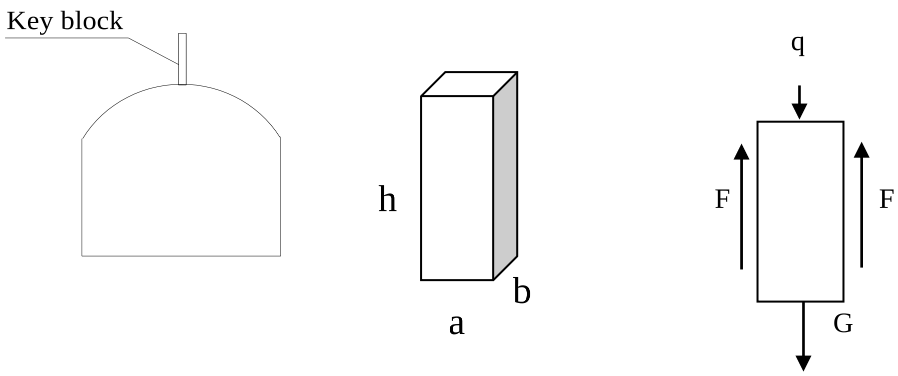

Fig. 5 - Sketch map of position and parameters of key structural element

In order to facilitate the use of geotechnical engineer, the stability of one key structural element, as shown in Figure5, is chosen to study. To study the behaviors of the key structural element, the key structural element is assumed to be supported only by discontinuity. According to Morhr-Coulomb theory, the shear strength of the discontinuity can be written as [23]

$$\tau = c + \sigma_n \tan\phi \tag{4}$$

Where c is the cohesion, σ_n is the normal stress and ϕ is the friction angle.

The falling of the key structural element is assumed in the case where normal stress is large enough to equal to uniaxial compressive strength σ_c of rock and the convex blocks of the rock mass are cut without expanding. The dynamic condition of the key structural element can be written as:

$$F \geq q + G \tag{5}$$

Where F is the shear force, equality ($=$) means that the key structural element is at limiting equilibrium, q is the dynamic load from blasting, $G = Mg$ (M is the mass of the key structural element, g is the acceleration of gravity).

According to the elastic stresses theory, q can be obtained as:

$$q = \rho C_p Vab \tag{6}$$

Where ρ is the density, C_p is the P-wave velocity, V is the particle vibration velocity at the vertical direction, a is the length of the key structural element, b is the width of the key structural element.

The shear force F can be obtained as:

$$F = 2\beta(ah + bh)\tau \quad (7)$$

Where β $(0 < \beta < 1)$ is shear coefficient varying with the volume of the convex block and number of the discontinuities consisting the block, h is the height of the key structural element.

According to Eq. (4), (5), (6) and (7), the particle vibration critical velocity V_{kcrit} of key structural element at the vertical direction can be deduced as:

$$V_{kcrit} = \frac{2\beta(\sigma_c \tan\phi + C)}{\rho C_p}(\frac{h}{a} + \frac{h}{b}) - \frac{hg}{C_p} \quad (8)$$

Since the product of hg is far smaller than the value of C_p, V_{kcrit} can be obtained as:

$$V_{kcrit} = \frac{2\beta(\sigma_c \tan\phi + C)}{\rho C_p}(\frac{h}{a} + \frac{h}{b}) \quad (9)$$

The mechanical properties of intact surrounding rock of the Qipanshan railway tunnel are presented in Table 3. Based on field condition, assigning β to 0.1, then V_{kcrit} of the key structural element is calculated based on Eq. (9) as shown in Table 4, the result is in fair agreement with the results [24].

Tab. 3 - Mechanical properties of intact surrounding rock of the Qipanshan railway tunnel

ρ (kg/m3)	C_p (m/s)	ϕ (0)	C (MPa)	σ_c (MPa)
2400	4000	45	1.5	50

Tab. 4: V_{kcrit} of key structural element

h/a (m)	h/b (m)	V_{kcrit} (m/s)
0.1	0.1	0.22
0.2	0.2	0.42
0.3	0.3	0.64
0.4	0.4	0.86
0.5	0.5	1.08

To study the stability of other key blocks, the Table 4 can be referred to.

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Innovative Blasting Technologies of Tunnel Blasting

Blasting technologies of tunnel using electronic detonator

Electronic detonator is a technical breakthrough, which has played an important role in engineering blasting. Due to the freedom in setting initiating time and accuracy of delay time, electronic detonator can provide the safe and rapid advance in the case where the tunnel is in the complex environment. A series of trial blastings were carried out in two cases in order to compare effect of electronic detonator and nonel detonator.

(1) Case one

The Niuwanggai tunnel is located at Hezhou city in Guangxi province in China, and has a total length of 452m. The surrounding rock of the tunnel is fractured limestone. To compare the effect of electronic detonator and nonel detonator, a portion of 60m was blasted using electronic detonators, while the remaining portion was blasted using nonel detonator. An existing paralleling Huangtian railway tunnel is in the close proximity with the spacing of 34m, as shown in Figure6.

Fig. 6 - Location of Niuwanggai tunnel and Huangtian railway tunnel

The blast hole pattern of using nonel detonators is shown in Figure 7, which is widely used in China. The blasting vibration of side wall of Huangtian tunnel was measured. The arrangement of the measurement points are shown in Figure 8. One of the blasting vibration waveforms is shown in *Figure 9.*

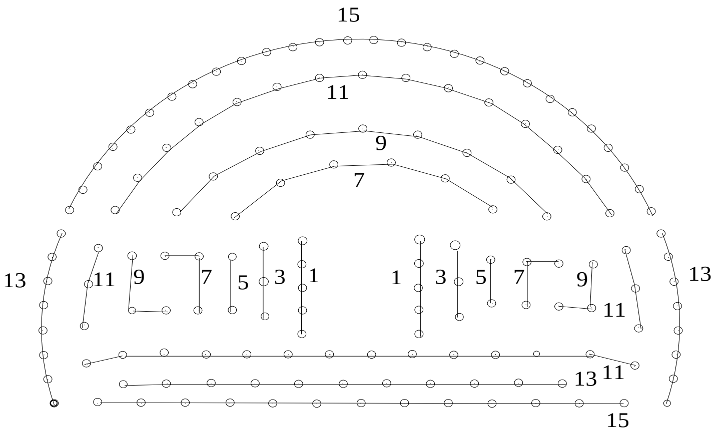

Fig. 7 - Blast holes pattern of using nonel detonators (the numbers indicate the sequence of blasting)

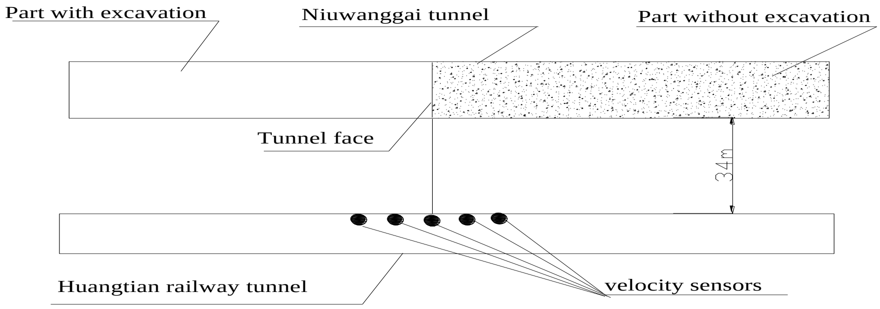

Fig .8 - Schematic diagram of measurement points

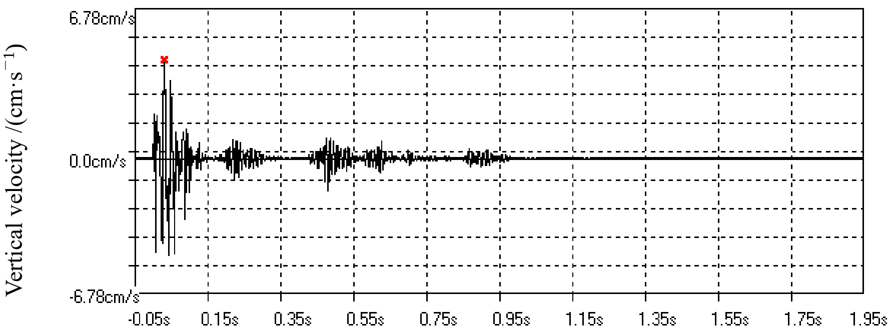

Fig. 9 - Blasting vibration waveform using nonel detonators

The blasthole pattern of using electronic detonators is shown in Figure 10, whose burden, spacing and explosive charge per hole were same as those using nonel detonators. Two cut holes were detonated at same time; the other blastholes were detonated one by one. One of the blasting vibration waveforms is shown in Figure11; the maximum of blasting vibration was in the range of 1-1.5cm/s.

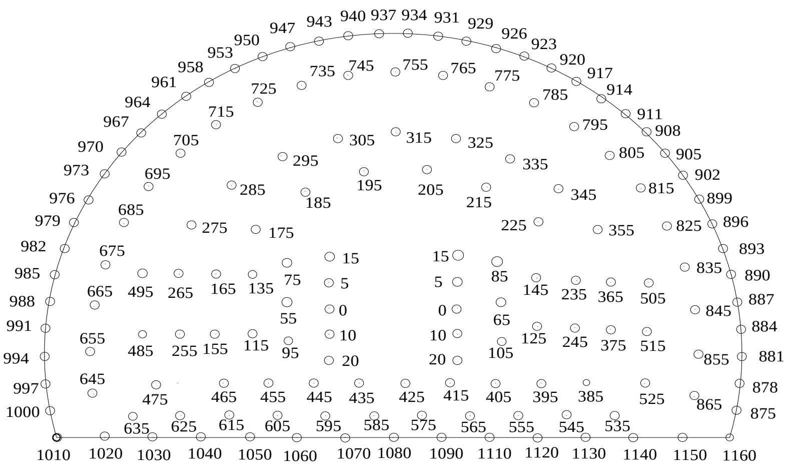

Fig. 10 - Blasthole pattern of using electronic detonators (the numbers indicate time of delay in the unit of milliseconds)

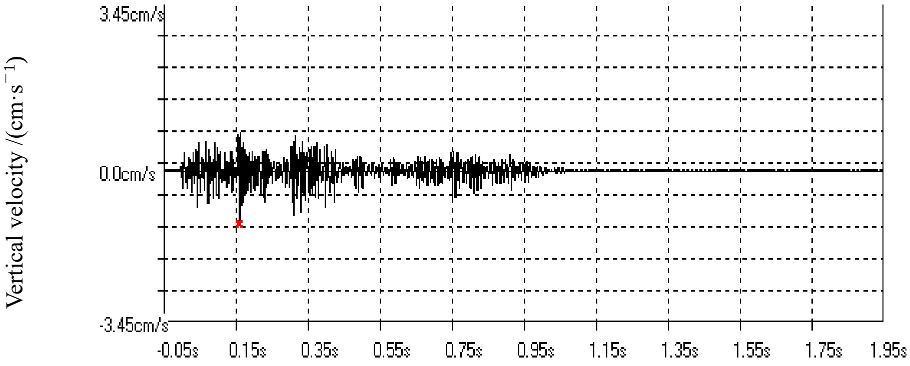

Fig. 11 - Blasting vibration waveform using electronic detonators

As observed from the measurements, the blasting vibration using electronic detonator is decreased about 70% compared to that of nonel detonator. One reason is the explosive charge detonated using electronic detonator in the same time is much less than that using nonel detonator. Another reason is that blasting parameters using nonel detonators are not optimal owing to the habit of workmen and limit of number of delay of nonel detonator in China.

(2) Case two

The Renhechang railway tunnel, which is located in the city of Chongqing in China, has a total length of 4466m. A portion of 2085m of it is under different villas, apartment buildings, avenues and one lake, with an overburden of 25-40m, as shown in Figure12. The surrounding rock is mostly fractured mudstone. According to the safety criterion of buildings (GB6722-2014), the ground blasting vibration must be in the range of 2-5cm/s.

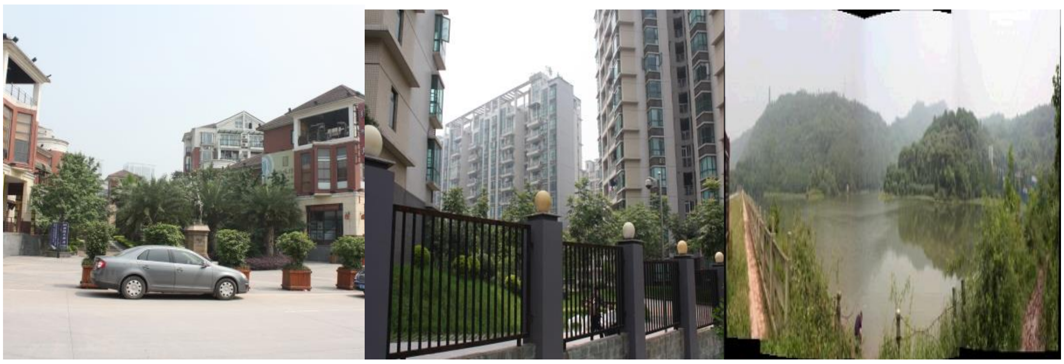

Fig. 12 - Buildings and a lake above the Renhechang tunnel

Based on the results of case one, a series of trial blasts were carried out using electronic detonators, which provided technical support for tunnel blasting in complex environment. At last, the blast holes pattern of using electronic detonators is determined, as shown in Figure13. The blast holes were detonated one by one, the ground blasting vibration was in the range of 1-2cm/s with advance of 2m, meeting the safety requirements (GB6722-2014). The result also stated that the blast holes were detonated one by one using electronic detonators, the delay intervals between blast holes are closely related to characteristics of surrounding rock, if the delay intervals is longer, the longer butt is left; if the delay interval is shorter, the ground blasting vibration is decreased a

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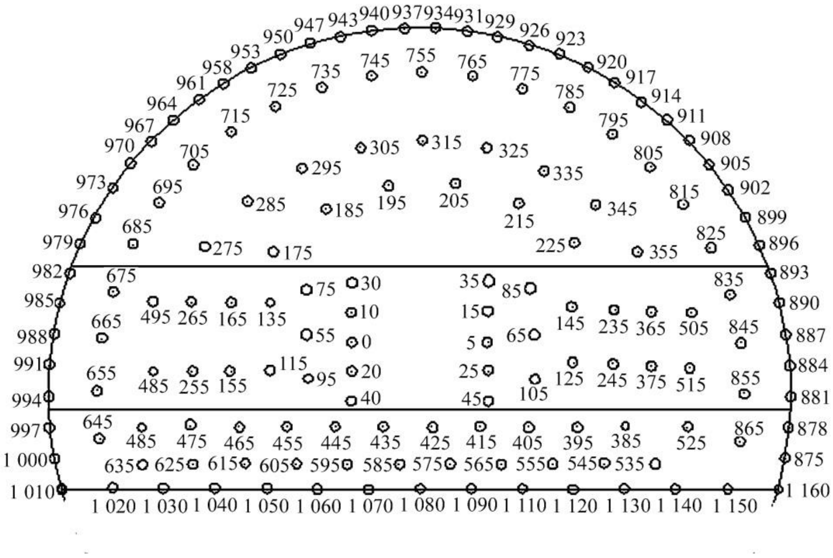


Fig. 13 - Delay time of tunnel blasting(unit:ms)

In order to decrease the cost of using electronic detonators in construction of tunnel, initiation systems combining electronic detonators with nonel detonators, in which the cut holes were detonated using electronic detonators while the other holes were detonated using nonel detonators, as shown in Figure 14, were tested. As shown in Figure 15, the blasting vibration waveform of the ground met the safety requirements (GB6722-2014). Due to delay time error of nonel detonators, detonators of the same delay are not fired at the same time, which benefits to decrease blasting vibration.

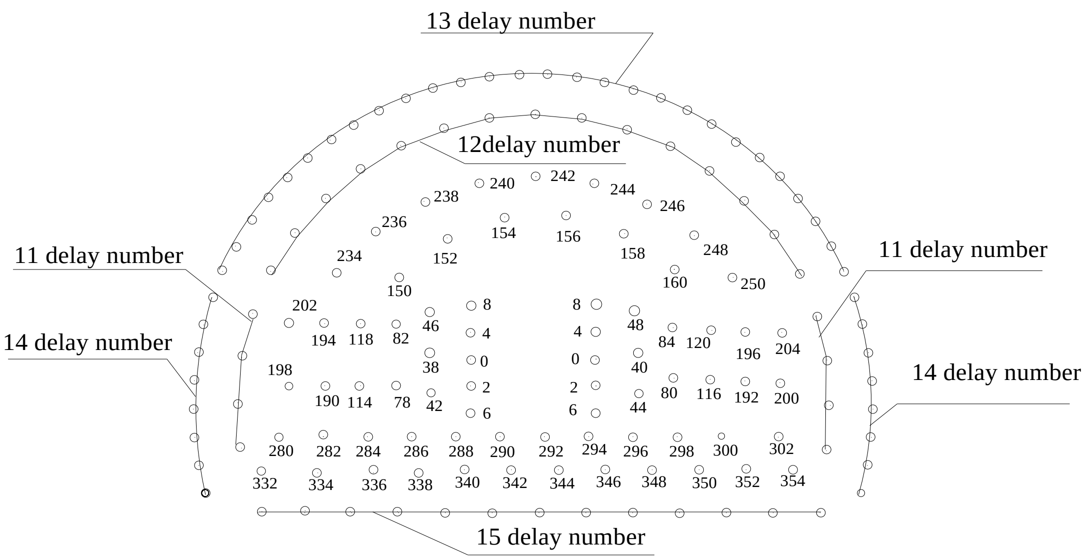
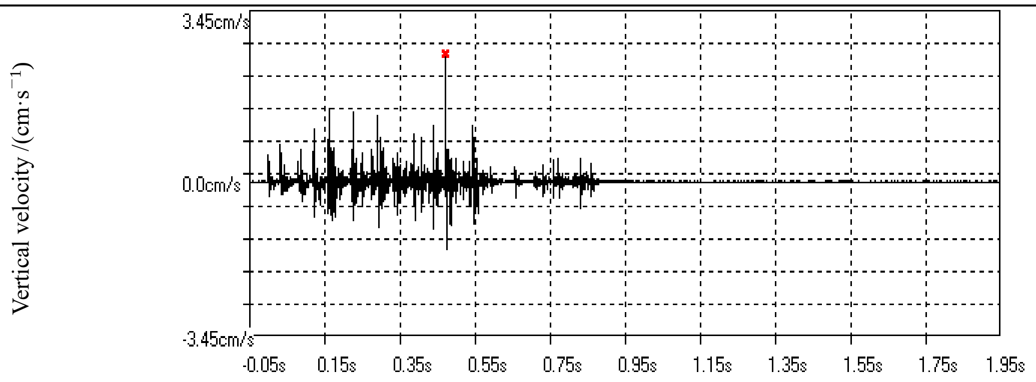


Fig. 14 - Sketch of mixed network of digital detonator and detonator with shock-conducting tube (unit: ms)



Time (ms)

Fig. 15 - Blasting vibration waveform of combining initiation system

At same time, the EDZ (excavation damage zone) resulting from blasting with nonel detonators and blasting with electronic detonators were measured and compared [25]. The extent of EDZ resulted from blasting using the nonel detonators in tunnel construction ranges from 1.5 to 2.3m (average 1.9m) with a P-wave velocity 13 to 36% lower than that of the rock far away from the tunnel opening. In contrast, the extent resulted from blasting using electronic detonator ranges from 0 to 1.4m (average 0.6 to 0.9m) with a P-wave velocity 0 to 18% lower than that of the rock far away from the tunnel opening. Therefore, the use of electronic detonators not only leads to a smaller extent of the EDZ, but also a lower degree of the rock breakage in the EDZ. Since the factors attributing to the formation of the two EDZs are almost the same, except the blasting impact, the superiority of using electronic detonators is thus justified.

DISCUSSIONS

The existing blast vibration laws are gained from far-field vibration data and do not favor to control blast vibration in close proximity behind tunnel face [10]. In general, in order to control the stability of surrounding rock of tunnel, blasting vibration law in near-field of blasting should be put forward. The tentative vibration propagation law (Eq.(1)) is in an attempt to meet this need, and used in the construction of Qipanshan tunnel [17], but it does not provide an insight into blast vibration mechanisms. There is no simple relationship between vibration and strain for waves radiating, further researches are needed to solve this [26].

Safety criterion in tunnel construction by drill-and-blast is very important, but very difficult to determine. Based on our study results and engineering experience, safety criterions for shotcrete and for tunnel without initial support can be assigned in the range from 30cm/s to 50cm/s. The surrounding rock is better, the safety criterion is bigger. Tunnels in complex condition like the close proximity of buildings or close under water are often constructed by machines in China, due to blast vibration from nonel detonator blasting threatening the safety of the tunnels or buildings. Electronic detonator gives rise to a revolution in initiating device, can replace machines, by which tunnels in complex condition are often constructed.

CONCLUSIONS

Based on a series of trial blasts and measurement of PPV in the roof of tunnel within the range of 5m behind tunnel face, a vibration propagation law is proposed in this study. Using the law, according to safety criterion, the maximum charge per delay, on which blasting vibration strongly depends, can be calculated. If the maximum charge per delay cannot meet the tunnel blasting using nonel detonators, then can use two innovative blasting techniques. One is blast holes being detonated one by one by using electronic detonators; another is blast holes detonated by combining initiation system of electronic detonators and nonel detonators. The use of electronic detonators not only leads to a smaller blast vibration but also a smaller extent of the EDZ.

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