

A Study on the Vibration Frequency of Blasting Excavation in Highly Stressed Rock Masses

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Abstract During blasting excavation in deep-buried tunnels and mines characterized by high in situ stress, the rock vibration is attributed not only to blast loading, but also to dynamic unloading caused by transient release of the in situ stress on excavation faces in the process of rock fragmentation by blasting. Understanding the vibration frequency characteristics under these two excitation sources is of important signification to determine appropriate vibration threshold limits for structure damage in deep-buried opening excavations. With a theoretical model developed for a deep-buried circular tunnel excavation by the millisecond delay blasting sequence, frequency characteristics and their influence factors are investigated and discussed for the vibrations induced by the blast loading, the dynamic unloading and the combined effects, respectively. The results show that the rising time of blast loading, the duration of dynamic unloading and the dimension of excavation boundaries are the main factors that affect the vibration frequency of blasting excavation in highly stressed rock masses. It is found that, the blast loading with a much shorter rising time accentuates higher vibration frequency than the dynamic unloading with a long duration, and it causes the blast loading vibration to be more readily attenuated as the propagation distance increases.

Thus, the unloading vibration may become the main vibration component at far distances where its low-frequency vibration may exceed the vibration limits. The vibration induced by the combined effects has two distinctly dominant frequency bands corresponding to the two vibration excitation sources. The frequency analyses of the vibration records from two underground projects excavated by blasting are presented to demonstrate this finding. The findings of this study also clearly reveal that, reducing the dimension of excavation boundaries is one of the most effective means to prevent the vibrational damage to structures as it increases the vibration frequency and meanwhile reduces the peak particle velocity.

Keywords Deep rock mass · In situ stress · Blasting excavation · Dynamic unloading · Vibration frequency

List of Symbols

a	Blasting excavation boundary radius
c_f	Crack propagation velocity
c_p	P-wave velocity in a rock mass
c_u	Rarefaction wave velocity in detonation gases
f	Frequency
F	Amplitude–frequency spectrum of vibration velocity
f_c	Mean frequency
f_d	Dominant frequency
i	Initiation sequence in millisecond delay blasting
L	Blasthole length
p_0	Far-field in situ stress
P_b	Peak pressure on the excavation boundary
P_e	Peak explosion pressure
r	Distance
r_b	Blasthole radius
r_c	Charge radius
r_c	Radius of a crushed zone

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r_f	Radius of a fractured zone
S	Spacing between adjacent blastholes
t	Time
t_d	Duration of blast loading
t_{du}	Duration of dynamic unloading
t_f	Falling time of blast loading
t_r	Rising time of blast loading
v	Radial velocity
V_d	Velocity of detonation
α	Attenuation exponent
γ	Ratio of specific heats for detonation gases
κ	Lateral coefficient of in situ stress
ρ	Rock mass density
ρ_e	Explosive density
σ_r	Radial stress
σ_θ	Circumferential stress
$\tau_{r\theta}$	Shear stress

1 Introduction

Deep rock mass excavation is now becoming an increasingly common construction work in the projects of hydropower, mining and radioactive waste disposal. Drill and blast is still an economical and viable method for the deep rock mass excavation due to its adaptability to different geological conditions. It is well known that during rock blasting excavation, only a smaller portion of the energy released in explosion is utilized directly for rock fragmentation, but most of the explosion energy is dissipated in the form of ground vibration, air blasts, flying rocks and noise (Hagan 1977). Among these negative effects, the rock vibration is a major concern for designers and constructors because it adversely affects the integrity of surrounding structures. Responses and damage of the structures subjected to vibration depend not only on peak particle velocity (PPV), but also on vibration frequency contents. Therefore, studying the frequency characteristics of vibration in blasting excavation will be a great help to determine appropriate critical PPVs for initiation of structure damage. Unfortunately however, in comparison to a large amounts of research achievements made in the PPV, much less attention has been paid to the vibration frequency characteristics and its mechanism.

It is generally acknowledged that the rock vibration during blasting excavation arises from explosion-induced seismic waves, and blast loading is the excitation source of rock vibration. With regards to the frequency of blast loading induced vibration, some work has been done and a substantial progress has been made in its mechanism and attenuation laws. The blast loading vibration frequency are influenced by a variety of factors, such as rock properties,

explosive properties, propagation distances of waves, blasting geometry and sequence. Singh and Roy (2010), Alvarez-Vigil et al. (2012) stated that each type of rock mass and each terrain has a dominant transmission frequency that favors wave propagation for that frequency. Rock masses consist of intact rocks and discontinuities of different sizes ranging from microcracks to faults, and the presence of these discontinuities contributes to the propagation of low-frequency vibration by filtering the higher frequencies (Park et al. 2009; Li et al. 2011b). Ling et al. (2005) investigated the effects of explosive charge on rock vibration frequency, and it is found that the ratio of the high-frequency energy to the total energy decreases with the increase of charge.

Deep rock masses of various natures are characterized by high in situ stress. It should be noted that when the highly stressed rock masses are excavated with the method of drill and blast, the in situ stress on excavation boundaries is suddenly released for an instant of rock fragmentation by blasting, which is a dynamic unloading process (Lu et al. 2012; Li et al. 2014; Zhu et al. 2014). Studies on the dynamic unloading disturbances can be traced to as early as the 1960s, when Miklowitz (1960) solved the plane-stress waves emanating from a suddenly punched hole in a stretched or stressed elastic plate. Carter and Booker (1990) then presented a solution to the transient stress distribution around a circular tunnel excavation in an stressed elastic rock, and they reported that when excavation is carried out by blasting, very rapid rates of stress removal will result in significant dynamic effects during the stress redistribution. The studies of Sainoki and Mitri (2014), Zhu et al. (2014) and Zhao et al. (2014) indicated that the dynamic effects due to the transient unloading are closely related to in situ stress level, rock properties and unloading rates. Moreover, Tao et al. (2013) and Li et al. (2014) emphasized the importance of the unloading paths in the dynamic effects.

The above researches concentrate on the stress variation in the immediate vicinity of the openings, and not much attention, however, has been dedicated to the rock vibration response triggered by the dynamic unloading. In fact, in large underground nuclear explosions, the seismic waves generated as a result of the sudden stress release or tectonic energy release have been presented by recorded long-period P waves and S waves, and in several cases they even exceed those due to the explosions (Toksöz and Kehr 1972; Burger et al. 1986). The work of Salamon (1974) showed that more than 60 % of the released tectonic strain energy is translated into seismic energy if an opening is excavated in one mining step, while only 3 % of the energy is translated into seismic waves if an opening is excavated in 64 steps. Lu et al. (2012) and Yang et al. (2013) emphasized the study on the unloading vibration occurring

in blasting excavation of deep rock masses, and they stated that when highly stressed rock masses are excavated by the method of drill and blast, the vibration in surrounding rock masses is attributed to the combined action of explosion and transient release of in situ stress on excavation faces. By numerical simulation, a comparison of rock vibration between the dynamic unloading and the blast loading was conducted, and it was concluded that as the in situ stress magnitude increases, the dynamic unloading induced vibration can dominate in the total vibrations. In combination with the analyses of the vibration records in blasts of underground projects, our previous work demonstrated the existence of the transient release of in situ stress on excavation faces and its dynamic effects. However, our previous demonstration is limited to the vibration intensity in terms of PPV, without taking the vibration frequency into account. Coincidentally, few other open literatures can be found to investigate the frequency characteristics of the vibration induced by the dynamic unloading or by the combination of blast loading and dynamic unloading.

In the present study, a simplified plane model is first developed for a deep-buried circular tunnel excavation by the full-face millisecond delay blasting sequence. For the vibrations induced respectively by the blast loading, the dynamic unloading and the combined action, frequency characteristics and their influence factors are subsequently investigated by using this model. Finally, the frequency analyses of the vibration signals measured from two underground projects are carried out to demonstrate the vibration frequency characteristics of blasting excavation in highly stressed rock masses.

2 Problem Description and Its Analytical Model

2.1 Process of the Blasting Excavation in Highly Stressed Rock Masses

When underground openings are excavated with the method of drill and blast, it is a common occurrence to detonate a round of blastholes simultaneously in the same delay. If the adjacent blastholes are detonated at precisely the same time, the radial compression waves from hole 1 will tend to close the cracks from hole 2 which try to spread in the direction normal to the connecting line of adjacent blastholes, while the circumferential tension waves from hole 1 will encourage the growth of cracks from hole 2 along the connecting line (Hustrulid 1999; Dare-Bryan et al. 2012). The stress waves from hole 2 will also have the same effects on the cracks from hole 1. With the creation of a highly cracked zone in the region between adjacent blastholes, detonation gases will preferentially escape in this direction due to the least resistance for the

gas pressure, which further extends the cracks along the connecting line of adjacent blastholes. For the blastholes detonated in deep rock masses, the presence of in situ stress suppresses the development of blast-induced tensile cracks around blastholes, and fractures are mainly aligned along the maximum in situ stress orientation perpendicular to the blasthole axis (Kutter and Fairhurst 1971; Donze et al. 1997; Yilmaz and Unlu 2013). In an underground opening excavation with the millisecond delay blasting sequence (for instance, Fig. 1), the maximum principal stress exerted on the rock masses around blastholes is generally parallel to the connecting line of blastholes due to the in situ stress redistribution after blasts of the former delays. Therefore, in most underground blasts, the blast-induced rock cracks are initiated and propagated preferentially along the connecting line of adjacent blastholes.

For the blasting excavation in deep-buried openings, when blast-induced cracks between adjacent blastholes are completely interpenetrated, a new free face, i.e. an excavation face is firstly created along the blasthole line, and meanwhile the normal component of in situ stress on the newly formed excavation face is also completely released. Obviously, the in situ stress release occurring on the excavation face has almost the same duration as the blast-induced crack propagation throughout the connecting line of adjacent blastholes. According to some high-speed photography and numerical simulation results (Preece et al. 1993; Minchinton and Lynch 1996; Zhu 2009; Fakhimi and Lanari 2014), the rock cracking in a blast is generally accomplished with 10^{-1} – 10^1 ms, which is a transient process.

Many studies indicate that the in situ stress release in such a short duration will trigger stress waves in surrounding rock masses, and the stress redistribution in the vicinity of the excavation face due to blasting excavation is a dynamic process that starts from the transient release of

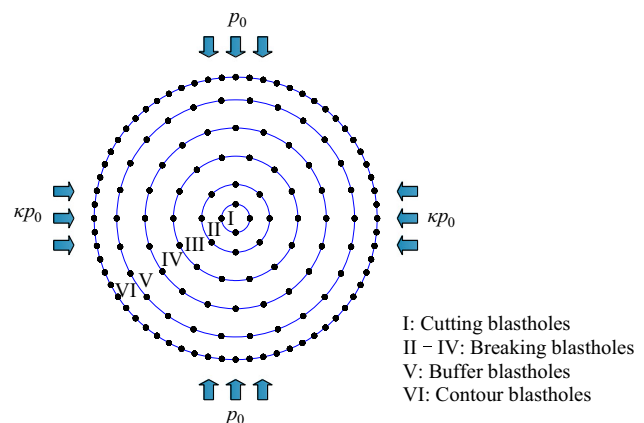


Fig. 1 A circular tunnel excavation with the method of full-face millisecond delay blasting

in situ stress to the final static stress state (Miklowitz 1960; Carter and Booker 1990; Li et al. 2014; Zhu et al. 2014). The stress redistribution during blasting excavation is traditionally assumed to be a quasi-static process, and it tends to be solved by a static solution. This approximation is generally acceptable at lower in situ stress levels. However, under high in situ stress conditions, the stress waves triggered by the dynamic unloading on the excavation face is rather significant where the quasi-static assumption is unacceptable. This means that during blasting excavation in highly stressed rock masses, the rock vibration originates not only from the stress waves of blast loading, but also from the stress waves of the dynamic unloading on the excavation face. Unfortunately, however, the latter excitation source for vibration is generally ignored by designers of mining and tunneling excavations.

2.2 Theoretical Model

The study on the vibration frequency begins with the development of a model for blasting excavation in highly stressed rock masses. It is assumed that a circular tunnel with a radius of R is excavated in an infinite geologic body, under the in situ stress condition of vertical stress p_0 and horizontal stress κp_0 , respectively, as shown in Fig. 1. A full-face millisecond delay blasting sequence is used in the tunnel excavation, as the cutting blastholes (Round I) are detonated first, followed by the breaking blastholes (Round II–IV), the buffer blastholes (Round V) and the contour blastholes (Round VI) from inner rounds to outer rounds with the delay intervals of 50–150 ms. In this model, the blastholes in the same delay are detonated at precisely the same time without considering the delay deviation of detonators. Under this scenario, the excavation faces created in each delay of blast are guaranteed to align along the blasthole lines.

A fully three-dimensional model of blasting vibration which incorporates many influence factors probably submerges the essence of the problem investigated in this study. Thus, as a theoretical model, the circular tunnel excavation in the present study is simplified to a plane strain problem, and furthermore let the tunnel be located in a homogeneous, isotropic and elastic medium. Actually, during an underground opening excavation, each blast cycle and relevant in situ stress release occur over a finite span (length) of the opening. Besides, in a blast cycle, the explosives filled at different depths within charge columns are not detonated synchronously due to the finite velocity of detonation. This means that the blast loading and the in situ stress unloading are distributed non-uniformly along the blasthole axis. Quite clearly, the plane strain model is limited in this regard. Although the solution to the wave radiation is based on a two-dimensional model, the effects

of blasthole length and velocity of detonation are still taken into account in calculating the duration for the blast loading and the in situ stress unloading so that they are closer to the reality. Rock discontinuities and spatial structure of the tunnel are other factors affecting the blasting excavation-induced rock responses, which is beyond the present scope.

Under the scenario of multi-hole blasts, the concept of equivalent vibration source is introduced here to solve the seismic wave propagation analytically. The cutting holes are detonated in a semi-infinite rock medium, and it is generally accepted that a crushed zone and a fractured zone are generated around a blasthole by explosion shock waves and subsequent explosion gas pressure. It is seen from Fig. 1 that an array of blastholes are detonated simultaneously in the same round, and thus the rock masses in the region of the initial cut are fractured by the superimposed blasting effects of multiple blastholes. Therefore, the envelope of the fractured zones around each hole can be regarded as the boundary of blasting excavation for the blast of cutting blastholes. While the breaking holes, buffer holes and contour holes are all detonated under a free-face condition created by the blast of the previous round of blastholes, and blast-induced rock cracks are propagated and interconnected preferentially along the connecting line of adjacent blastholes as the explosion energy is more readily released towards the free faces. Therefore, the connecting line of adjacent blastholes in the same round can be treated as the blasting excavation boundary for the blasts of breaking holes, buffer holes and contour holes.

Let us denote the radius of the blasting excavation boundary as a_i , and then for the blast of the cutting holes,

$$a_i = r_i + r_f \quad (i = \text{I}) \quad (1a)$$

and for the blasts of the breaking holes, buffer holes and contour holes,

$$a_i = r_i \quad (i = \text{II–VI}) \quad (1b)$$

where the subscript i represents the initiation sequence of millisecond-delay detonators, r_i is distance from the blasthole in the i th round to the tunnel center, and r_f is the radius of the fractured zone around a blasthole.

2.3 Blast Loading

After introducing the concept of equivalent vibration source into the multi-hole blasts in Fig. 1, the blast loading induced vibration per delay can be transformed into the problem of seismic wave radiation from a pressurized cylindrical cavity. Such wave radiation in the two-dimensional case has been widely studied by many scholars with a Fourier transform approach, and the solution has been given in the standard texts (see, for example, Eringen and Suhubi 1975; Miklowitz 1978). On this basis, Blair (2003)

proposed a faster and more efficient solution by re-formulating the integral for the standard solution in terms of an inverse Fourier transform and then solving the problem with the fast Fourier transform (FFT) techniques. Afterwards, Blair (2010) derived a scale-independent analytic model for the wave radiation resulting from realistic sources in a blasthole of given length and finite velocity of detonation. From the complete solution, the FFT solution in the two-dimensional case can also be obtained when both the length and the velocity of detonation approach infinity. Referring to the works of Eringen and Suhubi (1975), and Blair (2003), the solution in this study is also implemented by using the Fourier transform approach due to its elegant form.

An important assumption in this study is that the blast loading induced vibration originates from the pressures on the blasting excavation boundaries. Thus, to obtain the vibration waveforms would require the blast loading pressures on the blasting excavation boundaries. Despite the blast loading is one of the most important parameters in rock fragmentation by blasting, direct measurements of the blast loading pressure on blasthole walls have not adequately been carried out due to lacking of feasible methods. Instead, various semi-empirical formulae and detonation theories are used to estimate it. Henrych and Major (1979) proposed the following simplified equation to evaluate the peak explosion pressure exerted on the borehole wall for a cylindrical charge

$$P_e = \frac{\rho_e V_d^2}{2(\gamma + 1)} \tag{2}$$

where P_e is the peak explosion pressure, ρ_e is the explosive density, V_d is the velocity of detonation, and γ is the ratio of specific heats for detonation gases, usually being 3.0 for many explosives.

The explosion pressure defined above refers to the blasthole pressure for a coupled charge filling completely a blasthole. However, decoupled charges are usually used in the field, especially in contour blasts. The following calibration equation is used to consider the decoupled effect for a cylindrical charge

$$P_e = \frac{\rho_e V_d^2}{2(\gamma + 1)} \left(\frac{r_c}{r_b}\right)^{2\gamma} \tag{3}$$

where r_c is the charge radius and r_b is the blasthole radius.

From Eqs. (2) or (3), the peak explosion pressure on the blasthole walls can be obtained. But it needs to be transferred equivalently into the blasting excavation boundaries to solve the theoretical model developed for multi-hole blasts. It is generally accepted that blast-induced stress waves around a blasthole attenuate with increasing propagation distance in a fashion of negative power function

(Shin et al. 2011; Li et al. 2011a). Therefore, for the cutting hole blast, the peak pressure applied to the blasting excavation boundary is given by

$$P_b = P_e \left(\frac{a_i}{r_b}\right)^{-\alpha} \quad (i = I) \tag{4}$$

where P_b is the peak pressure applied to the blasting excavation boundary, and α is the attenuation exponent. Xahykaeb (1974) suggested $\alpha = 2 + \nu/(1 - \nu)$ in the crushed zone and $\alpha = 2 - \nu/(1 - \nu)$ in the fractured zone, in which ν is the Poisson’s ratio of rock masses. Thus, Eq. (4) can be written as

$$P_b = P_e \left(\frac{r_c}{r_b}\right)^{-2-\frac{\nu}{1-\nu}} \left(\frac{r_f}{r_c}\right)^{-2+\frac{\nu}{1-\nu}} \tag{5}$$

where r_c and r_f are the radii of the crushed zone and the fractured zone around a blasthole, respectively. Extents of the crushed zone and the fractured zone are related to a variety of parameters, such as explosive types, rock mass properties and blasting parameters. However, because of the extreme complexity of rock cracking by blasting, their quantities reported by different researchers are quite different, approximately 2–10 times the blasthole radius and 10–100 times the blasthole radius, respectively (Xahykaeb 1974; Esen et al. 2003; Mandal and Singh 2009). In this study, $r_c = 2.0r_b$ and $r_f = 10.0r_b$ are considered.

For blasts of the multiple breaking holes, buffer holes and contour holes, the blasting excavation boundaries are the connecting line of blasthole centers in the same round. Therefore, the equivalent blasting pressures on the blasting excavation boundaries can be obtained from the Saint-Venant’s principle. Then

$$P_b = \frac{2r_b}{S} P_e \tag{6}$$

Since the actual blast loading pressure varies with time, the time history of the blast loading has to be considered to accurately calculate the frequency of blast-induced vibration. In this study, the pressure–time profile of the blast loading is simplified to a triangular load function for convenience in solution and analysis. Thus, the boundary condition for the blast loading induced vibration is expressed as follows:

$$\sigma_b(a_i, t) = \begin{cases} \frac{t}{t_r} P_{bi} & (0 \leq t \leq t_r) \\ \frac{t_d - t}{t_d - t_r} P_{bi} & (t_r < t \leq t_d) \end{cases} \tag{7}$$

where t_r and t_d are the rising time and duration of the blasting pressure history, respectively.

Many publications cite blast loading duration in the order of hundreds of microseconds (Sarahan et al. 2006; Yilmaz and Unlu 2013). Actually, these pressure–time

profiles were proposed on the condition of instantaneous detonation, and are suitable to be used in blasting of a spherical charge. Lu et al. (2012) introduced a pressure–time profile for blasting a cylindrical charge by performing a combined calculation of detonation propagation, blast-hole volume expansion, rock cracking, stemming ejection and one-dimension flow of detonation gases. They stated that after the detonation waves are propagated through the column of explosive, the explosion pressure applied to the blasthole wall rises to a maximum, and when the rarefaction waves reflected from the blasthole bottom reach the orifice, the gas pressure mostly drops to the same level as the atmosphere pressure. Thus, the rising time of blast loading to its peak is determined approximately by

$$t_r = \frac{L}{V_d} \quad (8)$$

and the duration of blast loading can be estimated by

$$t_d = \frac{L}{V_d} + \frac{\sqrt{\left(\frac{1}{4}S^2 + L^2\right)}}{c_f} + \frac{L}{c_{u1}} + \frac{L}{c_{u2}} \quad (9)$$

where c_{u1} is the average velocity at which the rarefaction waves propagate in the detonation gases from orifice to bottom after the ejection of stemming, and c_{u2} is the average velocity of rarefaction wave reflections. For most commercial explosives used in China, the velocity of rarefaction waves propagating in the detonation gases ranges from 500 to 1000 m/s.

2.4 Dynamic Unloading

It is well known that the excavation of an underground opening by the removal of rock masses which are initially stressed can be mechanically equivalent to a superposition of the constant internal stresses and the application of reversed tractions on the blasting excavation boundary

(Carter and Booker 1990; Li et al. 2014; Zhu et al. 2014), as shown in Fig. 2. The radial compressive stress σ_r and the shear stress $\tau_{r\phi}$ exerted on the inner excavation boundary are originated from the far-field in situ stresses p_0 and κp_0 pre-loaded on the external boundaries, and thus they can not trigger any dynamic effects in surrounding rock masses. While, as the inner excavation boundary generated by blasts is created almost instantaneously, the reversed tractions (the radial tensile stress and shear stress in Fig. 2) are impulsive loads varying from 0 to $-\sigma_r$ ($-\tau_{r\phi}$), and they will produce elastic waves passing through the medium which give rise to vibration in surrounding rock masses. These stress waves may also result in transient stresses greater than the final static stresses in magnitude (Carter and Booker 1990). Therefore, it is appropriate in many instances to analytically calculate the dynamic effects of the excavation process just by applying these impulsive tractions on the inner excavation boundary. For the stress field, however, adding the initial stress into the solution of the reversed tractions can give the complete solution.

For purpose of determining the removal process of the initially stressed rock masses from the cavity surface, at least three parameters are required to describe the time-dependent tractions, including the initial in situ stress on the blasting excavation boundary, the unloading duration and the unloading path. For the full-face excavation with the millisecond delay blasting technology shown in Fig. 1, various types of blastholes are detonated sequentially from inner rounds to outer rounds. The blast of blastholes in each round generates a new free face, and accordingly, the dynamic unloading occurs on these blasting excavation boundaries corresponding to each round of blastholes. According to Eq. (9), the duration of blast loading is in the order of 10 ms. While the delay interval of blasts between adjacent rounds of blastholes is at least 50 ms. Thus, before detonating the current round of blastholes, the former

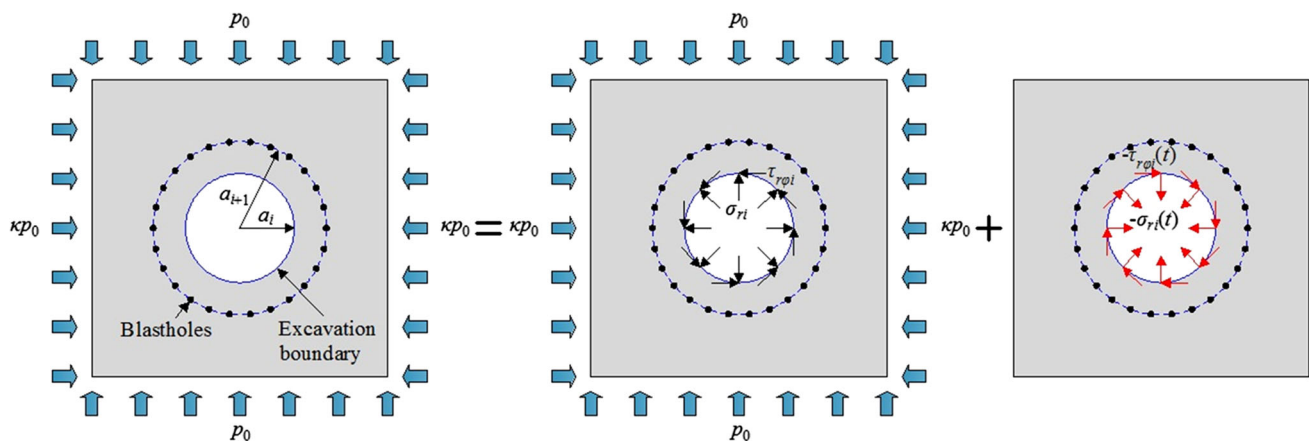


Fig. 2 Mechanical model for the two-dimensional circular tunnel excavation in stressed rock masses

round has been blasted and a new cavity has been created. Shallow-hole blasts used in most full-face excavations use blastholes of 0.5–1.5 m in burden (the distance between adjacent rounds of blastholes). If the rock mass is characterized by P-wave velocity of 4000–6000 m/s and S-wave velocity of 2000–3000 m/s, the unloading stress waves, which are triggered in the blast of the former round, propagate through the burden for no more than 1.0 ms. That is to say, before detonating the current round of blastholes, the unloading stress waves associated with the former round has passed the blasting excavation boundary corresponding to the current round. Therefore, for the millisecond delay blasting sequence in Fig. 1, the initial in situ stress on the blasting excavation boundary is a redistributed stress after the blast of the former delay. Under the assumption of plane strain, it is available by the following formula:

$$\sigma_{ri} = \frac{p_0}{2} \left[(1 + \kappa) \left(1 - \frac{a_{i-1}^2}{a_i^2} \right) - (1 - \kappa) \left(1 - 4 \frac{a_{i-1}^2}{a_i^2} + 3 \frac{a_{i-1}^4}{a_i^4} \right) \cos 2\varphi \right] \tag{10a}$$

$$\tau_{r\varphi i} = \frac{p_0}{2} (1 - \kappa) \left(1 + 2 \frac{a_{i-1}^2}{a_i^2} - 3 \frac{a_{i-1}^4}{a_i^4} \right) \sin 2\varphi \tag{10b}$$

where σ_{ri} and $\tau_{r\varphi i}$ are the redistributed radial stress and shear stress corresponding to the blast of the i th round, κ is the lateral coefficient of far-field in situ stress, φ is the polar angle.

Under the hydrostatic stress field, namely $\kappa = 1$, the above problem can be solved analytically. The stress on the blasting excavation boundary is

$$\sigma_{ri} = \left(1 - \frac{a_{i-1}^2}{a_i^2} \right) p_0, \quad \tau_{r\varphi i} = 0 \tag{11}$$

Because it is a considerable challenge to measure the release process of in situ stress directly on the blasting excavation boundary, the dynamic unloading path and its duration have not been fully understood up to now. Instead, assumptions of linear paths, cosine paths and exponential paths are made by researchers to describe the dynamic unloading process (Li et al. 2014). In this study, the linear unloading path is adopted to analytically solve this problem. As discussed earlier, the duration of the dynamic unloading is approximately equal to that of blast-induced cracking throughout the connecting line of adjacent blastholes. It is should be noted that in practical blasts with three-dimensional blastholes, the seismic wave radiation in the near field (generally within 100 times blasthole radius for the long explosive columns characterized by length/radius >100) is dominated completely by P-Mach and S-Mach wave propagation, dependent on the velocity of detonation within charge columns (Blair 2010, 2014). Due to the finite velocity of detonation, rock cracks are initiated

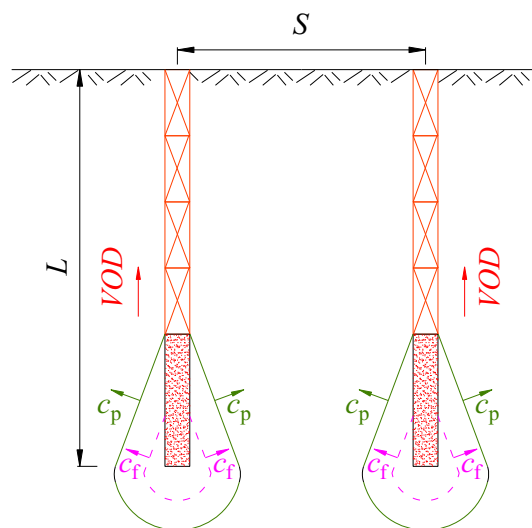


Fig. 3 Schema of the blast-induced crack propagation between adjacent blastholes in the three-dimensional case

at different time for the rock masses at different depths along the blasthole axis, as shown in Fig. 3. Thus, the effects of blasthole length and velocity of detonation should be considered in the calculation of duration for the crack propagation and the in situ stress release. If the adjacent blastholes are detonated at precisely the same time and the rock cracks are considered to be propagated at a steady velocity, the duration of the dynamic unloading on excavation faces can be estimated by the following equation:

$$t_{du} = \frac{\sqrt{\left(\frac{1}{2}S\right)^2 + L^2}}{c_f} \tag{12}$$

where t_{du} is the duration of the dynamic unloading, S is the spacing between adjacent blastholes, L is the blasthole length and c_f is the average velocity of crack propagation. The propagation velocity of the cracks generated by the blast-induced stress wave is slower than that of the wave itself, approximately 20–30 % of the P-wave velocity in rock masses according to the Griffith’s rupture criterion.

Considering the case where the radial stress under the hydrostatic stress field is released at a constant rate over the duration of t_{du} , the boundary condition for the dynamic unloading induced vibration can be described as

$$\sigma_u(a_i, t) = \begin{cases} -\frac{t}{t_{du}} \sigma_{ri} & (0 \leq t \leq t_{du}) \\ -\sigma_{ri} & (t > t_{du}) \end{cases} \tag{13}$$

By the application of the impulsive tractions on the inner excavation boundary, the classical problem of a circular tunnel excavation in the initially stressed elastic medium has been solved by Carter and Booker (1990) with

the Laplace transformation approach under the condition of plane strain. Actually, on the basis of the model that treats the excavation unloading as a superposition of the initial pressure and the tensile traction, the dynamic unloading induced vibration can also be transformed into the plane strain problem of seismic wave radiation from a cylindrical cavity as similar as the blast loading induced vibration, except for the differences in time character and sign of the input loads. The Fourier transform technique has another advantage that the spectrum for the standard solution can be altered by a simple multiplication in frequency domain to account for various input loads (Blair 2003). Therefore, the solution to the dynamic unloading induced vibration is also carried out by the Fourier transform due to its more elegant form and faster computation efficiency. The formal solution to some problems of this kind are available in the literatures of Eringen and Suhubi (1975), and Blair (2003).

It should be noted that all the above discussion regarding the blast-induced rock cracking and the duration of dynamic unloading is based on the conceptual ideas in which blastholes in the same delay are detonated at precisely the same time, generate the same stress waveforms and these waves interact in an ideal manner to create a highly cracked zone between adjacent blastholes. Actually, it is impossible for any timing devices to have perfect accuracy. Even the best electronic detonators still have scatter in times and are not accurate enough to guarantee the precise detonation and ideal wave interaction between adjacent blastholes. Furthermore, due to variation in the local geology and dynamic alteration of the rock masses surrounding blastholes as the blasts progress, these stress waveforms from neighboring holes will suffer significant changes in their traveling process, and thus even the identically charged blastholes using electronic delays will produce markedly different stress waves in shape (Blair

1993). According to the study of Blair (2009) by using an analytical model that considers ideal stress wave propagation, even if the ideal wave superposition did occur between neighboring holes, it is highly localised and probably plays no significant role in promoting rock cracking and fragmentation, especially within an extended volume of rock mass. Considering these uncertainties, the ideal stress wave superposition is difficult to occur to any great degree, and blast-induced rock cracking is fundamentally caused by the stress wave propagation from a blasthole and the subsequent action of explosion gases. Under this scenario, the parameter $1/2$ in Eq. (12) that implies the ideal stress wave interaction between adjacent blastholes should be modified as an uncertain parameter β ranging from 0 to 1. Actually, as the spacing between adjacent blastholes S is generally much smaller than the blasthole length L for most underground full-face blasts, the variation of β just causes very slight changes in the value of the duration of dynamic unloading when using Eq. (12).

3 Vibration Frequency Results and Discussion

For the sake of calculating the vibration frequency, the circular tunnel excavation shown in Fig. 1 is specialized with various drilling and blasting parameters as listed in Table 1. The excavation of the tunnel with a radius of 5.0 m is divided into six delays of blasts. Odd series of non-electric millisecond (MS) delayed detonators labeled as MS1–MS11 are adopted to fire various rounds of blastholes. The explosive properties are selected as density $\rho_e = 1000 \text{ kg/m}^3$ and velocity of detonation $V_d = 3600 \text{ m/s}$, and then the equivalent blast loading peaks on the blasting excavation boundaries is available from Eqs. (2)–

Table 1 Drilling and blasting parameters and loads for the millisecond delay blasting sequence

Blasthole type	Cutting hole		Breaking hole		Buffer hole	Contour hole
	I	II	III	IV	V	VI
Initiation sequence	I	II	III	IV	V	VI
Detonator series	MS1	MS3	MS5	MS7	MS9	MS11
Delay time (ms)	0	50	110	200	310	460
Blasthole diameter (mm)	42.0	42.0	42.0	42.0	42.0	42.0
Blasthole length (m)	3.0	3.0	3.0	3.0	3.0	3.0
Charge diameter (mm)	42.0	32.0	32.0	32.0	28.5 ^a	25.0
Spacing (m)	0.7	0.8	1.0	1.0	1.0	0.5
Distance to the tunnel center (m)	0.5	1.2	2.2	3.2	4.2	5.0
Radius of the excavation boundary (m)	0.7	1.2	2.2	3.2	4.2	5.0
Peak blast loading on the excavation boundary (MPa)	21.0	16.6	13.3	13.3	6.6	6.1
In situ stress on the excavation boundary (MPa)	20.0	13.2	14.0	10.5	8.4	5.9

^a The buffer blastholes are filled with the half-and-half mixing charge of 32 mm and 25 mm in diameters, and thus a mean diameter is adopted in the table

(6), as listed in Table 1. The rock masses is characterized by the elastic constants of density $\rho = 2700 \text{ kg/m}^3$, Young modulus $E = 50 \text{ GPa}$, and Poisson’s ratio $\nu = 0.22$. In the present study, the hydrostatic in situ stress field $p_0 = 20 \text{ MPa}$ is considered. Substitution these parameters into Eq. (11) yields the initial in situ stresses on the blasting excavation boundaries corresponding to the millisecond-delay initiation sequence, as also listed in Table 1. For the blasthole length of 3.0 m used in the presented study, the rising time and the duration of the blast loading approximate 0.8 and 12.0 ms, respectively, from Eqs. (8, 9), and the duration of the dynamic unloading in all of the rounds is about 2.6 ms from Eq. (12).

After the velocity–time histories of vibration are obtained by the above calculations in Sect. 2, the Fourier transformation is carried out to capture frequency information of the vibration signals. The dominant frequency of vibration f_d is determined generally from the maximum peak in the amplitude–frequency spectrum (see Fig. 4). However, if there are two or more peaks of almost equal amplitudes, the determination of a unique dominant frequency becomes ambiguous. To overcome this deficiency, the mean frequency or also called centroid frequency is also employed here to characterize the frequency composition better. The mean frequency of the amplitude–frequency spectrum is defined as

$$f_c = \frac{\sum_{n=1}^m (F_n f_n)}{\sum_{n=1}^m F_n} \tag{14}$$

where f_c is the mean frequency or centroid frequency, and F_n is the amplitude corresponding to the frequency f_n in the amplitude–frequency spectrum.

3.1 Frequency of the Blast Loading Induced Vibration and Its Influence Factors

The blast loading induced vibration is connected with the parameters of the blasting source, the rock properties and

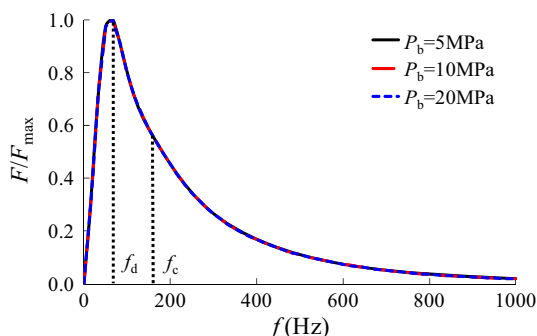


Fig. 4 Amplitude–frequency spectra of the blast loading induced vibration under different peak pressures

the distance from the blasting source. For the rock properties given above, this study focuses on the effects of the blasting source parameters on vibration frequency.

3.1.1 Influence of the Peak Blast Loading Pressure

From Eq. (3), the peak blasting pressure depends on explosive properties and charge structure. Low-density and low-detonation velocity explosives and decoupled charges generate low blasting pressures, resulting in decrease of the vibration amplitudes in surrounding rock masses. Figure 4 gives the amplitude–frequency spectra for the blast loading induced vibration at the 10 m distance to the tunnel center under different peak pressures (i.e. $P_b = 5, 10$ and 20 MPa), where the rising time t_r and the duration t_d are valued as 0.8 and 12.0 ms, respectively, and the radius of the blasting excavation boundary a is selected as 5.0 m. To make a better comparison of these spectra calculated under different conditions, the ration between the current value of the amplitude of spectrum to its maximum value is plotted on axis y in this figure and other figures hereinafter. From an analysis of these completely coincident spectrum curves in Fig. 4, it follows that the peak blast loading pressure has no effect on the frequency composition of blast loading induced vibration.

3.1.2 Influence of the Rising Time of Blast Loading

Some publications claimed that the rising time of blast loading or vibration waveforms is related to explosive types, blasthole length and confinement (Sarahan et al. 2006; Leidig et al. 2010; Lu et al. 2012). For instance, the explosion experiments conducted by Leidig et al. (2010) using three different types of explosives with a wide range of velocities of detonation show that, black powder with relatively long blast duration and opening of long fractures accentuates low-frequency vibration waveforms, while Composition B causes more high-frequency vibration waveforms as detonation gases are unable to drive the long fractures. While detailed analytical models developed by Blair (2010, 2014) do not show a noticeable broadening in vibration waveforms as velocity of detonation decreases and blasthole length increases. Instead, the seismic attenuation Q is found to be the only mechanism that affects the rise time of vibration waveforms. The study of Simha (1996) also reported that harder rocks generally generate high loading peak with short rise time while the contrary is true for softer rocks. Leaving such an unclear problem aside for now, this study directly changes the rising time from 0.8 to 3.2 ms (i.e. $t_r = 0.8, 1.6$ and 3.2 ms) to investigate its effects on the vibration frequency.

The amplitude–frequency spectra of the blast loading induced vibration at the 10 m distance is shown in Fig. 5.

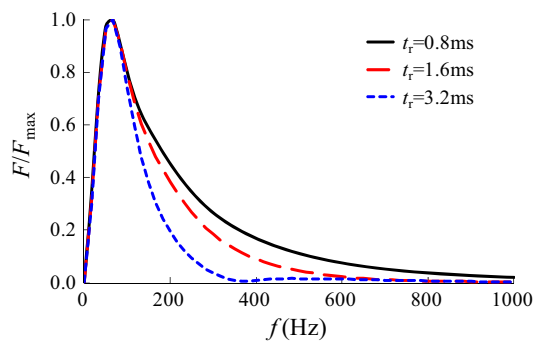


Fig. 5 Amplitude–frequency spectra of the blast loading induced vibration under different rising time

Here the other parameters are considered as follows: the peak blast loading pressure $P_b = 5$ MPa, the falling time of blast loading $t_f = 11.2$ ms, and the radius of the blasting excavation boundary $a = 5.0$ m. It is seen from Fig. 5 that, at $t_r = 0.8$ ms the frequency up to more than 1000 Hz is present in the spectrum, while at $t_r = 3.2$ ms the amplitude of spectrum is equal to zero even at a frequency of 400 Hz. With the increase of the rising time of blast loading, the spectrum moves into the region of lower frequencies and becomes narrower, resulting in a considerable reduction in the mean frequency, although the dominant frequency of vibration remains unchanged. Consequently, the rising time of blast loading is one of the factors that influence the frequency composition of blast loading induced vibration.

3.1.3 Influence of the Falling Time of Blast Loading

The blast loading pressure suffers from attenuation mainly as a result of the expansion of detonation gases. Therefore, the falling time of blast loading is highly dependent on blasthole length and stemming effects. Deep-hole blasts with good stemming retard the gas venting through the stemming column, and then lengthen the interaction time between the blast loading and surrounding rock masses, which contributes to fracturing rock blocks adequately. Furthermore, the burden distance is another factor that influences the gas expansion rate and the falling time of blast loading. At a smaller burden distance, an opening occurs at the mid-point of burden due to significant bending under the blasting pressure, and it becomes another path for the gas venting in addition to the stemming column. As the burden distance increases, the gases try to force a path to the atmosphere through the stemming column rather than opening a path in the burden owing to the resistance of burden. Therefore, the blast loading pressure falls more slowly at a larger burden distance.

After subtraction of the rising time of 0.8 ms, the falling time of blast loading is considered to be 11.2 ms in this

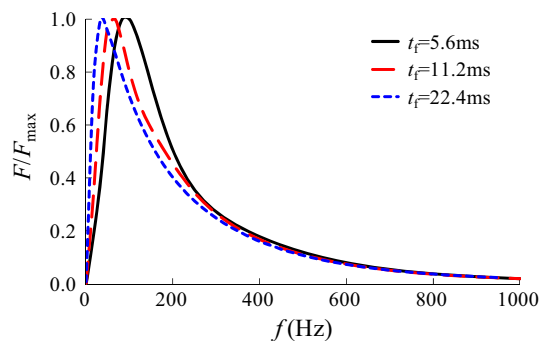


Fig. 6 Amplitude–frequency spectra of the blast loading induced vibration under different falling time

study. Here the falling time of blast loading is varied from 5.6 to 22.4 ms to investigate its effects on the vibration frequency. The amplitude–frequency spectrum curves are shown in Fig. 6 for the blasting source having the different falling time ($t_f = 5.6, 11.2$ and 22.4 ms) and the constant peak pressure ($P_b = 5$ MPa), rising time ($t_r = 0.8$ ms) and radius of the blasting excavation boundary ($a = 5.0$ m). Variation in the falling time of blast loading does not influence the frequency composition of blast loading induced vibration, all ranging from 0 to 1000 Hz. However, it is seen from Fig. 6 that the increase of the falling time reduces the dominant frequency and the mean frequency.

3.1.4 Influence of the Dimension of Blasting Excavation Boundary

Dimension of the blasting excavation boundaries is mainly determined by layout of blastholes in blasting design. It is seen from Table 1 that, the radii of the blasting excavation boundaries increase gradually from inner rounds to outer rounds, and it is smallest for the cutting hole blast while is largest for the contour hole blast. For the blast of the cutting holes, the dimension of the excavation boundary is certainly also related to the extent of the fractured zone, which depends on explosive properties, charge structure, rock mass properties, etc. When the excavation boundaries with different radii ($a = 1.0, 2.0$ and 5.0 m) are exerted by the same blast loading ($P_b = 5$ MPa, $t_r = 0.8$ ms, $t_f = 11.2$ ms), the amplitude–frequency spectra of the blast loading induced vibration at the 5 m distance to the boundaries are shown in Fig. 7. At the excavation radius of 1.0 m, a maximum frequency far more than 1000 Hz can be found from the tendency of the spectrum curve, while at the excavation radius of 5.0 m the maximum value is approximately 1000 Hz. As the radius increases from 1.0 to 5.0 m, the dominant frequency is reduced from 250.0 to 66.7 Hz, and the mean frequency is reduced from 383.5 to

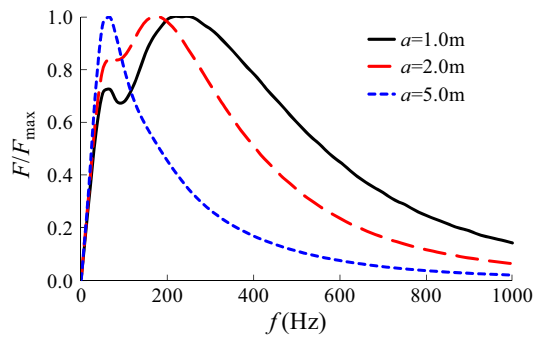


Fig. 7 Amplitude–frequency spectra of the blast loading induced vibration under different excavation boundaries

155.5 Hz. This means that the dimension of the blasting excavation boundary has a significant effect on the frequency composition of blast loading induced vibration, and with the increase of the excavation boundary, the spectrum moves into the lower-frequency region and the vibration frequency decreases.

3.2 Frequency of the Dynamic Unloading Induced Vibration and Its Influence Factors

According to the studies of Carter and Booker (1990) and Cao et al. (2016), the vibration velocity–time history induced by the dynamic unloading depends on the initial in situ stress on the blasting excavation boundary σ_r , the unloading duration t_{du} , and the excavation boundary dimension a , as well as rock properties λ , G , and the distance r . According to the study in Sect. 3.1, similarly, the initial in situ stress on the excavation boundary has no impact on the frequency composition of unloading induced vibration, and as the excavation boundary increases, the vibration frequency decreases for the given rock properties. In this section, only the effect of the unloading duration on the frequency composition is investigated.

From Eq. (12), the duration of the dynamic unloading is determined mainly by blasthole length and rock properties because the spacing is generally much smaller than the blasthole length. Generally, the shallow blastholes blasted in harder rocks generate relatively shorter unloading duration. When the unloading duration t_{du} is varied from 1.5 to 6.0 ms (i.e. 1.5, 3.0 and 6.0 ms), and the initial in situ stress of 5.0 MPa is acted on the blasting excavation boundary with a radius of 5.0 m, the amplitude–frequency spectra are shown in Fig. 8 for the dynamic unloading induced vibration at the 10 m distance to the tunnel center. The influence of the unloading duration variation on the unloading vibration frequency is much in the same way as that of the rising time of blast loading on the blasting vibration frequency (see Fig. 5). At $t_{du} = 1.5$ ms, the vibration frequency lies in the band of 0–1000 Hz, and its

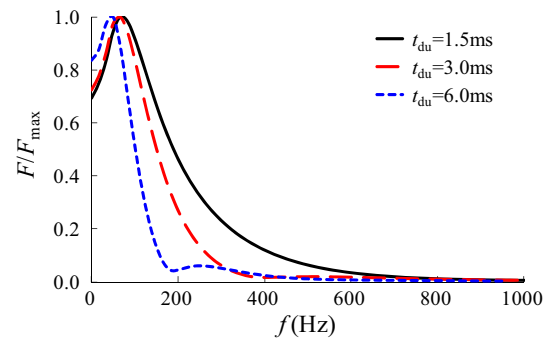


Fig. 8 Amplitude–frequency spectra of the dynamic unloading induced vibration under different duration

dominant frequency and mean frequency are 66.7 and 134.9 Hz, respectively. While at $t_{du} = 6.0$ ms, the frequency band is in the range of 0–600 Hz, and the dominant frequency and mean frequency are 50.0 and 75.8 Hz, respectively. Thus it can be concluded that as the unloading duration increases, the spectrum of the dynamic unloading induced vibration moves into the region of lower frequencies, leading to a significant reduction in the mean frequency but a slight reduction in the dominant frequency.

3.3 Comparisons of Vibration Frequency Between the Blast Loading and the Dynamic Unloading

In conclusion, at an observation point in a given rock mass, the vibration frequency due to the blast loading (or the dynamic unloading) is mainly determined by the rising time of blast loading (or the duration of dynamic unloading) and the dimension of the excavation boundary. The longer the rising time of blast loading (or the duration of dynamic unloading) is and the larger the excavation boundary is, the lower the vibration frequency is.

For the millisecond delay blasting shown in Figs. 1, 9 gives the amplitude–frequency spectrum curves of the blasting vibration and the unloading vibration at a fixed point. The excavation boundaries for the equivalent blast loading are same as those for the dynamic loading under the scenario of multi-hole blasts. Because the duration of the dynamic unloading is much longer than the rising time of the blast loading, in each single-delay blast, the frequency band of the unloading vibration is narrower and its low-frequency energy is more abundant compared to the blasting vibration. The dominant frequency and the mean frequency of the unloading vibration are lower than those of the blasting vibration without exception, and especially in the mean frequency, the difference is more significant. It is well known that low-frequency vibration has greater potential of damage to structures than high-frequency vibration for a certain velocity as the natural frequencies of structures are relatively low (Aldas 2010; Singh and Roy

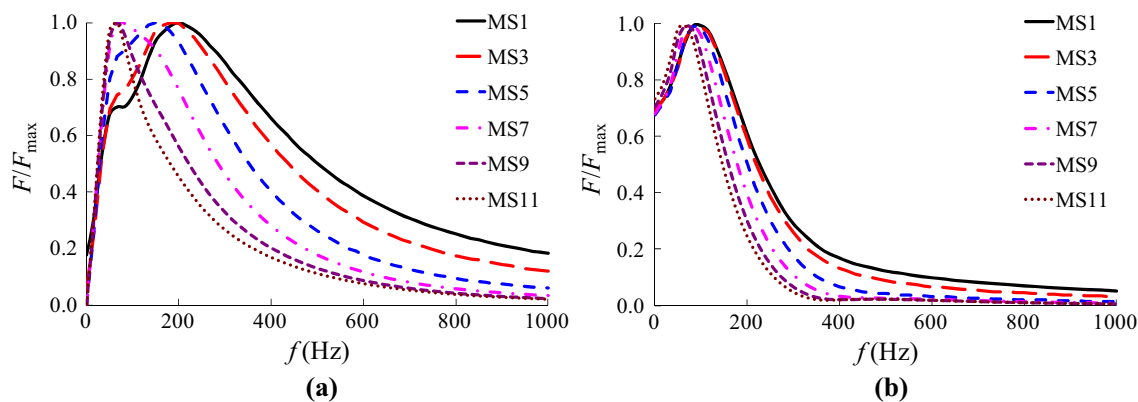


Fig. 9 Amplitude–frequency spectra of the single-delay vibrations for the millisecond delay blasting. **a** Blast loading induced vibration. **b** Dynamic unloading induced vibration

2010). Therefore, when the unloading vibration has the same intensity as the blasting vibration, it will cause more harm to structures.

As rock materials generally contribute to the propagation of low-frequency vibration by filtering the higher frequencies (Park et al. 2009; Li et al. 2011b), and thus it can be predicted that the blasting vibration is more readily attenuated. Taking the blast of the blastholes in Round IV (MS7 delay) for instance, the PPVs caused respectively by the blast loading and the dynamic unloading at various distances are plotted in Fig. 10. It can be found from this figure that, compared to the dynamic unload induced vibration, the PPVs of the blasting vibration are attenuated more quickly as the distance increases. Under a moderate level of in situ stress, for example $p_0 = 20$ MPa, the blasting vibration is dominant in the whole analysis region because the equivalent blast loading peak on the excavation boundary is in the excess of the in situ stress on it. Certainly, the shorter rising time of the blast loading which results in larger PPV is additional factor for it. When the in situ stress reaches up to a higher magnitude of 40 MPa, the PPVs of the blasting vibration are still greater than those of the unloading vibration within the 10 m distance to the tunnel wall. However, beyond this critical distance,

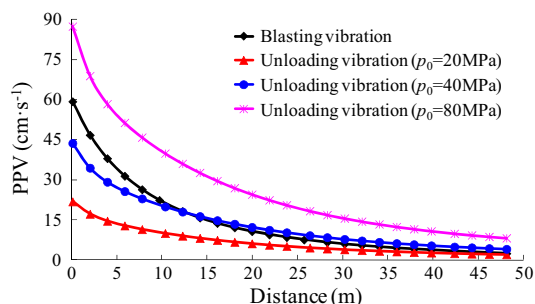


Fig. 10 Comparisons of the PPV attenuations between the blasting vibration and the unloading vibration

the unloading vibration exceeds the blasting vibration and becomes the major vibration component at far distances because the blasting vibration attenuates faster. Therefore, extra care must be taken for the unloading vibration at far distances where it may exceed the vibration limits in low frequencies. If the in situ stress is increased continuously, the unloading vibration will exceed the blasting vibration in the whole surrounding rock masses.

From Fig. 9, it is seen that the variation of the excavation boundary dimensions in different rounds (see Table 1) results in different frequency composition between the single-delay blasts. For the contour hole blast (MS11 delay), its excavation boundary is largest, and thus its frequency bands are narrowest, dominant frequencies and mean frequencies are lowest for both the blasting vibration and the unloading vibration. While the contrary is true for the cutting hole blast (MS1 delay). Therefore, during the underground excavation by blasting, sufficient attention should also be paid to the vibration arising from the contour hole blasts, although the PPV is controlled by using decoupled charges. Because great differences are presented in the vibration frequencies between the single-delay blasts due to the various excavation boundary dimensions, it is inappropriate to roughly analyze all of the vibration waves in a millisecond delay blast and propose a global frequency value. Instead, a one-by-one analysis of these single-delay vibrations is recommendable.

3.4 Frequency of the Vibration Induced by the Combined Action of Blast Loading and Dynamic Unloading

The studies above show that when highly stressed rock masses are excavated by the method of drill and blast, the dynamic unloading occurring on the blasting excavation boundary triggers rock vibration which is comparable to the blast loading induced vibration in intensity if the in situ

stress reaches up to a higher level, and the vibration in surrounding rock masses is attributed to the combined action of blast loading and dynamic unloading. However, it is generally accepted that the explosion or blast loading is the excitation for the vibrational waves in blasting excavation, without considering the effects of the dynamic unloading on PPV and vibration frequency. Therefore, investigation of the coupling vibration induced by the combined action is of important significance to understand the vibration frequency characteristics and prevent vibrational damage to structures during the blasting excavation in highly stressed rock masses.

Taking the blast of the breaking holes in Round IV (MS7 delay) for instance again, Fig. 11 gives the amplitude–frequency spectrum curves of the coupling vibration at the 10 m distance to the tunnel center. The coupling vibration is implemented by a time-domain superposition of the waves caused by the blast loading and those caused by the dynamic unloading. From the comparison between Figs. 9 and 11, it is found that only one peak is presented in the amplitude–frequency spectrum of the individual vibration which is induced by the blast loading alone or the dynamic unloading alone, while the coupling vibration induced by the combined action has two peaks of almost equal amplitudes in the spectrum when $p_0 = 20$ MPa. The inflection point between the two peaks is located at around 100 Hz, and this divides the spectrum into two dominant frequency bands, 0–100 and 100–400 Hz, respectively. According to Fig. 9, the frequency characteristics of the blasting vibration differ significantly from those of the unloading vibration, and thus it causes the coupling vibration to have two dominant frequency bands.

Under different magnitudes of the in situ stress, the amplitude–frequency spectra of the coupling vibration are also plotted in Fig. 11. It can be seen that the increasing in situ stresses result in the amplitudes increasing significantly in the region of lower frequencies, but increasing slightly in the region of higher frequencies. It means that

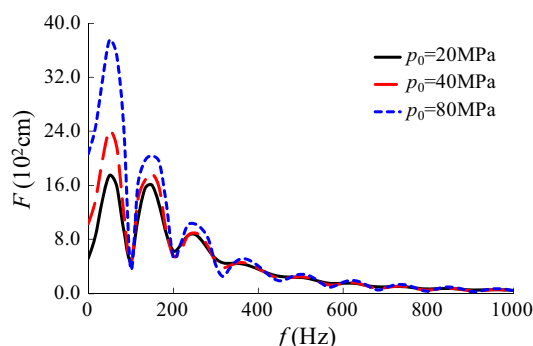


Fig. 11 Amplitude–frequency spectra of the vibration induced by the combined action of blast loading and dynamic unloading

the in situ stress level mainly affects the amplitudes of the low-frequency vibration. The amplitude of the unloading vibration is proportional directly to the in situ stress on the excavation boundary (Cao et al. 2016). Therefore, it can be concluded that the low-frequency component in the coupling vibration originates mainly from the dynamic unloading, while the high-frequency component results mainly from the blast loading.

During underground blasts associated with tunneling and mining under high in situ stress conditions, the recorded vibration waves are superposition of blasting vibration and unloading vibration. To study the unloading vibration or other responses due to the dynamic unloading, a performance that separates the waves caused by the dynamic unloading from those caused by the blast loading should be carried out. Actually, such a separation is very difficult because the explosion and the in situ stress release on the excavation boundary occur almost simultaneously and the coupling waves recorded in the field have no clear identification points in time histories. However, the frequency characteristics that the blasting vibration frequency is higher than the unloading vibration frequency and the coupling vibration has two dominant frequency bands, provides a possible approach for this separation.

4 Case Studies

Southwest China is one of the most active tectonic movement areas in the world. The tectonic compression and uplift result in high mountains and deep canyons forming in this area. This geography provides an advantage for reserving hydropower resources, but also brings a trouble of high in situ stress field to project constructions. A large number of huge hydropower projects have been built or are being built in Southwest China, and most of these projects whose water diversion and power generation systems are arranged underground have encountered large-scale blasting excavation in high-stressed rock masses. In this section, the vibration signals measured from two hydropower projects in Southwest China are investigated to demonstrate the vibration frequency characteristics found in the above theoretical analyses. The first project is the main powerhouse excavation in the Pubugou Hydropower Station, and the second one is the diversion tunnel excavation in the Jinping-II Hydropower Station.

4.1 Project Background and Vibration Measurement

4.1.1 Pubugou Main Powerhouse

The Pubugou Hydropower Station is located in Hanyuan County, Sichuan Province, China. Its underground

powerhouse system is located in the left bank and mainly consists of a main powerhouse, a auxiliary powerhouse, a transformer chamber, a gate chamber, diversion tunnels and tailrace tunnels. The main powerhouse and the transformer chamber are constructed in parallel with a spacing of 41.9 m. The main powerhouse has a height of 70.2 m, and it is excavated in nine horizontal layers with an excavation height of 8.0 m approximately in each layer. Excavation of the second layer to the seventh layer use an procedure that an middle cut with 18.8 m in width is first blasted prior to the two sides by 20–30 m. The middle cut excavation is executed by the millisecond delay blasting sequence with eight delays. Odd series of non-electric millisecond delayed detonators from 1 to 15 are adopted to fire various rows of blastholes, as shown in Fig. 12a. During a blast of the middle cut excavation in the fourth layer, we measured the vibration velocities by employing a digital data logging and analysis system. In this survey, the velocity sensors were arranged on the floor of the fourth layer in the main powerhouse, and the side wall of the main transformer chamber directly towards the blasting area. The body waves directly from the blast were captured by the measurement points on the side wall of the main transformer chamber. Thus, the signals recorded at these points are chosen to analyze to prevent face waves from contaminating analysis results, as shown in Fig. 12b, c.

According to the field surveys and back-analysis results, the principal in situ stresses approximate 21.1–27.3, 15.5–23.3 and 10.2–12.3 MPa respectively for the three orthogonal components in the area of the underground powerhouse (Yang et al. 2013). Both the maximum principal stress and the minimum principal stress are approximately horizontal, and the angle between the maximum principal stress and the longitudinal axis of the powerhouse is about 20–30°. The intermediate principal stress is approximately vertical.

During the middle cut blast, the in situ stress exerted on the rock mass to be excavated results mainly from the clamping action of the side walls in the horizontally transversal direction, namely the σ_T shown in Fig. 12a. While the longitudinal stress σ_L and vertical stress σ_V on the rock mass are much smaller due to presence of the free faces created by previous excavations. Therefore, the horizontally transversal velocities are analyzed to investigate the influence of the transversal stress release on vibration frequency.

4.1.2 Jinping-II Diversion Tunnel

The Jinping-II Hydropower Station is located on the Great Jinping River Bend of the Yalong River, Sichuan Province, China. This power station takes advantage of a 310 m natural drop of water along the bend for power generation.

It is mainly consists of a sluice dam, an underground powerhouse and a diversion system, which includes four diversion tunnels constructed in parallel with spacing of 60 m. The tunnels have an average length of 16.67 km and a maximum depth of 2525 m, and they are the longest and deepest hydroelectric tunnel projects in the world. The maximum in situ stress from the survey in this area is about 42 MPa, and the regressed maximum stress reaches up to 72 MPa at the deepest point. These tunnels provide a unique opportunity to investigate the excavation responses in high-stressed rock masses due to its deep burial and high in situ stress.

The No. 2 and No. 4 diversion tunnels which have a horseshoe-shaped cross-section with 13.0 m in diameter are excavated with the method of drill and blast. To ensure shaping quality and the tunnel stability, the blasting construction in the tunnels proceeds in two phases, and an upper bench with a height of 8.0 m is first excavated followed by a lower bench with 5.0 m in height. The upper bench blast is divided into ten delays and the detonators in odd series from 1 to 19 are used to fire various rounds of blastholes, as shown in Fig. 13a. During a blast of the upper bench in the No. 2 diversion tunnel, the sensors were arranged on the floor of the No. 2 tunnel itself, as well as on the wall of the No. 1 tunnel nearby to measure the rock vibration velocities. Likewise, just the vertical vibration signals recorded in the adjacent tunnel are analyzed in the present study, as represented in Fig. 13b, c.

4.2 Frequency Analyses of the Measured Vibration Signals

Due to the influence of the excavation boundary dimension on the vibration frequency, the frequency spectrum analyses are carried out for the single-delay vibration signals, rather than all of the vibration waves. In consideration of the vibration superposition in the same delay due to the detonator accuracy, the single delay that has smaller number of blastholes is selected. Additionally, because the single-delay vibration signals in the first four delays are not separated clearly from each other, the ones in the MS9 and MS11 delays for the Pubugou project, and in the MS11 and MS13 delays for the Jinping-II project are chose to make frequency spectrum analyses in the present study.

Figure 14 presents the amplitude–frequency spectra of the measured single-delay vibration signals. It is found that for the blasting excavation in highly stressed rock masses, all of the measured single-delay vibration signals have two dominant frequency bands, which agrees well with the theoretic analysis results above. For the middle cut blast in the Pubugou main powerhouse, the demarcation points between the two dominant frequency bands are located within 80–100 Hz without exceptions, and they are all

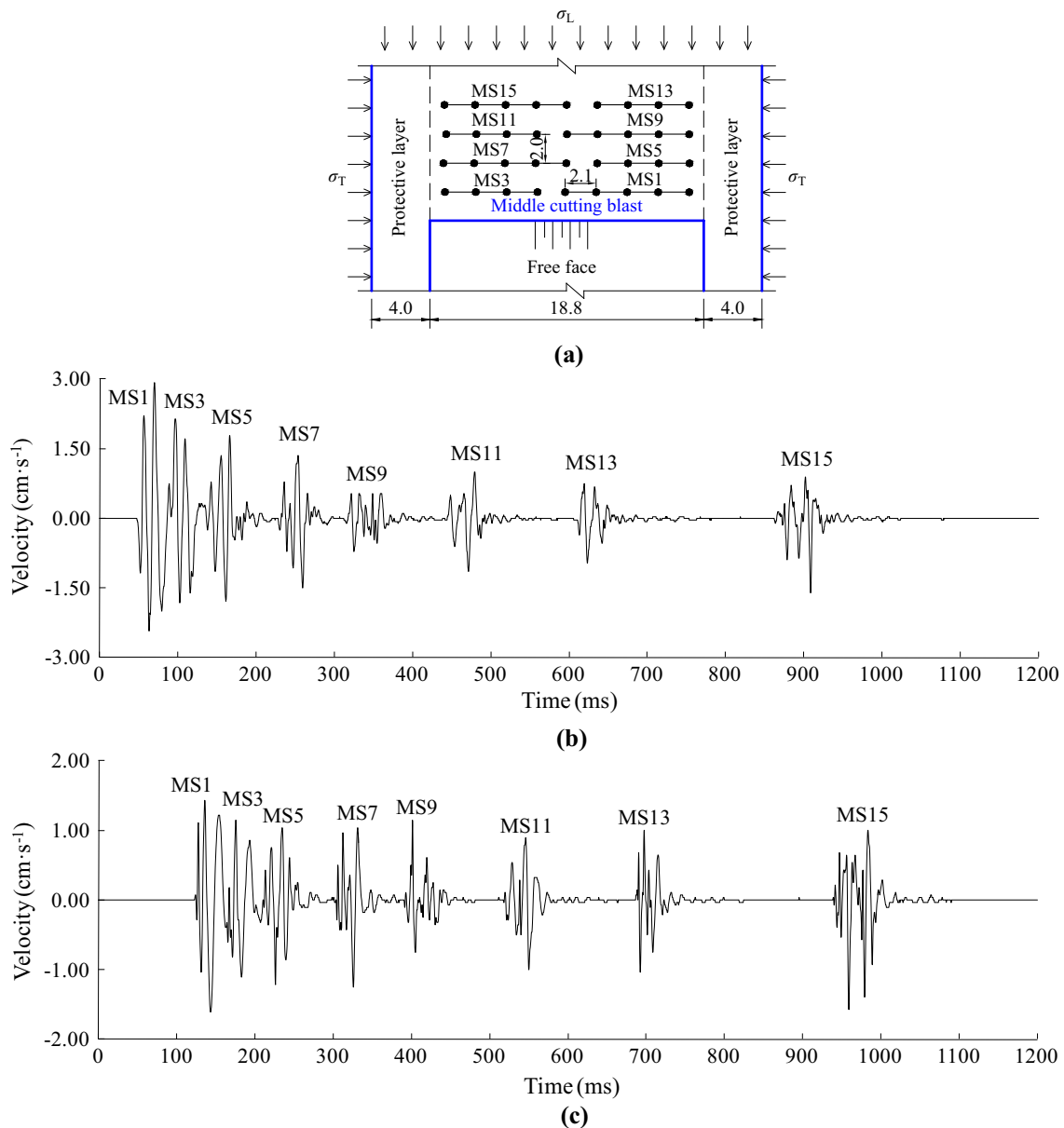


Fig. 12 Blasting design of the middle cut blast in the fourth layer of the Pubugou main powerhouse and velocity–time histories recorded at the main transformer chamber. **a** Diagrammatic representation of the

blasting design. **b** Horizontally transversal velocity–time histories at 1# measurement point. **c** Horizontally transversal velocity–time histories at 2# measurement point

around in 180–210 Hz for the upper bench blast in the Jinping-II diversion tunnel. The other single-delay vibration signals also have the same frequency characteristics as those plotted in Fig. 14. Our previous study analyzed the amplitude–frequency spectra for an open-pit blast in which its rock properties and drilling and blasting parameters are similar with the Pubugou project in this study, however, its in situ stress acted on the rock masses can be ignored (Yang et al. 2013). It was found that the vibration in the open-pit blast has only one dominant frequency band. This indicates that in the highly stressed rock blasts, the

vibration with two dominant frequency bands is not caused by some accidental factors, for example the delay deviation of detonators, but instead, is resulted from the certain excitation sources, namely, the blast loading and the dynamic unloading. From Fig. 14 and the theoretical analyses above, it is seen that the dominant frequencies of the unloading vibration and the blasting vibration are around in 50–70 and 100–110 Hz, respectively, for the Pubugou project, and in 130–170 and 220–250 Hz, respectively, for the Jinping-II project. The relative amplitude peaks at the dominant frequencies in different

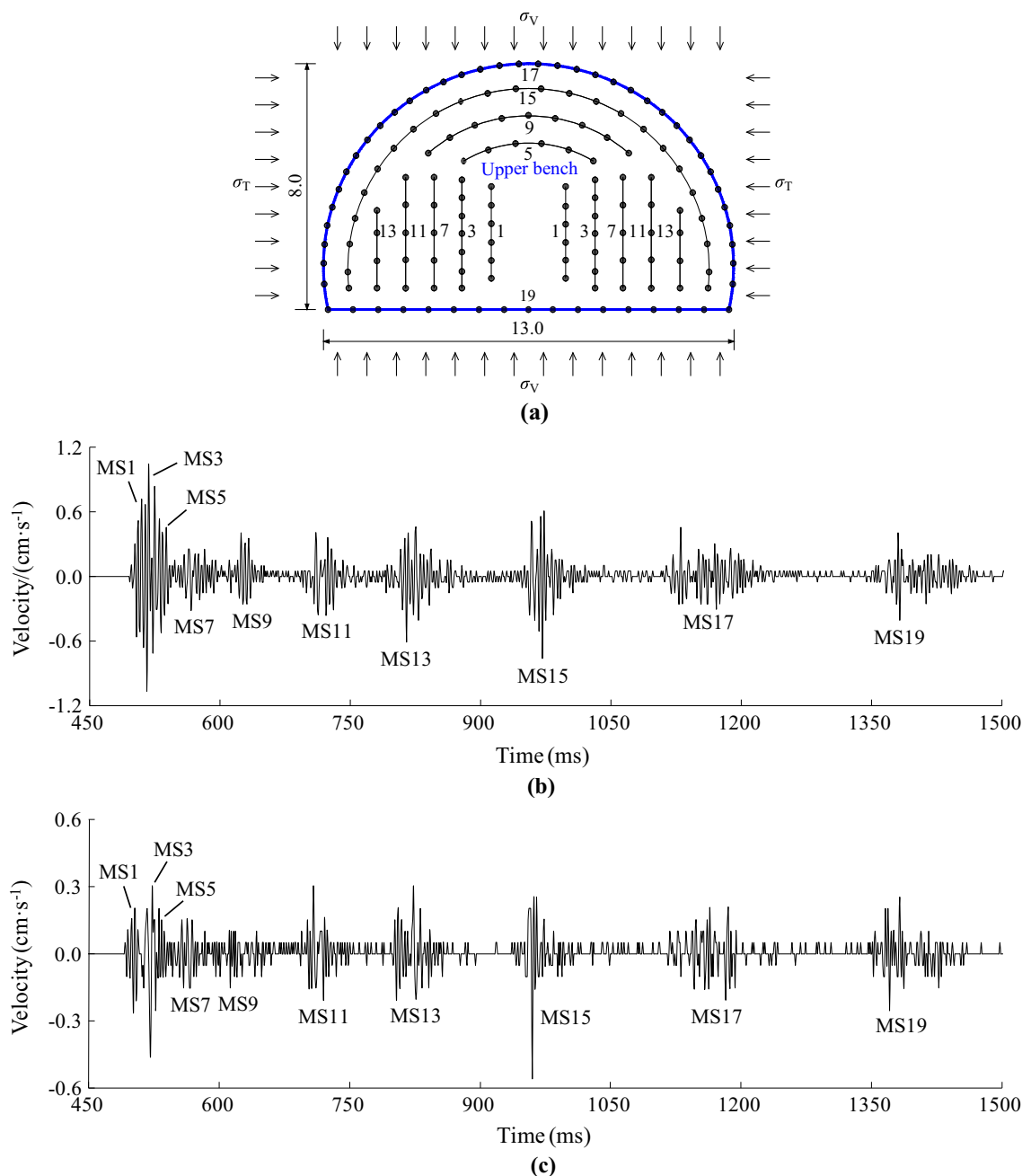


Fig. 13 Blasthole initiation sequence of the upper bench blast in the Jinping diversion tunnel and velocity-time histories recorded at the adjacent tunnel. **a** Blasthole layout and its initiation sequence.

b Vertical velocity-time histories at 1# measurement point. **c** Vertical velocity-time histories at 2# measurement point

bands largely depend on the peak blasting pressure and the in situ stress applied on the excavation boundaries.

Since the propagation of blast-induced cracks is slower than that of the blast-induced stress wave itself, in principle, the dynamic unloading vibration will arrive at the measurement points after the blasting vibration. Based on the above conclusions, it can be supposed that the relatively low-frequency vibration component will arrive after

the high-frequency component per single-delay vibration signals. Thus, a joint time-frequency analysis (JTFA) is performed to track how the frequency content varies with time. The short-time Fourier transform (STFT) is the simplest and most straight analysis method processing the time-varying characteristics of vibration frequency. But it is inherently defective in processing non-stationary random signals of blasting vibration because it can not

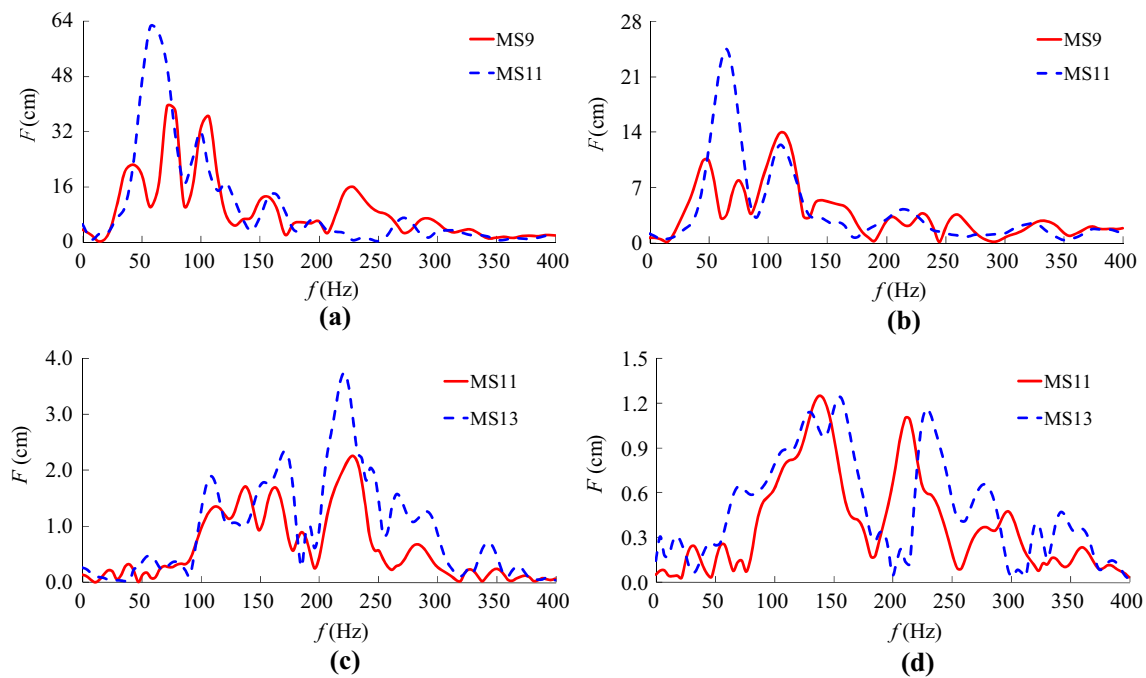


Fig. 14 Amplitude–frequency spectra of the measured single-delay vibration signals. **a** 1# measurement point in the Pubugou project. **b** 2# measurement point in the Pubugou project. **c** 1# measurement point in the Jinping-II project. **d** 2# measurement point in the Jinping-II project

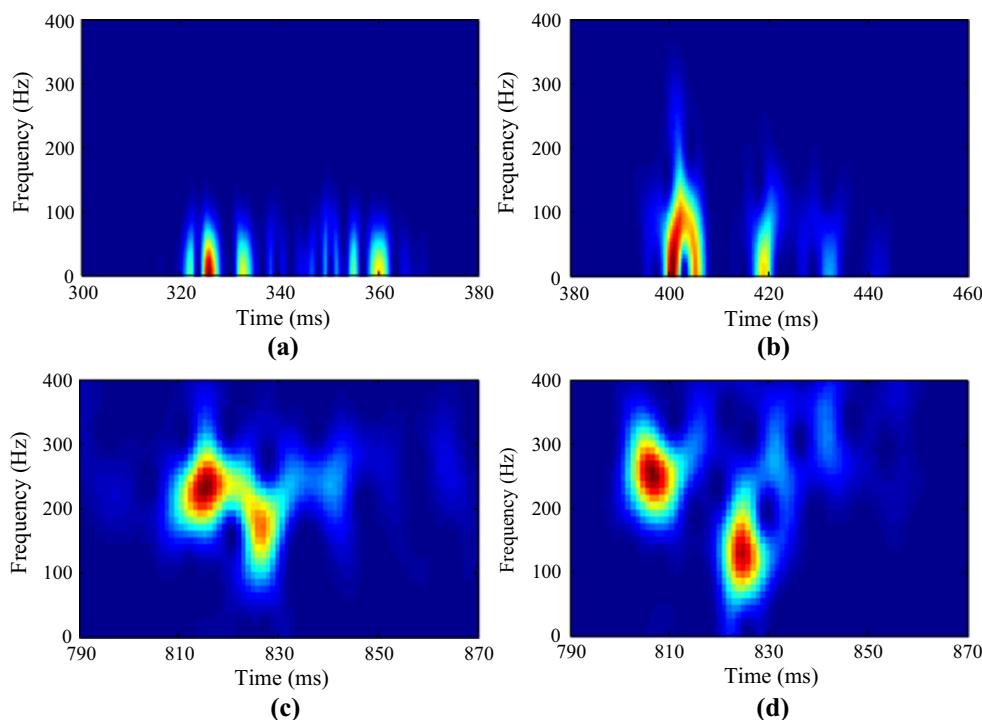
provide high resolution concurrently both in time domain and in frequency domain. The Wigner–Ville Distribution (WVD) approach overcomes this defect to a certain degree, and has been successfully applied to process non-stationary signals of blasting vibration. In this study, the reassigned smoothing pseudo WVD approach is adopted to implement the time–frequency analysis with the aid of the time–frequency analysis toolbox of Matlab (Leon 1995).

The time–frequency contour lines are represented in Fig. 15 for the measured single-delay vibration signals. It is also clearly shown that the vibration signals per delay have two distinct sub-bands of frequency, corresponding to the waves from blast loading and those from dynamic unloading. From the time perspective, the waves arriving first at the observation points are located in the regions of higher frequencies, while those arriving subsequently move into the relatively low-frequency regions. This finding demonstrates the above supposition. At the tail of waveforms, the frequency content shifts once again to the regions of higher frequencies, but with much lower amplitudes. It is mostly resulted from the disordered superposition of the waves from different mechanisms at the tail. But admittedly, due to the wave superposition effects in the time domain or other more complex factors, some single-delay vibration signals (for example, see Fig. 15a) do not fully conform the frequency variation law that changes from high to low with time.

5 Conclusions

Responses and damage of the structures subjected to construction vibration are highly dependent on vibration frequency. In the present study, the vibration frequency characteristics of blasting excavation in highly stressed rock masses are investigated with the methods of theoretical analyses and case studies. The theoretical analysis results show that when highly stressed rock masses are excavated with the method of drill and blast, the rock vibration is attributed to the combined action of the blast loading and the dynamic unloading. Frequency composition for the vibration in a given rock mass is influenced mainly by the rising time of blast loading, the duration of dynamic unloading and the dimension of excavation boundaries. The longer the duration of loading or unloading is and the larger the excavation boundary is, the lower the vibration frequency is. Because the rising time of the blast loading is much shorter than the duration of the dynamic unloading, the frequency of the blast loading induced vibration is higher than that of the dynamic unloading induced vibration. It causes the blasting vibration to be more readily attenuated with the increase of the propagation distance. Generally, the blasting vibration dominates in the near field, while at far distances the unloading vibration may exceed the blasting vibration and becomes the main component in surrounding rock masses. Therefore, extra care must be taken for the unloading

Fig. 15 Time–frequency contour lines of the measured single-delay vibration signals. **a** MS9 delay at 1# point of the Pubugou project. **b** MS9 delay at 2# point of the Pubugou project. **c** MS13 delay at 1# point of the Jinping-II project. **d** MS13 delay at 2# point of the Jinping-II project



vibration at far distances where it may exceed the vibration limits in low frequencies. The vibration induced by the combined action of blast loading and dynamic unloading has two dominant frequency bands, and the low-frequency one originates primarily from the dynamic unloading while the high-frequency one results mainly from the blast loading, which is confirmed by the analyses of the measured vibration signals in two underground blasts. This characteristic on the vibration frequency may provide a promising means to identify and separate the unloading vibration from the measured signals in highly stressed rock blasting.

Dimension of the blasting excavation boundary is one of the most important factors that influence the vibration frequency. The frequency compositions of the single-delay vibrations are not identical for the full-face millisecond delay blasting in which the excavation boundary dimension varies in different delays. Therefore, a detailed frequency analysis of the single-delay vibrations one by one instead of a global frequency value for all of the vibration waves is recommendable to present a true picture for the vibration frequency characteristics. Low-frequency vibration has greater potential to cause structure damage than does high-frequency vibration for a certain velocity. Thus, controlling the blasting scale and reducing the excavation boundary dimension in a blast is an effective means to prevent the vibrational hazard to structures because it increases the vibration frequency as well as reduces the PPV.

It should be pointed out that the vibration frequency analyses presented in this paper is mainly based on the simplified model for rock blasting excavation. Some factors that may affect the vibration frequency characteristics are not considered in this paper, such as drilling parameters, blasthole layout, interaction of multiple-blasthole blasts and detonator delay time and its accuracy. Further studies are required for these influence factors. Moreover, more vibration signals measured in the field should be collected and their more detailed analyses should be carried out to understand the vibration frequency of blasting excavation in highly stressed rock masses much better.

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