Spatial distribution of vibration and damage of high rock slope under blast loading

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Abstract. The safety of the high rock slope under blasting loading is of great concern during the engineering construction. A better understanding of vibration distribution and reasonable monitoring scheme are essential to control the dynamic response induced by blasting excavation of high rock slope. Based on the excavation of WuDongde high rock slope in southwest of China, vibration amplification characteristic around the slope surface was investigated carefully with different kinds of experiment. The Peak Particle Velocity (PPV) of blasting vibration at the slope surface and flat ground was compared. Results demonstrate that the PPV at the slope surface is large than that of flat ground and the amplification effect is obvious. The partial amplification law of slope surface is revealed as the amplification factor of vibration at the outside of the berm is much larger than that of inside. The amplification effect in the vertical direction is stronger than the radial and tangential direction. Then numerical simulation was employed to investigate the vibration amplification characteristic with more working conditions. Results agree well with the experiment and reveal that the local amplification characteristic could be obviously found around the berm. The blasting energy, geometry of the bench and rock mass quality could affect the amplification effect significantly. The suggestion of blasting vibration monitoring scheme for high rock slope was proposed according to different objectives based the understanding of vibration amplification. If the aim is to evaluate the dynamic stability or get the blasting vibration attenuation law of high rock slope, monitoring points should be arranged at the inside of the berm, while the most unfavorable response of rock mass is expected to be obtained, the out edge of the berm should be selected as the monitoring position. The study expects to provide a good reference for the blasting vibration control and measurement of high rock slope.

1. Introduction
Explosives are a worthy and indispensable source of energy required for fragmentation, excavation and displacement of the rock mass [1-2]. In a properly designed blasting, the major part of the explosion energy is used in crushing and breaking the rock. However, some energy also may cause many adverse effects, for example ground vibration, air blasts, fly rocks and noise [3-5]. The ground shock and vibration can have an environmental impact on neighbors, and cause structural damage to those structures such as buildings, bridges, dams, tunnels, etc [6]. Hence, more and more attention has been focused on the spatial distribution and prediction of blasting vibration in rock mass. The better understanding of blasting vibration has a great importance in the minimization of the environmental complaints [7-9].
The analysis and design of reinforced protection structures against short-duration dynamic loading have been extensively studied in recent years. High rock slope is an important structure which is often employed in the hydropower and mine projects. In recent years, a large number of huge hydropower stations whose height of rock slope exceeds 400 m are being built in the southwest of China as shown in Fig. 1. Berms are set every 15~30 m to make the traffic and slag removing more convenient. The unique geometry of slope surface formed by excavation makes the vibration distribution around the berm more complex.

![Fig.1 Several famous high dam abutment slopes in Southwest China](image)

Links between surface geometry, free surface, local geology and amplified wave propagation have been reported by many researchers. It has been proved that when a big structure with small protuberances at the surface is disturbed by the earthquake or blasting, the vibration amplification could be found at the protruding zone because of the small mass and stiffness of the protuberance. But comprehensive literature review conducted as a part of the present study indicated that there are few publications available on the vibration distribution around the slope surface under blasting loading.

Analytical and numerical solutions of blasting investigation encounter serious limitations when the problem geometry is complicated and a greater number of influencing parameters are to be incorporated. Site monitoring data provides the ideal approaches to solve this problem. Blasting vibration monitoring plays an important role in assessing the dynamic response of blasting excavation, which could supply much important information such as PPV, frequency, and waveform, etc. The study of dynamic stability analysis, safety evaluation and blasting damage determination all requires the accurate measurement results of vibration. But it should be point out that the correct vibration measurement scheme should be conducted based on the better understanding of vibration distribution and specific monitoring targets. However, there is still some lack of knowledge about the investigation of the reasonable monitoring scheme of high rock slope under blasting loading.

In the present study, based on the excavation of WuDongde high rock slope in south of China, vibration amplification characteristic around the slope surface was investigated carefully with site experiments. Then numerical simulation with the finite element software LS-DYNA was implemented to reproduce blasting vibration distribution around the slope surface, and sensitivity analysis of more kinds of factors such as geometry of the bench, rock mass quality and geological defect were implemented. At last, the suggestion of blasting vibration monitoring scheme for high rock slope was proposed according to different objectives.

2. Experiment investigation of blasting vibration distribution of the high rock slope

If the toe of bench at every elevation of high rock slope is connected, the rock mass located in bench could be considered as the small protuberance of the main rock slope as shown in Fig. 2. The unique geometry of slope makes the blasting vibration attenuating characteristic quite different from that of conventional bench blasting. Hence the site experiment was implemented to investigate the vibration distribution of high rock slope based on the excavation of WuDongde high rock slope.
Fig. 2 Schematic of blasting wave propagation for the unique geometry of hydraulic rock slope

2.1. Field experiments introduction based the excavation of WuDongde high rock slope

WuDongde hydropower station is one the most famous hydro project in southwest of China, which is located in the valley which is between Huidong County in Sichuan province and Luquan County in Yunnan province. The total installed capacity is about 10200 MW and the dam is a double curvature arch dam. The height of dam abutment rock slope is about 350 m and the rock Lithology of the slope body is limestone. The natural slope angles of left bank range from 45° to 75°, while at the right bank that are between 55° and 75°. Site experiments were implemented to investigate the blasting vibration amplification during the excavation of high rock slope from elevation 1030m to 910m. Two kinds of measurement program were designed to compare the vibration distribution of high rock slope and flat ground. Fig.3 and Fig.4 plot the excavation sequence schematic and the arrangement of the experiment zones and vibration measurement points. The first plan is fixing the vibration points at the inside and outside of the every berm to investigate the blasting vibration attenuation characteristic of the high rock slope.

Fig.3 Schematic of excavation sequence and the arrangement of the experiment zones

In the second plan, vibration points are fixed at the flat ground used as the reference object, but it should be emphasized that the detonation distance equals to that of points fixed at the slope surface.
The experiments were implemented at the same bench to ensure the quality of rock mass of two experiments is similar. The same blasting parameters were employed in two kinds of experiment to avoid the interference of other factors. The MINI-SEIS blasting monitoring equipment was employed to measure the blasting vibration during experiment. Fig. 5 plots the arrangement of blasting holes, blasting network and vibration monitoring equipment.
2.2. The experiment results of blasting vibration amplification characteristic

During the blasting excavation of WuDongde high rock slope from the elevation of 1030 m to 910 m, the above experiments were implemented more than twenty times. Fig. 6 gives the comparison of the radial PPV between slope surface around the berm and the flat ground. To investigate the vibration amplification around the berm carefully, PPV at the inside and outside of the berm was plotted respectively.

It can be seen that the PPV of the points around the berm is larger than that of the points at the flat ground. The magnifying multiples of the vibration at the inside of the berm is about 1.1~1.2, but for the points at the outside of the berm, that is about 1.8~2.5. Results demonstrate that the elevation amplification of blast vibration exists around the berm of high rock slope, but the degree of vibration amplification at the outside is much larger than that of inside. The edge and elevation effect makes PPV distribution around the berm quite different from that of flat ground. Comparison results of outside and inside of the berm reveal that the vibration amplification induced by edge effect is more obvious than that of elevation effect.
To investigate the amplification effect of blasting vibration at different directions, Fig. 7 plots the vibration amplification factor in three directions at the inside and outside of different bench. The determination of the amplification factor is setting the PPV of points at the flat ground as the benchmark, while the amplification factor is the ratio of PPV around the berm and flat ground.

![Graph showing vibration amplification factor in three directions](image)

(a) The points at the inside of the berm

(b) The points at the outside of the berm

**Fig. 7** The vibration amplification factor in three directions at the inside and outside of the berm

The amplification degree decreases as the detonation distance increases in three directions. The attenuation law of PPV conforms to logarithmic characteristic as a whole. As the detonation distance increases, the blasting seismic wave is weakened by the damping of the rock mass. Both at the inside and outside of the berm, the amplification factor in the vertical direction is largest, and the radial direction takes the second place, while the tangential direction is least. The amplification factor in the vertical direction is about 2~3.5, but in the radial and tangential direction, that is only about 1.5.

Results demonstrate that the elevation amplification of blasting vibration in high rock slope mainly appears in the vertical direction, while for other two direction, the enlarge degree is much weaker. It can be explained that the existing of free surface makes the clamp action in the vertical direction is less than other directions, which makes the vibration amplification stronger under the same seismic wave.

2.3. The impact of blasting energy and height of bench for the vibration amplification

To reveal the impact factors of blasting vibration amplification of high rock slope, more kinds of production experiments were implemented based on the excavation between EL.950 and 850m. Fig. 8 plots the amplification factors of inside and outside of the berm when different charge weight per delay was adopted.
Fig. 8 The amplification factor of vibration under different charge weight per delay

Results demonstrate that the amplification factor at the inside and outside of the berm increases when the charge weight per delay is enlarged. The exponential distribution could be obviously found while the correlation coefficient exceeds 0.9. The increasing speed of the amplification factor at the outside is larger than that of inside. For instance, the gap between the inside and outside the berm is about 1.5 times when the charge weight per delay is 6 kg, but if the charge weight per delay is 30 kg, that is about 3.0 times. It clearly shows that the increase of charge weight per delay could strengthen the elevation amplification of vibration. That means the vibration amplification not only depends on the unique geometry of slope surface, but also is affected obviously by the blasting energy. This conclusion is consistent with the results of amplification degree versus different detonation distance in section 2.2.

From the elevation of 1000m to 800m, different kinds of bench height was designed, which provides a good condition for the sensitivity analysis of bench height in the vibration amplification. Fig. 9 plots the amplification factor of inside and outside of the berm with different bench height.

Fig. 9 The amplification factor of vibration under different bench height

It can be seen that the height of bench affects the amplification degree of PPV obviously. The typical parabolic relationship could be found between the amplification factor and height of bench. A maximum of amplification factor happened when the height of bench is about 13m for WuDongde high rock slope in the present study. Results demonstrate that the degree of amplification has not been always enhanced with the increase of elevation. The final PPV is affected by the combination of amplification effect and the attenuation of seismic wave. When the bench height is too large, the attenuation of seismic wave is preferred and the elevation amplification decreases.
3. Numerical simulation of blasting vibration amplification of high rock slope
As the full size experiment is very expensive and time-consuming, and the working condition of experiment is limited because of the environment. On the other hand, numerical method, derived from sound mechanical principles and validated against experimental data, indicates a promising approach to study this problem. In the next section, the numerical simulation of blasting vibration amplification of high rock slope was implemented with a commercial software LS-DYNA, and the spatial distribution of blasting vibration around the slope surface was investigated carefully.

3.1. Numerical model and parameters validation
Geometry and material parameters of WuDongde high rock slope were employed in the numerical simulation. As the corresponding FEM mesh shown in Fig.10, a 3D dynamic model was conducted with LS-DYNA. The minimize boundary size is the 20 times of the height for single bench in the numerical model. The radial dimension of the elements increased with the radius to improve the calculation accuracy. The boundary conditions were specified as follows: the top and nature surface were free face, the lower and right sides were non-reflecting boundaries.

Assumed to be isotropic and homogenous material, the slope region is a limestone rock mass characterized by the elastic modulus E=20000 MPa, the density ρ=2610 kg/m3 and the Poisson's ratio μ=0.22. The Jones–Wilkens–Lee (JWL) equation of state (EOS) can model the pressure generated by the expansion of the detonation product of the chemical explosive. It has been widely used in engineering calculations and can be written as:

\[
p = A \left( 1 - \frac{\omega}{R_0 V} \right) e^{-R_0 V} + B \left( 1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + \frac{\omega E}{V} \quad \text{MERGEFORMAT (1)}
\]

where A, R1, B, R2 and μ are material constants, P is the pressure, V is the relative volume of detonation product and E is the specific energy with an initial value of E0. Material Type 9 of LS-DYNA (*MAT_NULL) is used to calculate the pressure P from a specified EOS, which defines the relationship between pressure, density and internal energy. As for the air, the polynomial EOS is usually employed, in which the pressure P is expressed as:

\[
P = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + (C_4 + C_5 \mu + C_6 \mu^2)e \quad \text{MERGEFORMAT (2)}
\]

Where e is the internal energy per volume. The compression of the material is defined by the parameter μ=(ρ/ρ0)-1, with ρ and ρ0 being the current and initial density of the material, respectively. As a matter of fact, the air is often modeled as an ideal gas by setting C0=C1=C2=C3=0 and C4=C5=C6=0.401. Air mass density and initial internal energy e0 are 1.255 kg/m3 and 0.25 J/cm3, respectively.

During the numerical simulation of blasting vibration of high rock slope, the damping parameters determination would directly affect the accuracy of the calculation results. The damping in the model is done through the Rayleigh classical approach by making the damping matrix equal a linear combination of the mass and stiffness matrix. Appropriate damping parameters can be obtained by
trial calculation in support of the field measurements. In the present study, calibration of damping parameters is implemented by trial calculation based on the comparison with measurement. The arrangement of vibration measuring points at the high rock slope as shown in Fig.4 were selected to make trial calculation and determine the appropriate damping parameters. Fig.11 plots the simulated and measured attenuation of peak particle vibration in the rock mass as a function of scaled distance from the charge center.

Based many times of trial calculation, the result demonstrates that when values of mass and stiffness damping used in our case are 9.0 and 0.00010 respectively, the simulated PPV attenuation is seen to match well the test data at all the vibration measuring points. In the present study, the damping parameters selected by calibration were used in the numerical simulation of blasting vibration to achieve a better understanding of vibration amplification of hydro high rock slope.

3.2. Spatial distribution of PPV around the high rock slope

Four types of points were marked around the slope surface as shown in Fig.12 for the convenient investigation and comparison of vibration amplification. Type ‘A’, type ‘B’ and type ‘C’ are fixed at the inside, middle and outside of the berm, while and type ‘D’ is at the middle of bench. All nodes of the slope surface and berm were selected as the target points and the curve of PPV versus elevation difference was plotted in the Fig.12.

The amplification characteristic of numerical simulation agrees well with that of site experiment. The amplification factor of points at the outside of the berm (Type ‘C’) is largest, while at the inside (Type ‘A’) the amplified degree is least. For example, at the bench near the current blasting zone, the amplification coefficient at the outside of the berm is about 2.5 while at the inside of the berm that is only 1.07. The sequence of the PPV around the berm at each bench for marked points is
VC>VB>VA>VD. The high degree of vibration amplification could be found at the outside and middle of the berm (‘B’ and ‘C’), while at the inside of the berm and middle of the slope surface that is not obvious. Results demonstrate that edge of the berm affect the vibration amplification obviously, the high amplification degree could be found when it is close to the outside of the berm.

The overall law is that PPV decreased with the increase of detonate distance, but several gibbous shapes could be found in the distribution curve. The position of gibbous shape is just located at the berm of slope surface. Results demonstrate that the vibration amplification of high rock slope is just local amplification, which only focuses on a small zone around the berm. Fig.13 plots the magnifying scope distribution at the bench of different elevation.

![Fig.13 The magnifying scope distribution of vibration at the every bench](image)

It can be seen that the area of amplification zone decreases sharply when the detonation distance increases. As can be seen form one bench, the area of amplification is less than 10% of the whole step area, which means that the amplification is just partial. From the whole amplification zone distribution of high rock slope, the exponential attenuation characteristic could be found obviously. It can be explained that the final value of PPV is the combination of edge effect and the attenuation of seismic wave. If the detonation is large enough, the attenuation is preferred and the elevation amplification decreases.

3.3 The impactor factors of vibration amplification

The bench could be thought as a protuberance compared with the slope body. The geometry of the bench plays an important role in the vibration amplification of high rock slope. The main factors of bench geometry are the angle, width and height of bench. The sensitivity analysis of these factors was implemented with numerical simulation respectively. Fig.14 plots the relationship between the amplification factor and slope angle.

![Fig.14 The relationship between the amplification factor and slope angle](image)

It can be seen that the amplification factor increases as the slope angle increase. Regression results show typical linear relationship between the amplification factor and slope angle. But at the outside of the berm, the increase size of amplification factor is more than that of inside. Results
demonstrate that the slope angle could affect the vibration amplification obviously, and for the high steep slope the amplification effect of blasting vibration could not be ignored. Fig.15 plots the relationship between the amplification factor and bench height.

**Fig.15** The relationship between the amplification factor and bench height

During the site experiment, the comparison of different bench height was studied but the working condition was limited. More working condition of bench height was implemented in the numerical simulation. The results demonstrate that the numerical results agree well with that of site experiment, which verifies that the numerical simulation employed in the present study is effective. It can be seen that the typical parabolic relationship could be found between the amplification factor and height of bench for both inside and outside of the berm. There is a special bench height, which makes the amplification coefficient obtain the maximum value. The final value of PPV is affected by the combination of enlargement of elevation effect and the attenuation of seismic wave. Fig.16 plots the relationship between the amplification factor and width of the berm.

**Fig.16** The relationship between the amplification factor and width of the berm

The relationship between the width of the berm and amplification factor is similar to that of bench height. As the width of the berm increases, the vibration amplification factor increases to a certain value and then decreases. A maximum of amplification factor could be found when the width of bench is about 3.5 m. It should be pointed out that the regular width of the berm of WuDongde high rock slope is 3m, which makes the vibration amplification obvious.

Results of width and height of the berm demonstrate that the final value of PPV is affected by the combination of enlargement of elevation effect and the attenuation of seismic wave. When the height or width is too large, the attenuation of seismic wave is preferred and the elevation amplification decreases.

To investigate effect of the rock mass quality for the vibration amplification, different elastic modulus was employed in the numerical simulation, while other material parameters were determined
with fixed relationship based on elastic mechanics. Fig.17 plots corresponding relationship between the amplification factor and different rock mass quality.

**Fig.17** Relationship between the amplification factor and elastic modulus of rock mass

It can be seen that the amplification factor decreases when the elastic modulus increases both at the outside and inside of the berm. The relationship characteristic is almost linear as the correlation coefficient exceeds 0.9. For the rock mass of poor quality, the gap of amplification degree between the inside and outside is larger. Results demonstrate that the quality of rock mass could affect the vibration amplification of slope obviously, and the amplification degree could be enlarged in rock mass of poor quality.

4. **Blasting vibration monitoring scheme suggestion for high rock slope**

Dynamic response of blasting excavation could be obtained with vibration monitoring approach. As investigated in the previous section, the vibration amplification characteristic was verified by field experiments and numerical simulations. Based on the better understanding of the vibration distribution of high rock slope, it is necessary to propose a reasonable vibration monitoring approach to make the results more accurate. Usually, four kinds of measuring point feasible position implemented in the engineering practice is as follow: outside of the berm, inside of the berm, midpoint of the berm and sometimes the embedded measuring points or middle of slope surface when the condition permits. In the next section, the reasonable vibration monitoring scheme for high rock slope was investigated according to different objectives.

4.1. **Object I: Determine the blasting vibration attenuation law of high rock slope**

The capability to predict the blasting vibration attenuation law is important for the blasting excavation of high rock slope, the optimal blasting parameters can be determined with a better understanding. The monitoring points could only be fixed at the berm of slope, and sometimes small amount of points can be buried in the slope body but it is very expensive and time-consuming. It is very meaningful to get the vibration attenuation law by implementing the vibration monitoring around the slope surface.

Many empirical relationships have been presented which predict the PPV at any points considering mostly two parameters namely the maximum charge per delay and distance from the blast to the measuring point [21-22]. So in the present study, the conventional formula is employed to describe the attenuation law of high rock slope, and if all points adopts the same formula, the more accurate combination can still be obtained by comparison. Based on the numerical simulation and experiment results, the comparison of vibration attenuation law obtained with different combination of vibration points is plotted in Fig.18.
The result of many points in slope body as shown in Fig. 18(a) could be thought as the ideal result and set as the standard. It can be seen that when the point was fixed at the middle of the bench and inside of the berm, the results match well with that benchmark. But the attenuation laws obtained from the outside and middle of the berm is far from the standard. Results demonstrate that if the monitoring points are fixed at the inside of the berm, the similar vibration attenuation law would be obtained compared with the points that buried in the slope body. But if the points are arranged at the outside of the berm, the huge error and wrong judgment would be induced. So we can come to conclude that if the measurement target is getting the vibration attenuation law, the monitoring points should be fixed at the inside of the berm.

4.2. Object II: Obtaining the most unfavorable blasting effect

Compared with the overall control of whole high rock slope, the most unfavorable blasting effect at the local position is another key problem. PPV has been accepted as an important indicator of structural or rock mass damage. The PPV threshold value of three different levels of damage degree for seven kinds of conventional rock medium was shown in Fig. 19.

The determination of the most unfavorable effect of blasting is actually monitoring the largest PPV. Based on the results of experiments and numerical simulation, the vibration amplification could be found obviously at the outside of the berm, which means the largest PPV often happens at this
position. So if the aim is to obtain the most unfavorable response of the slope during blasting excavation, the monitoring points should be arranged at the outside of the berm.

4.3. Object III: Assessing the whole stability of high rock slope

PPV could play an important role in the stability evaluation of high rock slope according to the existing literature [20-23]. The focus of this procession is obtaining the PPV which could reflect the vibration and stress level of slope body. If the inappropriate PPV is employed, the error evaluation of slope stability would be obtained.

As shown in Fig.12, when the target is set at the outside of the berm, vibration magnitude would be much larger than that of slope body because of the elevation and edge amplification. If the stability is determined by the vibration at this location, obvious misunderstanding would be produced. The same conclusion could also be found at the middle of the berm. But if the target is set at the inside of the berm, the PPV is close to that of slope body. More importantly, the weak amplification at the inside of the berm is helpful for the safety evaluation of the high rock slope, which could provide a certain safety redundancy. So if the aim is to determine the stability of whole slope, the most ideal measuring point position is at the inside of the berm.

5. Conclusions and discussions

The vibration amplification effect of high rock slope under blasting loading was investigated with site experiments and numerical simulation, and the suggestion of vibration scheme of high rock slope was proposed. The following conclusions and understandings may be drawn from the present study:

(1) Results of site experiments demonstrate that the elevation amplification of blast vibration could be found around the berm of high rock slope, but the degree of vibration amplification at the outside is much larger than that of inside. The vibration amplification mainly focuses on the vertical direction, while the amplification degree of other two directions is much lower. The increase of charge weight per delay could strengthen the elevation amplification of vibration with exponential way.

(2) Numerical simulation results agree well with site experiments, and a more comprehensive analysis of the vibration amplification was finished. Results reveal that small gibbous shapes could be found in the PPV distribution around the berm, the vibration amplification is just a partial amplification effect which could only be found in a small area around the berm. The geometry of the bench and rock mass quality could affect the vibration amplification obviously.

(3) The suggestion of blasting vibration monitoring scheme for high rock slope was proposed according to different objectives. If the aim is to evaluate the dynamic stability or get the blasting vibration attenuation law of high rock slope, monitoring points should be arranged at the inside of the berm, but while the most unfavorable response of rock mass is expected to be obtained, the out edge of the berm should be selected as the monitoring position.

It should be pointed out that the emphasis of this paper is to present the partial amplification effect of high rock slope. The numerical simulation method is conventional and the anisotropic and inhomogeneous of the rock mass in reality are ignored. Otherwise, partial amplification effect verified by numerical simulation and field measurement still provide a good reference for the blasting induced response of high rock slope. Suggestion monitoring scheme object to different targets could also be used as an effective tool in engineering practice.

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