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Spectral prediction and control of blast vibrations during the excavation of high dam abutment slopes with millisecond-delay blasting

P. Li[a,b], W.B. Lu[b,c,*], X.X. Wu[a,b], M. Chen[b,c], P. Yan[b,c], Y.G. Hu[a,b]

[a] Changjiang River Scientific Research Institute, Wuhan 430010, China
[b] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
[c] Key Laboratory of Rock Mechanics in Hydraulic Structural Engineering Ministry of Education, Wuhan University, Wuhan 430072, China

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ABSTRACT

In hydropower projects in Southwest China, large-scale, high-intensity blasts are required to excavate high rock slopes. In these cases, traditional prediction and control methods for blast vibrations are invalid. Thus, a method to predict the time history of blast vibrations on high slopes is proposed, and a blast vibration spectral control scheme based on this method is presented. Additionally, a case study for the abutment slope excavation of the Xiluodu hydropower project is presented. The results indicate that if the delay interval is <20 ms or $>$ 50 ms, a large amount of energy is distributed in the resonant frequency band of the slope; with optimized delay interval of 20–25 ms and 45–50 ms, the low-frequency compositions of blast vibrations are considerably fewer, and spectral control can be implemented more effectively. Delay intervals of 25 and 50 ms are adopted in practice considering the detonator limitation.

1. Introduction

Many large-scale hydropower projects in Southwest China are being constructed or are currently in the planning phase. These hydropower projects involve extensive blast excavations of dam abutment slopes with heights between 400 and 700 m, as illustrated in Fig. 1. Large-scale delay blasting with millisecond delays (as shown in Fig. 2) is widely adopted to improve machinery efficiency and accelerate the excavation progress; this method uses up to 300 kg of maximum charge weight per delay and 20–30 t of total charge weight. Under such circumstances, the blast vibrations may jeopardize the dynamic stability of the dam abutment slopes and should be strictly controlled during the excavation period.

However, traditional vibration control methods, such as waveform interference and optimization of the maximum charge weight per delay, focus on vibration peak prediction and control. Waveform interference uses the proper delay intervals to cancel out vibration waveforms from different delays to reduce vibration peaks. Many researchers (Blair [1], Wheeler [2], Yamamoto et al. [3,4], Aldas and Ecevitoglu [5]) have performed relevant studies on this method. The results have shown that wave interference can be realized only with extremely accurate detonators and simple initiating networks (Moji et al. [6], Hoshino et al. [7], Zhang and Lindqvist [8], Zhang and Naarttijaervi [9]). In fact, vibration peak control via the optimization of the maximum charge weight per delay may also make it difficult to meet the construction requirements of dam abutment slopes and could even fail to control vibrations in some cases. For example, the vibrations in the near or middle zones could be contained; however, in the far zone, vibrations could become unstable because of the superposition of vibrations from each delay and the resonance effect due to the increased low-frequency part of the vibrations. Therefore, the spectral responses of high slopes induced by blast vibrations should also be predicted and controlled.

Spectral prediction of blast vibrations is accomplished by using predictions of the entire time history of the blast vibrations and Fourier transforms. In the 1980s, Blair [1] and Hinzen [10] proposed a time-history prediction method of blast vibrations based on measured seed waveforms from single blasts. Then, the method was developed into many other forms to obtain more accurate predictions (Blair [11], Yang [12]). The precision of those methods depends largely on the quantity of seed waves and the accuracy of the detonators and thus requires many blast experiments to be performed and monitored for an accurate prediction, which might be prohibitively expensive. In recent years, with the rapid development of computers and numerical simulation methods, various low-cost numerical methods, such as the finite element method (FEM), finite difference method (FDM), and discrete element method (DEM), have been used to predict the time-history of blast vibrations. The computational requirements to simulate the entire

* Corresponding author at: State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China.
E-mail address: wblu@whu.edu.cn (W.B. Lu).

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Fig. 1. Typical high dam abutment slopes in Southwest China.

time history of the blast vibrations can be reduced considerably by simplifying the blast source via equivalently applying the pressure pulse on the bench face (Toraño et al. [13]), the outer boundary of the plastic zone (Shin et al. [14]), the boundary of the crushed zone (Li et al. [15]), or the elastic boundary (Yang et al. [16]). Considering additional influential factors and performing the corresponding calibration, several of the simulation methods (Toraño et al. [13], Yang et al. [16]) can yield good accuracy in far zones when modeling a single blast hole shot and a single delay blast of a row of holes. The simulation of vibrations from production blasts, particularly large-scale blasts with millisecond delays for high dam abutment slopes, is still challenging using only numerical methods. Therefore, this work proposes a method that uses both measured seed waves and a numerical simulation method and provides a feasible scheme to predict large-scale blasts in dam projects with high abutment slopes. It should be noticed that there are clearly 3 components of the blast vibration, Longitudinal, Transverse and Vertical components. The Transverse component of vibration is essentially random and still so hard to simulate (Blair, [17]). However the Transverse component of vibration is usually not the largest component of measured vibration records on high slope, so it is not the main concern of this study.

After predicting the vibration spectra, spectral control can be achieved by optimizing the blast design to minimize the predicted vibration amplitudes in unexpected spectral bands. Blair and Yang have conducted representative studies of spectral control. Blair [18] proposed a structural vibration factor to evaluate the relative energy distributed in the resonant frequency band of the protected structure and applied it in spectral control. Yang [19] noted that if the potential shift frequency $f = 1/\Delta\tau$ ($\Delta\tau$ is the adopted delay interval) lies in the frequency range supported by the ground or structures, the main frequency of the production blast will shift to the potential shift frequency, which provides a frequency shifting scheme for spectral control. However, these methods have not been applied in practice for actual dam abutment slope excavations. In this regard, this study further investigates the theories behind these methods and presents a practical scheme for the spectral prediction and control of blast vibrations during high-slope excavation.

2. Theories of the spectral control of blast vibrations on high slopes

The effect of blast vibrations on the stability of high rock slopes is primarily manifested in two aspects: first, the repeated action of blast vibration loads can reduce the strength parameters of the structural planes in the rock masses, which could lead to the instability of a potential landslide mass; second, the inertia force of the blast vibrations might increase the sliding force of the slope, which makes the slope unstable.

To achieve spectral control of blast vibrations, an evaluation parameter that represents the stability of the high rock slope should be established. A safety coefficient is typically used to evaluate the stability of the potential landslide mass based on the limit equilibrium method. In this study, the structural vibration factor (SVF) created by Blair [18] is used to estimate the influence of blast vibrations on the entire high slope. Additionally, the relationships among the evaluation parameters, vibration spectra, and blast parameters should be derived, and the blast design can be optimized accordingly.

2.1. Spectral control based on dynamic stability limit equilibrium analysis

The limit equilibrium method is a traditional method that can analyze the dynamic stability of a potential landslide mass. The stability safety coefficient of the slope under blasting vibration loads will continuously change over time, which is influenced by the vibrations' amplitudes and spectra, as well as numerous other factors.

Lu et al. [20] proposed a time-history analysis method based on the limit equilibrium method that considers the influence of the aforementioned factors on the dynamic stability of the slope. In this method, the potential landslide mass is divided into several blocks. Then, the blast vibrations' inertia forces that act on each block at any time are derived and used in the dynamic stability limit equilibrium analysis. The influence of the spectral difference on the stability of the high slope can be determined by using the measured blast vibration waveforms that contain different spectral compositions. On this basis, the safety

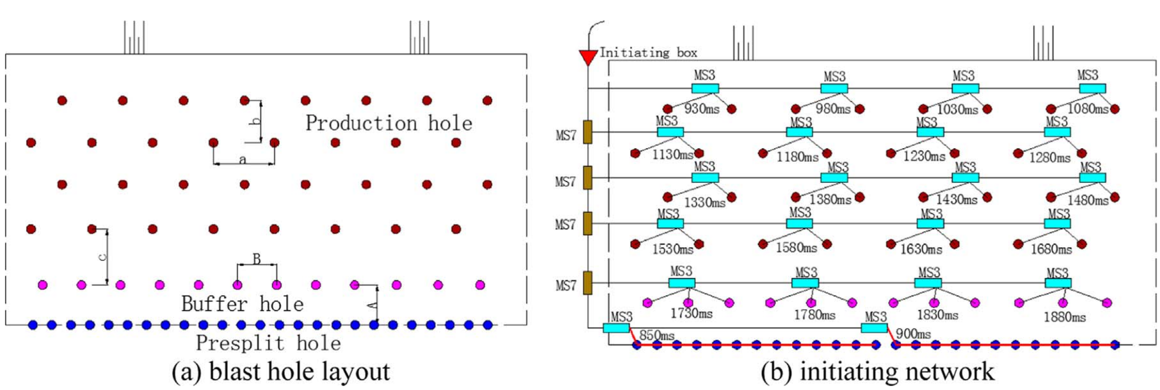

Fig. 2. Typical blast hole layout and initiating network of delay blasting with millisecond delays on dam abutment slopes.