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# Degradation of a discrete infilled joint shear strength subjected to repeated blast-induced vibrations

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ABSTRACT

This paper presents the results of a series of numerical modeling experiments aimed at quantifying blast-induced degradation of shear strength of discontinuities. Near-field vibration history of a single-row production blast in a limestone quarry was used as input to the numerical model. For this purpose, two rock blocks, representing a stiff massive sulfide rock and a weaker limestone rock, were simulated using the 2D Particle Flow Code (PFC2D). Rock mass containing a single inclined joint was modeled as Mohr-Coulomb. The results show that the crack generation rate is increased in both samples after repetitive vibration loading. Joint shear strength degradation rate in the stiffer massive sulfide rock sample is higher than the softer limestone rock, which is attributed to the higher seismic impedance mismatch. The results show that even low-amplitude blasting vibrations (<80 mm/s), when repeated as in multi-hole blasts, can significantly degrade joint shear strength in the nearby pit walls.



## 1. Introduction

Blasting is one of the key activities in mining cycle which has a direct impact on the downstream operations. Although it is considered as the most effective means of rock breakage, blasting has some associated drawbacks such as ground vibration, back break and fly rock that should be controlled to minimize its unfavorable effects. Increasing the explosive charge weight in blast holes can lead to finer rock fragments; however, this can result in higher blast-induced vibrations in the surrounding rock masses. This can jeopardise not only the safety of adjacent buildings, but even adversely influence the stability of nearby pit walls.

The damage potential of blast-induced vibrations on the residential or commercial structures has been well studied, and appropriate guidelines and regulations have been developed in terms of both amplitude and frequency content of the vibrations, maximum charge weight and minimum distance to reduce these effects on structures [1–3]. However, in terms of predicting potential damage to pit walls, which are much closer to the blasts than residences, such precise guidelines do not exist. This is mainly attributed to the complexity of the problem that involves not only the structural and strength characteristics of the target rock mass, but also has to account for the problem of repeated loading of the pit wall.

Based on the proximity to the blasting location, blast-induced rock damages can be classified into near-field and far-field damage [4,5]. In near-field damage, the rock mass surrounding a blast hole is repeatedly subjected to high frequency and high amplitude vibrations, both of which decay significantly with distance [6]. The blast-induced rock damage in near-field has received considerable attention in the past, investigating the effects of shock waves and explosion gas pressure on rock fracture [7–9]. Away from the immediate vicinity of a blast, the stress waves have insufficient amplitude to cause damage to intact rock [10]. However, due to strain accumulation along discontinuities, the overall strength of the rock mass may decrease. Progressive degradation of joint shear strength as a result of repetitive blast loading in open pit mines can lead to structurally controlled slope failure. Despite several studies that have stated the effects of blasting on degradation of joint shear strength and consequently the instabilities in mining operations [11–15], only limited investigations have been carried out to analyze and quantify this phenomenon [16].

In order to understand the response of jointed rock masses to seismic loads in the near field, suitable measurement methods (i.e. high-frequency high-g accelerometers) should be used to study the initiation sequence and the corresponding amplitude and frequency content of blast-induced vibrations. Accelerometers are capable of recording extremely high vibrations and are very suitable for measuring near the blast holes [e.g. [17,18]].

Many researchers have used continuum and discontinuum numerical methods to simulate blast-induced and impact-induced

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damage [19–28]. These simulations mainly focused on estimation and measurement of vibration in rock mass, displacement measurement, capturing damage propagation and instabilities in rock mass. In a more advanced modeling approach, Onederra et al. used hybrid stress blasting model, based on distinct element lattice scheme, to simulate the effects of a single-hole blast in a concrete block [22]. However, it can be argued that in most of these studies the effects of discontinuities on blast-induced rock mass damage have been overlooked. Limited studies have been conducted to investigate the interaction of stress waves with discontinuities in the rock mass [29–32]. The main purpose of these studies was to understand the wave propagation and transmission rate in a jointed rock mass medium.

This paper aims to contribute to our understanding of blast-induced rock mass damage. It presents the results of a series of numerical modeling experiments used to investigate the effects of blast-induced vibration on the joint shear strength degradation. For this purpose, the blast-induced vibrations of a single row production blast in a quarry was used as an input to load a jointed rock sample simulated with PFC2D. The simulations allowed to investigate the interaction between blast-induced stress waves and the joint surface, and to quantify the damage inflicted along the joint due to repeated loading.

## 2. Methodology

Blast-induced vibrations from a single row production blast were recorded at two stations on two adjacent benches in close proximity to a blast. The recorded vibration loads were used as an input to dynamically load two jointed rock blocks simulated by PFC2D. The response of a stiff massive sulfide rock and a softer limestone rock was simulated in this study, and the damage inflicted by vibration loads on the joint surface of the rock samples was quantified.

A blast monitoring program that was carried out in a limestone quarry provided reliable blast vibration records for the current study [4]. As shown in Fig. 1a, a single row production blast consisting of 7 double-decked holes was monitored at two seismic stations S1 and S2 that are located at different distances from the blast holes, and on adjacent benches. The blast holes had a diameter of 155 mm and a depth of 16 m. The holes were charged with emulsion explosive (density: 1.25 g/cm$^3$). The inter-deck material consisted of 19 mm size gravel. The initiation system was a combination of surface delay and shock tube-based down-hole detonators (500 ms) with an inter-deck delay interval of 42 ms between the upper and lower decks.

The bottom deck was detonated before the upper one in each hole (see Fig. 1b for a decked blasthole cross section) and all decks were initiated with a 454 g Pentolite booster. The charge weight of the bottom decks was approximately 123 kg and that of the top one was 132 kg. For practical purpose, they can be considered as the same (except for the last bottom deck which had only 76 kg of explosive). Each explosive deck was instrumented with velocity-of-detonation (VoD) probes to ascertain that they all detonated properly. The results showed that each explosive deck detonated with an average VoD of 5300 m/s, in accordance with the specification for the product in that diameter. The single-row blast had a hole spacing of 4 m and a burden of 3.6 m.

The vibration sensors consisted of tri-axial high-frequency and high-amplitude accelerometers (Kistler 8702; resonant frequency 54 kHz; 100 g capacity). The accelerometers were bolted and grouted into the rock with quick-setting cement. The tri-axial seismic station S1 was located on the same bench where the blasting was done, and the other station, S2, located on the bench immediately above and 3 m behind the crest. The respective distances for the seismic sensors are shown in Fig. 1a.

The acceleration records at stations S1 and S2 are shown in Fig. 2a and b, respectively. At the closer station S1, all the 14 explosive decks can be clearly identified on all three axes (i.e. longitudinal, transverse and vertical). There were only slight variations in their respective delay times compared to their nominal delays. The corresponding events at station S2 are less clearly defined, as expected due partly to the greater distance, but more due to the more complex travel path for the vibrations because of the presence of an additional bench face. Nevertheless, the detonation event for each deck can still be clearly identified in both the vertical and the transverse components of the vibrations. There are additional details on these vibration records, which show significantly different vibration amplitudes for the respective decks in each hole, with the upper deck yielding a much larger vibration

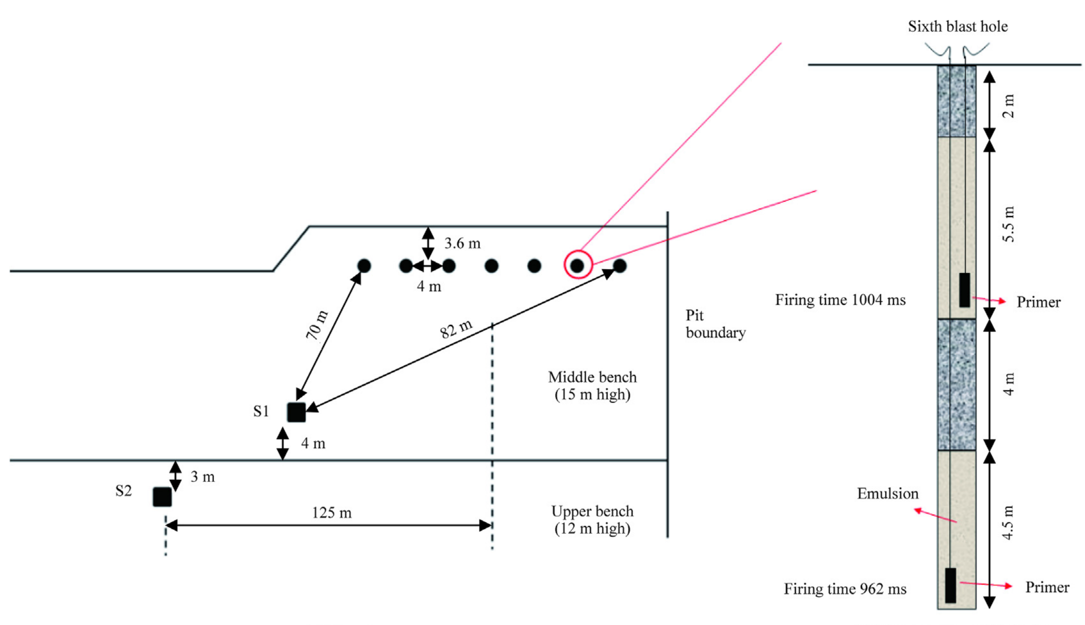


**Fig. 1.** Plan view of the blast area and two recording stations S1 and S2, and a cross-section of one decked blasthole [4].

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