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Research Paper

Numerical simulation of the blast response of cemented paste backfilled stopes

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ABSTRACT

The effects of underground blasting on stress wave propagation, blast response and generation of pore water pressures in cemented paste backfilled (CPB) stopes is researched in this study. Through LS-DYNA the effects of sequencing of detonation and number and blasthole proximity on the total and residual pore pressures exerted in the fill was explored. Results show that liquefaction risk decreases as explosives are detonated in rows located perpendicular to stope's exposed face with delay times in excess of two milliseconds. Cementation of CPB was not observed to affect blast induced pressures in fully saturated backfills but decreases liquefaction risk.

1. Introduction

The extraction of minerals from underground mines results in the creation of voids, usually called stopes. In order to provide support for the surrounding rock mass, ensure long-term stability of the mine and limit excavations exposure; these stopes are filled with a mixture of mine waste materials, water and a binder agent [26]. The decision on the type of fill used, e.g. rock backfill, paste backfill or hydraulic backfill, is intimately related to mining methods, mining strategy and mining sequences [22].

Cemented Paste Backfill (CPB) is made by mixing recycled full stream tailings, mine process water and cement. This mixture is pumped or gravity delivered to the deposition point, commonly located at the top of the stope, through reticulation pipes. To initially retain the fill inside the stope, a structural barricade is constructed across the access drive. These barricades are designed to resist the maximum horizontal stress exerted by the fill at the different curing ages. During the first hours of deposition, the total horizontal stress on the barricade is equivalent to the total vertical stress of the overlying fill [11,9,10]. However, as a result of the consolidation and arching of the fill and other chemical reactions (e.g. cementation and self-desiccation phenomena), the total horizontal pressure at the barricade decreases well below the total vertical stress. Several relationships have been proposed to quantify the pressures acting on the barricades under a range of conditions related to drainage and friction on the rock walls (e.g. [21,27,15,19]. However, most of these solutions are based on static equilibrium of forces, and thus, they neglect the important effects that dynamic loads may have on the geomechanical response of the fill and the structural stability of the barricades.

Dynamic loading resulting from seismic events (e.g. earthquakes and rockbursts) and blasting production have been shown to increase the water pressures within the fill and the horizontal loads exerted at the barricade location [10]. Under increased residual pore water pressure, liquefaction of the fill might be triggered, i.e. residual excess pore pressure equals the vertical confining stress of the soil. In such a scenario, the pressure on the barricade may rise to as high as the fill overburden pressure. The effects of seismic loads on CPB pore pressure build-up have been studied in the recent past by a few authors through cyclic shear testing [16,25,7]. These authors have concluded that CPB can liquefy (i.e. cyclic mobility type of response) if a critical combination of cyclic shear stresses and a number of cycles is applied to the fill. On the other hand, the blast response of CPB, specifically the build-up of pore pressure during and after (residual) the passage of the compression wave have barely been studied. This is the main subject of study of this article.

1.1. Background

Blast wave response of soils is challenging since many of the traditional soil dynamics assumptions for small strain shear waves are not applicable. For instance, it is usually stated that saturated soil does not experience a change in the effective stress when subjected to changes in total compressive stress. This is based on the assumption that the soil solid particles are rigid and hence do not deform and the bulk modulus of water is high enough to render the material essentially incompressible. This assumption is no necessarily valid under blast

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loading since water component (or even solid particles) could deform under peak pressures than can reach several mega-Pascals [36].

From a practical point of view, several empirical relations have been proposed to predict the residual excess pore pressure after the passage of the stress wave as a function of explosive mass and distance, peak particle velocity (PPV) and peak volumetric strain [3]. The common approach is to quantify the liquefaction potential through the pore pressure ratio (PPR), which is usually defined as the ratio between the peak residual pore pressure increase, Δu, divided by the initial vertical effective stress, σ'_{vc}. It must be mentioned that the term "residual" is used throughout the article in reference to residual plastic strains (accompanied by residual pore pressure) resulting from the contraction-dilation process of the material when blast pressure has dissipated completely. In this context, shock loading tests conducted by Veyera and Charlie [33], Veyera et al. [32] and Charlie and Doehring (2006), have shown that liquefaction of sands can be triggered by a single large compressive pulse or a series of small compressive loadings at peak strains in excess of about 0.01. Similarly, single detonation field tests conducted by Charlie et al. [4] and Al-Qasimi et al. [1] have demostrated that liquefaction occurred at peak strains exceeding 0.06 and 0.04%. Under multiple detonations, Al-Qasimi et al. [1] found liquefaction for peak strain exceeding 0.008%. Most of these researches have concluded that the PPR in sands is dependent on a series of factors such as soil's density and confining stress.

Most of the experimental approaches used in the past (e.g. shock tubes, controlled detonation in centrifuge tests) may not be economically feasible when dealing with the dynamics of CPB due to the high sophistication of equipment or the high costs associated with mine field work using explosives. However, with recent advances in computer technology, numerical analysis has become a viable option to simulate the full scale blast response of backfilled stopes. A few authors have used this approach in the past. Wei et al. [37] and van Gool [31] used finite discrete (i.e. ELFEN) and finite element software (ABAQUS), respectively, to investigate the propagation of compressional waves and the potential for ore dilution of CPB. However, these studies have not captured the response of CPB under various blast loadings and detonation patterns, and the generation of transient and residual pore water pressure has not received attention.

In this study, numerical simulations are performed to parametrically investigate the blast response of saturated CPB using the commercial explicit nonlinear finite element code LS-DYNA. The propagation of blast induced waves in rock and CPB are firstly studied and numerical accuracy evaluated against experimentally determined attenuation curves. Following this, the effects of blasthole proximity, number of blastholes and sequencing of detonation on the total pressures and pore pressure developed within the fill during and after the passage of the compressional stress wave are investigated.

2. Numerical approach

2.1. Numerical software

In this study, the software LS-DYNA is used to model the response of CPB backfills. This is a FEA hydro-code typically used to model highly non-linear events. It has been used extensively in recent years to model the response of structures subjected to blast loads (e.g. [38,5]) and to study the propagation of shock waves in rock [36,35]. It has also occasionally been employed to study the blast response of saturated soils [17] and the response of buried structures in soils [6,13].

The software combines the capabilities of the Lagrangian and the Eulerian algorithms into the ALE algorithm, which remains one of the most used algorithms for blast response studies [30]. In the ALE method the finite element mesh moves independently from the material flow which ensures continued integrity between components under large deformations [5]. A multimaterial formulation (MMALE), in which two or more different materials are mixed within the same element, is possible in LS-DYNA. This type of formulation yields a precise approximation of the effects of high energy events in the surrounding media; however, it presents high computational costs due to the continuous remapping of state variables as the mesh moves. Regarding this, computational times for each run were improved in this research by using supercomputing resources at the University of Western Australia as part of the iVEC-Australian high-performance national facility.

In the blast response of backfilled stopes four types of materials are involved, namely: rock, CPB, air and explosive. The explosives are located within the rock mass which surrounds the backfilled stope. The air is used to model the access drive at the barricade location in order to better mimic the reflection of compressional waves at this point.

2.2. Material models

2.2.1. Explosive

The common approach when studying the response of backfill stopes under blasting (e.g. [37,31]) is to simplify the pressures generated by the explosive in the surrounding rock by utilizing a time varying pressure that is applied to a cylindrical "equivalent cavity", i.e. zone beyond cracking zone of the blasthole where elastic wave propagation is expected to occur. This approach has been demonstrated to be adequate for single detonations, although it may oversimplify the resulting pressures from multiple detonations. In this study, the non-ideal pressure generated by the expansion of the detonation product of the explosive is fully simulated through the Jones-Wilkens-Lee (JWL) equation of state (EOS):

$$P = A\left(1-\frac{w}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{w}{R_2 V}\right)e^{-R_2 V} + \frac{wE_0}{V} \tag{1}$$

where P is the pressure inside the explosive; V is the relative volume; E_o is the initial internal energy; A, B, R_1 and R_2 are material constants; and w is the Grüneisen constant.

The explosive is modelled through LS-DYNA's High Explosive Burn model, i.e. Material Type 8. When "programmed burned" is selected the material requires a predefined detonation initiation, i.e. time and location of lighting, from which the actual detonation time, t_l, is computed. The closest detonation point determines t_l when multiple detonations are defined. Once detonation begins, the burn fraction of gas, F, controls the energy released into the rock, according to the maximum value between Beta Burn (F_1) and Programmed Burned (F_2). In F_1, any volumetric compression will cause detonation while in F_2 the explosive can compress behaving as an elastic perfectly plastic material [20].

$$F = \max(F_1, F_2) \tag{2}$$

$$F_1 = \frac{2(t-t_l)VOD}{3\Delta x} \tag{3}$$

$$F_2 = \frac{1-V}{1-V_{CJ}} \tag{4}$$

where t is the current time, VOD is the detonation velocity, Δx is the characteristic length of element, V is relative volume and V_{CJ} is the Chapman-Jouget volume. At all moments the pressure in the high explosive (P) is computed from the corresponding EOS pressure (P_{EOS}) and the burn fraction (F), as follows:

$$P = FP_{EOS} \tag{5}$$

2.2.2. Air

The air is modelled by null material model with a linear polynomial equation of state. The relationship between pressure, P, and internal energy per unit initial volume, E_0, is given by the following equation:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E_0 \tag{6}$$

where μ is defined as $\mu = \rho/\rho_0 - 1$, where ρ/ρ_0 is the ratio of current air density to initial density; $C_0, C_1, C_2, C_3, C_4, C_5$ and C_6 are the equation