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Dynamic response of mine pit walls

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ABSTRACT

Any wall control program at a mine site should naturally include an understanding of the dynamic response of a pit wall to blast loads. If blasts are fired close to the base of the pit wall and have sufficient energy over an appropriate frequency range then they could induce dynamic motion of a significant portion of the wall. In this regard it is important to determine the natural (resonant) behaviour of a pit wall. Unfortunately, this resonant behaviour cannot be determined using a full-scale blast simply because the natural response is contaminated by the spectral influence of the blast delay sequence. Thus the pit wall of interest is loaded (at its base) by a single blast event simulated as a short duration, broadband displacement pulse. In the present investigation, the wall response to such a load is determined using the dynamic finite element method (DFEM). The DFEM results from two- and three-dimensional models show that even for the elastic case it is not possible to excite the wall in any strongly resonant modes. This weak (lossy) resonance is due to significant radiation damping, whereby vibrational energy dissipates into the surrounding medium and does not remain trapped near the wall region. Detailed responses were obtained for walls of elastic and viscoelastic material as well as walls with horizontal layers and a damaged crest zone; in all cases the most significant motions were invariably found in the wall crest regions. However, due to the weak resonances, it is not possible to unambiguously identify wall resonant behaviour in any practical sense, and this is shown to be consistent with field measurements taken for the firing of single (seed) blastholes. In light of such results it is shown that, irrespective of the delay accuracy in any full-scale blast, there is little potential to control the wall response by varying the blast delay sequence.

1. Introduction

An important component of any program for wall control at a mine site requires an understanding of the dynamic response of a wall to blast loads. If in-pit blasts have sufficient energy over an appropriate frequency range then they could induce dynamic motion of a significant portion of a pit wall, especially if the blasts are close to the base of the wall. In this regard, Blair[1] had raised the possibility that sufficiently large blasts could induce whole-body resonance of an entire wall section. He also sketched the outline of a dynamically distorted wall shape that appeared consistent with measured vibrations at the toe and crest of a particular berm. The standard way of detecting any possible resonance is to use the transfer function method, which involves the selection of a reference measurement point (such as the berm toe), having a measured amplitude response, $A_1(f)$, as a function of frequency, f, and a target measurement point (such as the berm crest), having a measured amplitude response $A_2(f)$. The transfer function estimating the relative response of the target point with respect to the reference point is given by the spectral ratio $A_2(f)/A_1(f)$. Based on this approach, the results of Blair[1] show that, for the site of interest, the maximum relative response of the crest with respect to the toe was 2.7 and occurred at a frequency of 24.9 Hz. More recently, Osterman[2] also used the transfer function approach to investigate pit wall resonance.

The dynamic response of any structure (such as an isolated sphere, an underground opening or an open pit) depends not only on the material properties but also on the size and shape of the structure as well as the location and source characteristics of the applied load. For example an isolated sphere of uniform elastic material will exhibit a strong resonant response under radial impact. This is because the impact energy essentially remains trapped within the sphere. In fact for a perfectly elastic and non-contacting sphere in a perfect vacuum, classical physics dictates that the response will persist for infinite time. If such a sphere is viscoelastic then the response will still be resonant, but will decrease with time. On the other hand, an underground opening in uniform and unbounded elastic material will exhibit only a weak resonant response to an impact in the surrounding material, and this response will decrease with time. In this case the impact energy does not remain trapped in the vicinity of the opening and radiates out into the infinite extent of the surrounding material. In the field of structural dynamics, this loss mechanism is classified as radiation damping; it is characterized by a lossy resonant response, even in a perfectly elastic material. An example of these lossy modes is given in Fig. 3 of Blair[3]

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who analysed the response of a cylindrical cavity in a uniform elastic material subject to an incident planar P-wave. These modes are very weak resonances observable as small oscillations in the transfer function representing the response of the cylindrical cavity. Another example of lossy modes is given in Siggins and Stokes[4] who analysed the response of a large elastic underground opening to a vertical force applied to the roof of the opening. Such a load is an efficient generator of elastic surface waves over the boundary of the opening. Siggins and Stokes[4] show moderate oscillations in their transfer functions representing the response of the underground opening. The weak resonances in[3] and the stronger resonances in[4] are due to circulating Rayleigh waves over the boundaries of the openings; the lossy modes arise because the amplitude of these surface waves gradually decreases with time, even for perfectly elastic materials.

A pit wall impacted by a single explosive event at its base is also inefficient in trapping the input energy. In this case the resulting vibration waves interact with vertical and horizontal surfaces that reflect the incident energy and also produce surface waves; all these waves will then travel away from the pit wall region. In other words, the wall response only persists with duration similar to that of the explosive event. Thus under such conditions it is also expected that the pit wall will suffer significant radiation damping and so exhibit only a weak resonant response, even for elastic materials. This rationale does not support the claim of Osterman[2] who concluded from analysis of production blast data that a highwall exhibits strong, clear resonances (see his Fig. 12). However, any production blast is simply a delayed sequence of single blasthole events, and Osterman[2] confused wall resonance with the influence of this delay sequence. This aspect is considered in more detail in Section 8.

Unlike the cases presented in[3] and [4], there is no analytical solution for radiation damping associated with a pit wall. Thus a solution to this difficult problem is sought using a numerical model. Hence the main aim of the present work is to use a dynamic finite element model (DFEM) to investigate the response of a pit wall (especially its crest region) due to a single explosive event at the base of the wall.

2. The two-dimensional model for a pit wall

Fig. 1 shows the basic two-dimensional plane-strain DFEM arrangement for a pit wall 70 m high; the source is applied in a horizontal direction 40 m from the base of the wall, as indicated by the arrows. The model required approximately 13 million elements, with energy absorbing dashpots attached to the far boundaries as shown. Numerical solutions for the horizontal (X) and vertical (Z) displacements will be obtained only over the vertical and horizontal portions of the wall zone; the remaining (dominant) bulk of the model as well as the energy absorbing boundaries are required in order to simulate a region of infinite

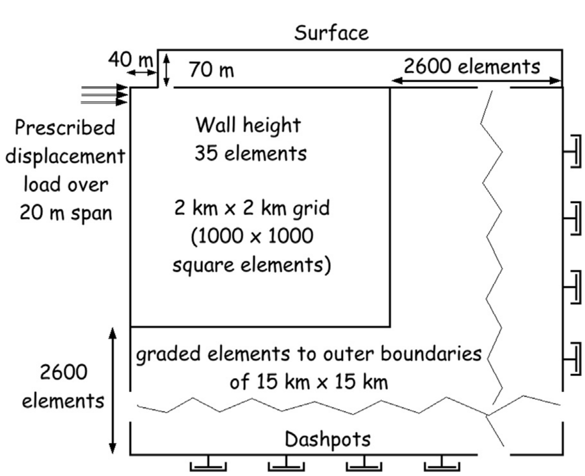

Fig. 1. DFEM for the analysis of wall response.

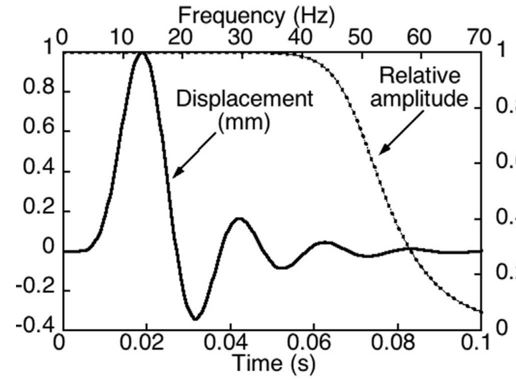

Fig. 2. Time and frequency representation of the applied load.

extent for positive X and negative Z. Fig. 2 shows the driving displacement function of the single explosive event, which has a peak of 1.0 mm applied at the base of the wall, and is given by an 8th order Butterworth response with a cut-off frequency f_C = 50 Hz. Fig. 2 also shows the relative amplitude spectrum, $S(f)$, of the explosive load, which is maximally flat up to 40 Hz, and has measurable energy over the required frequency range (0 – 70 Hz). This relative response is given by

$$S(f) = \left(\sqrt{1 + \left[\frac{f}{f_C} \right]^{16}} \right)^{-1} \tag{1}$$

Viscoelastic elements were also used in the DFEM in order to simulate realistic rock material with a given seismic Q; the non-constant-Q (NCQ) model described in[7] was used in the present investigation.

3. Spectral analysis of highwall motions

The spectral components of the DFEM-predicted time waveforms at the wall crest are evaluated using two distinct techniques: the maximum entropy method (MEM) as described in[5] and the minimum bias method (MB) as described in.[6] The MEM is a non-Fourier method and thus does not suffer from the spectral contamination associated with the finite time windows required for Fourier methods. However, care must be taken when using this approach; under the right conditions it can produce excellent results, but it can also produce false peaks and oscillations, especially with noisy data.[5] The MB is a Fourier-based technique that uses multiple sine tapers to reduce spectral contamination; it is implemented using a fast Fourier transform (FFT) method. It is thus advisable to use both methods to give improved confidence in the spectral analysis of the DFEM waveforms.

3.1. Model with uniform properties

The DFEM was run for 4 models with varying P-wave velocities: V_P = 4000 m/s, elastic and viscoelastic (Q = 50); V_P = 3000 m/s, Q = 50; V_P = 2500 m/s, Q = 20. The last model is representative of a reasonably weak material such as a surface oxide. Fig. 3 shows the transfer function, $T_X(f)$, for the X-direction motion at the crest of the highwall for the 4 models under consideration. The transfer functions are defined as $T_X(f) = M_X(f)/S(f)$, where $M_X(f)$ is the amplitude spectrum of the DFEM X-component waveform (using either MB or MEM) and $S(f)$ is the source amplitude function as defined by Eq. (1). A detailed investigation of these transfer functions showed that there was practically no difference between MEM and MB estimations, and thus all transfer functions presented are obtained using the MB technique. The results of Fig. 3 demonstrate that the resonances at the crest of the highwall are not dominant, even for the elastic case. Fig. 3 also illustrates the following: the highwall crest resonances do not occur at uniform