Seismic waveforms from explosive sources located in boreholes and initiated in different directions

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A B S T R A C T

A study of the effect of explosive source orientation in a borehole on the nature of emanating seismic waves was made. High frequency triaxial accelerometers mounted on the surface and in boreholes in underground mines were the diagnostic sensors. A variety of explosive sources initiated with the detonation reaction propagating towards the detector and away from the detector were studied in highly competent rock. The results show significant differences in both the amplitude and the frequency spectra of the signal for the two modes. The respective azimuthal distribution of P and S wave amplitudes from propagating linear sources are also found to be at variance with those predicted by existing theoretical approaches.

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1. Introduction

In blasting the processes of rock breakage and blast induced damage are direct consequences of the dynamic loading of the borehole by the explosive detonation and expanding gases. Proper blast design and control requires characterization of both the loading source and its action on the rock mass. The study of wave propagation from blasting not only permits the analysis of stresses induced by the shock wave itself, but also provides essential information on the loading conditions at the source. A key component in the study of rock excavation by blasting is the understanding of the propagation of waves in rock from a cylindrical source.

The theoretical study of wave propagation from a cylindrical source has been treated by several authors. The first analytical solution to this problem was provided by Heelan (1953) on the basis of linear elasticity. This solution, although approximate, has been found mathematically and physically well-founded and computationally inexpensive. It has also been adapted for a viscoelastic material through the introduction of complex wave velocities (Blair and Minchinton, 2006). An exact analytical (full-field) solution was developed by Meredith, 1990; Meredith et al., 1993; Tubman, 1984, and Tubman et al., 1984. A comprehensive summary of this solution can be found in Blair (2007).

The Heelan solution was found to produce results close to numerical and full-field solutions (Blair and Minchinton, 2006), albeit with approximations that limit its validity in the far-field and only for frequencies within certain limits (Blair, 2007). The solution was found to hold provided: Ωa<0.1 (frequency limitation), and Ωa/r/a>5 (far field limitation) where Ωa aω0/Vp is a dimensionless frequency, a is borehole radius, ω0 is the average angular frequency of the pressure function, Vp is the medium P-wave velocity, and r is the radial distance from the source to the observation point in cylindrical coordinates (i.e., horizontal distance). Both restrictions combined imply that the Heelan solution is not valid if r/a<50, irrespective of the frequency.

Regardless of the method to determine seismic radiation, the solution to the problem of uniform axial loading of a cylindrical cavity in a solid necessarily implies non-uniform wave propagation for varying angle between the direction of wave propagation and the cylinder axis. When applied to borehole blasting, this means that as the angle between the blasthole axis and the direction to the point of observation changes, so does the amplitude of body waves. In particular, in the linear elastic case, the theory predicts vertically polarized S-waves (or SV-waves) to be dominant for a wide range of angles, with peak amplitudes at 45° angles from the borehole axis. P-waves are dominant only for angles close to normal, with the maximum at 90°. The Heelan solution offers a simple, yet reliable (for certain range of distance and frequency, as indicated above) expressions to visualize the phenomenon. According to this solution, given a transient pressure function p(t) acting radially on the walls of a short cylindrical cavity in an infinite medium, the displacement field induced at an observation point located in the far field at a distance r from the source can be expressed as:

\[
\begin{bmatrix}
    u_P \\
    w_P
\end{bmatrix} = \begin{bmatrix}
    F_1(\phi) \frac{d}{dr} \left( \frac{p(t-r/V_P)}{r} \right) \frac{\sin \phi}{\phi} \\
    0
\end{bmatrix} \begin{bmatrix}
    1 \\
    0
\end{bmatrix}
\] (1)
Experimental studies of wave propagation from blasting in boreholes with explicit identification and analysis of P and S-waves are not extensive. Reported measurements of blast induced seismic waves are typically limited to the peak particle velocity (PPV) values without any waveform or wave type analysis. Among the few examples of more complete wave measurement and analysis is the work of White and Sengbush (1963). They conducted experiments in shale to determine relative amplitudes of P and S-waves from a cylindrical source, and compared their results with the Heelan model predictions. They found shear waves to be significantly higher than the theoretical approach due to a strong water-pulse effect in the blasthole. These measurements were limited to the far field, at distances over 90 m, in a medium with relatively low P and S-wave velocities (~2100 and 900 m/s, respectively).

Compression wave amplitude and rise time for a range of distances (~4.5 to 13 m) and angles (~60° to 60° from the horizontal plane) were studied by Starfield and Pugliese (1968) by using oriented strain gauges. They show experimentally that even relatively short charges induce cylindrical radiation, as opposed to spherical, as commonly assumed. The influence of charge length on amplitude and frequency of seismic signals was studied by Grant et al. (1987) by measuring seismic signals from blasting at 20 m distance with radially oriented accelerometers. Their results show trends of increasing amplitude and decreasing average frequency with increasing charge length. Although these two studies did not distinguish between P and S-waves, they provide interesting insights on seismic radiation and superposition of waves.

Vanbrabant et al. (2002) reported measurements of P and S-waves from underground blast experiments, conducted with triaxial geophones. Although their work shows full analysis of the wave types and provides useful comparisons with a strain-softening elasto-plastic model, the use of geophones to measure stress waves in the near field (distances from 5 to 15 m) with their limited frequency response, suggests that the results should be viewed with some caution, as higher frequency waves are likely to be represented poorly.

Finally, in the context of production blasting in mining, Trivino and Mohanty (2009) reported measurements of both single-hole and multiple-hole blasts in an underground mine by using high

\[
\begin{align*}
\frac{u_S}{w_S} &= \left[ \frac{F_2(\phi)}{F_1(\phi)} \frac{d}{dt}(p(t-r/V_S)) \right] \left[ \frac{\cos^2 \phi}{\sin \phi} \right] \\
F_1(\phi) &= \frac{\Delta}{4\pi u V_p} \left( 1 - 2\cos^2 \phi \frac{V_S^2}{V_p^2} \right) \\
F_2(\phi) &= \frac{\Delta}{4\pi u V_S} \sin 2\phi
\end{align*}
\]

where \( \Delta \) is the volume of the loaded cylindrical void, and \( \mu \) is shear modulus. The functions or coefficients \( F_1 \) and \( F_2 \) describe the angular variation of the peak amplitude of the radiated P and S-waves with the angle \( \phi \). Fig. 1 shows a polar plot of these two functions that represent the relative amplitudes of P and vertically polarized S-waves from a small cylindrical source that loads the cylinder wall uniformly and in a radial direction. No loading of the ends of the cylinder occurs.

Fig. 1. Relative P and SV-wave amplitudes for a cylindrical source with only radial pressure in an infinite elastic medium. The source is represented by a small cylindrical charge at the center of the coordinate system, with vertical axis of symmetry. Radii in the figure are proportional to \( F_1(\phi) \) (for P-waves) and \( F_2(\phi) \) (for S-waves) (after Heelan, 1953).

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**Fig. 2.** Distribution of boreholes at the surface test site. 45 and 75 mm boreholes are identified as B45 and B75 respectively. Blastholes are indicated by \( \bullet \) and the numbers immediately above the symbol denote position in firing sequence, depth range or mid-depth for long and short charges respectively, and charge weight.
amplitude and high frequency response accelerometers. P and S-waves from both single and multiple-hole blasts were identified and characterized in terms of amplitude and frequency. This work showed strong differences in wave amplitudes between direct and reverse initiation modes (i.e. detonation front in the explosive column propagating towards the observation point or away from it).

2. Experiments and instrumentation

Three test sites were used to carry out the experimental program: one surface test site and two underground mine sites. The surface test site was an open area with exposed granitic rock. The blast experiments were conducted in 45 and 75 mm diameter, 6 m long water-filled vertical boreholes. The specific test area contained 27 boreholes in an area of approximately 12 m². Fig. 2 shows a plan view of the test site indicating the relative location of boreholes as well as a general view of the test area.

Table 1

<table>
<thead>
<tr>
<th>Test site</th>
<th>Charge type</th>
<th>Explosive type</th>
<th>Borehole diameter</th>
<th>Explosive amount</th>
<th>Charge length</th>
<th>Coupling</th>
<th>Number of blasts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>Short</td>
<td>Emulsion</td>
<td>45 mm</td>
<td>0.1 kg</td>
<td>0.08 m</td>
<td>90%</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>75 mm</td>
<td>0.1 kg</td>
<td>0.02 m</td>
<td>90%</td>
<td>1</td>
</tr>
<tr>
<td>Long</td>
<td>Emulsion</td>
<td>45 mm</td>
<td>1.6 kg</td>
<td>2 m</td>
<td>67%</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Det. cord</td>
<td>45 mm</td>
<td>0.041 kg</td>
<td>2 m</td>
<td>16%</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Mine A</td>
<td>Short</td>
<td>Pentolite</td>
<td>60 mm</td>
<td>0.23 kg</td>
<td>0.13 m</td>
<td>77%</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Boosters*</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.45 kg</td>
<td>0.26 m</td>
<td>77%</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.68 kg</td>
<td>0.39 m</td>
<td>77%</td>
<td>1</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.91 kg</td>
<td>0.52 m</td>
<td>77%</td>
<td>7</td>
</tr>
<tr>
<td>Long</td>
<td>Emulsion</td>
<td>60 mm</td>
<td>0.56 kg</td>
<td>0.4 m</td>
<td>67%</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Det. cord</td>
<td>60 mm</td>
<td>0.44 kg</td>
<td>3 m</td>
<td>67%</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Mine B</td>
<td>Short</td>
<td>Water gel</td>
<td>114 mm</td>
<td>2 kg</td>
<td>0.2 m</td>
<td>-90%</td>
<td>2</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Long</td>
<td>Water gel</td>
<td>114 mm</td>
<td>34 kg</td>
<td>3.5 m</td>
<td>-90%</td>
<td>3</td>
</tr>
</tbody>
</table>

* Det. cord denotes PETN explosive, which has a much higher detonation pressure compared to other explosives. Pentolite boosters denote PETN/TNT.

The natural rock at this test site is a massive granite with few joints. Although the area used for the study is relatively flat, the surrounding rock surface is undulated, presenting variable elevations, and it is partly covered with layers of soil and vegetation. The water table existing in the area is approximately 2 m below the surface and all explosive detonations were carried out within the water-bearing rock.

The other two test sites are located in operating underground mines, in which several boreholes were drilled for the purpose of installing seismic instrumentation and conducting controlled blast experiments. Both test sites, including instrumentation, explosive charges and surrounding area are illustrated in Fig. 3. In the first mine (Fig. 3a), the blast monitoring program was executed between approximately 750 and 900 m below surface. The values of P and S-wave velocities typically obtained for the rock mass at this mine are around 6000 and 3400 m/s, respectively. The major rock units strike E-W and dip 60° to 70° to the north. In the second mine (Fig. 3b), blast experiments were executed between 2650 and 2680 m below surface. P and S-wave velocities at this site are typically 5900 and 3500 m/s, respectively.

Small-scale blast experiments in the natural rock mass were carried out to study propagation of stress waves in the near field. A total of 34 single-hole blasts (11 at the surface site, 18 at mine A, 5 at mine B) fired with both short (point-like) and extended (line) sources of explosive were monitored with high amplitude (up to 1000 g) triaxial wide frequency band (>54 kHz resonant frequency) accelerometer stations embedded in the rock. Analog and digital data acquisition systems with up to 32 high-frequency (>40 kHz) channels were used in the investigation.

Various explosive types were used for the experiments: emulsion, water gel, detonating cord, and pentolite (PETN/TNT) boosters. Details of the explosive charges used in all three test sites are shown in Table 1. In this table, as well as for later analysis and discussion, explosive charges are grouped by length in short and long charges, with the former being up to 0.5 m and the later from 2 m and longer. In all cases the blastholes were flooded with water, and no stemming or sealing material was used below or above the explosive. Also, all blasts were initiated with shock tube detonators. ‘Direct’ and ‘reverse’ priming methods (the former being the case of detonation front moving towards the point of observation, and the latter being the opposite) were employed to study their respective effects on the energy...
release and its vibration characteristics. At the surface test site and one of the mines (mine A), the explosive columns were formed by tapping cartridges next to each other in series, and lowering them by a cable into the blasthole. At the second mine (mine B), explosive cartridges were loaded by gravity into the blasthole with a plug at the bottom (i.e. the cartridges were dropped into the blasthole). The blast sequence in both mines was from the bottom up in each blasthole. In the surface test site the blast sequence is shown in Fig. 2. In all cases it is estimated that if any damage occurred in the proximity of any explosive charge caused by a previous blast in the sequence, the effect on the recorded seismic signals should be negligible.

The triaxial accelerometers had a maximum amplitude range of 100 g to 1000 g and a flat frequency range from 0.5 Hz to 12 kHz. In the underground mines the accelerometers were grouted in-hole, while at the surface test site they were spring mounted and carefully inserted into monitor holes parallel to the blasthole (with the exception of the accelerometers controlling the long charges of emulsion, which were mounted on the rock surface farther away from the test area, due to expected high vibration amplitudes). This allowed the recovery of the sensors for re-use after testing. In all cases, the orientation of each component of the triaxial sensors was known.

The spring mounting system (shown in Fig. 4) was specifically designed to mount the accelerometers in boreholes providing a strong attachment to the rock. They were made of stainless steel and were provided with a manual system to expand and contract once inserted into the borehole at depths up to 6 m. The effectiveness of the mounting system was tested in laboratory by comparing recorded vibration signals on excited granite blocks with surface mounted accelerometers. The results were satisfactory, as no significant differences were detected on the measurements.

### 3. Experimental results

The recorded vibration data is analyzed in terms of both particle acceleration and particle velocity. Acceleration data is converted to velocity through numerical integration. However, in such conversions, any DC drift in the acceleration record often adds significant error to particle velocity values. Thus, as is common practice, a numerical filter is applied during the integration process to eliminate this effect. In this case, a combination of sharp Butterworth high-pass filter (threshold typically 100 Hz or less) and a de-trending algorithm is applied to the data, so as to minimize the baseline shift over time. The peak particle velocity (PPV) values were found to be not significantly affected by this procedure, due to the relatively low energy content at low frequencies.

Acceleration and velocity time histories are referred to a spherical coordinate system with origin in the explosive charge, as shown in Fig. 5 (note that the Heelan model uses a different coordinate system). In this coordinate system, the P-wave is expected to be preferably along the \( r \) direction, whereas the SV-wave is expected to generate motion along the \( \theta \) direction. In the subsequent sections of this paper, the plane containing the borehole axis and the point of observation is referred as the \( r-\theta \) plane. Also, the relative location of an observation point with respect to the explosive charge is indicated by the radial distance (\( r \)), and azimuthal angle (\( \theta \)), as shown in Fig. 5. This angle \( \theta \) ranges from \( 0^\circ \) in the case of the sensor in the same direction as the detonation, to \( 180^\circ \) in the opposite direction. Thus, direct initiation mode corresponds to \( \theta<90^\circ \) and reverse mode to \( \theta>90^\circ \).

Fig. 6 shows typical traces (three components of acceleration) recorded from a single-hole blast, while Fig. 7 shows the integrated data (three components of velocity) from the same signals expressed in spherical coordinates \((r, \theta, \varphi)\), as indicated above.

The process of filtering to counteract the drift of signals over time is shown in Fig. 8. In practice, the filtering procedure is applied to both acceleration and velocity data; however, acceleration records remain virtually unaffected by the filter. The details of the filtering process are as follows: a) eliminate initial DC component (adjusts the “zero level” by subtracting the average amplitude before the arrival of the waves to the full trace); b) de-trend signal from linear trend (linear correction applied from the ‘first break’ to the end of the trace); c) apply zero-phase high-pass Butterworth filter (sharp filter to severely attenuate frequencies below a threshold (typically 100 Hz) while nearly unaffected those above it), and d) de-trend signal from multi-linear trend (multi-linear, i.e., continuous correction of multiple linear segments, applied from the ‘first break’ to the end of the trace).

Fig. 9 shows an example of the application of the filtering process on a velocity time history, including the corresponding amplitude spectra calculated by fast Fourier transform. The increasing drift...
over time of the unfiltered signal is clearly an artifact resulting from a small DC component in the acceleration record. Aside from the correction of this drift, it is clear that the overall shape of the signal in the time domain remains nearly unchanged after the application of the filter. In the frequency domain, significant attenuation of frequencies up to around 300 Hz is observed, even though the applied Butterworth filter has a much lower threshold (50 Hz in this case). This is mainly a consequence of the linear de-trending filter, and shows that the lower frequencies (<300 Hz) do not carry significant wave energy.

3.1. Control of wave arrival times

The initiation time for all control blasts was accurately recorded, allowing precise determination of arrival times of the seismic waves. Additionally, particle motion was analyzed for all recorded signals through stereographic projection and coordinates rotation (Trivino, 2012; Trivino and Mohanty, 2009). As a method of control for the identification of P and S-waves, their arrival times (first breaks) were plotted against the direct distance from source (point of initiation) to sensor for each test site, as shown in Fig. 10. These graphs show consistency of arrival times for both P and S-waves, which strongly supports their correct identification. The higher scatter observed for S-waves is attributed to the difficulties in picking the arrival time of these waves, mainly due to contamination by waves with earlier arrivals (P-wave and in some cases P-wave reflections).

The results for P and S-wave velocities for each test site are shown in the respective graphs in Fig. 10. The ranges of distances at each test site are: from 1 to 3.5 m for the surface test site, from 30 to 110 m for mine A, and from 14 to 30 m for mine B.

3.2. Amplitude of stress waves

Fig. 10 shows the combined results of PPA (peak particle acceleration) and PPV associated with both P and S-waves as a function of ‘scaled distance’ (i.e. distance/square root of explosive charge weight) for all three test sites. It shows that similar charges (i.e. charges of same length group, either short or long, and from the same test site) generally show clear trends of increasing PPA and PPV with decreasing scaled distance for both P and S-waves. Furthermore, despite the different rock and explosive types and various test conditions, the signals in all three test sites follow approximately the same trends. This similarity is particularly significant in the case of PPV and most noteworthy for short charges. This finding supports the consistency of the data, as all three test sites consisted of competent rock with similar P and S-wave velocities (from 5.9 to 6.2 km/s for P-waves and from 3.3 to 3.6 km/s for S-waves, as shown in Fig. 10). The results from detonating cord (labeled as PETN and represented by ‘square’ points in Fig. 11) and boosters (PETN/TNT, represented by ‘+’ points) indicate a trend of slightly higher amplitudes of P-waves compared to emulsion and water gel in terms of both PPA and PPV. This is directly attributed to the higher detonation pressures generated by the PETN and PETN/TNT charges (typically 50% higher for det. cord, and around 100% higher for pentolite boosters, with respect to emulsion). The difference is less significant in the case of S-waves, where the results from these explosives charges are similar for the short charges of emulsion and water gel.

Upon comparison between short and long charges (excluding PETN and PETN/TNT charges), it is also clear that long charges exhibit a lower trend in terms of PPA from both P and S-waves, and in terms of PPV from S-waves only. This difference is not so significant in terms of PPV from P-waves.
Even though the matching trend of PPV for long and short charge somehow validates the use of the square-root scaling law, it is important to keep in mind that blast induced seismic signals are the result of complex superposition of waves generated along the explosive column and by reflections and refractions along the travel path between the source and measurement location. Hence, the shape and amplitude of the signals for a given blast configuration and medium properties varies with the orientation of the source with respect to the observation point, not only due to the effect of the cylindrical loading (as shown in Fig. 1), but also due to the variations in arrival times of the different signals. This is further analyzed in Sections 3.5 and 3.6.

3.3. Frequency content of stress waves

The frequency content of the stress waves is calculated by applying a discrete fast Fourier transform to the recorded signals. In this work, the procedure is applied to the full trace of both acceleration and velocity time histories in the radial direction (or close to radial, when the three accelerometer components are not available). Although this necessarily implies that the frequency analysis is mostly influenced by P-waves, it was found that differences in average frequency between P and S-waves were not significant for the purpose of this work (see Trivino and Mohanty, 2009 for independent frequency analysis from both P and S-waves). Also, analysis executed over directions other than radial does not provide significant variations in the results. Additionally, analysis of a complete waveform (as opposed to using only a few cycles containing the peak amplitudes) was found to bring less bias to the results due to user criterion to choose the signals for analysis. For example, Fig. 12 shows the radial component of velocity from a single cartridge of emulsion and its respective amplitude spectrum.

In order to compare the frequency content of signals the analysis is carried out in terms of average frequency calculated according to the following expression:

\[
\bar{f} = \frac{\sum_{i} A(f_i) f_i}{\sum_{i} A(f_i)}
\]

where \(\bar{f}\) is the average frequency (Hz), \(f_i\) represents the individual frequencies in the spectrum (Hz), and \(A(f_i)\) is the amplitude associated with each frequency \(f_i\). In order to prevent noise from severely affecting the average frequency, only frequencies with amplitudes greater than 20% of the peak amplitude in the spectrum were considered.

Fig. 13 shows the average frequencies of the signals recorded at the three test sites in terms of acceleration and velocity. The results show average frequencies to be between 2 and 13 kHz in terms of acceleration and between 0.8 and 8 kHz in terms of velocity. The results from surface mounted sensors were excluded from this analysis, as these record lower frequencies because of their greater distance from the source, and also partly due to the presence of relatively fractured ground and weathering conditions near the free surface.

In this data the range of distances for a particular test site or blast type (long or short charges) seems to be relatively short to determine a reliable trend, given the large dispersion of results. However, the relatively lower average frequency for direct primed long charges, especially for PPV is to be noted, and an explanation for which is discussed in a later section.

3.4. P and S-waves from short charges

Fig. 14 shows the amplitude and orientation of P and S-waves for various blast experiments with relatively short charges of explosive (0.1 to 2 kg, 0.02 to 0.5 m long) executed at the three test sites. The lines plotted in each graph indicate the magnitude and orientations of the peak P and S-waves projected on the plane containing the blasthole axis and along the source-sensor direction. The mid points of these lines show the relative location of the sensor with respect to the source, with the blasthole axis being collinear with the vertical axis (labelled as Distance z) and the explosive being bottom initiated. The results presented here are in terms of particle velocity.

These figures show that for a range of distances and orientations, S-waves are usually smaller, but of amplitudes comparable to P-waves (S/P ratios usually higher than 0.5 but generally closer to 1). An exception to this is the case of very sharp angles between the blasthole and the source-sensor direction, where recorded S/P ratios are between
Fig. 10. P and S-wave velocities obtained for each test site.

Fig. 11. Peak particle acceleration (PPA) and Peak particle velocity (PPV) associated to P and S-waves as a function of scaled distance and mode of initiation of explosive column (i.e. direct vs. reverse initiation).
0.1 and 0.35 (Fig. 14c). The cases where no S-wave amplitudes are shown (Fig. 14a) are due to excessive noise in the signals to reliably identify S-waves, and do not necessarily indicate low amplitudes for these waves.

In contrast to the analytical prediction (e.g. Heelan model, Fig. 1), measured S/P ratios are never significantly greater than 1, even for angles close to 45°. The primary cause for this discrepancy is attributed to the presence of material attenuation or damping in real materials, which attenuates S-waves faster than P-waves and is not considered in the elastic models (Trivino et al., 2009). Also, at angles close to 90° (perpendicular to the blasthole) S-waves still exhibit amplitudes close to P-waves (Fig. 14a, b, c). This is also not in accord with analytical and numerical models (Trivino et al., 2009) which predict an S/P ratio equal to zero at 90° (i.e. no S-wave is generated in the direction perpendicular to the blasthole, see Fig. 1).

Two main reasons may explain this situation: first, heterogeneity, anisotropy and discontinuities within the rock mass may cause deviations of waves, all of which is not considered by the models with a non-fracturing homogeneous isotropic medium. Second, any small deviation of the direction source-sensor from the plane of loading (i.e. the plane perpendicular to the borehole axis at the point source) can lead to a significant change in the S/P ratio, given the rapid theoretical increase on this value for increasing or decreasing azimuth angle from 90°. Such deviations necessarily occur in practice, as the real explosive charges are not point sources (they are up to 0.4 m long, with a length to diameter ratio of 9) and due to errors of coordinates.

Finally, the orientation of peak P-wave motion is in most cases very close to the radial direction, as expected, however S-waves show peak orientations close to tangential motion (i.e. perpendicular to radial) only in some cases. This is attributable to noise present in the signals caused mostly by the P-wave coda.

3.5. P and S-waves from long charges

As the interaction of seismic waves depends on their spatial and temporal origin, the stress field generated from a blast depends on both the initiation method and the velocity of detonation, VOD. Hence, the effect of initiation mode on seismic signals was specifically studied in this investigation, with the purpose of providing experimental data to quantify its influence on the generated stress field. Fig. 15 shows...
3.6. Frequency content in direct and reverse initiation modes

In this analysis the data from the surface test site is excluded due to the effect of the near free surface (let us remember that the Heelan solution is for a source in an infinite medium with no boundaries whatsoever). Fig. 13 shows that direct primed mode tends to produce lower concentration of energy towards one particular frequency (~1 kHz), the reverse mode exhibits a more or less uniform distribution of peaks between 0 and 4 kHz, with an average of 2.2 kHz and a periodicity of around 0.4 kHz.

Similarly, Fig. 17 shows the case of 3 m column of emulsion in direct and reverse mode. Although in this case the average frequencies are similar (1.8 vs. 2 kHz), once again the direct mode shows a stronger concentration of energy towards the average frequency whereas in reverse mode at least 5 significant peaks are observed more or less periodically distributed between 0 and 5 kHz. Note, in both Figs. 16 and 17, the differences in amplitude scale (in both time and frequency domain) and, hence, the much higher energy of waves recorded in direct mode with respect to reverse mode.

The amplitude spectra corresponding to reverse mode (Figs. 16b and 17b) exhibit a clear oscillatory nature, which seems to be a consequence of the cancellation by destructive interference of certain frequencies. By using simple linear superposition of waves, it can be shown that in perfectly reverse mode (i.e. the observation point directly below the bottom initiated explosive column) certain frequencies are cancelled with a periodicity given by the following expression:

$$ f_R = \frac{1}{L} \left( \frac{1}{\sqrt{\rho V_p}} + \frac{1}{\sqrt{\rho V_D}} \right)^{-1} $$

A comparison of waveforms and frequency spectra in direct and reverse mode for 6 m columns of explosive recorded at one of the underground mines (mine A) is shown in Fig. 16. From the frequency spectra in this figure it is clear that there are significant differences on the distribution of frequencies between the two initiation modes. While the direct initiation mode shows a strong concentration of energy towards one particular frequency (~1 kHz), the reverse mode exhibits a more or less uniform distribution of peaks between 0 and 4 kHz, with an average of 2.2 kHz and a periodicity of around 0.4 kHz.

Fig. 14. Amplitude and orientation of P and S-wave (PPV) for short explosive charges, projected on the plane containing the borehole axis and the line joining the center of the explosive charge and the sensor. In each case the center of the charge is located at (0,0) and the borehole axis is collinear with the vertical axis. The length and orientation of the lines labeled as P and S represent the maximum amplitude of the respective waves and their orientation represents the direction of particle motion at the time of the peak.

the peak amplitudes of P and S-waves along various directions for several configurations of long charges of explosive (2 to 6 m long, with length to diameter ratios from 30 to 100). As in Fig. 14, the blastholes are vertical with the explosive center at the origin, and the arrows indicate the direction of ignition.

In all cases, it is observed that the peak amplitudes of waves in direct mode (sensor above center of explosive in these graphs) are larger than those in reverse mode (sensor below explosive center) at similar distances. This is true for both P and S-waves. Also, the direct/reverse ratio is observed to be greater for directions of observation closer to the borehole axis. These measurements support results of analytical and numerical models (Blair and Minchinton, 2006; Trivino et al., 2009), which predict higher amplitudes in direct initiation mode. These models use either linear (elastic model) or non-linear (viscoelastic model in fracturing medium) superposition of waves originated by small charges initiated sequentially along the explosive column. Linear elastic models however tend to significantly overestimate both S/P and direct/reverse ratios (Trivino et al., 2009; Vanbrabant et al., 2002).
where $L$ is the length of the explosive charge. In the case of the 6 and 3 m explosive columns with a $V_{OD} = 5300 \, \text{m/s}$ (measured) and $V_p = 6200 \, \text{m/s}$, the values of the frequency $f_R$ are approximately 475 and 950 Hz respectively. These values are remarkably close to the period-icity of the oscillation of the amplitude spectra shown in Figs. 16b and 17b, which supports the idea of wave superposition as valid to model the initiation of explosive charges with finite VOD. In a similar way, it is possible to show that the direct initiation mode also exhibits an oscillatory nature with periodic frequency given by:

$$
 f_D = L^{-1} \left( \frac{1}{V_{OD}} - \frac{1}{V_p} \right)^{-1}
$$

(7)

For the 6 and 3 m columns shown in Figs. 16a and 17a, and using the same values of VOD and $V_p$ indicated for the reverse mode, the periodic frequency $f_D$ equals 6000 and 12,000 Hz, respectively. A plausible explanation of the missing oscillations at these high frequencies, as shown in Fig. 17, would be that for the source–receiver distance in question, these frequencies are greatly attenuated naturally.

A third example corresponding to the surface test site at much closer distances (1.9 m from the explosive center) is shown in Fig. 18. Although the less significant differences between direct and reverse modes in this case, the qualitative differences in both time and frequency domain are the same as found from the measurements in mine A. While the direct mode shows significantly larger amplitudes, the reverse mode

Fig. 15. Amplitude and orientation of P and S-wave PPV for long explosive charges, projected on the plane containing the borehole axis and the line joining the center of the explosive charge and the sensor. Arrows indicate direction of explosive initiation.
exhibits a highly oscillatory nature in the frequency domain. The less significant differences in this case may be partly due to the shallower angles of measurement (35° and 145°), the higher explosive's VOD, and possibly due to the effect of the free surface, as the center of the explosive charge is only 4 m below surface.

The differences observed between direct and reverse mode, in terms of both amplitude and frequency content were found to be to a great extent due to the superposition of waves originating along the explosive column at varying time. These differences are mainly controlled by P-wave velocity, velocity of detonation VOD, and the shape of the in-hole pressure function (Trivino, 2012). In the examples shown, P-wave velocities are somewhat close to the explosive's VOD, leading in direct mode for example to a constructive superposition of P-waves generated along the blasthole. In contrast, in reverse mode the superposition of waves generated along the blasthole is likely to result in more destructive interference and hence, lower amplitudes are obtained.

4. Discussion

The Heelan solution and evidently all solutions for seismic radiation in an infinite space do not account for the presence of any boundaries or free surfaces. In contrast, the experiments presented here, particularly those at the surface test site, were carried out in proximity to such boundaries, providing an opportunity of interference with the direct ray-path signals, which are the target of the study. This potential issue was confronted by designing the experiments in such way that the effect of reflections on the recorded signals was minimized (with the only exception of the two measurements of long charges at the surface test site where the sensors were mounted on the rock surface). Upon evaluation of the potential influence of reflections on free surfaces (or at the boundary with back-filled stopes in the underground mines) it was found that for most recorded signals, P-wave reflections had arrival times beyond those of direct S-waves and the influence of these reflections was not significant. Only the experiments with 2 m detonating cord at the surface test site seem to have been affected by reflections on the free boundary. This may explain in part the observed deviations of S-wave particle motion from the theoretical (θ) direction (see Fig. 14a, b).

In mine B the proximity of tunnels and a back-filled stope also provided opportunity for reflections to interfere with the measurements, however, given that these boundaries were relatively small (for the distances travelled by signals) and non-planar, it is estimated that the noise caused by such reflections does not invalidate the recorded S-waves. Nonetheless, some contamination of signals should have occurred and hence recorded S-waves in this mine are somewhat less reliable than those in mine A.

The specific finding that the average frequency in direct mode is lower than in reverse mode may be thought as counterintuitive. Generally speaking, when a source emitting a steady signal is in relative motion towards an observation point, the observer perceives a signal of higher frequency than the one being emitted due to the Doppler effect. In the opposite case, i.e. when the observation point and source are moving relatively away from each other, the signal observed is of lower frequency than the one being emitted. Hence, if an explosion in direct mode is thought of being similar to the case of the source moving towards the observation point, it would be reasonable to expect higher frequencies. This however is not the case with the measured signals, for lower average frequencies are generally obtained from experimental data. This discrepancy is neither a failure of the Doppler theory nor an error in our measurements or analysis. It is simply due to the fact that the detonation of an explosive column is not equivalent to a...
moving source emitting a steady signal, resulting from a difference of phase between the two cases. While the phase of the explosive source is constant at any point along the explosive column at the time the detonating front reaches that point, the phase of a moving source changes as the source advances.

The reduction in average frequency observed from direct initiation mode blasts may be partly explained as a result of superposition of waves emitted along the explosive column (i.e. from ‘small’ cylindrical charges). This superposition modifies the amplitude associated with all frequencies in the spectrum, and tends to enhance lower frequencies while causing destructive superposition at discrete frequency intervals. These frequency intervals are clearly seen in amplitude spectra recorded in reverse initiation mode.

5. Conclusions

Significant variations from trend in terms of amplitude and frequency are found from measurements of wave propagation from blasting in relatively homogeneous media. Even though models of seismic radiation from a cylindrical source partly explain differences in amplitude of both P and S-waves for varying orientation of the explosive charge with respect to the observation point, major part of the scatter is found to be associated with the in-hole initiation mode and the relative location of the observation point with respect to the source. These findings support the analytical and numerical models that use superposition of waves, which predict results consistent (although not necessarily accurate) with those found here. Variations in both amplitude and frequency content of waves seem to be the consequence of the added contribution of the explosive along the column, which is initiated at a finite VOD.

Fig. 17. Radial components of velocity and their amplitude spectra for 3 m long columns of explosive (mine A, blasts correspond to Fig. 15c). a) Direct mode, 4.4 kg of emulsion, \( r = 62 \text{ m } \theta = 10^\circ \). b) Reverse mode, 4.4 kg of emulsion, \( r = 50 \text{ m } \theta = 167^\circ \).

The measurement of P-waves from 6 m explosive columns in direct and reverse modes, for example, yields a direct/reverse ratio (i.e. the ratio between amplitudes in direct and reverse initiation mode) of over 4 in terms of PPV. The same experiments showed a reduction in average frequency for both cases with respect to short charges, while long charges in direct mode showed the lowest average frequencies. Moreover, the shape of the amplitude spectra in direct and reverse modes was significantly different, with the former having a clear concentration towards one particular frequency, while the later showed a spread out spectrum over a larger frequency range. Additionally, frequency spectra in reverse mode were found to show a pronounced oscillatory nature, which is a consequence of the cancellation of certain frequencies due to the added contribution of the explosive being detonated at finite velocity along the column (i.e. finite VOD).

Finally, the results presented in this paper are of essential significance on the investigation of mechanisms of rock breakage by blasting and the associated blast induced damage. The authors are currently working on the design and calibration of realistic models for the simulation of rock blasting. This work includes the proper study of stress waves generated by the explosive’s shock, as well as the gas expansion phase. The measured seismic signals, including the analysis of amplitude and frequency content, as well as the relative location of target points, amongst other variables, are fundamental for the calibration of such models. This broader study is intended to be applied for the estimation and control of overbreak by blasting in underground mines.

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References

Fig. 18. Radial components of velocity and their amplitude spectra for 2 m long columns of explosive (surface test site, blasts correspond to Fig. 15a). a) Direct mode, 0.04 kg det. cord, \( r = 1.9 \) m \( \theta = 35^\circ \). b) Reverse mode, 0.04 kg det. cord, \( r = 1.9 \) m \( \theta = 145^\circ \).