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MINESEIS - A MATLAB GUI PROGRAM TO CALCULATE SYNTHETIC
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MINESEIS—A MATLAB GUI PROGRAM TO CALCULATE SYNTHETIC SEISMOGRAMS FROM A LINEAR, MULTI-SHOT BLAST SOURCE MODEL

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Geophysics Group – EES-3, Los Alamos National Laboratory

Sponsored by U.S. Department of Energy
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ABSTRACT

Modeling ground motions from multi-shot, delay-fired mining blasts is important to the understanding of their source characteristics such as spectrum modulation. MineSeis is a MATLAB® (a computer language) Graphical User Interface (GUI) program developed for the effective modeling of these multi-shot mining explosions. The program provides a convenient and interactive tool for modeling studies.

Multi-shot, delay-fired mining blasts are modeled as the time-delayed linear superposition of identical single shot sources in the program. These single shots are in turn modeled as the combination of an isotropic explosion source and a spall source. Mueller and Murphy's (1971) model for underground nuclear explosions is used as the explosion source model. A modification of Anandakrishnan *et al.*'s (1997) spall model is developed as the spall source model. Delays both due to the delay-firing and due to the single-shot location differences are taken into account in calculating the time delays of the superposition. Both synthetic and observed single-shot seismograms can be used to construct the superpositions.

The program uses MATLAB GUI for input and output to facilitate user interaction with the program. With user provided source and path parameters, the program calculates and displays the source time functions, the single shot synthetic seismograms and the superimposed synthetic seismograms. In addition, the program provides tools so that the user can manipulate the results, such as filtering, zooming and creating hard copies.

Key Words: computer code, mining blasts, linear superposition

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OBJECTIVE

The objective of this study is to design and implement a modeling tool so that people can model the multi-shot, delay-fired mining explosions conveniently and in an interactive manner. A modification of the source model developed by Anandakrishnan *et al.* (1997) for the spall component of a cast-blast source is also proposed such that the source conserves momentum.

RESEARCH ACCOMPLISHED

Introduction

Because of their ability to trigger the future International Monitoring System (IMS) of the Comprehensive Test Ban Treaty (CTBT), large-scale, mining blasts are monitored and studied by verification seismologists for the purpose of discriminating them from possible clandestine nuclear tests. One important component of these studies is the modeling of ground motions from these blasts with theoretical and empirical source models. The modeling exercises provide physical bases to regional discriminants and help to explain the observed signal characteristics.

Since industrial chemical blasts of large enough magnitude to trigger the IMS are all multi-shot, delay-fired explosions, a convenient way to model them is to linearly superimpose individual shot sources in the shot array with corresponding time delays (Chapman *et al.*, 1992; Reamer *et al.*, 1992; Barker and McLaughlin, 1992). The superposition assumes a linear relationship between signals from individual shots. This linearity was experimentally validated for small chemical explosions (2.27 kg) with scaled source separation of 147 m/kt^{1/3} (Stump and Reinke, 1988).

The program MineSeis has been developed to implement the synthetic seismogram modeling of multi-shot blast sources with the linear superposition of single shot sources. Single-shot source model used in the modeling is the spherical explosion plus spall model proposed by Barker and McLaughlin (1992). Mueller and Murphy's (1971) model is used as the spherical explosion model. A modification of Anandakrishnan *et al.*'s (1997) spall model is developed for the spall component. The program is implemented with the MATLAB Graphical User Interface (GUI), providing the user with easy, interactive control of the calculation.

Formulation

The explosion model used in this program is Mueller and Murphy's (1971) source time function for isotropic explosion sources. In the frequency domain, the function is expressed as (Stump, 1985; Yang, 1997)

$$\bar{\psi}(\omega) = \frac{r_{el} v_p^2}{4\rho v_s^2} \frac{\left[\frac{(P_{0s} - P_{0c})k v_p / r_{el}}{(k v_p / r_{el})^2 + \omega^2} + P_{0c} \pi \delta(\omega) \right] - i \left[\frac{(P_{0s} - P_{0c})\omega}{(k v_p / r_{el})^2 + \omega^2} - \frac{P_{0c}}{\omega} \right]}{\left(\frac{v_p}{r_{el}} \right)^2 - \frac{1}{4} \left(\frac{v_p}{v_s} \right)^2 \omega^2 + i \frac{v_p}{r_{el}} \omega} \quad (1)$$

where

- v_p = P wave velocity of source region medium
- v_s = S wave velocity of source region medium
- ρ = density of source region medium
- r_{el} = elastic radius of source
- P_{0s} = peak shock pressure at elastic radius
- P_{0c} = static pressure at elastic radius
- k = medium-dependant factor relating to pressure decay
- δ = Dirac delta function
- ω = angular frequency.

The inverse Fourier transform of Equation 1 (or the time function), $\psi(t)$, is called the reduced displacement potential (RDP). Its relationship with the source moment for a point source is

$$M(t) = 4\pi\rho v_p^2\psi(t) \quad (2).$$

To model the spall phenomenon in a cast blast, Barker *et al.* (1993) extended the force model of spall accompanying an underground explosion proposed by Day *et al.* (1983) to include 1) the effect of potential energy loss due to the falling of spalled material to the pit and 2) a horizontal term due to the horizontal mass movement. The expression of the vertical force f_z and horizontal force f_h of their spall model is

$$\begin{aligned} f_z &= f_{z1} + f_{z2} + f_{z3} \\ &= \{m_T V_{0z} \delta(t)\} - \\ &\quad - \{m_T g [H(t) - H(t - T_s)]\} + \\ &\quad + \{m_T V_{1z} \delta(t - T_s)\} \end{aligned} \quad (3a)$$

$$f_h = m_T V_h [\delta(t) - \delta(t - T_s)] \quad (3b)$$

where

- m_T = spalled mass
- V_{0z} = vertical escape velocity of spalled mass
- V_{1z} = vertical impact velocity of spalled mass
- V_h = horizontal velocity of spalled mass
- T_s = dwell time
- $\delta(t)$ = Dirac delta function
- $H(t)$ = Heaviside step function.

According to ballistic dynamics, $V_{1z} = (V_{0z}^2 + 2h_{ff}g)^{1/2}$ and $T_s = (V_{0z} + V_{1z})/g$. h_{ff} is the final vertical position change of the spalled material. Although there is kinetic energy change in the system, the model conserves momentum.

In real situations, the spall initiation and impact are smoother than delta like. A smoothed version of this source model with finite spall rise and spall impact pulses of equal widths is

$$\begin{aligned} f_z &= f_{z1} + f_{z2} + f_{z3} \\ &= \left\{ m_T V_{0z} \left[\frac{30t^4}{T_{sr}^5} - \frac{60t^3}{T_{sr}^4} + \frac{30t^2}{T_{sr}^3} \right] [H(t) - H(t - T_{sr})] \right\} - \\ &\quad - \left\{ m_T g \left[\left[\frac{6t^5}{T_{sr}^5} - \frac{15t^4}{T_{sr}^4} + \frac{10t^3}{T_{sr}^3} \right] [H(t) - H(t - T_{sr})] + [H(t - T_{sr}) - H(t - T_s)] + \right. \right. \\ &\quad \left. \left. + \left[1 - \left(\frac{6(t - T_s)^5}{T_{sr}^5} - \frac{15(t - T_s)^4}{T_{sr}^4} + \frac{10(t - T_s)^3}{T_{sr}^3} \right) \right] [H(t - T_s) - H(t - T_s - T_{sr})] \right] \right\} + \\ &\quad + \left\{ m_T V_{1z} \left[\frac{30(t - T_s)^4}{T_{sr}^5} - \frac{60(t - T_s)^3}{T_{sr}^4} + \frac{30(t - T_s)^2}{T_{sr}^3} \right] [H(t - T_s) - H(t - T_s - T_{sr})] \right\} \end{aligned} \quad (4a)$$

$$\begin{aligned} f_h &= f_{h1} + f_{h2} \\ &= \left\{ m_T V_h \left[\frac{30t^4}{T_{sr}^5} - \frac{60t^3}{T_{sr}^4} + \frac{30t^2}{T_{sr}^3} \right] [H(t) - H(t - T_{sr})] \right\} - \\ &\quad - \left\{ m_T V_h \left[\frac{30(t - T_s)^4}{T_{sr}^5} - \frac{60(t - T_s)^3}{T_{sr}^4} + \frac{30(t - T_s)^2}{T_{sr}^3} \right] [H(t - T_s) - H(t - T_s - T_{sr})] \right\} \end{aligned} \quad (4b)$$

where T_{sr} is the rise or impact pulse width and $T_{sr} \leq T_s$.

The source process of a cast blast could be more complex with sub-processes such as material bulking and void collapse upon impact. These complexities can be accounted for to some degree by a spall model with the impact pulse width wider than the rise pulse width. If we desire a smoothed spall model with independent rise and impact pulse widths, a model that conserves momentum is

$$\begin{aligned}
 f_z &= f_{z1} + f_{z2} + f_{z3} \\
 &= \left\{ m_T V_{0z} \left(\frac{30t^4}{T_{sr}^5} - \frac{60t^3}{T_{sr}^4} + \frac{30t^2}{T_{sr}^3} \right) [H(t) - H(t - T_{sr})] \right\} - \\
 &\quad - \left\{ m_T g \left[\left(\frac{6t^5}{T_{sr}^5} - \frac{15t^4}{T_{sr}^4} + \frac{10t^3}{T_{sr}^3} \right) [H(t) - H(t - T_{sr})] + [H(t - T_{sr}) - H(t - T'_s)] + \right. \right. \\
 &\quad \left. \left. + 1 - \left(\frac{6(t - T'_s)^5}{T_{sf}^5} - \frac{15(t - T'_s)^4}{T_{sf}^4} + \frac{10(t - T'_s)^3}{T_{sf}^3} \right) \right] [(H(t - T'_s) - H(t - T'_s - T_{sf}))] \right\} + \\
 &\quad + \left\{ m_T V_{1z} \left[\frac{30(t - T'_s)^4}{T_{sf}^5} - \frac{60(t - T'_s)^3}{T_{sf}^4} + \frac{30(t - T'_s)^2}{T_{sf}^3} \right] [H(t - T'_s) - H(t - T'_s - T_{sf})] \right\}
 \end{aligned} \tag{5a}$$

$$\begin{aligned}
 f_h &= f_{h1} + f_{h2} \\
 &= \left\{ m_T V_h \left(\frac{30t^4}{T_{sr}^5} - \frac{60t^3}{T_{sr}^4} + \frac{30t^2}{T_{sr}^3} \right) [H(t) - H(t - T_{sr})] \right\} - \\
 &\quad - \left\{ m_T V_h \left[\frac{30(t - T'_s)^4}{T_{sf}^5} - \frac{60(t - T'_s)^3}{T_{sf}^4} + \frac{30(t - T'_s)^2}{T_{sf}^3} \right] [H(t - T'_s) - H(t - T'_s - T_{sf})] \right\}
 \end{aligned} \tag{5b}$$

where T_{sr} is the rise pulse width; T_{sf} is the impact pulse width, and $T_{sf} \geq T_{sr}$. $T'_s = T_s - (T_{sf} - T_{sr})/2 > 0$. The conditions $T_{sr} \leq T'_s$ and $T'_s > 0$ impose constraints on T_{sr} and T_{sf} . This model is a modification of Anandakrishnan *et al.*'s (1997) spall model.

A special case is when there is no horizontal spall and no vertical position change. In this case, $V_h = 0$; $V_{1z} = V_{0z}$, and the model can be used to model those blasts where there is no material cast, such as coal-bulking shots. Further, if $T_{sf} = T_{sr}$, the model simplifies to the spall model proposed by Stump (1985) for underground explosions.

According to Day and McLaughlin (1991), the force representation of spall $f_s(t)$ can be approximated by its moment tensor representation $M_s(t)$ as

$$f_s(t) = \rho h \frac{d^2}{dt^2} [M_s(t)] \tag{6}$$

where ρ is the medium density and h is the depth of the spall surface during an underground explosion. For the spall model of near-surface industrial blasts, Equation 6 is still valid if we treat h as the distance perpendicular to the spall surface. This distance is commonly referred to as "burden" in the mining industry.

In MineSeis, the single shots in a multi-shot blast are modeled as point sources with second-order source moment-tensor representations for both the explosion and the spall. For the isotropic explosion, the moment tensor is $M_e(t)\mathbf{I}$, where $\mathbf{I}$ is the identity second-order tensor and $M_e(t)$ is the source time function (Equation 2). The spall source consists of two components representing the vertical and horizontal movement of the cast material. From Equation (3.20) of Aki and Richards (1980), the moment tensor representation of the vertical spall is

$$M_{sz}(t) \begin{bmatrix} \lambda & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda + 2\mu \end{bmatrix} \quad (7a)$$

where λ and μ are Lamé constants. This representation is based on the assumption that the vertical spall can be modeled as a horizontal opening crack. Following Anandakrishnan *et al.* (1997), the horizontal spall moment tensor is

$$M_{sh}(t) \begin{bmatrix} \lambda + 2\mu \cos^2 \phi & 2\mu \sin \phi \cos \phi & 0 \\ 2\mu \sin \phi \cos \phi & \lambda + 2\mu \sin^2 \phi & 0 \\ 0 & 0 & \lambda \end{bmatrix} \quad (7b)$$

where ϕ is the angle between the direction of the horizontal movement of the cast material and x_1 (north). The angle is measured clockwise from x_1 . $M_{sz}(t)$ and $M_{sh}(t)$ are source time functions calculated with Equation 6 from f_z and f_h respectively. If there is no material cast, $M_{sh}(t) = 0$.

Single-shot synthetic seismograms are calculated from Canonical Green's functions. Because the program is designed to model regional and near-regional data, I assume that differences in Green's functions due to the source spatial finiteness can be neglected, thus use the same Green's functions for all the single shots in the blast. An alternative approach to obtain single-shot seismograms is to use recorded ground motions from a single, calibration shot.

In addition to the time delay of the firing sequence, the time delay due to the location differences of the single shots needs to be taken into account when single shot synthetics are superimposed. These source-spatial-finiteness introduced delays can be comparable to or even larger than the delays due to the delay-firing. Considering both delays, the superimposed signal is expressed as

$$U(t) = \sum_{i=1}^P A_i u(t - T_i - \tau_i) \quad (9)$$

where u is the single shot synthetics; P is the total number of shots in the blast; A_i is a scaling factor and T_i is the time delay between i^{th} shot and the reference shot (first shot) because of delay-firing. τ_i is the P -wave travel time difference between i^{th} shot and the reference shot due to their location difference and

$$\tau_i = \frac{r_0 \sin \chi}{v_{p0}} \left[\left(1 + \frac{r_i^2}{r_0^2} - \frac{2r_i \cos \zeta_i}{r_0} \right)^{1/2} - 1 \right] \quad (10)$$

where r_0 is the distance between the receiver and the reference shot; r_i is the distance between the i^{th} shot and the reference shot; ζ_i is the angle between the line connecting the i^{th} shot and the reference shot, and the line connecting the receiver and the reference shot; v_{p0} is the P -wave velocity of the source region medium and χ is the P -wave take-off angle (Figure 1). Since the term $\sin \chi / v_{p0}$ is the ray parameter for a planar layered velocity model, it can be replaced with the inverse of the P -wave velocity at depth (P_n). Here I assume that receivers are located beyond crossover distances, which is generally true for regional and near-regional observations. The parameters r_i and ζ_i in Equation 10 are calculated from the burden a and spacing b of the shots in the shot array with the assumption that the shot array has a simple, rectangular shape with parallel straight rows, equal burden for all shots and equal spacing between shots. More complex shot patterns, such as chevron shaped patterns, can not be modeled by the program.

Figure 1 Geometric relationships between the i^{th} shot, the reference shot and the receiver.

Implementation

The program was written with MATLAB Graphical User Interface (GUI) technique to facilitate user interaction with the program. MATLAB is a commercial computer language oriented toward technical computing and data visualization. The program consists of four main figure windows containing plotting panels, User Interface Controls (Uicontrols) and User Interface Menus (Uimenu). The first window (Figure 2) is for the viewing, filtering and printing of time series and their spectra resulting from different stages of the calculation. The other three windows (Figure 3) are for inputting source and path parameters and for calculating the source time functions, impulse superposition and synthetic seismograms. The user can input source parameters either by moving sliders or by typing in numbers. For source time functions, the up-dated results are plotted in the plot window every time any one of the source parameters is changed. It gives the user a visual idea of how the source parameters affect the source time function. In addition to being plotted on the screen, the results from each stage of the calculation can be filtered (if they are seismograms), saved to disk or printed as hard copies.

By default, the program uses frequency-domain superposition method in which time-delays in the time-domain transform to phase-terms in the frequency-domain. This method gives more accurate results since in the time-domain, it is almost always necessary to shift the time-delays to the nearest sampling data-points, which introduces error especially when sampling rates are low. Figure 4 gives such an example. In the upper panel is the superposition of impulses according to the delay pattern of a multi-shot blast. Individual shots have unit amplitudes. The sampling rate is 1000 sec^{-1} . Although there are time-shifts due to the discrete sampling, each impulse remains as an individual data point and no stacking of impulses occurred. When the sampling rate is reduced to 40 sec^{-1} (the lower panel), the time series becomes very different with some data points having amplitudes six times greater than what they should be. Figure 5 compares the spectral results of frequency-domain superposition and time-domain superposition with a sampling rate of 40 sec^{-1} . The radial component single-shot seismogram shown in Figure 1 was used for the superposition. Below 5 hertz, the two methods yielded virtually the same spectra. But as the frequency increases, differences begin to appear. Note the spurious spectral peak around 12 hertz in the time-domain superposition result due to delay shifting. It can also be seen from the lower panel in Figure 4.

There is a drawback with the frequency-domain superposition method. The method requires much longer computation time than the time-domain method when sampling rate is low. Nevertheless, if the user is interested in the high-frequency portion of the synthetics — in the example here, above $1/4$ of the Nyquist frequency — this is the price that has to be paid. The time-domain superposition method is provided as an alternative in the program.

Figure 2 Main plot panel with an example single-shot seismograms displayed.

Figure 3 Panels for parameter input.

Figure 4 Impulse superposition according to the time-delay of a multi-shot blast with different sampling rates.

Figure 5 Spectral comparison between frequency-domain and time-domain superposition methods.

MineSeis was programmed on a Sun Ultrasparc workstation and has been ported to PC and Macintosh platforms. A complete UNIX version package can be obtained from the Los Alamos National Laboratory Geophysics Group anonymous ftp site: www.geophysics.lanl.gov/pub/seismic. The name of the file is `mineseis1.1.tar.gz`. The tar-file contains a detailed report on the program including the program usage. Some sample data files are also included. The author can be contacted at xyang@lanl.gov for comments and/or for obtaining PC or Macintosh version package.

CONCLUSIONS AND RECOMMENDATIONS

Modeling industrial chemical blasts is an important tool in understanding their seismic characteristics. This MATLAB GUI program enables the user to model these blasts in a convenient and interactive manner. In addition to modeling mining blast, the program can also be used to study explosion and spall models, for example, examining the depth effect, source scaling, etc..

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