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Geometrical and Inhomogeneous Raypath Effects on the Characterization of Open-pit Seismicity

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ABSTRACT: Typical open-pit seismic monitoring applications attempt to assess the slip potential behind the rock face during a wall retreat. They employ sub-surface sensor arrays several hundreds of meters in size, localized within the respective wall, for which event locations can be obtained using a homogeneous wave velocity model. More recently, seismic technology is asked to provide a characterization of the seismicity associated with the entire pit. In case of a pit-wide seismic sensor array several kilometers wide, a reliable analysis requires that the mine geometry and the presence of geological strata be accounted for. The shortest 'visible' ray-path technique, originally employed in computer graphics, allows for the use of a homogeneous velocity model with appropriate corrections, thus widening the effective monitoring area and improving accuracy and reliability of event locations. The Fast Marching Method is proposed to resolve event locations using an arbitrary 3D velocity model derived based on the mine geometry and structural geology information. Interestingly, this technique provides a general framework to account for excavations or caves in locating seismicity occurred in underground mining applications.

1. INTRODUCTION

The most important task in monitoring mine seismicity is to provide fast, precise and robust location of seismic events. Event location consists of two steps, the forward solution – which calculates the expected propagation time of a particular seismic wave for a given source-receiver position, and the inversion – which minimizes the difference between the expected and observed data. The data are represented by first arrival times of P and S waves at different sensors. Wave propagation depends on the properties of the medium crossed, commonly represented as a simplified wave velocity model. There are two basic approaches for travel time estimation: ray-tracing and wave-front tracking. The former method uses high frequency ray approximation of the wave equation solution [1], while the latter employs various techniques to obtain a numerical solution of the eikonal equation [2, 3, 4].

In a mining environment, geological structures, the presence of naturally occurring cavities, as well as man-made excavations can be highly complex and require a general 3D velocity model that incorporates layers, blocks and voids, with large wave velocity gradients. With the increasing complexity in the velocity model, the evaluation of the forward solution will be more computationally time consuming, regardless of the specific algorithm employed. Worth noting, given the frequency bandwidth of the passive seismic monitoring, the choice of a homogeneous velocity model can be justified from a seismological point of view in case of underground applications, and is working reasonably well in practice. Based on this simplification, the forward solution is obtained at a minimum computational cost, which is essential for real-time monitoring.

In case of open-pit applications, however, the geometry of the free surface, which obviously is dictated by the actual stage of the mining operation, makes the attracted homogeneous velocity model assumption justifiable only for restricted volumes, which allow for source-sensor visibility. This imposes limitations on the overall efficiency of open-pit passive seismic monitoring applications. The present study focuses on several conceptual aspects. First, it proposes an approach to allow for the use of a homogeneous velocity model in the presence of complex open-pit geometry for the location of microseismic events. Second, the analysis considers the general case of an arbitrary 3D velocity model. This conceptual work can be applied to any specific mine.

2. HOMOGENEOUS VELOCITY MODEL AND SHORTEST 'VISIBLE' RAY-PATH

Under the heterogeneous velocity model assumption, the only element that needs to be considered in the implementation of a ray-tracing technique is the geometry of the open-pit mine. This geometry can be generically represented by the removal from the half-space of a sub-space equivalent in volume and shape to an inverse trunk of cone. Modern open-pit mining, however, acquires high precision information about the geometry of its operation. This includes a large amount of data for a detailed shape of the mining surface, which requires a need for an algorithm capable to allow for a fast and efficient use of this information for seismic monitoring purpose.

In the following we suggest an approach commonly employed in computer graphics. Before performing any ray tracing operation, the open-pit geometry is stored in uniform-level octtree, which allows for a fast traversing of the entire geometry in order to find the ray-surface intersection point [5]. The algorithm uses the Huygens–Fresnel principle [6] and searches for the shortest path that does not intersect but only touches the pit surface. It somewhat resembles to the finding of the so-called creeping wave [1].

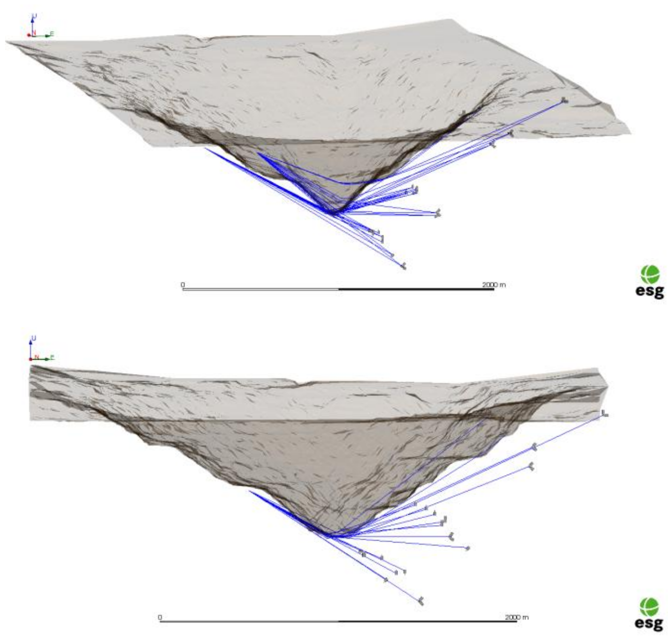


Fig. 1. Shortest path ray-tracing (blue lines) from three (top) and one (bottom) hypothetical seismic sources for an open-pit seismic monitoring array (see also [7]).

The combined use of the expected octtree structure ray-surface intersection and bisections allows for a fast computation of the first wave arrival times. In a sense, this approach includes elements of both the traditional ray-tracing shooting and bending. Figure 1 shows examples of such ray-tracing for hypothetical source locations.

Apart from illuminating areas previously completely hidden to the seismic monitoring array, this ray-tracing technique provides enhanced accuracy for some of the event locations reported earlier by avoiding erroneous straight ray forward solution for particular sensors that actually are not visible from the source. Note that such sensors were dropped out in earlier inversions, due to their high time residuals.

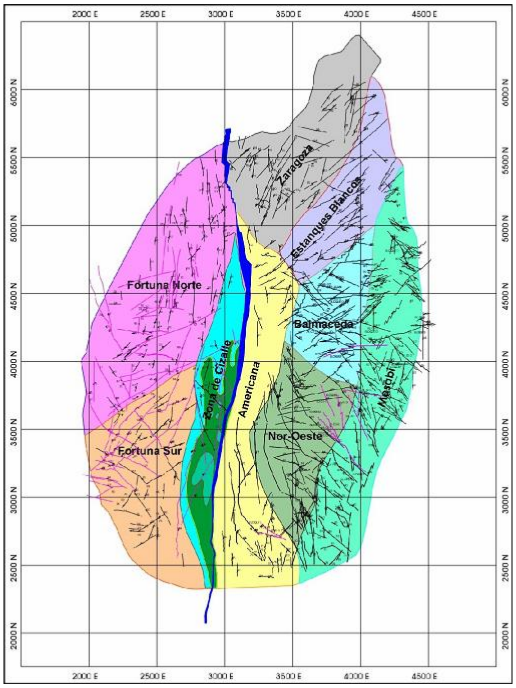
3. GENERAL 3D VELOCITY MODEL

For methodological purposes only, we attempt to mimic the 3D velocity model of an open-pit mine by deriving it from available geological information, as shown in Figure 2 [8]. This geological model includes several major subdivisions in plan-view, as well as in a west-east cross-section of the mine. Since our study is for testing purposes only, we assign different wave velocity values for various geological units, and use the cross-section as a guide on the geological unit distribution with depth, attempting to incorporate apparent sub-vertical trends (Figure 2b).

Algorithm implementation allows for and provides means to construct an arbitrary 3D grid velocity model that incorporates velocity interfaces of virtually any shape. As mentioned above, seismic wave travel time calculation for a 3D velocity model is possible based on either the ray approximation (ray-tracing) or wave-front reconstruction approach. Despite theoretical advancements in ray-tracing theory, its practical implementation still poses challenges. As such, both ray-tracing methods of shooting and bending have significant shortcomings when sharp contrasts in velocity are present, although the ray shooting method is preferable for its robustness [9, 10]. Analytical solutions for ray propagation exist only for a limited class of velocity models [1]. This implies that ray-tracing is going to generally be carried numerically, by solving step-by-step a system of differential ray equations using Runge-Kutta-like methods. Such methods though suffer from poor stability and are really time consuming.

A new approach to travel time calculation was pioneered by introducing a finite difference algorithm for the step-by-step integration of the wave-front propagation time along an expanding 2D square [2]. This approach was briefly discussed in [4], arguing that due to the fact that a simplified 2D square geometry usually differs from the shape of the first-arrival wave-front. Therefore, actual computed times may not be those of the first arrivals. This particularly happens in the case of a velocity model with sharp velocity contrasts. Interestingly, the above approach gave rise to a class of algorithms that overcome mentioned problems and it is still widely used.

(a)



(b)

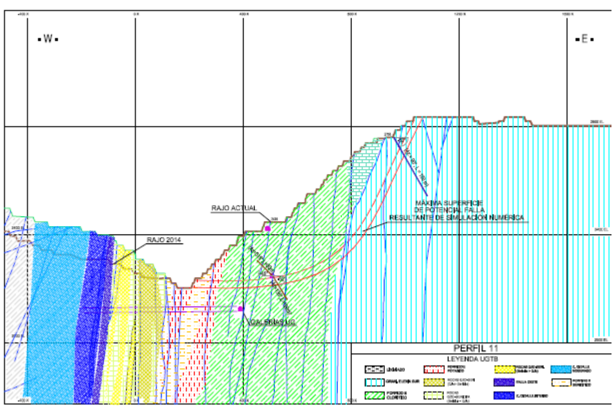


Fig. 2. Major geological subdivisions at Chuquicamata mine [7]: (a) north-east plan-view, and (b) west-east cross-section.

In the following, the evaluation of the forward solution for a 3D velocity model is carried out using the Fast Marching Method (FMM), which represents a novel approach to wave-front reconstruction proposed by [3]. FMM is an effective algorithm for the numerical solution of the eikonal equation

$$\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2 = \frac{1}{V(x,y,z)^2} \qquad (1)$$

where T is the travel time field at a point with (x, y, z) space coordinates, and V denotes velocity at this space point. FMM finds the "weak" entropy solution to the eq. 1, a solution that doesn`t need to be differentiable everywhere and at the same time it satisfies the integral formulation of the eikonal equation.

Basic implementation of the FMM uses first order upwind differential scheme

$$\begin{bmatrix} max(D_k^{-x}T, -D_k^{+x}T, 0)^2 + \\ max\left(D_k^{-y}T, -D_k^{+y}T, 0\right)^2 + \\ max(D_k^{-z}T, -D_k^{+z}T, 0)^2 \end{bmatrix}^{\frac{1}{2}} = V_k^{-1}, \qquad (2)$$

where k is the grid node index, T is the travel time field, V_k denotes the wave velocity at node k, and the forward and backward finite difference operators are defined as follows

$$D^{+x} = \frac{T(x+\delta x) - T(x)}{\delta x}$$
$$D^{-x} = \frac{T(x) - T(x-\delta x)}{\delta x} \qquad (3)$$

FMM evaluates the travel times in a downwind order from already known values upwind. Evaluation is done for a narrow band that represents advancing wave-front. Each grid node can be in one of three states: *alive*, *close*, or *far*. The first state denotes those nodes for which the travel time is already defined; the second state represents nodes in the narrow band with preliminary estimates of travel times, whereas the last state marks nodes for which the travel time is still unknown. The use of priority queue structure for the grid nodes in the narrow band provides the necessary acceleration for finding the node whose travel time is the smallest and thus to change its state from *close* to *alive*, or - in other words - to known. FMM guaranties a solution for the first wave-front arrivals.

The present FMM algorithm follows the ideas proposed by [4]. It provides a special treatment for the grid cells intersected by a velocity interface, and additional control of the advancing wave-front curvature. Figure 3 shows screen-shots generated by the eikonal solver for the open-pit example with a test 3D velocity model.

Apart from the graphical linear approximation of concentrically smooth isochrones, the only clearly visible change in the wave-front curvature is related to sharpest velocity contrast at the border of the granite formation (Figure 3a). Had the velocity model been real for this site, it could be an argument in favour of the heterogeneous velocity model employed above. Although running the FMM eikonal solver takes approximately 5 s for a 100 x 100 x 100 grid and one source location, it only needs to be done once for the site and the respective sensor array. Afterwards, the location algorithm uses the data from the grid file stored on the hard drive, by applying the source-sensor reciprocity principle. Experiments show that for a layered velocity model the use of direct ray-tracing calculation is only 3-4 times faster than that of the grid-time-field file obtained from the eikonal solver for the same site. Note that this ratio does not appear to depend on the grid size.

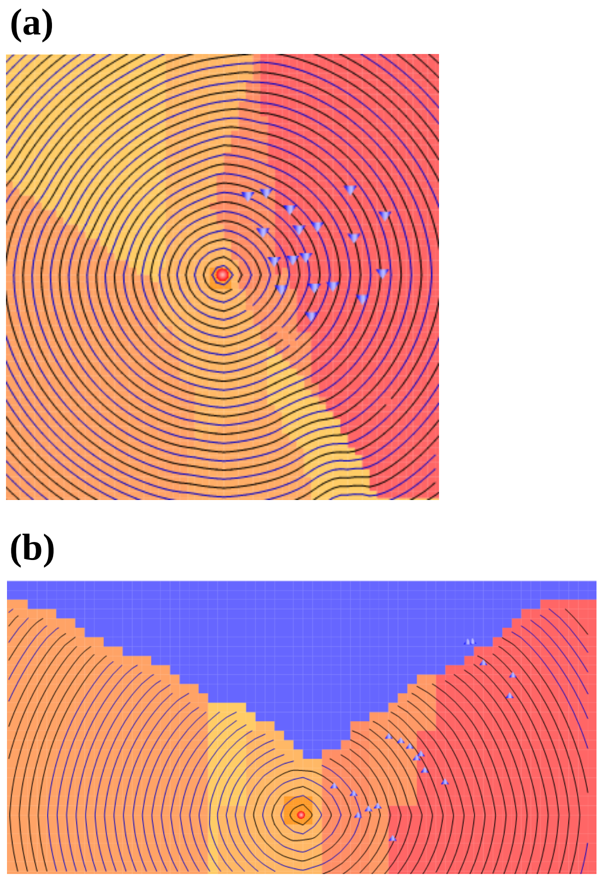


Fig. 3. Time field isochrones for a hypothetical seismic source represented by the central red circle: (a) north-east plan view, and (b) west-east cross-section. Both projections intersect the 3D space through the source. The small blue cones represent the projections on the corresponding plane of all the seismic sensors within the microseismic monitoring array. P-wave velocity distribution is color-coded from red to blue, where blue represents zero velocity in the pit, and red corresponds to 6000 m/s assigned for the granite formation.

4. CONCLUSIONS

The presence of complex geological structures, naturally occurring cavities, and man-made excavations in open-pit mining limits the use of a homogeneous velocity model in event locations. As detailed information about the site geometry becomes available, it opens the possibility for advanced microseismic data processing, taking advantage of recent developments in computer science and geophysics. Using recent advancements in computer graphics, the shortest 'visible' ray-path technique allows for the use of a homogeneous velocity model in open-pit applications, with appropriate corrections. Besides widening the effective area a particular seismic array configuration can monitor, it improves the accuracy and reliability of seismic events locations.

In order to further improve event locations for microseismicity associated with open-pit applications, an eikonal solver based on the Fast Marching Method is proposed. This algorithm is capable to resolve event locations using an arbitrary 3D velocity model derived based on the complex geological and structural information available nowadays for a mine site. Besides being capable to account for the open-pit geometry, this method provides a general framework to include large underground excavations or caves.

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