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Application of a moment tensor inversion code developed for mining-induced seismicity to fracture monitoring of civil engineering materials

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ABSTRACT

A moment tensor inversion (MTI) code originally developed to compute source mechanisms from mining-induced seismicity data is now being used in the laboratory in a civil engineering research environment. Quantitative seismology methods designed for geological environments are being tested with the aim of developing techniques to assess and monitor fracture processes in structural concrete members such as bridge girders. In this paper, we highlight aspects of the MTI_Toolbox programme that make it applicable to performing inversions on acoustic emission (AE) data recorded by networks of uniaxial sensors. The influence of the configuration of a seismic network on the conditioning of the least-squares system and subsequent moment tensor results for a real, 3-D network are compared to a hypothetical 2-D version of the same network. This comparative analysis is undertaken for different cases: for networks consisting entirely of triaxial or uniaxial sensors; for both P and S-waves, and for P-waves only. The aim is to guide the optimal design of sensor configurations where only uniaxial sensors can be installed. Finally, the findings of recent laboratory experiments where the MTI_Toolbox has been applied to a concrete beam test are presented and discussed.

1 . Introduction

Well-established seismology techniques are now being utilised in the civil/structural engineering environment, with concrete and rock as the propagating media. The focus of recent work is the analysis of acoustic emission (AE) waveform data recorded during load testing of concrete specimens in the laboratory. A comprehensive introduction to acoustic emission monitoring can be found in, e.g. Grosse and Ohtsu (2008). Qualitative techniques such as *b*-value analysis based on Gutenberg and Richter's original work (Gutenberg and Richter, 1949) have been paid particular attention to because they are relatively straightforward to implement (Carpinteri et al., 2009; Colombo et al., 2003; Kurz et al., 2006; Schumacher et al., 2011; Shiotani et al., 2000). Quantitative seismology techniques such as moment tensor inversion (MTI) are still being evaluated in the laboratory (Finck et al., 2003; Katsaga et al., 2007; Köppel, 2002; Ohtsu, 1991; Yuyama et al., 1999). For both approaches, the aim is to develop real-time tools to monitor fracture processes and assess the health of in-service structural concrete members such as bridge girders. The underlying assumption is that AEs produced from fracture processes in concrete are essentially the same phenomenon as earthquakes, albeit on different scales. The AE measurements supplement the mechanical test data and provide a wealth of information describing the progress of fracture in time and space, and also allow the mode of failure to be estimated. Once again, the starting point for the fracture mechanism quantification in concrete is in the laboratory.

In this paper we highlight aspects of a MTI code, named MTI_Toolbox and developed by Andersen (2001) for mining seismology applications, that make it applicable to civil engineering problems where a relatively small number of uniaxial sensors (when compared with in-mine systems) is utilised. The influence of the network configuration on the conditioning of the least-squares system of equations and resulting moment tensors is tested for 3-D and 2-D network layouts. The tests are performed on theoretical amplitudes and polarity data, for P and/or S-waves of a specified moment tensor source, calculated for uniaxial and triaxial sensor orientations. The theoretical data is inverted using an absolute, single event MTI method coded in the MTI_Toolbox. The conditioning of the system is compared for the different cases. The events are then grouped into spatial clusters and a hybrid MTI method applied, which is designed to reduce the impact of outliers (Andersen, 2001). Finally, the findings of a recent laboratory experiment where the MTI_Toolbox was applied to AE from a concrete beam test are summarised.

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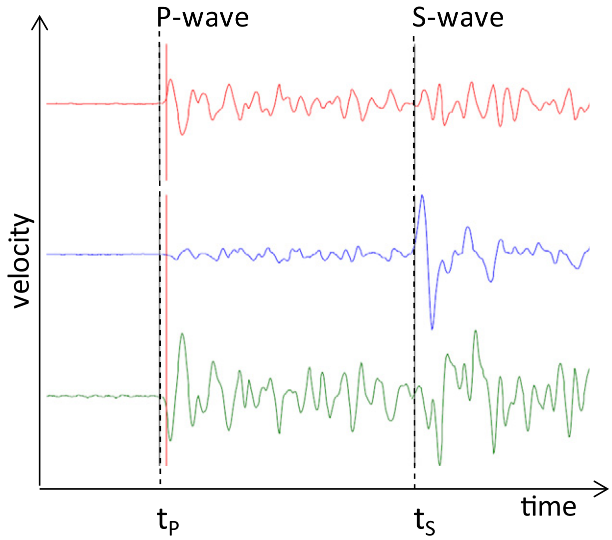

Fig. 1. Example seismograms recorded by an underground triaxial sensor showing distinct P- and S-wave arrivals (from Andersen, 2001).

2 . Background

Quantitative seismology techniques are valuable as they allow fracture positions and failure mechanisms to be remotely estimated as the laboratory test progresses. Such techniques include event location estimation methods (Geiger, 1910), source mechanism analysis through MTI (Aki and Richards, 2002), etc. There are numerous examples of different MTI methods applied to mining-induced seismicity (e.g., Andersen, 2001; Brawn, 1989; Collins et al., 2002; Goldbach et al., 2008; McGarr, 1992; Trifu and Shumila, 2010; Urbancic et al., 1996; Wiejacz, 1991). Many of these studies use triaxial data since rotation into P–SV–SH serves as a worthwhile data quality check.

In concrete mechanics, an absolute MTI approach was adapted and applied by Ohtsu (1991) for quantitative AE analysis of reinforced concrete structures. Ohtsu's simplified Green's functions for moment tensor analysis (SiGMA) software has been used by several researchers as the results are suited for analysis of fracture in concrete (Ohtsu and Shigeishi, 2003). The code has been popular because it is well suited for material fracture applications as it categorises the sources as tensile, shear, or mixed-mode. Grosse has achieved significant results using a relative MTI code by Dahm (1996). For example, the code was used to characterise AE events during a reinforcing bar pull-out experiment (Grosse et al., 1997). Köppel used the same code to characterise sources from his own pull-out tests as well as from a large-scale prestressed bridge girder test (Köppel and Grosse, 2000; Köppel and Vogel, 2000). Yuyama et al. (1999) applied MTI extensively to study the fracture mechanics of concrete beams strengthened with fibre reinforced polymer (FRP) sheets and reinforced concrete column foundations. The largest tests do date using MTI were performed by Katsaga et al. (2007) on deep reinforced concrete beams where the researchers made useful observations regarding the evolution of the ratio of tensile to shear-type events as failure of the specimen was approaching.

Over a decade ago, a moment tensor inversion (MTI) code was implemented to compute source mechanisms from mining-induced seismicity data (Andersen, 2001). The code, named MTI_Toolbox, was fairly extensively applied to mining research problems (e.g. Goldbach et al., 2008; Linzer et al., 2002; Miley et al., 2003). Six different MTI methods are coded in the MTI_Toolbox: a single event MTI method based on the far-field formulation given by Aki and Richards (2002); two relative methods based on Dahm (1996) and three hybrid methods developed by Andersen (2001). The relative and hybrid methods apply to spatial clusters of data and employ different schemes to evaluate and correct the path propagation described by the Green's functions. The cluster methods are based on the assumption of a common ray path between each event in the cluster and individual sensors. The relative methods use the concept of a common ray path to estimate the Green's functions of other events in the cluster, whereas the hybrid methods apply a relative weighting or correction factor to the input data to correct for focussing and defocussing of the ray path due to scattering.

The MTI_Toolbox was used quite extensively for mining research problems, an example of which is described by Goldbach et al. (2008). This study differs from the others due to the combined use of uniaxial and triaxial data; the use of the Doppler shift in frequencies to resolve ambiguity in the fault plane solutions; the use of cluster weighting schemes (hybrid MTI); and, the rotation of radiation patterns and fault plane solutions into the plane of the reef to enable easier associations with the on-reef mining geometry. One paper that explicitly notes the use of uniaxial data for the MTI of induced sources is by Trifu and Shumila (2002). These authors use a time-domain approach, with the low frequency far-field

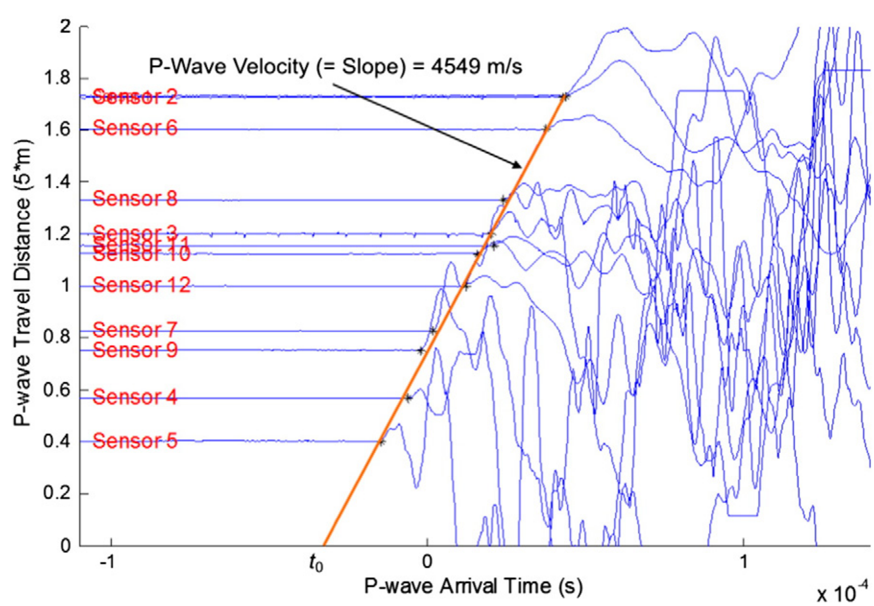

Fig. 2. Example AE waveforms from concrete fracture recorded by uniaxial sensors showing P-wave arrival times. The '*' denotes the picked P-wave arrival time using an autoregressive picker based on the AKAIKE Information Criterion (Kurz et al., 2005). The estimated event time is denoted by t_0.