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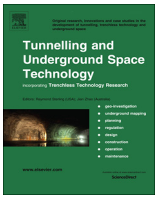

Sectional velocity model for microseismic source location in tunnels

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ABSTRACT

Microseismic (MS) source location is the foundation of MS monitoring and warning. The accuracy of MS source location depends on the accuracy of the velocities used in the location algorithm. In this work, a suitable sectional velocity model for MS source location in tunnels is proposed. In the model, the velocities from the MS source to the MS sensors in any one group are almost the same but those to different groups of MS sensors may be different. An efficient global optimization algorithm (particle swarm optimization) is applied to search for the MS source location and sectional velocity. Results from a tunnel simulation show that the velocities obtained using the sectional velocity model are close to the actual ones and location accuracy is greatly improved. The average location error is reduced by 78.3% (from 13.05 to 2.83 m). The proposed model was applied to MS source location in the deeply-buried tunnels of the Jinping II hydropower station in China. The case shows that the sectional velocities obtained are in accordance with the geological conditions. The locations of rockburst and MS events in the rockburst development process are clustered in the actual rockburst area. The method is good for rockburst monitoring and warning in the tunnels. In addition, the impact of error in the velocity on MS source location accuracy in tunnels is discussed. In tunnels, error in velocity is found to have a great impact on MS source location accuracy.

1. Introduction

Microseismic (MS) monitoring techniques involving three-dimensional monitoring of seismic events through microcracking in rock have been widely used around the world for many years to monitor rockmass stability — with different degrees of success. Nowadays, the technology is frequently used in tunnel engineering (Martin, 1997; Stephen and Young, 1998; Milev et al., 2001; Hirata et al., 2007; Feng et al., 2012; Feng et al., 2013a,b). A particular example is in the deeply-buried tunnels of the Jinping II hydropower station in Sichuan Province, China. The tunnels of this hydropower station have a maximum burial depth of 2525 m. Rockbursts occurred frequently during the excavation of the tunnels, which caused serious casualties and economic loss (Shan and Yan, 2010; Zhang et al., 2012). For example, on 28 November 2009, an extremely intense rockburst occurred in the drainage tunnel during excavation which caused seven deaths and one injury as well as the total destruction of a tunnel boring machine. Therefore, a high-performance integrated seismic system was adopted in the tunnels for rockburst monitoring and warning in order to reduce the rockburst risk and ensure construction safety.

The location of an MS event is assumed to be the point within an MS source that triggers a set of MS sensors used to locate it. MS source location is the foundation of MS monitoring. A reasonably accurate location is important for many reasons (Mendecki, 1997), such as:

- To indicate the location of potential rockbursts;
- all subsequent seismological processing (e.g. seismic source parameters and attenuation or velocity inversion) depends on such locations;
- all subsequent interpretation of individual events depends on the locations (e.g. events far from the mining activity, close to a shaft, or, more generally, in places not subject to numerical modeling, may raise concern);
- all subsequent interpretation of seismicity (e.g. clustering and specific localization around planes, migration, spatio-temporal gradients of seismic parameters, and other patterns) are judged by their locations and timing.

In MS monitoring, therefore, we should try to ensure the accuracy of MS source location and reduce the influence various factors have on the accuracy of MS event location. Studies have shown that the accuracy of the velocity used in the location algorithm has a serious impact on the accuracy of MS source location (Ge

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and Mottahed, 1994; Mendecki, 1997; Stephen et al., 2003; Wang and Ge, 2008). Thus, when the wave velocity of rockmass used differs from the actual one, an error arises in MS source location. A rockmass is inhomogeneous, discontinuous and contains many structural planes. Even if the vibration signal travels in a single stratum, the velocity will be different in different directions and areas. For this reason, an anisotropic velocity model should be adopted for MS source location (Nelson and John, 1990; Smith and Ekstrom, 1996; Aki, 1977; Maxwell and Young, 1993; Mooney et al., 1998; Irina, 2009). An anisotropic velocity model acknowledges that the propagation velocity of the vibration signal from the MS source to each MS sensor may be different. However, it is difficult to obtain accurate rockmass velocities in all directions through field tests. It also requires a lot of manpower and material resources. Moreover, such field tests need constant updating because rockmass velocities change in different areas. Crosson (1976) was the first to propose the location method referred to as 'simultaneous least-squares estimation of hypocenter and velocity parameters' (SSH). The method takes the velocity as an unknown parameter and inverts the velocity, source location, and seismogenic time simultaneously. The errors induced by using the velocity of man-made vibrations in the location can be avoided by this method. The SSH method does not need any input velocities, but much information about the velocity structure can be obtained. Therefore, it has been widely used. However, MS source location, velocity, and seismogenic time are related to each other. Also, if there are too many unknowns in the system, the solution to the MS source location equations becomes unstable (Chen et al., 2009). There are, inevitably, a lot of unknowns involved when an anisotropic velocity model is used, so the problem is hard to solve and it is difficult to obtain the MS source location accurately. Therefore, a simplified single-velocity model is often used in seismic source location (Douglas, 1976; Lee and Lahr, 1975; Tian and Chen, 2002; Chen et al., 2009). The single-velocity model assumes that the propagation velocity of the vibration signal from the MS source to each sensor is the same. As the single-velocity model is concise, it has been widely used in many areas for seismic source location, e.g. earthquake location, and mining and oil reservoir development. However, the simplified single velocity used is different from the actual one. This will lead to some errors in the MS source location and the location accuracy will be reduced.

The quality of a velocity model mainly depends on: (1) whether or not it properly expresses the rockmass properties and the wave propagation path, and (2) whether or not it is concise and good for finding the MS source location. In order to improve the precision of MS source location in tunnels, after an analysis of the MS signal propagation characteristics in tunnels, a suitable velocity model is proposed in this paper for MS source location in tunnels. This is referred to as the 'sectional velocity model'. As there are a lot of unknowns involved, it is easy to become locked in a local minimum value during the optimization process. Therefore, an efficient global optimization algorithm, particle swarm optimization (PSO), is used to search for the MS source location and sectional velocities. Sectional velocity is constantly updated dynamically as tunnel excavation proceeds and the MS sensors move. The sectional velocity model is subsequently applied to the deeply-buried tunnels of the Jinping II hydropower station for MS source location. In addition, the impact of velocity error on MS source location accuracy is discussed.

2. Sectional velocity model in tunnels

2.1. Sectional velocity model

The basic engineering and MS monitoring situation in a tunnel is shown in Fig. 1. Due to the limited space, personnel, and safety equipment available, MS sensors are laid out behind the working face in distributed groups (Feng et al., 2013a,b; Chen et al., 2013). MS sensors which are close to each other in the axial direction along the tunnel are regarded as a group (see Fig. 1). The qth group of sensors are denoted by $S_{q1}, \ldots, S_{qn_q}$. The main MS sources during excavation of the tunnel occur around the working face (Zhao et al., 2013), as shown in Fig. 1 where the MS source is labeled as O. The number q is used to label the group of MS sensors. The number of sensors in group u ($u = 1, 2, \ldots, q$) is n_u. The name of the wth MS sensor in group u is therefore S_{uw}. The velocities of the P-wave and S-wave from the MS source to the MS sensor S_{uw} are V^P_{uw} and V^S_{uw}, respectively.

An anisotropic velocity model fully expresses the inhomogeneous and discontinuity of the rockmass. There is no constraint relationship among the velocities. The single-velocity model greatly simplifies the velocity structure and assumes that the velocity from the MS source to each MS sensor is the same. However, the geological conditions in different sections of a tunnel are not the same. So, the propagation paths and velocities from the MS source to each MS sensor are also different. For example, in Fig. 1, the propagation sections of the vibrational signal from the source O to the first group of MS sensors and to the second group of MS sensors are clearly different. However, the propagation sections of the vibrational signal from the source O to the MS sensors in any one particular group are not significantly different. For example, the propagation sections of the vibration from the source O to the sensors in the first group are almost the same. Based on this idea, this paper proposes a sectional velocity model for MS source location in the tunnel. In this model, the velocities of the MS source vibration with respect to the sensors in any one group are almost the same, but to each group of MS sensors they may be different. To sum up, the various velocity models can be summarized as follow:

- Anisotropic velocity model: the velocities from the MS source to each MS sensor can be different. There is no constraint relationship among the velocities.

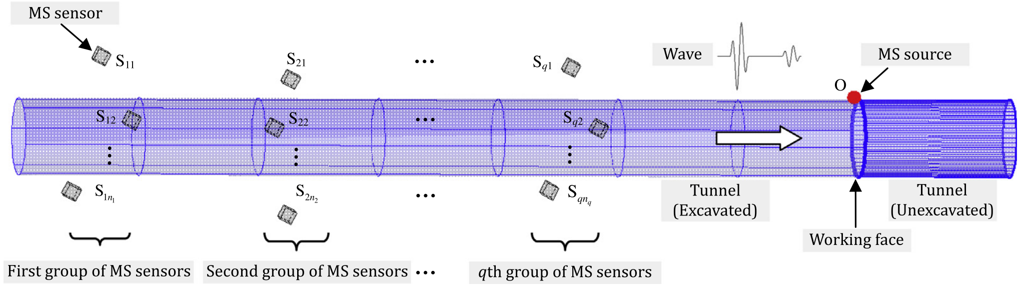

Fig. 1. Diagram showing MS monitoring in a tunnel.