Tunnelling and Underground Space Technology 63 (2017) 183–193

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Performance and feasibility analysis of two microseismic location methods used in tunnel engineering

Guang-Liang Feng, Xia-Ting Feng *, Bing-Rui Chen, Ya-Xun Xiao

State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China

ARTICLE INFO

Article history:
Received 8 May 2016
Received in revised form 11 January 2017
Accepted 13 January 2017

Keywords:
Rock mechanics
Microseismic source location
Particle swarm optimization
Rockburst event
Jinping II hydropower station

ABSTRACT

The location of microseismic (MS) sources is of fundamental importance in MS monitoring and risk warning. Location accuracy, efficiency and stability are affected by location methods heavily. In this paper, feasibility of two location methods (TDP&S and TDP-S methods) recently used in MS monitoring in tunnel is studied. An efficient global-optimization algorithm, particle swarm optimization (PSO), is introduced to analyze the performance (efficiency, accuracy and stability) of the two methods successfully in a tunnel engineering condition. Results obtained via numerical experimentation show that in a tunnel engineering condition the locations of MS sources with PSO algorithm could be accurately obtained using both the two location method. The relative location errors are mostly in 5.0%. The solution efficiency is greatly improved when using TDP-S location method (the average solution speed increase is 73.9%). And it is less sensitive to the MS source position. However, the TDP&S method is better when there are errors in arrival-times. We should dynamically choose the better location method according to the actual situation. The two methods should be used together to meet the engineering demand sometimes. The two location methods with PSO algorithm were used to find rockburst events in the deeply-buried tunnels of the Jinping II hydropower station in China. The results in this real engineering application agreed with the numerical experimentation results. These results will lay a foundation of the development of MS technique in tunnel engineering.

1. Introduction

Microseismic (MS) monitoring techniques involving three-dimensional monitoring of MS events due to microcracking in rocks have been used for monitoring MS risk for many years. The technology has already widely used in South Africa, Canada, Japan, Australia, North America, China et al. Significant achievements have been obtained in mines, tunnels, slopes, underground powerhouse, oil and gas exploration and electricity generation by hot dry rock (Mendecki, 1997; Tezuka and Niitsuma, 2000; Hong et al., 2006; Li et al., 2007; Trifu and Suorineni, 2009; Kaiser, 2009; Li, 2009; Feng et al., 2012, 2013; Feng et al., 2015a,b,c; Xu et al., 2015a,b, 2016; Lu et al., 2015; Ma et al., 2015, 2016; Dai et al., 2016, 2017).

MS source location is of great importance and forms the foundation of MS monitoring technology (Mendecki, 1997; Ge, 2005,2012; Feng et al., 2015c). The interpretation of microseismicity and warning of risks during MS-monitored engineering both depend on the results of MS source location. An accurate, quick and stable method of MS source location are the basic for MS events which can be used as a guide to indicate the likely locations of potential risks, and to control and reduce this risk. Research on MS source location has always been a subject of intense interest in the field of MS and seismic monitoring. The first major method used to locate earthquakes was based on geometrical drawing. Its history can be traced back to the time of the invention of the seismograph. In 1912, a source location method based on mathematical calculation was first proposed by the German physicist Geiger (1912). This is the so-called 'Geiger method', which manages to convert the original nonlinear location problem into a linear one. In the 1970s, with the rapid development and wide application of computer technology, the concept behind the Geiger method became widely used in earthquake location work. Subsequently, a large number of improved location methods were put forward and fully developed (Lee and Lahr, 1975; Klein, 1978; Lienert et al., 1986; Prugger and Gendzwill, 1988; Nelson and John, 1990). Tian and Chen (2002) reviewed the basic theories of various approaches to seismic location, especially the classic method attributed to Geiger and various linear methods based on it, i.e., the joint hypocenter determination, simultaneous structure and hypocenter determination, relative location technique, and

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* Corresponding author.
E-mail addresses: xtfeng@whrsm.ac.cn, xia.ting.feng@gmail.com (X.-T. Feng).

http://dx.doi.org/10.1016/j.tust.2017.01.006
0886-7798/

double-difference location algorithm. In addition, the location method in space and non-linear location methods are also been summarized.

Classical absolute methods for location of MS source are based on minimizing the residuals between the predicted and observed travel times from the source to the sensors. Two classical absolute methods for MS source location are used in MS monitoring in tunnel engineering recently. One is using the observed and theoretical travel-time differences of *P*-wave and also *S*-wave (TDP&S). The other is using observed and theoretical travel-time differences between *P*- and *S*-waves (TDP-S). The fundamental and equations of the two location methods are different. The first one uses the information of *P*- and *S*-waves separately and the latter one is based on the differences between *P*- and *S*-waves.

Errors in MS source location are inevitable because of a variety of practical reasons (Ge, 2012). The errors are usually acceptable and can meet the engineering demand. However, in tunnel engineering, due to the limited space, personnel, and safety equipment available, MS sensors have to laid out behind the working face of the tunnel. Therefore, the MS sources are always laid out the array of MS sensors. This is not good for MS source location. The location accuracy, efficiency and stability will be influenced heavily in the tunnel engineering condition. It leads that the two classical absolute methods used in tunnel engineering recently described above may be not acceptable and cannot meet the tunnel engineering demand. There is no reference discussing the two classical absolute methods in a tunnel engineering condition. And it is hard to find a tool or a suitable method to conduct the study. As the MS source location is of great importance, the feasibility and performance of these two methods need a deeply analysis in order to find out whether the methods can be used and which one is better in a tunnel engineering condition.

Therefore, in the paper, feasibility of the two classical absolute MS location methods is studied in a tunnel engineering condition. And a thorough comparison of the efficiency, stability and accuracy of the two methods in a tunnel engineering condition is made. An efficient, global optimization algorithm, particle swarm optimization (PSO), is introduced to make the study possible. Synthetic tests are conducted. In addition, rockburst events in a deeply-buried project (the Jinping II hydropower station in China) were further used to test the feasibility and performance. The results will lay a foundation of the application and development of MS technique in tunnel engineering.

2. Methodology

2.1. The TDP&S method

The coordinates of the MS source are denoted by (x_0, y_0, z_0) and the number of sensors is n. The coordinates of sensor S_i are represented by (x_i, y_i, z_i). The seismogenic time of the MS source is t_0. The triggered arrival times of the *P*- and *S*-waves at sensor S_i are t_i^P and t_i^S, respectively. The distance between the MS source and sensor S_i is R_i. The velocities of the *P*- and *S*-waves from the MS source to the sensor S_i are V^P and V^S, respectively. The TDP&S method is using the observed and theoretical travel-time differences of *P*- wave and also *S*-wave of every MS sensors. The target function can be expressed as

$$f = \sum_{i=1}^{n}\left(\left(t_i^P - t_0 - R_i/V^P\right)^m + \left(t_i^S - t_0 - R_i/V^S\right)^m\right). \tag{1}$$

In the expression, f is the time residual and m is the norm (generally taken to be 1 or 2 corresponding to whether a L1 or L2 norm approach is used). We use $m = 1$ in this paper. The formula for computing R_i is

$$R_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2}. \tag{2}$$

When the target function f attains its minimum value (equal to zero or tends to 0), the solutions obtained for (x_0, y_0, z_0), V^P and V^S are the optimum values for the MS source location and velocities, respectively.

2.2. The TDP-S method

For sensor S_i, the observed and theoretical travel-time differences between the *P*- and *S*-wave are noted as Δt_i^{obs} and Δt_i^{cal}, respectively, so that

$$\Delta t_i^{obs} = t_i^P - t_i^S, \tag{3}$$

$$\Delta t_i^{cal} = R_i/V_P - R_i/V_S. \tag{4}$$

Then the target function for MS source location based on the observed and theoretical travel-time differences between *P*- and *S*-waves is given by

$$f = \sum_{i=1}^{n}\left(\Delta t_i^{obs} - \Delta t_i^{cal}\right)^m, \tag{5}$$

and therefore,

$$f = \sum_{i=1}^{n}\left[t_i^P - t_i^S - R_i(1/V_P - 1/V_S)\right]^m. \tag{6}$$

If we take $V = 1/V_P - 1/V_S$ to be a constructed velocity, then Eq. (6) can be rewritten as

$$f = \sum_{i=1}^{n}\left(t_i^P - t_i^S - R_iV\right)^m. \tag{7}$$

When the target function f attains its minimum value (equal to zero or tends to 0), the solutions obtained for (x_0, y_0, z_0) and V are the optimum values for the MS source location and velocity, respectively.

2.3. Particle swarm optimization algorithm

As the number of unknowns is large (6 in target function Eq. (1) and 4 in Eq. (7)), the calculation may easily fall into a local optimal solution, producing inaccurate results. Therefore, it is necessary to choose a powerful global-search algorithm in order to accurately find the true solution. Particle swarm optimization (PSO) is an emerging and intelligent method of optimization (Kennedy and Eberhart, 1995). It is a powerful global optimization algorithm and has been successfully used in many areas. An introduction to PSO is given below (Kennedy and Eberhart, 1995; Feng et al., 2015c).

PSO can be visualized as idealized ‘feeding of a flock of birds’ in which the process of food location is embodied by the birds’ collective wisdom and the algorithm simulates the behavior of the flocking birds. In PSO, each single solution is a ‘bird’ in the search space (more formally referred to as a ‘particle’). All of the particles have fitness values that are calculated using the fitness function that is to be optimized; they also have velocities which direct the ‘flying’ of the birds (particles). The particles are ‘flown’ through the problem space by following the current optimum particles. PSO is initialized using a group of random particles (solutions) and then the algorithm iteratively searches for optima. The iteration time is called the ‘flying time’. In each iteration, every particle is updated by following two ‘best’ values. The first one is the best solution (fitness) it has achieved so far. The fitness value is also stored and referred to as ‘pbest’. The other ‘best’ value tracked by the particle swarm optimizer is the best value obtained so far by