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A Highly Accurate Method of Locating Microseismic Events Associated With Rockburst Development Processes in Tunnels

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ABSTRACT Rockbursts occur frequently and cause serious damage in deep tunnels. Microseismic (MS) source location is of great importance and forms the foundation of the MS monitoring technology used in tunnel rockburst hazard mechanism analysis. A highly accurate method for locating MS events that occur during rockburst development in tunnels is proposed here. An anisotropic velocity model, rockburst event monitor, and a global optimization algorithm (particle swarm optimization) are used in tandem to make the proposed method feasible and the location accuracy better. Simulation results show the MS sources can be located more accurately using the proposed method. The average location error is reduced by 20.16 m. Our method was used to locate MS events associated with rockburst development processes occurring in the deep tunnels of the Jinping II hydropower station in China. The location accuracy of the MS events in the rockburst development process is significantly improved. The case study shows that the located MS events are clustered together more closely in the rockburst area. The average distance of all the MS events to the position of the rockburst is reduced from 23.77 to 13.43 m. The method is highly conducive to in-depth analysis of rockburst development processes and investigation of their mechanisms of formation.

INDEX TERMS Tunnel, rockburst, microseismic monitoring, particle swarm optimization, Jinping II hydropower station.

I. INTRODUCTION

In numerous civil engineering projects, there has been an increasing need to construct deep, long and large tunnels. As the burial depth of the tunnel increases, rockbursts occur more frequently and cause serious numbers of casualties, mechanical damage, delays to projects, and economic losses. Many deeply-buried, civil tunnels in Switzerland, China, Pakistan and Peru have experienced rockbursts to various degrees [1], [2]. A rockburst is a catastrophic event triggered by a process of progressive failure of rocks. The phenomenon has been one of the biggest problems that urgently need to be solved to ensure safe construction in tunnels [3]–[7]. Research on rockbursts has long been a subject of intense interest and a hot topic in the field of rock mechanics. Numerous seminars on rockburst disasters have been held around the world in order to effectively reduce the rockburst risk. Examples include meetings such as the academic salons "New ideas, New theories" held by the Chinese Association for Science and Technology, "Proceedings of the International Symposium on Rockburst and Seismicity" successively held every four years by South Africa, the United States, Canada, Poland, Australia and China, etc.

Three dimensional microseismic(MS) monitoring techniques involving monitoring of microcracking in rocks have been widely used around the world for many years to monitor rockbursts—with different degrees of success [2], [5], [7]–[17]. The technology has already become an established method for research and management of rockburst monitoring in deep mining [17], and has also been introduced in tunnel engineering [2], [5], [7], [13], [14]. Using sensors laid out spatially with different azimuths, seismic waves from MS events during rock fracture can be captured. By analyzing these seismic waves from MS events, the location of the rock fractures can subsequently be obtained. The results of such location studies have been widely used to study the spatiotemporal evolution of, and mechanisms underlying the formation of, the fractures involved in the rockburst development process in tunnels.

Research on MS source location has been a subject of intense interest in the field of MS monitoring and rockburst mechanism analysis in tunnelling engineering. However, errors in MS source location are inevitable because of a variety of practical reasons [18], especially in tunneling engineering [14], [19]. MS location methods based on isotropic velocity model are often used in tunnel engineering [7], [19]. The isotropic velocity model assumes that the propagation velocity of the vibration signal from the MS source to each sensor is the same. It makes the location concise and feasible, but does not match the actual situation. And a fixed-point blasting technique is usually used to calibrate the velocity. the ray paths of the MS waves from the MS events and blast event to the MS sensors will be different because the position of the blasting fixed-point and rockburst are usually not the same. 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 mainly occurred near working face are laid out the array of MS sensors. It is not good for MS source location and the location accuracy is influenced heavily [7], [19]. It has restricted more in-depth research into rockburst development processes.

To improve the accuracy of MS event location in rockburst development processes in tunnels, a location method is proposed in this paper. The MS events associated with rockburst development processes are located with a better accuracy after the rockburst occurred. The method is therefore highly conducive to in-depth analysis of the rockburst development processes and investigation of their mechanisms of formation. The method successfully implements location finding based on an anisotropic velocity model and solves the consistency problem of ray paths of the seismic waves. Simulation tests were conducted to analyze the performance of the proposed method. As a further test, the method was also applied to MS source location in the rockburst development processes in deep tunnels (2525m) of the Jinping II hydropower station in China.

II. METHODOLOGY

A. TARGET FUNCTION FOR MS SOURCE LOCATION BASED ON ANISOTROPIC VELOCITY MODEL

The coordinates of the MS source are denoted by (x_0, y_0, z_0) and those of the ith sensor S_i by (x_i, y_i, z_i) where $i \leq n$ and n is the number of sensors. The origin time of the MS source is t_0. The arrival times of P- and S-waves at the ith sensor are t_i^P and t_i^S, respectively, and the distance between the MS source and this sensor is R_i. The velocities of the P- and S-waves from the MS source to the ith sensor are V_i^P and V_i^S, respectively. The target function for MS source location based on minimizing the residuals between the theoretical and observed travel times from the MS source to the sensors can be expressed as

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

In this expression, f is the time residual and m is the norm (generally taken to be 1 or 2 corresponding to the L1 or L2 norm approach used). One difficulty with the L2 method for MS source location is that the input errors often do not follow a normal distribution, as the method assumes [18]. Therefore, $m = 1$ is used in this paper. 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) are the optimum values for the MS source location. The formula for computing R_i is

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

The velocities of the MS waves from the MS source to the MS sensors are used in the (1). Therefore, the accuracy of the resulting MS source location depends on the accuracy of these velocities. Anisotropicvelocity model is usually used to calibrate the velocities and it makes the assumption that the propagation velocity of the seismic signal from the MS source to each sensor is the same. This makes the calculations concise and feasible, but does not match the actual situation! 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 parts of the rockmass. Therefore, an anisotropic velocity model is used in this work. The velocities from the MS source to each MS sensor can be different. The inhomogeneous, discontinuous characteristics of the rockmass, as well as structural planes in the rockmass, are taken into account in the anisotropic velocity model. The velocities from the MS source to each MS sensor will thus be different and there is no constraining relation between the velocities (which agrees with the actual situation). The location error when the anisotropy of the rockmass is accounted for is reduced and the MS source location accuracy will thus be improved. Therefore, if the target function for MS source location given in (1), based on an anisotropic velocity model, is successfully solved, the MS source location accuracy will be improved.

However, it is usually difficult to solve (1) with an anisotropic velocity model. In the first place, it is hard to obtain the rockmass velocities in all directionsas they are difficult to measure *in situ* in tunnel. Also, if the anisotropic velocities are treated as unknowns in the target function, there will be too many unknowns to get a right location solution. That is, the equation set is underdetermined. More precisely, the number of unknowns is $2n + 4$ ($2n$ for velocities, 3 for source location and 1 for origin time), while the number of equations is usually only n. In order to improve the accuracy of MS event location in rockburst development processes in tunnels, we have to solve this problem.

B. RELATION IN ANISOTROPIC VELOCITIES BASED ON ROCKBURST EVENT

After a rockburst occurred in a tunnel, the rockburst location can be measured *in situ* and its coordinates can be calculated. The coordinates of the rockburst event source is denoted by (a, b, c) here. The energy released during the rockburst causes the rockmass to vibrate and this triggers the surrounding MS sensors via the formation of stress waves. Then, rockburst-induced MS event occurs. By using the rockburst-induced MS event, combining (1) and (2), the target function can be rewritten as (3), as shown at the bottom of the next page.

In this expression, t_i^P, t_i^S, x_i, y_i, z_i, a, b and c are all known. On the other hand, t_0, V_i^P and V_i^S are unknowns. The number of unknowns is $2n + 1$ ($2n$ for velocities and 1 for origin time). The equation set is still underdetermined and there are infinite solutions for the target function to meetthe minimum value which is equal to zero. Therefore, we can have $2n$ equations because every term in the (1) must be zero to satisfy the minimum value which is equal to zero due to being absolute values. Therefore, a relationship among the anisotropic velocities can be revealed based on the (3) with the rockburst event.

Solving the target function (3) and eliminating the origin time t_0 by setting $f = 0$, the following relation between the anisotropic velocities can be found

$$\begin{aligned} V_u^P &= V_v^P\sqrt{(x_u-a)^2+(y_u-b)^2+(z_u-c)^2} \\ &\quad \Big/\left(\sqrt{(x_v-a)^2+(y_v-b)^2+(z_v-c)^2}+V_v^P(t_u^P-t_v^P)\right) \\ &= V_u^S\sqrt{(x_u-a)^2+(y_u-b)^2+(z_u-c)^2} \\ &\quad \Big/\left(\sqrt{(x_u-a)^2+(y_u-b)^2+(z_u-c)^2}+V_u^S(t_u^P-t_u^S)\right) \end{aligned} \tag{4}$$

where u and v are the uth and vth sensor respectively ($u \leq n$ and $v \leq n$).

Then (4) can be used together to add some constraints when we locate other MS sources near the rockburst area by (1) with the anisotropic velocity model. The number of equations has increased by $2n - 1$ because of (4) which makes the number of unknowns less than the number of equations. Thus, the equation set will be overdetermined and in this case we can find the location result with a minimum error. Therefore, MS source location based on the anisotropic velocity model becomes feasible.

As the MS events associated with the rockburst development process are almost in the same area where the rockburst occurred, the ray paths of the seismic waves from the MS events and rockburst event to the MS sensors will almost be the same. Therefore, the relationship in the anisotropic velocities based on the rockburst event (4) is suitable and accurate relatively for the location of MS events in the rockburst development process. A fixed-point blasting technique is usually used to calibrate the velocity when MS monitoring in mines and underground powerhouses and caverns [8], [18], [20]. The same technique continues to be used in MS source location monitoring in tunnels.For the commonly used method of fixed-point blasting, the ray paths of the seismic waves from the MS events and blast event to the MS sensors will be different because the position of the blasting fixed-point and rockburst are not the same. Therefore, it is not appropriate to use the relationship of the anisotropic velocities based on a blasting event to locate MS event intherockburst development process.

C. A GLOBAL OPTIMIZATION ALGORITHM

When the anisotropic velocity model is used, the target function is complicated. The number of unknowns is large and they are related to each other. Optimization to find the MS source location can easily fall into local minima, producing inaccurate results, especially in a tunnel engineering situation [19]. As a result, 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 [20], [21]. It is a powerful global optimization algorithm and has been successfully used in many areas, e.g. function optimization, system identification, neural network training, etc.

Introduction to PSO can be found in related paper [14], [21]. Interested readers can refer to these works for further details. The particle' velocities and positions are updated using the expressions:

$$V_{md} = c_0V_{md}+c_1r_1(P_{md}-X_{md})+c_2r_2(P_{gd}-X_{md}) \tag{5a}$$

$$X_{md} = X_{md} + V_{md} \tag{5b}$$

where d is the dimension and V_{md} is the velocity of particle m. The particles' velocities in each dimension are restricted to a maximum value. If the sum of the accelerations would cause the velocity in that dimension to exceed the maximum velocity (which is specified by the user), then the velocity in that dimension is limited to the maximum velocity. Also in Eq. (5), c_0 is the inertial weight (a constant used to control the convergence velocity) and c_1 and c_2 are the learning rates (usually, $c_1 = c_2 = 2$). The parameters r_1 and r_2 are uniformly distributed random numbers between 0 and 1. The variable X_{md} is the current value for particle m and P_{md} and P_{gd} are the 'pbest' and 'gbest' values, respectively, as stated before.The PSO algorithm is used to search for the MS source location in this paper because of its powerful global-search capability. It is worthy of note that PSO is merely used as a technique embedded in the proposed methodology here and other different optimizers can also be tested and used.

To sum up, the location method for MS events in rockburst development processes in tunnels as proposed here has three main features. Firstly, an anisotropic velocity model is used. The inhomogeneous and discontinuous characteristics of the rockmass, as well as the structural planes within, are encompassed by the anisotropic velocity model which helps improve MS source location accuracy. Secondly, a rockburst event is used to find a relationship in anisotropic veloci-

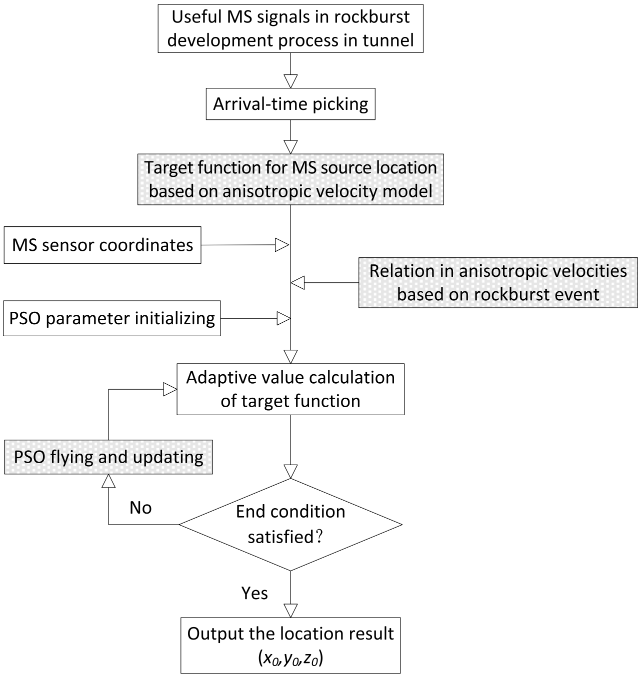


FIGURE 1. A flow chart illustrating the solution process used in the new highly accurate location method for locating the MS events involved in rockburst development processes in tunnels.

ties. This makes MS source location using an anisotropic velocity model feasible. Moreover, the relationship between anisotropic velocities is appropriate and accurate relatively for the location of MS events in the rockburst development process which further improves the location accuracy. Lastly, a global PSO optimization algorithm is used. The solutions obtained will not fall into local optima easily, which will further improve the location accuracy. Overall, the proposed method is feasible and can, theoretically, significantly improve the MS source location accuracy. The solution process employed in the proposed method is shown in Fig. 1.

The conditions of using the proposed methodology are listed as follow:

- For MS source location in tunneling engineering;
- After rockburst occurred, not before;
- The rockburst pit should not be too large;
- Both the arrival-times of P- and S-waves for every MS sensors used are clear enough to pick.

III. PERFORMANCE ANALYSIS

A. NUMERICAL EXPERIMENTATION: OVERVIEW

In this section, we used numerical experimentation to test the performance of the proposed location method. As shown in Fig. 2, a rockburst occurs near the working face of a circular tunnel of 12.4 m diameter. There are 50 useful MS events in the rockburst development process which are distributed around the rockburst. The MS events near the rockburst are generated randomly. Eight MS sensors are laid out behind the working face (denoted by S_{11}–S_{14} and S_{21}–S_{24}) whose coordinates are shown in Table 1. (S_{11}–S_{14} are the first group of MS sensors, and S_{21}–S_{24} the second.) The simulated MS sensor layout is spatially discrete and no more than 3 MS sensors lie in any one plane. The coordinates of the rockburst event and the P- and S-wave arrival-times for each sensor are shown in Table 2 and Table 3, respectively. In order to show the solution process of the proposed method, the coordinates and P- and S-wave arrival-times for the first simulated MS event are also listed in Table 3. The origin time of MS source No. 1 (example event) is set to zero. In the simulation, there is no error in coordinates of MS sensors, coordinates of the rockburst event or the P- and S-wave arrival-times.

TABLE 1. Coordinates of the eight MS sensors used in the simulation.

MS sensor	Coordinates (m)		
	x	y	z
S_{11}	32	9.9	–37.2
S_{12}	34	0.3	–28.3
S_{13}	30	–9.7	–37.8
S_{14}	33	–0.4	–46.3
S_{21}	75	10.2	–37.8
S_{22}	72	0.3	–29.7
S_{23}	76	–9.6	–37.5
S_{24}	73	–0.5	–47.1

TABLE 2. Coordinates of the rockburst event and the first MS event.

MS source	Coordinates (m)		
	x	y	z
Rockburst event	127.61	7.60	–33.04
No. 1	128.95	9.10	–33.17

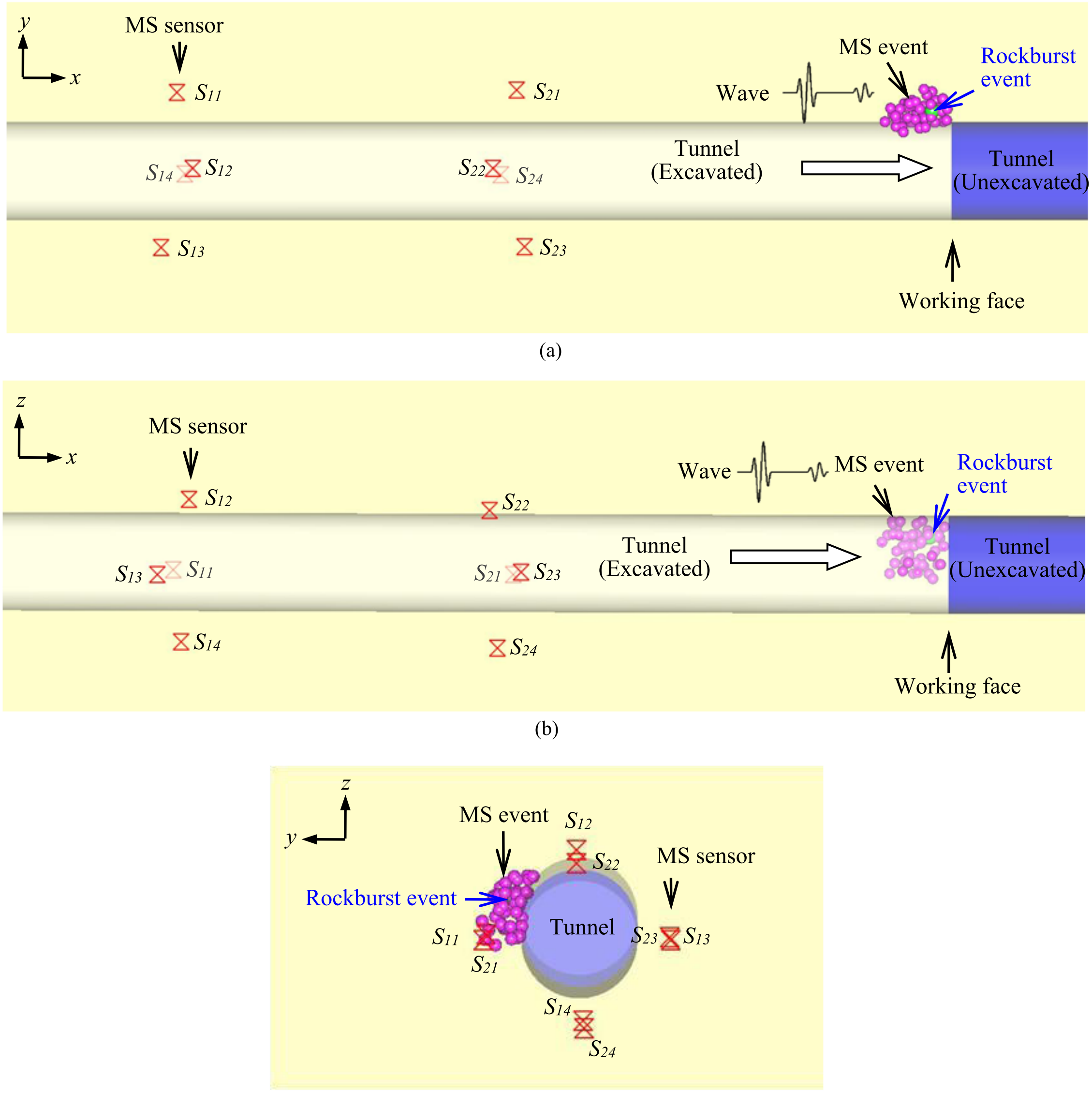
TABLE 3. Arrival-times of the P- and S-waves of therockburstandthefirst MS event.

MS sensor	Arrival-times (s)			
	Rockburst event		First MS event (No.1)	
	t^P	t^S	t^P	t^S
S_{11}	50.01679440	50.02900851	0.01702404	0.02940516
S_{12}	50.01656291	50.02860867	0.01682144	0.02905521
S_{13}	50.01823320	50.03149370	0.01852366	0.03199542
S_{14}	50.01683596	50.02908029	0.01708883	0.02951708
S_{21}	50.00881481	50.01511110	0.00902658	0.01547414
S_{22}	50.00954002	50.01635432	0.00980215	0.01680368
S_{23}	50.01055402	50.01809260	0.01089018	0.01866889
S_{24}	50.00951394	50.01630961	0.00976144	0.01673390

B. DATA PROCESSING

In order to analyze the feasibility and performance of the proposed method, the commonly used method for locating of MS

$$f=\sum_{i=1}^{n}\left(\left|t_i^P-t_0-\sqrt{(x_i-a)^2+(y_i-b)^2+(z_i-c)^2}/V_i^P\right|+\left|t_i^S-t_0-\sqrt{(x_i-a)^2+(y_i-b)^2+(z_i-c)^2}/V_i^S\right|\right) \quad (3)$$



(a)

(b)

(c)

FIGURE 2. Plan, side, and cross-section views of the simulated MS events, MS sensors, and rockburst event in a tunnel. (a) plan view, (b) side view, and(c) cross-section view.

TABLE 4. Performance analysis strategy.

Location method	Velocity model	Calibration event
Common	Isotropic velocity	Early blast event
Proposed	Anisotropic velocity	Rockburst event

events before rockburstoccurs (based on fixed-point blasting and isotropic velocity model) is also used. The performance analysis strategy is show in Table 4. Subsequently, the feasibility and relative location accuracy of the new method can be analyzed based on the location results obtained.

According to the information available about the rockburst-induced MS events occurring during MS monitoring in the tunnel, we can find the anisotropic velocity relationships relating to the rockburst development process. Inserting the knowns (rockburst event position, MS sensor coordinates, and P- and S-wave arrival-times) into (4), we get the following results for the anisotropic velocities for this rockburst:

$$\begin{aligned}
V_1^P &= 95.73/(0.00023149 + 94.01/V_2^P)\\
&= 95.73/(-0.00143880 + 99.25/V_3^P)\\
&= 95.73/(-0.00004155 + 95.87/V_4^P)\\
&= 95.73/(0.00797960 + 52.89/V_5^P)\\
&= 95.73/(0.00725438 + 56.19/V_6^P)\\
&= 95.73/(0.00624038 + 54.58/V_7^P)\\
&= 95.73/(0.00728046 + 56.97/V_8^P)\\
&= 95.73/(-0.01221411 + 95.73/V_1^S)\\
&= 95.73/(-0.01181426 + 94.01/V_2^S)\\
&= 95.73/(-0.01469930 + 99.25/V_3^S)
\end{aligned}$$

$$
\begin{aligned}
&= 95.73/(-0.01228588 + 95.87/V_4^S)\\
&= 95.73/(0.00168330 + 52.89/V_5^S)\\
&= 95.73/(0.0004408 + 56.19/V_6^S)\\
&= 95.73/(-0.00129820 + 54.58/V_7^S)\\
&= 95.73/(0.00048479 + 56.97/V_8^S) \qquad (6)
\end{aligned}
$$

The PSO algorithm can now be used to search for the MS source location taking advantage of its powerful global-search capability. The steps involved in the MS source location process based on the PSO algorithm are as follows:

Step 1: Initialize the inertial weight c_0, learning rates c_1 and c_2, population size m, end condition of fitness value, e, maximum flying time N_g, upper and lower limits of the unknown, the particle's position X_i, and its flying velocity V_i. Set the flying times of the particle $n = 0$. Then go to Step 2.

Step 2: Insert the X_i values into (1) and calculate the fitness value Q_i for each particle. The global optimum X_g^b and the best X_i^b among the particles can then be found based on their fitness values. Then go to Step 3.

Step 3: If the end condition of the fitness value $Q_i > \varepsilon$ or flying time $n > N_g$ is reached, output the global optimum X_g^b and end the search. Otherwise go to Step 4.

Step 4: Set $n = n + 1$ and update the particle flying speed V_i and the unknown X_i values according to (5a) and (5b), respectively. Then go to Step 2.

As an example, the PSO parameters were set to: $c_1 = c_2 = 2$, $c_0 = 0.8$, $m = 1,000$, maximum flying time $N_g = 1,000$, and fitness condition $e = 10^{-10}$. We take MS event No. 1 as an example. The changes occurring during the searching process (as a function of particle flying time) when solving for MS source No. 1 are shown in Fig. 3. There is a search result for each of the particle flying times. In the early stages of the solution process (flying times from 0 to 50), the search results fluctuate strongly. Then, the search results gradually stabilized as the flying time increased. Finally, the search results converged and remained stable after a certain time. The location result is (128.95, 9.10, -33.17) which is the same as the actual location shown in Table 2. The analysis above shows that by using the proposed location method, the MS source location can be obtained accurately after a certain number of particle swarm flying times. Therefore, the proposed method is feasible. It is worthy of note that the settings of the PSO parameters could be optimized in order to find the location result more quickly or reduce the computational cost.

C. RESULT ANALYSIS

All of the MS events in the rockburst development process were located based on the two methods with PSO algorithm. The results are shown in Figs. 4 and 5. It is worth noting that the actual source positions of the MS events in Fig. 4 overlap with the search results found using the location method as the two sets of results are almost the same. The reader can compare Fig. 4 with Fig. 2 to clarify this. From Fig. 4, we can see that the MS source location accuracy is significantly improved when the location method is used. The MS events are more concentrated in the area in which the rockburst occurred. This is in agreement with the actual situation and will be very helpful in future research on rockburst development processes and formation mechanisms after the rockburst occurred. The location accuracy based on the two methods is illustrated in Fig. 5. Fig. 5(a) shows that the average location error decreases by 20.16 m. The location accuracy is thus significantly better. In addition, Fig. 5(b) shows that the errors in the origin times of all the MS events in the rockburst development process are significantly reduced as well. The source positions and origin times are correlated with each other. That is, accurate results for the origin time will ensure the accuracy of the source locations.

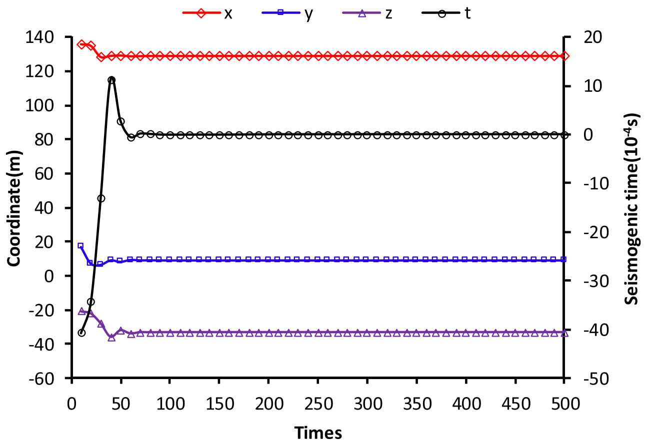


FIGURE 3. **Particle flying and searching process (MS source No. 1, first 500 flying times).**

The simulation results above show that the proposed method is feasible and the accurate of MS events is better. The evolution mechanism and characteristics of these MS events are important aspects of research on the rockburst development process. Appropriate early-warning and rockburst prevention and control measures can be conducted more accurately depending on the evolution mechanism and characteristics determined in order to efficiently reduce the risk of rockbursts. We now consider an engineering case to further analyze and prove its performance.

IV. ENGINEERING APPLICATION

A. JINPING II HYDROPOWER STATION: BACKGROUND

An extended period of MS monitoring, rockburst analysis and warning was conducted in the deep excavations of the Jinping II hydropower project which is located on the Yalong River in Sichuan Province, southwestern China [2]. The tunnel system generally lies at a depth of between 1,900 and 2,400 m, with a maximum depth of about 2,525 m. Rockbursts were encountered frequently. Some extreme rockburst examples have been described and some of them led to serious casualties and economic losses [22]. This project and the MS monitoring were described in detail in other works [5], [22]–[24] in detail— interested readers can refer to these works for further details. The MS sensors were made in South Africa

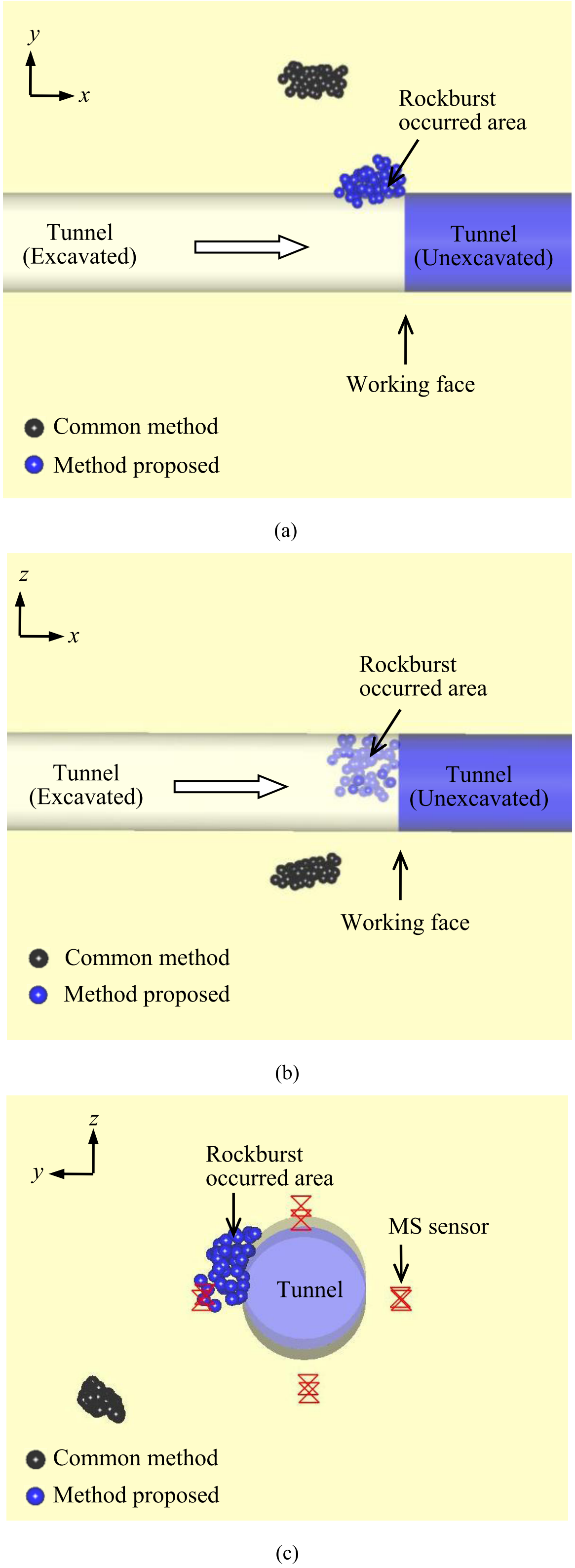


FIGURE 4. Plan, Plan, side, and cross-section views of the MS event source locations based on the two location methods. (a) plan view, (b) side view, and (c) cross-section view.

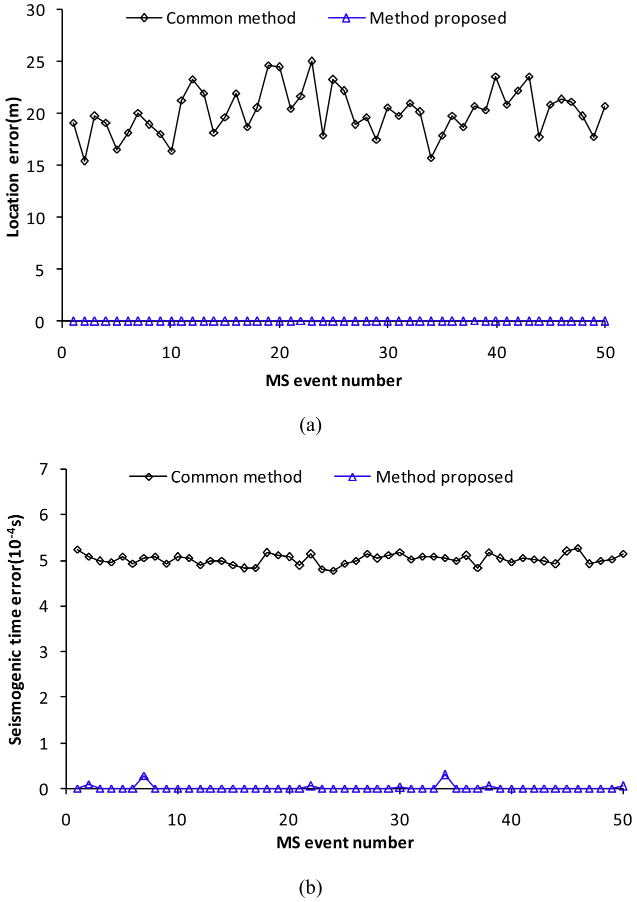


FIGURE 5. The errors associated with the location results obtained for the MS events in the rockburst development process based on the two methods: (a) location errors, and (b) seismogenic time errors.

FIGURE 6. Photograph of the intense rockburst which occurred at chainage K10+4350–356 on 18 August 2010.

and had a natural frequency of 14 Hz and an approximate usable frequency range that varied from 7 to 2,000 Hz. The layout of MS sensors has been described and proved feasible. Detailed information on the MS monitoring network can be found in related references [5], [7], [24].

B. CASE ANALYSIS

At 8:13 on 18 August 2010, an intense rockburst occurred in the 3# headrace tunnel at chainage K10+350–356 with a

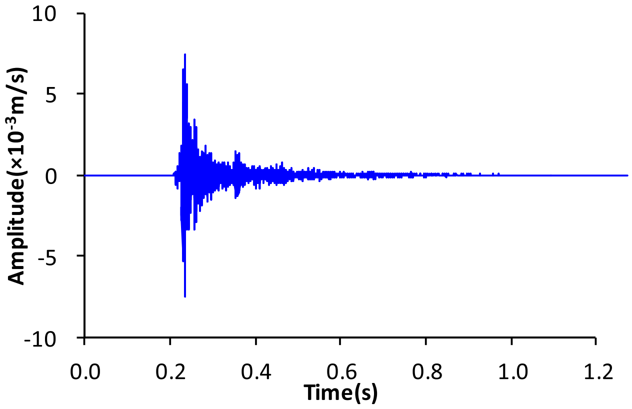


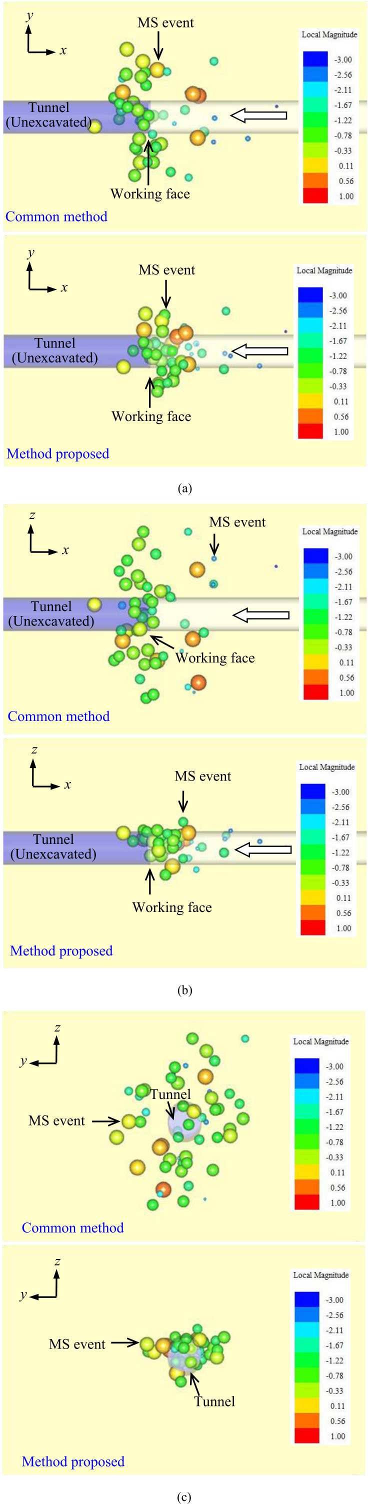
FIGURE 7. Waveform from the rockburst event as monitored by one sensor.

TABLE 5. Information on the rockburst.

Time (Y/M/D H:M)	Coordinates (m) *x*	*y*	*z*	Intensity	Burial depth(m)
2010/8/1808:13	10348	5.4	−34.7	Intense	2130

maximum depth of 1.5 m. A picture of the intense rockburst is shown in Fig. 6. The rockburst caused some minor mechanical damage and delayed tunnel construction but fortunately there were no casualties. Rockbolts and steel mesh were installed after the rockburst occurred. The rock consisted of marble, which is brittle and has high strength. The depth where the rockburst occurred is 2,130 m, as shown in Table 5. The coordinates of the deepest point in the rockburst pit were used as the coordinates of the rockburst. When a rockburst occurs, energy is released which triggers nearby MS sensors and also sets off other rockburst-induced MS events. Seismic waves from MS events are subsequently captured by the MS system. We can analyze the seismic waves from MS events from the rockburst event and elucidate the arrival-times of the *P*- and *S*- waves. This information forms the necessary input data for source location. The waveforms recorded due to the rockburst are captured by several MS sensors. An example is shown in Fig. 7.

The two methods were used to locate the MS events in the rockburst development process. The procedure is the same as that used above in the simulation analysis. The results are shown in Figs. 8. Using the proposed method, the close spatial clustering of the MS activity is more apparent and the location accuracy is significantly better. The MS events are clustered together more closely in the rockburst area in the *x*, *y*, and *z* directions. This agrees well with the actual situation. The method is therefore more conducive to analysis of the rockburst development process and its formation mechanism. The improvement afforded by using the location method can be expressed more quantitatively: the average distance of all the MS events to the position of the rockburst is reduced from 23.77 to 13.43 m.



(a)

(b)

(c)

FIGURE 8. Plan, side, and cross-section views of the MS event source locations based on the different location methods: (a) plan view, (b) side view, and (c) cross-section view. The color of the sphere represents the magnitude of the MS event and its size the energy of the MS event (larger size implies more energy released. the diameter of the tunnel is 12.4m).

The engineering application discussed here shows that the location accuracy is improved when the location method is used. However, we note that the location accuracy is not as good as that achieved earlier in the simulations. This is a characteristic of engineering *in situ* monitoring. The errors in coordinates of MS sensors, coordinates of the rockburst event or the *P*- and *S*-wave arrival-times are not considered in simulations in order to study the improvement of using anisotropic velocity model together with rockbusrt event. These errors are exist in *in situ* monitoring. It is worth noting that it is impossible for the location results derived to be *exactly* the same as the actual ones as it is inevitable that there will always be some location error. Location accuracy is, unfortunately, affected by many different factors.

V. CONCLUSION

A highly accurate method of locating MS events associated with the rockburst development process in tunnels is proposed in this work. An anisotropic velocity model is used as part of the location method. A rockburst event is then used to find relationships in the anisotropic velocities. An efficient global optimization algorithm (PSO) is then used to find the location of the MS events in the rockburst development process. The proposed method significantly improves the MS source location accuracy.

The results of a simulation show that the location method is feasible and superior in accuracy. The MS source locations could be accurately obtained after a certain swarm flying time and the final location accuracy was improved — the average location error was reduced by 20.16m.

As a more practical test, the proposed method was successfully applied to locate the MS events associated with a rockburst that occurred in a deep tunnel (2,525 m) of the Jinping II hydropower station in China. The results show that the closeness of the spatial clustering of the MS activity is more apparent using the location method and the location accuracy of the MS events is significantly better. The MS events located by the proposed method are clustered together more closely in the rockburst area. The average distance of all the MS events to the position of the rockburst was reduced from 23.77 to 13.43 m using the method. The method is therefore more conducive to analyzing rockburst development processes and their mechanisms of formation.

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