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A Multi-Step Source Localization Method With Narrowing Velocity Interval of Cyber-Physical Systems in Buildings

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ABSTRACT The localization for sources in the heterogeneous and complex media is of vital significance, which can be applied to monitor the invisible cracks and determine the potential damage areas of buildings with safety hazards. Based on the localization function with the model of arrival time difference (TD), a multi-step localization method (MLM) without premeasured velocity for heterogeneous and complex propagation media was proposed. The velocity interval used for localization was narrowed and optimized continuously through the multi-step localization, where the optimal velocity interval was determined when the velocity differences were less than the threshold. Then, the optimal localization results with higher accuracy corresponding to this velocity interval can be obtained with the TD algorithm. A source locating test was performed at a building of masonry structure. In addition, the locating accuracy was compared and discussed between the optimized MLM, the one-step method without premeasured velocity, and the traditional method with different premeasured velocity values. Results show that MLM is obviously superior to both the one-step method and the traditional method. The developed MLM can not only eliminate the errors caused by premeasured velocity, but also can improve the locating accuracy in the heterogeneous and complex media, which is an efficient and effective method for engineering applications.

INDEX TERMS Heterogeneous media, microseismic monitoring, multi-step localization, optimization, wave velocity.

I. INTRODUCTION

It has been proved that the micorseismic monitoring technology has an important ability for the characterization of physical processes related to nondestructive testing, underground tunnel excavation, fluid injections, as well as extractions in hydrocarbon and geothermal reservoirs [1]–[6]. Especially, the microseismic monitoring systems are widely applied in the field of mining engineering, which have shown effective results in the mines of South Africa, Australia, Canada, and China [7]–[11]. In general, the stress wave is generated through the deformation and failure of rockmass or other propagation media, to release the accumulated energy. Hence, the crack will appear and propagate. Then, there will be microseismic events during the monitoring process, whose safety and reliability are the basic requirement for data transmission, batch processes, and large-scale industrial applications [12]–[16]. Although the microseismic monitoring technology has been applied maturely in the above fields, it is rarely applied for the localization of invisible cracks in the buildings with heterogeneous media, which is important for the structure safety under dynamic disturbance. As the urban development, many new buildings, subways, and underground garages are constructing vigorously. However, they are constructed near the existing buildings with a large population. The structure safety of these buildings is worrying as the construction destroys the original stress balance and causes the continuous dynamic disturbance [17], [18]. Through the microseismic monitoring technology, the invisible cracks and microseismic events in the buildings can be located, to protect the structure safety. The localization results directly affects the performance of microseismic monitoring, inversion of the velocity structure, and explanation of the source mechanisms [19]. Thus, it can be considered that the accuracy of localization method is a fundamental and significant problem for the microseismic monitoring technology.

In recent years, many localization methods have been discussed and developed to improve the locating accuracy, which mainly includes the analytical localization method and the iterative localization method. The basic thought of the analytical localization method is to solve the explicit formulas for source coordinates through the nonlinear governing equations [20]–[24]. Smith and Abel [25] presented three noniterative methods for locating sources in the three-dimensional space, which were the spherical-interpolation method, spherical-intersection method, and plan-intersection method, respectively. However, the objective function was established using the distance between any two sensors, which cannot be as stable as the model of arrival time difference. By applying the model of arrival time difference, Mellen *et al.* [26] proposed the analytical solutions for the sensors network that contains greater than 3 sensors. Nevertheless, the velocity was set as a fixed value, which can only be applied in the single propagation media with the known *P*-wave velocity. It is difficult to locate sources with high accuracy in the media with unknown *P*-wave velocity or the heterogeneous and complex media. Ge [27] summarized the main analytical localization methods including the INGLADA method and USBM method. The *P*-wave velocity is usually taken as the known parameter in the localization process, which fails to characterize the temporal and spatial change of *P*-wave velocity. By taking the wave velocity as an unknown parameter, Dong *et al.* [28] and Dong and Li [29] proposed three dimensional analytical solutions without premeasured velocity for cuboid and cube monitoring networks, respectively. Based on the three-dimensional analytical solutions without premeasured velocity, Li and Dong [30] presented the analytical solutions for random monitoring networks with 6 sensors. In addition, the accurate analytical localization method was developed when the number of sensors is greater than six, for locating sources in unknown velocity mining system [31]. However, there is a serious requirement for the accuracy of input data when applying the analytical methods. Otherwise, the locating accuracy will even be lower than it should be. Actually, the errors of input data are inevitable commonly. Besides, the analytical methods cannot adjust the velocity range to adapt to the specific propagation media, which may cause the unreasonable and inaccurate localization results.

Compared to the analytical localization method, the iterative method is more practical and accurate, since it can seek the optimal results in the whole range by using the advantage of multiple sensors. Therefore, it is more suitable and accurate for locating numerous sources with multiple sensors. As for the iterative localization methods, they are mostly developed on account of the thoughts of Geiger. Based on the Geiger algorithm, many researchers presented numerous optimization methods including the parameter separation, the joint inversion of three-dimensional velocity structure and seismic source, as well as the separate calculation for coupled velocity and seismic source [32]–[36]. Dong *et al.* [37] proposed three iterative localization methods including TT, TD, and TDQ, which can locate sources without the need of premeasuring velocity. It is proved that the TD method is accurate and stable, which can eliminate the locating error caused by the premeasured velocity. However, the propagation media is assumed as heterogeneous, which means that the *P*-wave velocity value is assumed as a fixed value. This assumption will only adapt to some specific monitoring areas, where the propagation media is simple and single, or the velocity differences between different propagation media are too small to take into account. Obviously, the application scope of the assumption that the *P*-wave velocity is fixed is relatively limited.

It is necessary to note that the accurate localization method for heterogeneous and complex media is a significant problem to be solved. A multi-step localization method (MLM) without premeasured velocity is proposed to improve the locating accuracy, which optimizes and narrows the velocity interval in the localization process for heterogeneous and complex media. Although the TD method is relative accurate and efficient in the existing methods, it does not constrain the velocity value, which means that the velocity value used in the computational process is only greater than 0. Thus, there will be a long computation time due to the great range of velocity value. In addition, it is possible to obtain a local optimum, instead of the global optimum, using the TD method. On the contrary, the proposed MLM can effectively avoid converging on the local optimum and reduce computation time greatly. The MLM can obtain the global optimum with high computational efficiency due to the narrowed and optimized velocity interval. A microseismic source locating test was performed in a masonry structure building, which constituted of bricks, concrete and other building materials. Furthermore, the results of localization method with premeasured velocity are combined, to clarify and verify the accuracy and effectiveness of the proposed MLM. We hope the MLM can not only improve the locating accuracy and efficiency by solving the global optimum in the narrowed and optimized velocity interval, but also can provide some useful ideas for monitoring the invisible cracks and determining the potential damage areas in some large and focused buildings, where the stability of structures should be guaranteed.

II. THE MULTI-STEP LOCALIZATION METHOD

The coordinates of a microseismic source and the triggered sensors are assumed as $P\ (x, y, z)$ and $S_j\ (x_j, y_j, z_j)$ $(j = 1, 2, 3, \ldots n)$, respectively. The average propagation

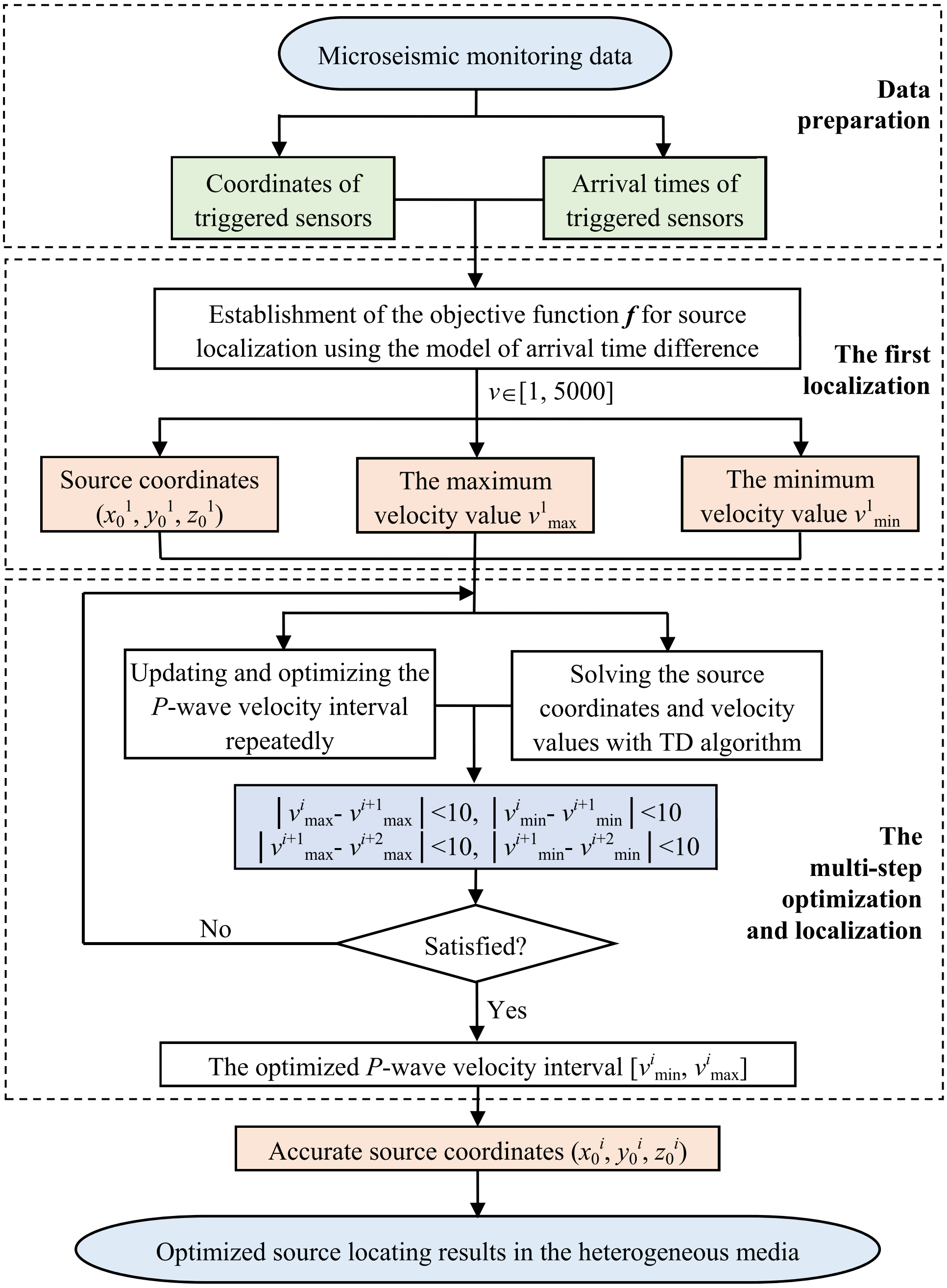


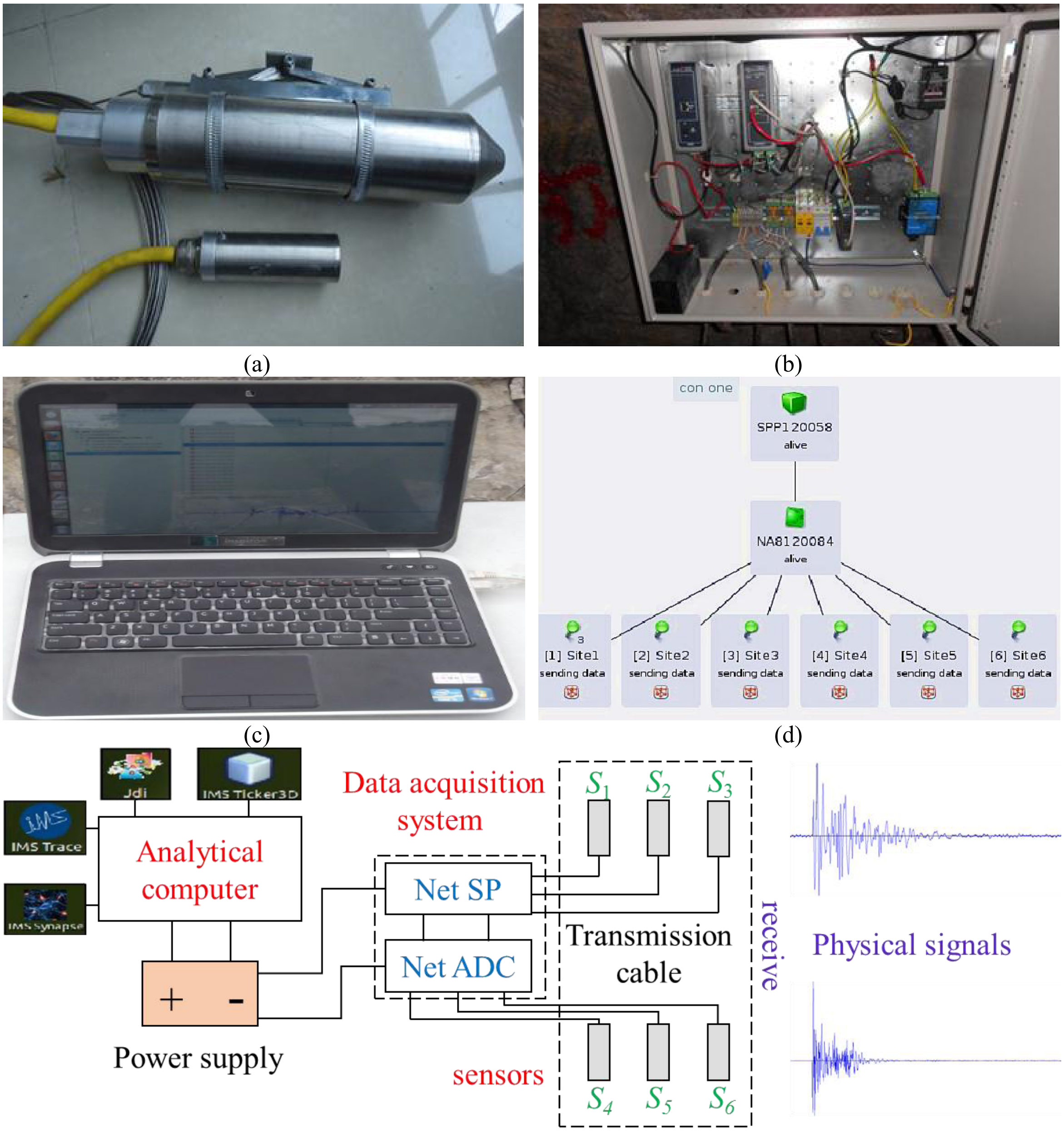
FIGURE 1. The flowchart for locating microseismic sources in the heterogeneous media using the proposed MLM.

velocity of *P*-wave in the media is represented with parameter v. Then, the governing equation for the source coordinates can be established in the Cartesian coordinate system:

$$t_{ij}^{mea} - t_{ij}^{cal} = \left(\frac{\partial t}{\partial x}\right)_{ij} \Delta x + \left(\frac{\partial t}{\partial y}\right)_{ij} \Delta y + \left(\frac{\partial t}{\partial z}\right)_{ij} \Delta z + \left(\frac{\partial t}{\partial v}\right)_{ij} \Delta v + \Delta t_{0i} + e_{ij} \quad (1)$$

where t_{ij}^{mea} and t_{ij}^{cal} are the measured and calculated travel times from the i-th event to the j-th sensors. t_{0i} is the origin time of the i-th event. Δ denotes the perturbation of a parameter. e_{ij} represents higher-order terms of perturbations and data error.

The difference between the measured travel time t_{ij}^{mea} and the calculated travel time t_{ij}^{cal} can be used to describe the deviation degree. The fitting degree and locating accuracy will be better when the deviation degree is smaller. Based on the quadratic sum of differences between all the regression values and all the measured values, the objective function with the model of arrival time difference can be established as (2).



(a) (b) (c) (d) (e)

FIGURE 2. **The portable microseismic monitoring system used at the test building. The graph (a) shows the sensors, where the bigger one is the three-component sensor and the smaller one is the single-component sensor. The graphs (b) and (c) show the data acquisition system and the analytical computer, respectively. The graph (d) exhibits the structure and hierarchies of this system. The graph (e) explains the working principle of this system, where the physical signals are received by sensors and transmitted to the analytical computer. Then, the analytical results are used to guide the actual work, which achieves the effect of a cyber-physical system.**

Obviously, the unknowns x, y, z, and v should minimize the function value, to obtain the accurate and stable localization results.

$$f\,(x, y, z, v) = \sum_{i,j=1}^{n} \left(t_{ij}^{mea} - t_{ij}^{cal}\right)^2 = \min \tag{2}$$

Since the above equation is a non-negative quadratic function with the independent variables x, y, z, and v, the minimum value is always there for sure. It is feasible to obtain the source coordinates (x, y, z) and average velocity value v for an arbitrary source locating problem, as long as the number of triggered sensors is greater than 4.

However, it is common that plenty of microseismic sources in the monitoring area need to be localized in the meanwhile for many practical applications. As the propagation media is usually heterogeneous and the P-waves triggered by different

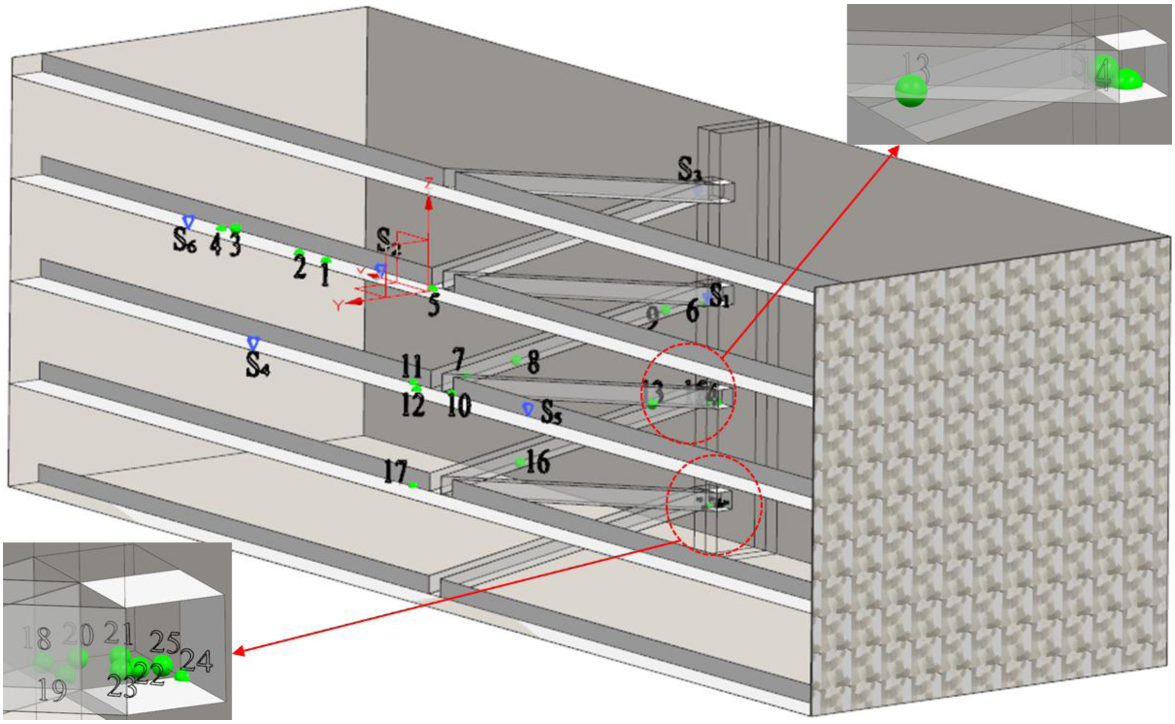


FIGURE 3. The simplified model of test building. The locations of 6 sensors and 25 microseismic sources are represented with blue triangles and green spheres, respectively.

TABLE 1. The coordinates of sensors S_1 to S_6.

Sensors	Coordinates/m		
	x	y	z
S_1	-0.500	-5.861	-1.706
S_2	2.490	0	0
S_3	1.310	-4.750	1.530
S_4	7.978	1.009	-3.278
S_5	-5.162	-0.141	-3.278
S_6	11.002	0.966	0

microseismic sources have various travel paths, then there must be differences for the average propagation velocity of different microseismic sources. The locating accuracy will be affected seriously by performing the TD locating algorithm only once due to the inaccuracy of *P*-wave velocity interval. Thus, the *P*-wave velocity interval should be optimized by performing the TD algorithm for many times, to improve the locating accuracy in the heterogeneous propagation media. The optimization method is summarized and stated below.

Fig. 1 shows the flowchart of the whole localization process for the microseismic sources in the heterogeneous media using the proposed MLM. According to the characteristic of *P*-wave velocity and propagation media, the velocity interval is set as $\left[v_{\min}^{0}, v_{\max}^{0}\right]$ in the first localization process, where $v_{\min}^{0}$ and $v_{\max}^{0}$ are the lower limit and the upper limit, respectively. For example, the velocity interval can be set as [1, 5000] in a masonry structure building. As mentioned before, the source coordinates (x_0, y_0, z_0) and corresponding average velocity value v of different microseismic sources can be obtained easily. Then, we can find the maximum velocity value $v_{\max}^{1}$ and the minimum velocity value $v_{\min}^{1}$ among all the velocity values in the first localization process, which are shown below.

$$\begin{cases} v_{\min}^{1} = I\left[f\left(x, y, z, v\right)\right] & v \in \left[v_{\min}^{0}, v_{\max}^{0}\right] \\ v_{\max}^{1} = I\left[f\left(x, y, z, v\right)\right] & v \in \left[v_{\min}^{0}, v_{\max}^{0}\right] \end{cases} \tag{3}$$

where the function I is the inversion function used to solve the velocity value and source coordinates. Therefore, the maximum velocity value $v_{\max}^{1}$ and the minimum velocity value $v_{\min}^{1}$can obtained and selected as the upper limit and

TABLE 2. The authentic coordinates, as well as the first localization results and errors of each sources.

No.	Authentic coordinates/m			Localization results/m			Velocity/m•s^{-1}	Localization errors/m		
	x	*y*	*z*	*x*	*y*	*z*	*v*	*x*	*y*	*z*
1	4.500	0	0	4.646	1.956	1.500	1325.2	0.146	1.956	1.500
2	5.500	0	0	5.284	0.712	1.500	1048.6	0.216	0.712	1.500
3	7.475	1.103	1.100	6.727	-2.134	1.479	353.9	0.748	3.237	0.379
4	10.003	-0.500	0	7.491	-2.883	1.384	**183.2**	2.512	2.383	1.384
5	0	-1.500	0	2.398	-2.657	-0.250	**1590.8**	2.398	1.157	0.250
6	1.000	-5.811	-1.706	-0.602	-12.714	-5.947	1138.5	1.602	6.903	4.241
7	2.458	-1.771	-2.943	0.071	-3.766	-7.674	1169.1	2.387	1.995	4.731
8	2.458	-2.841	-2.476	1.185	-3.264	-6.944	637.4	1.273	0.423	4.468
9	2.458	-4.071	-1.879	0.701	-5.706	-4.767	1187.4	1.757	1.635	2.888
10	-0.514	-0.481	-3.278	0.121	0.473	-9.464	795.7	0.635	0.954	6.186
11	1.278	-1.141	-3.278	0.439	-1.082	-8.939	618.3	0.839	0.059	5.661
12	-0.014	0.519	-3.278	0.849	0.940	-9.850	665.0	0.863	0.421	6.572
13	1.288	-3.371	-4.364	0.253	-2.525	-10.000	883.0	1.035	0.846	5.636
14	1.608	-4.851	-4.836	-1.904	-8.946	-9.319	1369.4	3.512	4.095	4.483
15	2.508	-4.551	-4.836	2.205	-4.296	-4.615	1021.0	0.303	0.255	0.221
16	2.508	-1.971	-5.900	1.091	-2.223	-6.364	808.6	1.417	0.252	0.464
17	1.278	-0.544	-6.375	1.149	-1.859	-6.336	579.6	0.129	1.315	0.039
18	1.938	-6.584	-8.065	-1.984	3.000	-2.820	498.3	3.922	9.584	5.245
19	1.338	-6.566	-8.065	-1.453	-10.622	-9.706	798.0	2.791	4.056	1.641
20	1.938	-7.124	-8.065	2.319	-5.596	-3.759	750.1	0.381	1.528	4.306
21	1.338	-8.254	-8.065	3.558	-7.472	-4.775	490.6	2.220	0.782	3.29
22	1.278	-8.254	-8.065	1.768	-6.343	-10.000	764.3	0.490	1.911	1.935
23	1.278	-8.104	-8.065	-0.467	-5.237	-5.174	778.3	1.745	2.867	2.891
24	0.618	-10.234	-8.065	3.547	-9.047	-8.120	627.8	2.929	1.187	0.055
25	1.278	-10.234	-8.065	0.425	-8.983	-9.839	768.5	0.853	1.251	1.774
Average values							834.0	1.484	2.071	2.870

Note: The bold values indicate the maximum velocity value $v^1_{\max}$ and the minimum velocity value $v^1_{\min}$ in the first localization process.

the lower limit for the velocity interval $[v_{\min}^1, v_{\max}^1]$ in the second localization process. Similarly, the maximum velocity value $v_{\max}^2$ and the minimum velocity value $v_{\min}^2$ can also be obtained from the second localization.

$$\begin{cases} v_{\min}^2 = I\left[f\left(x, y, z, v\right)\right] & v \in \left[v_{\min}^1, v_{\max}^1\right] \\ v_{\max}^2 = I\left[f\left(x, y, z, v\right)\right] & v \in \left[v_{\min}^1, v_{\max}^1\right] \end{cases} \quad (4)$$

The obtained results can be used to make up the velocity interval $[v_{\min}^2, v_{\max}^2]$ in the third localization process. The velocity interval can be narrowed and optimized by repeating the above localization processes using the TD algorithm until the following conditions are satisfied.

$$\begin{cases} \left|v_{\max}^i - v_{\max}^{i+1}\right| < 10, & \left|v_{\min}^i - v_{\min}^{i+1}\right| < 10 \\ \left|v_{\max}^{i+1} - v_{\max}^{i+2}\right| < 10, & \left|v_{\min}^{i+1} - v_{\min}^{i+2}\right| < 10 \end{cases} \quad (5)$$

where the threshold is 10 m/s. The maximum velocity value $v_{\max}^i$ and the minimum velocity value $v_{\min}^i$ are exactly the upper limit and the lower limit of the optimized and superior velocity interval $[v_{\min}^i, v_{\max}^i]$ in the heterogeneous propagation media. At this time, it can be considered that the process for optimization of *P*-wave velocity interval is finished completely. Also, the localization results corresponding to this velocity interval $[v_{\min}^i, v_{\max}^i]$ are the most accurate compared to the results of other velocity intervals. As a result, the locating accuracy can be improved greatly by narrowing and optimizing the velocity interval.

III. RESULTS

The microseismic sources locating test was performed at a building in Kaiyang County, Guizhou Province, China, which was built in the mountainside. Several tunnels have been excavated in this mountain, which was surrounded by multiple main roads and railways. The test building is a masonry structure with tiles covered on the surface, which mainly consists of bricks and concrete. Hence, the velocity value of

TABLE 3. The velocity values and average localization errors for each localization process.

Localization process	Velocity values/m•s^{-1}			Average localization errors/m			Err$_{xyz}$/m [2]
	$v_{\min}$	$v_{\max}$	v_{ave} [1]	x	y	z	
1st	183.2	1590.8	834.0	1.484	2.071	2.870	2.142
2nd	220.2	1577.2	783.5	1.567	2.122	3.023	2.237
3rd	301.0	1533.9	800.5	1.493	2.109	3.026	2.209
4th	420.5	1483.2	854.9	1.511	2.026	2.986	2.174
5th	448.5	1475.7	863.6	1.427	2.037	2.885	2.116
6th	477.2	1474.3	854.3	1.428	2.071	2.827	2.109
7th	520.8	1468.5	846.5	1.423	1.978	2.970	2.124
8th	535.8	1459.3	859.6	1.576	1.800	2.908	2.095
9th	572.1	1433.2	869.4	1.465	1.750	2.902	2.039
10th	577.3	1424.9	863.5	1.534	1.802	2.837	2.058
11st	580.0	1420.2	882.9	1.566	2.068	2.780	2.138

[1] v_{ave} indicates the average velocity value of 25 microseismic sources for each localization process.

[2] Err$_{xyz}$ indicates the average value of average localization errors for x, y, and z.

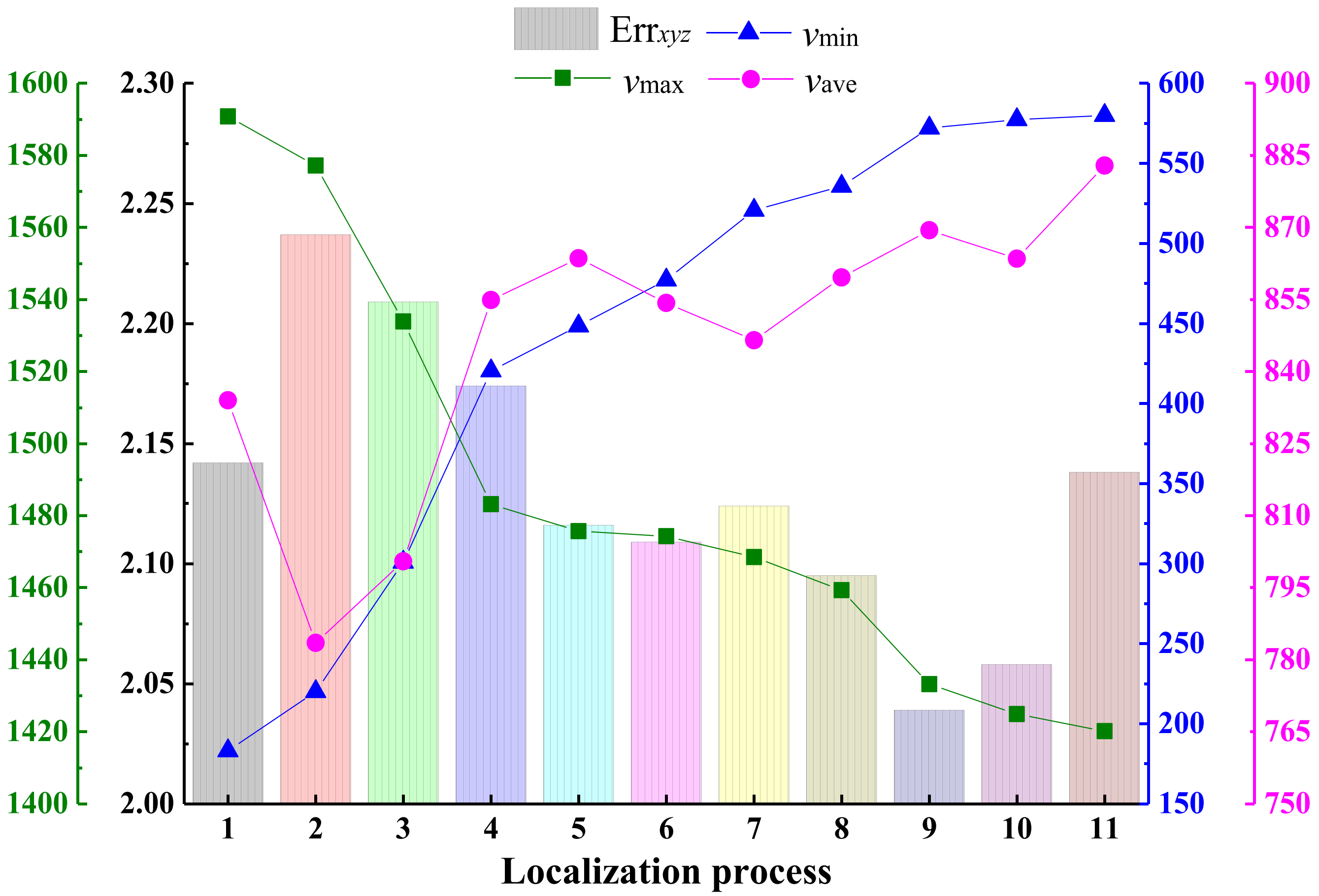


FIGURE 4. The change and comparison of velocity values for the 11 localization processes. The blue, green, and red broken lines indicate the minimum velocity, the maximum velocity, and the average velocity, respectively. The histograms indicate the Err$_{xyz}$ of each localization process.

P-wave will not be the same due to the difference of propagation media, the thickness of concrete, and the masonry structure itself. Besides, the building has been constructed and used for decades. The possible invisible cracks and slight damage will also affect the velocity structure, which causes the greater difficulty for the accurate localization of

TABLE 4. The velocity values, localization results and errors for the 9th localization process.

No.	Velocity/m•s^{-1}	Localization results/m			Localization errors/m		
	v	x	y	z	x	y	z
1	1261.1	4.892	1.168	1.498	0.392	1.168	1.498
2	916.0	5.563	0.054	1.492	0.063	0.054	1.492
3	849.7	6.084	-0.249	1.500	1.391	1.352	0.400
4	723.1	8.062	-0.850	1.500	1.941	0.350	1.500
5	1433.2	2.590	-3.005	-0.797	2.590	1.505	0.797
6	1117.8	-0.502	-13.287	-6.204	1.502	7.476	4.498
7	1169.5	0.067	-3.765	-7.676	2.391	1.994	4.733
8	679.4	0.964	-3.180	-6.333	1.494	0.339	3.857
9	1186.4	0.701	-5.677	-4.711	1.757	1.606	2.832
10	766.7	0.103	0.642	-9.982	0.617	1.123	6.704
11	596.2	0.562	-1.048	-9.258	0.716	0.093	5.980
12	655.2	0.894	0.943	-9.956	0.908	0.424	6.678
13	1025.6	-0.475	-2.799	-10.000	1.763	0.572	5.636
14	1345.0	-1.846	-9.270	-9.558	3.454	4.419	4.722
15	1017.7	2.257	-4.345	-4.478	0.251	0.206	0.358
16	806.9	0.974	-1.983	-6.059	1.534	0.012	0.159
17	572.1	1.206	-1.863	-6.419	0.072	1.319	0.044
18	643.7	-1.936	3.000	-2.586	3.874	9.584	5.479
19	847.1	-0.952	-7.182	-6.829	2.290	0.616	1.236
20	752.8	2.304	-5.601	-3.746	0.366	1.523	4.319
21	643.2	2.662	-9.139	-5.605	1.324	0.885	2.460
22	644.0	2.297	-5.821	-10.000	1.019	2.433	1.935
23	695.6	0.264	-5.055	-5.118	1.014	3.049	2.947
24	609.4	3.622	-8.865	-8.409	3.004	1.369	0.344
25	777.9	0.382	-9.966	-10.000	0.896	0.268	1.935

TABLE 5. The comparison results of localization errors for the three methods.

Method	Average localization errors/m			Err$_{xyz}$/m
	x	y	z	
1. One-step localization method (TD method)	1.484	2.071	2.870	2.142
2. MLM	1.465	1.750	2.902	2.039
3. TLM (v=1350 m/s)	1.931	2.061	3.205	2.399
4. TLM (v=2000 m/s)	2.409	2.154	3.342	2.635
5. TLM (v=3000 m/s)	2.662	2.332	3.217	2.737
6. TLM (v=4000 m/s)	2.722	2.363	3.447	2.844
7. TLM (v=5000 m/s)	2.850	2.461	3.439	2.917

micromseismic sources in the heterogeneous and complex media.

A portable microseismic monitoring system with 8 channels was laid in the building, which composed of 6 sensors, a data acquisition system, and an analytical computer. There were 5 single-component sensors and one three-component sensor. Fig. 2 shows the pictures of this portable microseismic monitoring system, where the graphs (d) and (e) explains the structure and hierarchies, as well as the working principle of this system, respectively. The simplified model of test building is shown in Fig. 3, where the blue triangles and green spheres indicate the sensors and

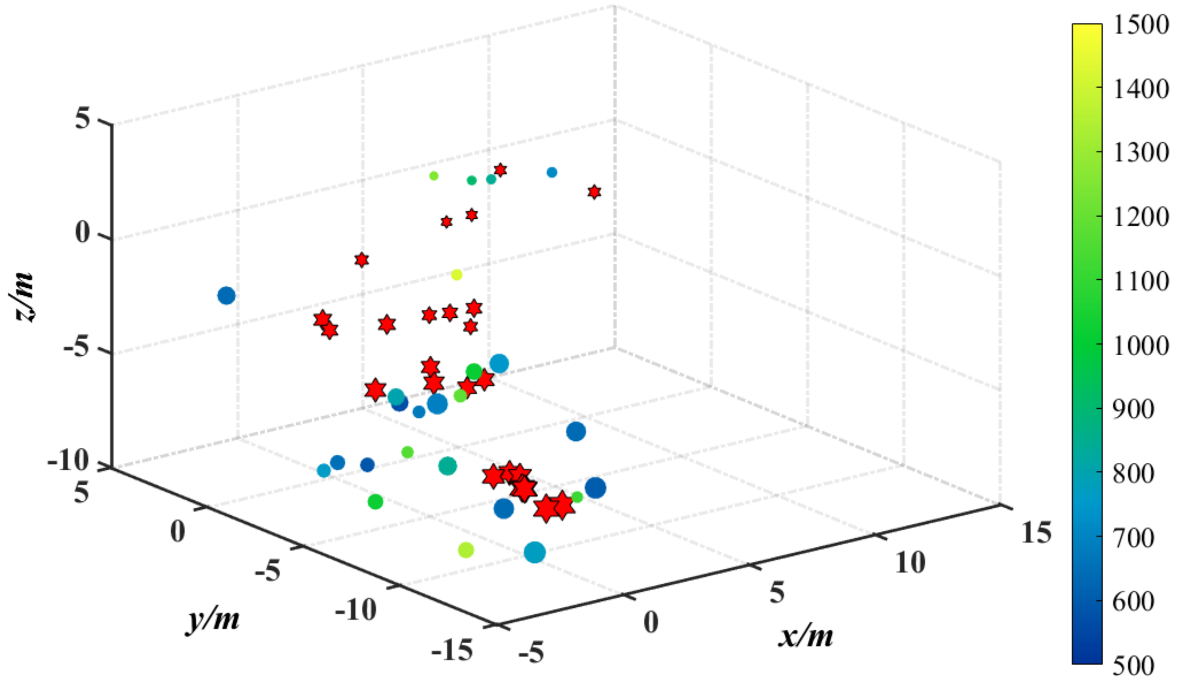


FIGURE 5. The three-dimensional distributions for the 9th localization results and the authentic coordinates. The red star symbols and circulars with different colors indicate the authentic coordinates and the 9th localization coordinates, respectively. The sizes of both two symbols indicate the serial numbers of the microseismic sources. The colors indicate the velocity values of *P*-wave in the travel paths for 25 microseismic sources.

microseismic sources, respectively. The sensors S_1 and S_3 were laid out at the staircase between the third floor and the fourth floor, as well as the staircase between the fourth floor and the fifth floor, respectively. The sensors S_2 and S_6 were distributed on the fourth floor, while the sensors S_4 and S_5 were distributed on the third floor. A total of 25 points were randomly selected as the microseismic sources for localization. Table 1 lists the coordinates of sensors S_1 to S_6. Considering the components of the masonry structure building, the initial velocity interval is set as [1, 5000], which can surely include the maximum velocity value. As long as the coordinates and arrival times of triggered sensors are obtained, the localization results can be solved using the TD algorithm. Table 2 lists the authentic coordinates, the localization results and errors, as well as the velocity values of selected microseismic sources for the first localization process.

Since the localization results and errors, as well as the velocity values have been solved, it is feasible to find the minimum velocity value $v_{\min}^1$ and the maximum velocity value $v_{\max}^1$ in the first localization process, which are 183.2 m/s and 1590.8 m/s, respectively. As clarified in the theory of MLM, the $v_{\min}^1$ and $v_{\max}^1$ should be taken as the lower limit and upper limit of the velocity interval for the second localization process. Similarly, the localization results, localization errors, the minimum velocity values, and the maximum velocity values can be obtained using the TD algorithm for the subsequent localization processes, until the velocity differences are less than the threshold 10 m/s. At this time, it can be regarded as the wave velocity and the localization algorithm are both stable, which is a significant issue for microseismic sources localization. Table 3 lists the velocity values and average localization errors for the localization processes from 1st to 11st. Fig. 4 shows the change and comparison for the minimum velocity values, the maximum velocity values, the average velocity values, and the average localization errors Err_{xyz} of all the 11 localization processes. Generally, the minimum velocity value increases continuously and the maximum velocity value keeps decreasing, while the increasing and decreasing rates change from fast to slow. Besides, the minimum velocity value and the maximum velocity value tend to be stable after the 9th localization process. Obviously, it can be considered that the velocity interval composed of the minimum velocity value $v_{\min}^9$ and the maximum velocity value $v_{\max}^9$ is exactly the superior range for the actual *P*-wave velocity in the test building, which contains complex and heterogeneous propagation media. Therefore, the localization results corresponding to the velocity interval $\left[v_{\min}^9, v_{\max}^9\right]$ are more accurate than other localization results.

As shown in Table 3, the average localization error of the 9th process is the minimum among the 11 localization processes. Thus, the optimal localization results are exactly solved from the 9th process, which are listed in Table 4. Fig. 5 shows the three-dimensional localization results for the 9th process, as well as the locations of 25 authentic coordinates. The sizes of two symbols indicate the serial

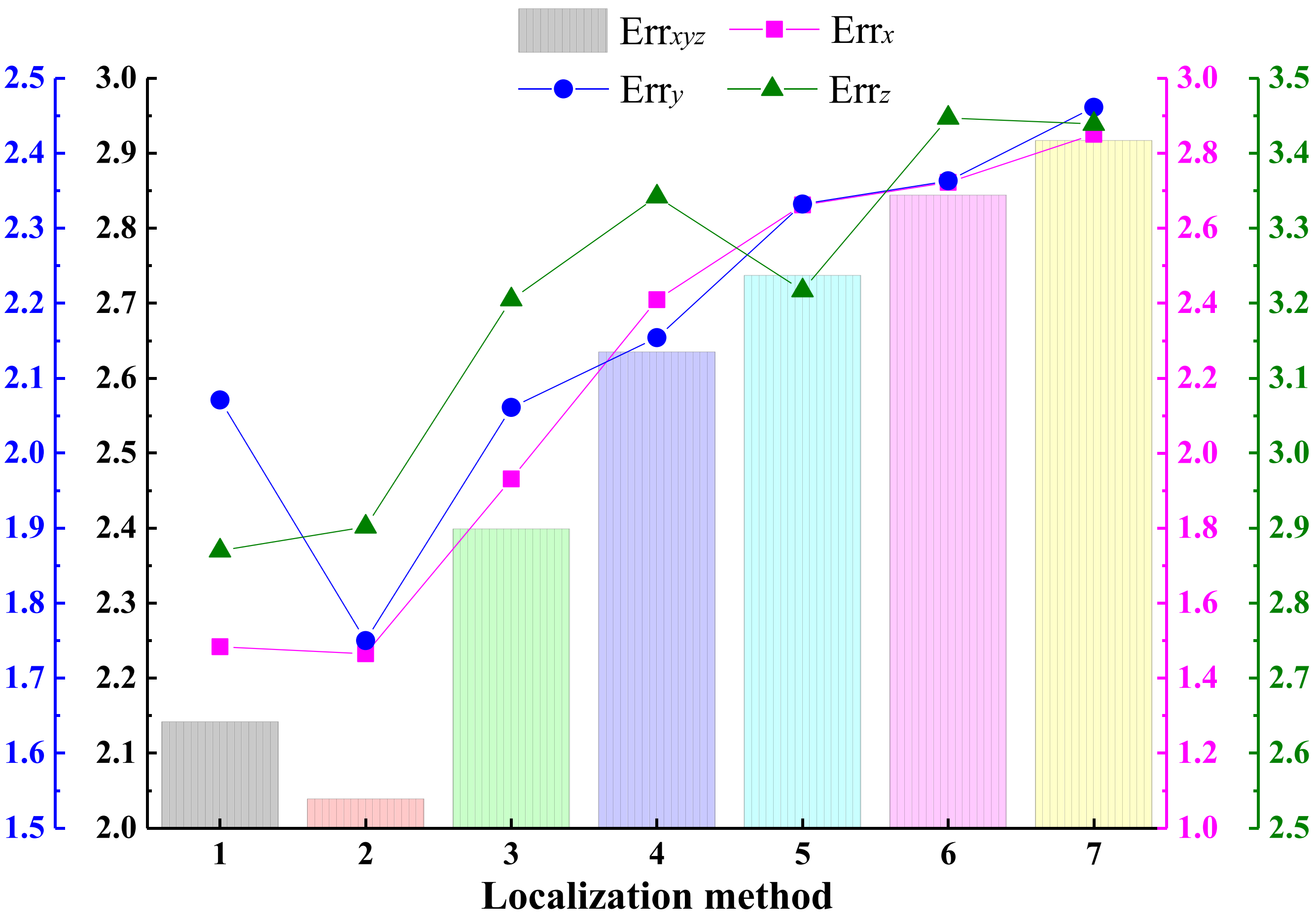


FIGURE 6. The comparison results of locating accuracy for the three methods. The red, blue, and green broken lines indicate the average localization errors for x, y, and z, respectively. The histograms indicate the Err$_{xyz}$ of each localization method.

numbers to distinguish different microseismic sources. The colors indicate the velocity values of *P*-wave in the travel paths for 25 microseismic sources. It can be seen that the distances between the 9th localization results and the authentic coordinates are small, which means that the localization method is optimized and the locating accuracy is improved effectively. Compared to the 1st localization process without optimization (TD method), the locating accuracy is improved by 5% using the proposed MLM with narrowing velocity interval, which is a significant improvement for sources localization of small scale in the heterogeneous and complex media. Through the comparison between the MLM and TD methods, the novelty of MLM lies in that it can solve the global optimum rather than a local optimum, in the optimized velocity range, instead of the whole velocity range. The computation time is reduced greatly, as well as the computation efficiency and locating accuracy is improved only with a part increase of localization program.

IV. DISCUSSION

In this paper, all the above localization processes were performed with narrowing velocity intervals rather than premeasured velocity. However, the traditional localization method (TLM) with premeasured velocity is still applied widely in many fields. It is worth comparing that the locating accuracy of the one-step localization method (the 1st localization process), the proposed MLM (the 9th localization process), and the TLM, to select the localization method with higher accuracy. As known to all, the *P*-wave velocity in the common media such as granite is around 3000-4000 m/s. Considering the heterogeneity and complexity of the propagation media in buildings, as well as the measuring accuracy for velocity, the premeasured velocity values for the TLM are set as 2000, 3000, 4000, 5000 m/s. In addition, we can add another premeasured velocity value for the TLM, which is 1350 m/s due to the optimal velocity interval is [572.1, 1433.2]. Therefore, the localization results and errors can be solved using the TD algorithm. The comparison results of the one-step localization method without premeasured velocity, the MLM without premeasured velocity, and the TLM with different premeasured velocity values are listed in Table 5. Fig. 6 shows the comparison results for the locating accuracy of the above localization methods.

As clarified before, the MLM is superior to the one-step localization method without premeasured velocity. Obviously, it can be seen that the locating accuracy of the

MLM is much higher than the TLM with different values of premeasured velocity. Through the comparison between the MLM and the TLM, the locating accuracy is improved by 15% for the TLM with the premeasured velocity of 1350m/s, which is the most accurate results among all the results of TLM. In addition, the one-step localization method without premeasured velocity is also more accurate than the TLM. Therefore, the order for locating accuracy of three methods can be sorted from better to poorer, which is the MLM, the one-step localization method without premeasured velocity, and the TLM. As the premeasured velocity is corresponding to the specific travel path of the manual source, it will not equal to the velocity values of other sources in the heterogeneous and complex media, which caused great temporal and spatial errors. It is summarized that the MLM can not only eliminate the locating errors caused by the premeasured velocity, but also can improve the locating accuracy and computation efficiency by narrowing the velocity interval, which is an efficient and effective method for locating invisible cracks and monitoring potential damage in buildings.

However, there are also several limitations of the proposed MLM. Firstly, as for the MLM, one more sensor must be triggered compared to the TLM. It can be satisfied for many common situations, but the localization difficulty will be caused for some small-scale microseismic monitoring system, where the number of sensors is limited. Secondly, the initial velocity interval should be determined appropriately when using the MLM. The determination of velocity interval depends on the characteristics of P-wave in the propagation media and the experience of calculation person. The accurate localization results will be obtained only with the reasonable and correct initial velocity interval, which include both the minimum velocity value and the maximum velocity value. Otherwise, the locating accuracy may not be improved significantly.

V. CONCLUSIONS

Currently, the accurate localization for sources in the heterogenous and complex media is a significant problem to be solved. Aiming at solving the vital problem, a MLM with narrowing the velocity interval was proposed on the basis of the TD algorithm. In this optimized localization method, the minimum velocity value and the maximum velocity value of the former localization process are taken as the lower limit and upper limit for the velocity interval, respectively, which is exactly the interval of the latter localization process. Similarly, the velocity interval can be optimized continuously, until the minimum and the maximum velocity differences between the adjacent localization processes are both less than the threshold value. At this time, it can be considered that the obtained velocity interval is the most suitable for the propagation media. Also, the localization results corresponding to this velocity interval are the most accurate among all the results of other localization processes. A source locating test was performed at a masonry structure building. Results show that the locating accuracy is improved by 5% compared to the one-step localization method without premeasured velocity. In addition, the locating results and errors of the TLM with different premeasured velocity values were solved and discussed. It is shown that the proposed MLM is obviously superior to the TLM, where the locating accuracy is improved by 15% at least. It is concluded that the multi-step can not only eliminate the locating error caused by the premeasured velocity, but also can improve the locating accuracy and efficiency for sources in the heterogenous and complex media by optimizing the velocity interval, which is a beneficial complement for the localization theory of microseismic sources. Furthermore, it can provide some useful ideas for ensuring the stability and safety of complicated and focused structures, where the invisible cracks and potential damage may occur. In the future work, the localization method for multiple specific media should be developed, which can be used to achieve the inversion of three-dimensional velocity structure. Then, the changes of source velocity structure can be used to understand and clarify the dynamics in human activity zones and assess the human influences.

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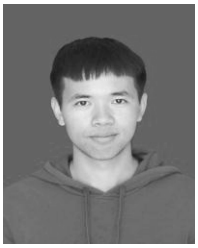

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