A fast automatic identification method for seismic belts based on Delaunay triangulation

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Abstract

Earthquake prediction practice and a large number of earthquake cases show that there may be abnormal images of small earthquake belts near the epicenter before strong earthquakes occur. For a static small earthquakes spatial distribution, due to the complexity of exhaustive algorithm, the fast automatic identification method of seismic belts has not yet been realized. Visual identification is still the main method of seismic belt discrimination. Based on the Delaunay triangulation, this paper presents a fast automatic identification method of seismic belts. The effectiveness of this method is proved by a 1000 random points test and an actual example of the 4-magnitude belts before the 2005 Jiujiang $M_{5.7}$ Earthquake. The results show that: (1) Using Delaunay triangulation method, we can fast get the spatial relationship between two neighboring points; (2) using the two neighboring relationships, it can automatically extend to cluster, which carries the key information of seismic belt; (3) using the technology of minimum enclosing rectangle (MER) for the identified cluster, we can get the shape and structural information of the MER, which can be called the “suspect seismic belt”; (4) after using the other restrictions to sort and filter the suspect seismic belt, we complete the identification of seismic belt; (5) the random and actual earthquakes trial calculation shows that the Delaunay triangulation method can realize a fast automatic identification of seismic belts; and (6) this automatic identification method may provide a research basis for earthquake prediction.

Keywords Seismic belt · Automatic recognition · Related earthquakes · Suspected seismic belt · Seismic belt clarity

1 Introduction

A big earthquake could kill thousands of people (such as 2008 Wenchuan $M_w 7.9$ Earthquake) and trigger a tsunami (such as 2011 East Japan $M_w 9.0$ Earthquake). Whether earthquakes can be predicted is one of the unsolved problems in science all over the world at present. Some scientists believe that earthquakes cannot be predicted [1]. There are other scientists who devote their lives to this scientific problem of earthquake prediction. Since the 1950s, people have discovered some pre-earthquake anomalies that may be related to the occurrence of strong

earthquakes such as seismic belt, seismic gap, seismic recurrence period, and so on [2–14]. Because of the similar distribution of acoustic emission in rock fracture experiment [15], the small earthquake seismic belt may have some unclear physical mechanism. The basic feature of seismic belt is that the seismic spatial distance on the belt is relatively short, and the seismic spatial distance outside the belt is relatively long. In the 1980s, some seismologists began to systematically research the seismic belts. Liu and Chen [2] studied the regional seismic images before 11 earthquakes with $M \geq 7$ and some earthquakes with $M \geq 6$ occurred in China from 1967 to 1976. The results showed

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that the occurrence of small seismically "belts" before large earthquakes with $M \geq 7$ was universal. Li et al. [14] systematically combed the seismic belts before 96 earthquakes by rescanning and showed that the ratio of belts before earthquakes of $M5$, $M6$ and $M7$ was 25%, 38% and 71%, respectively, which indicated that the belt image might be an important criterion for the occurrence of strong earthquakes of $M7$ or above to some extent. As we know, before any physical law is discovered, it must be tested in practice. However, it is very hard to test the universality of seismic belt anomalies before strong earthquakes. The main reason is the huge amount of calculation. For a static image of small earthquakes, it has too many seismic belt combinations. In theory, any three or more earthquakes can form a seismic belt. Taking the spatial distribution of 1000 small earthquakes as an example, there are more than 1.07×10^{301} seismic belts that can be drawn out ($C(1000,3) + C(1000,4) + \dots + C(1000,1000)$, where $C(n,k)$ is the combination symbol and $n \geq k$). Using the fastest computer at present to compute [16], it will take above 2.71×10^{276} years to complete. This is the main reason that prevents seismic belts from being tested. Therefore, it is particularly important to develop new algorithms to solve this problem. This paper presents a fast automatic identification method for seismic belts based on Delaunay triangulation.

2 The fast automatic identification method

The fast automatic identification method for seismic belts based on Delaunay triangulation was first proposed by Delaunay [17] to solve the meteorological problem of calculating average rainfall based on the rainfall of discrete weather stations. It is widely used in meteorology, surveying and mapping, finite element analysis and other fields. We use it to build the triangulated irregular network (TIN) firstly. Using TIN, we can get the distance between each adjacent earthquake. The distance carries the relationships between each adjacent point. In other words, the smaller the distance, the more significant the relationship between the two earthquakes is, and vice versa. Using an artificially determined distance as a threshold, we can eliminate some unrelated earthquakes. What remains are the couples of related earthquakes. By using the extensible property of the relationship between each of the two earthquakes, we can get multiple clusters of earthquakes, which carried the key information of seismic belt. To get the shape and structural information of seismic belt, we use the technology of Minimum Enclosing Rectangle (MER), which is called the "suspect seismic belt". The "suspected seismic belt" is actually a seismic belt. After using

the other restrictions to sort and filter the suspect seismic belt, we completed the identification of seismic belt.

In order to show the general applicability of this algorithm, we selected 1000 random earthquakes with coordinates ranging from 0 to 1 as example (Fig. 1).

To satisfy the definition of Delaunay triangulation, two important criteria must be met: (1) Characteristic of empty circle: Delaunay triangle network is unique (any four points cannot be common circle), and no other points exist in the circumferential circle of any triangle in Delaunay triangle network. (2) Maximizing the minimum angle characteristic: Delaunay triangulation has the largest minimum angle among the possible triangulation of scatter points. In this sense, Delaunay triangulation is the "nearest to regularization" triangulation. Specifically, it refers to the diagonal line of a convex quadrilateral formed by two adjacent triangles. After mutual exchange, the minimum angle of the six inner angles does not increase. Using the Delaunay triangulation algorithm [18, 19], we can get the triangulated irregular network (TIN) (Fig. 2).

As can be seen from Fig. 2, using TIN, we can not only know the structure of the whole network, but also obtain the distance information between two adjacent earthquakes. For earthquakes, the order of distances represents the order of correlation (i.e., the smaller the distance, the more significant the relationship between the two earthquakes is, and vice versa). We can use a distance threshold to interrupt the connection of unrelated earthquakes, so as to obtain the "relational earthquakes." Figure 3 shows different results of "relational earthquakes" screened by different distance thresholds. Threshold can help us establish

Fig. 1. One thousand random earthquakes distribution

Fig. 2. One thousand random earthquakes' distribution (black points) and the triangulated irregular network (gray line)

spatial connections between points that are close together and exclude points that are far away.

From the different results of "relational earthquakes" screened by different distance thresholds (Fig. 3), we can see that: (1) Under the same distance threshold, earthquakes that exceed the distance threshold are separated and earthquakes that do not exceed the distance threshold are linked together; (2) under different distance thresholds, the number and shape of "relational earthquakes" are different; (3) as the distance threshold decreases, the number of earthquakes constituting "relational earthquakes" increases gradually; and (4) the shape of "relational earthquake" in the case of small distance threshold includes the shape of "relational earthquake" in the case of large distance threshold.

In order to obtain the spatial range of "relational earthquake," we use the method of minimum enclosing rectangle (MER) [20] to calculate. MER algorithm is widely used in image edge detection and outline feature attribute extraction. It is an algorithm to calculate the minimum area rectangle including all two-dimensional scattered points [21, 22].

At present, the most frequently used criterion for determining the significance of seismic belts is proposed by Liu and Chen [2]. The restrictions are as follows: (1) The number of earthquakes constituting the seismic belt is more than 6; (2) the ratio of length to width of the belt is more than 5; (3) the ratio of distance of maximum empty section to the whole length of seismic belt is less than 1/3; and

(4) the ratio of the number of earthquakes on the belt to the number of earthquakes outside (we use a circle region with a radius of 1.2 times the length of the rectangle to represent the region of "outside") the belt is more than 75%. The calculation results are shown in Fig. 4. The black rectangular box (we called it "suspected seismic belts") in Fig. 4 is the result of calculation that fits restriction (1), and the red rectangular box (we called it "Seismic belts") is the one which fits all the restrictions.

In Fig. 4, it can be seen that we can effectively obtain the spatial range of "relational earthquake" by using MER algorithm. On this foundation, we can separate "seismic belt" and "suspected seismic belt" by using the criterion above. Because it only takes a few seconds to complete the whole recognition process with general PC computer, we call this algorithm a fast recognition algorithm.

3 Earthquake case

On November 26, 2005, a magnitude of 5.7 earthquake occurred in Jiujiang, Jiangxi Province (location of 29.7° N, 115.7° E). The earthquake occurred in an unexpected areas and killed 17 people. It is very difficult for scientists to find the abnormal to predict this earthquake. But, since 2002, the distribution of $M_L \geq 4.0$ earthquakes in East China has been "zonal" in space (Fig. 5a). In order to illustrate the relationship between the zonal distribution and the seismic belt, 200 km is used as a distance threshold to identify the seismic belt of the research region fast and automatically. The results are shown in Fig. 5. It can be seen that this method can effectively identify the belts "suspected seismic belts" (black rectangular box in Fig. 5d) and "seismic belts" (red rectangular box in Fig. 5d). From the relationship between identified seismic belt and the location of *Jiujiang M5.7 Earthquake*, we can see that this method may provide a research basis for earthquake prediction.

4 Conclusion and discussion

It is not very complex to judge whether a cluster of earthquakes is a seismic belt or not [2, 23]. The difficulty is in the "automatic" identification of seismic bands when there are multiple seismic bands. Visual recognition is still the main method in this research field. This paper provides a fast automatic recognition algorithm. This work may reduce the workload of visual identification.

How to find out the location of belted distribution from a bunch of scattered points automatically by computer

Fig. 3 Different results of "relational earthquakes" (blue-line segments) screened by different distance thresholds. (where **a** represents the distance threshold of 0.032; **b** represents the distance

threshold of 0.028; **c** represents the distance threshold of 0.024; and **d** represents the distance threshold of 0.020)

is an important problem in image identification. In case of small amount of data, we can use the exhaustive algorithm. Because of the complexity of the exhaustive algorithm in the case of large amount of data, this paper researched the algorithm of automatic identification of seismic belts.

From the above analysis, we can draw the following conclusions. Using the method of Delaunay triangulation and the distance threshold, we can exclude "unrelated earthquakes" and find "relational earthquakes." Using the two neighboring relationships, it can automatically extend

to cluster, which carries the shape and structure information of seismic belt. So, finding "relational earthquakes" is the key technology to identify seismic belts quickly in this paper. The random and actual earthquakes trial calculation shows that the Delaunay triangulation method can realize the fast automatic identification of seismic belts. For human beings, although the problem of earthquake prediction has not yet been solved, this paper may provide basic research ideas and solutions for automatic identification of anomalous belts before strong earthquakes.

Fig. 4 MER of each "relational earthquakes" under different distance thresholds.(where **a** represents the distance threshold of 0.032; **b** represents the distance threshold of 0.028; **c** represents the distance threshold of 0.024; **d** represents the distance threshold

of 0.020; black rectangles represent the "suspected seismic belts"; and red rectangles represent the "seismic belts." Other legends are shown in Fig. 3.)

For practical applications, the uncertainty of earthquake location and the completeness of earthquake magnitude cannot be ignored. They will affect the effect of this algorithm and then the recognition of seismic belts. We can try

a variety of results of earthquake location and magnitude and use the method provided in this paper to analyze the difference in seismic belt recognition results under different data input.

Fig. 5 Distribution of earthquakes above $M_{4.0}$ in eastern China mainland and its automatic identification process and results. (where red circle represents the earthquake with the time range of January 1, 2002, to November 25, 2005; yellow star represents the

location of *Jiujiang* $M_{5.7}$ earthquake; **a** represents the distribution of earthquakes; **b** represents the TIN; **c** represents the "relational earthquakes"; and **d** represents the "suspected seismic belt" (black rectangle) and "seismic belt" (red rectangle.)

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Authors' contributions WY designed the algorithm and calculated the earthquake cases, Telephone Number: (+86)10-59959314, Email: ywpro@163.com. XW, CH and GL checked the calculation results. ZL selected the earthquake cases and checked the results.

Data availability Name of code: the Code for Automatic Identification of the Seismic Belts, developer and contact address: YAN Wei, 5# Sanlihe Rd., Xicheng Str., Beijing, China, year first available: 2019,

hardware required: personal computer, software required: MATLAB trial version 2007, program language: MATLAB, program size: 20 k bit, source code: <https://github.com/ywyhz/ywAutomaticIdentityTIN>

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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