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Symmetry and tendency judgment of $Ms \geqslant 8.0$ strong earthquakes in Chile

Jin Junfang, Yin Shuyan and Yan Junping
College of Tourism and Environmental Sciences, Shanxi Normal University, Xi'an 710062, China

Abstract: The $Ms \geqslant 8.0$ strong earthquakes occurring in Chile since 1800 were analyzed using the ternary, quaternary, and quinary commensurability methods and the butterfly structure diagram, and it was believed that the earthquake signal in Chile in 2014 is relatively strong, a large earthquake is likely to occur in Chile in 2014. An analysis of spatial epicenter migrations showed that the longitudinal and latitudinal epicenter migrations have symmetry and synchronism, and there were five obvious northward migrations and four southward migrations. The symmetry axis of the longitudinal migrations is at about 71.7°W and that of the latitudinal migrations is at about 30°S; these spatial symmetry axes are located at the subduction zone on the western margin of South America, where two major plates (the Nazca Plate and the South American Plate) converge.
Key words: symmetry; tendency judgment; commensurability; butterfly structure; Chile

1 Introduction

In common natural disasters, earthquakes are characterized by a high degree of abruptness and large destructiveness. In addition, earthquakes can generate chain effects, causing a series of secondary disasters, thus making them the largest hazard to the safety of human life and property. Defending against and predicting earthquakes are more difficult than for other natural disasters such as floods, droughts, and typhoons, earthquake forecasting remains a difficult problem. Nonetheless, the studies of various earthquake prediction methods have been persisted since ancient times[1]. Prediction based on a commensurability information system has been studied as well. Commensurability is a representation of spatiotemporal symmetry. It is a kind of information system[2] and a periodic expansion; commensurability can also be considered as a mixed law after periodic superposition at different lengths[3]. At present, some researchers have obtained considerable success in using a commensurability information system for earthquake prediction. Zhu et al[4,5] employed the commensurability method to predict strong earthquake occurrence time. Long et al[6] judged the future earthquake tendency in the Sichuan-Yunnan region using the commensurability method and believed that it is likely to occur an $Ms \geqslant 6.7$ earthquake in 2008; subsequently, an Ms 8.0 earthquake occurred in Wenchuan, Sichuan province, on May 12, 2008. Yan et al[1] constructed an earthquake prediction system using the same method and thought that an $Ms \geqslant 7.2$ earthquake will occur in the Sichuan-Yunnan region in 2010; indeed, an Ms7.1 earthquake occurred in Yushu, Qinghai province, on April 14, 2010; the earthquake magnitude prediction error is within 0.1.

Based on these verified results, we judged the strong earthquake tendency in Chile using the commensurability method and the butterfly structure method, and analyzed the $Ms \geqslant 8.0$ strong earthquake tendency in Chile

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Corresponding author: Yin Shuyan, Tel: +86-29-85310525; E-mail: yinshy@snnu.edu.cn
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since 1800 using the temporal symmetry method to further explore the temporal symmetry and law of strong earthquakes in this region.

2 Overview of study area

Chile, locates at the western foot (18°–57°S, 81°30′–68°30′W) of the Andes Mountains and facing the Pacific Ocean westward, lies along the circum-Pacific seismic belt. Consequently, multiple large earthquakes and extra-large earthquakes had occurred in Chile[7]. Statistics show that an extra-large earthquake occurs once every about 20 years.

2.1 Data source

The data in this paper were mainly collected from the International Seismological Centre, and the scientific data about earthquakes, including primarily information of the $Ms \geq 8.0$ earthquakes in Chile since 1800 (Tab.1), were obtained from the sharing center.

2.2 Study methods

2.2.1 Commensurability information extraction method[8]

If one assumes that the distribution function $F(x)$ of a random variable is unknown, then $F_0(x)$ is the distribution function of a known type of population (e.g, an even distribution) and $(x_1, \cdots, x_n)$ is a sample from the population. To test H_0: $F(x) = F_0(x)$, that is, to test whether the population distribution is an even distribution, the values of all parameters in the even distribution are determined using the ternary spacing extrapolation method. Let the ternary commensurability equation be

$$X_m = X_j + X_k - X_i \tag{1}$$

where $m = j + k - i$. Within a given interval, we can estimate the confidence level $(1-\alpha)$ according to the actual interval frequency X of a composite value and the calculated interval frequency λ_x on the basis of the assumption that the data distribution is an even one. Therefore, X and λ_x become the factors expressing interval focusing.

Commensurability methods include ternary, quaternary, and quinary methods. In making a tendency judgment, the ternary commensurability method dominates the prediction results, and the quaternary and quinary commensurability methods are used as references.

2.2.2 Butterfly structure diagram method

A "butterfly structure" is a time series combination of four-year values and two groups of nested periods obtained by using curves to connect yearly values to show the periods. Using the butterfly structure method allows

Table 1 Parameters of $Ms \geq 8.0$ strong earthquakes in Chile

Sequence	Time(YY-MM-DD)	Latitude	Longitude	Place	Magnitude
1	1819-04-12	27°S	71.5°W	Copiapó	8.5
2	1822-11-20	33°S	71.63°W	Valparaiso, Quillota	8.5
3	1835-02-20	36.8°S	73°W	Concepción	8.5
4	1837-11-07	42.5°S	74°W	Castro	8.5
5	1868-08-13	18.6°S	71°W	Arica	8.5
6	1877-05-10	19.6°S	70.2°W	Vara	8.5
7	1906-08-17	33°S	72°W	Valparalso	8.2
8	1918-12-18	27.3°S	70.5°W	Copiapó	8.2
9	1922-11-11	28.55°S	70.76°W	Atacama	8.7
10	1943-04-06	30.75°S	72°W	Illapel	8.2
11	1960-05-22	38.24°S	73.05°W	Puerto Montt, Valdivia	9.5
12	1985-03-03	33.13°S	71.71°W	San Antonio, Valparalso	8.0
13	1995-07-30	23.29°S	70.1°W	Antofagasta	8.0
14	2010-02-27	35.85°S	72.72°W	Concepcion	8.8

one to analyze a temporal symmetry based on equal time intervals. Constructing yearly structure relationships and drawing two or more groups of butterfly structure diagrams with temporal symmetry confirm prediction year values and give the random probability of prediction results and the nonmission confidence level[9].

3 Analysis of results

3.1 Tendency judgment using ternary commensurability

The parameters for the calculation using ternary commensurability are as follows: $X_1 = 1819, X_2 = 1822, X_3 = 1835, X_4 = 1837, X_5 = 1868, X_6 = 1877, X_7 = 1906, X_8 = 1918, X_9 = 1922, X_{10} = 1943, X_{11} = 1960, X_{12} = 1985, X_{13} = 1995$, and $X_{14} = 2010$, where X_{15} is to be determined.

The calculation results yield two groups for 2011, one group for 2012, one group for 2013, three groups for 2014, one group for 2015, one group for 2017, two groups for 2018, one group for 2019, and two groups for 2020. The signal for 2014 is the strongest.

Thus, the following group(s) of year values with earthquake possibly occurring can be calculated:

$$X_9+X_{11}-X_5=X_{15}=2014,\quad X_9+X_{14}-X_8=X_{15}=2014,$$
$$X_{11}+X_{11}-X_7=X_{15}=2014$$

Verification calculations of historical strong earthquakes (Tab.2) yielded results consistent with actual year values, and two or more groups of ternary commensurability formulas could be written for each result; there were at most five groups (with five groups for the year 1960). It was proved that an infrequent *Ms*9.5 strong earthquake occurred on the sea floor near the Puerto Montt on May 22, 1960. This was the largest earthquake in the world on record and induced a strong tsunami, spreading to Japan far away on the other shore of the Pacific Ocean. In 2010, an *Ms*8.8 earthquake occurred in Concepcion, the second largest city of Chile. Thus, it can be seen that strong earthquakes in the Chile region exhibit good commensurability.

Table 2 Confirmation of historical strong earthquakes base on commensurable method

Year	Frequency	Year	Frequency	Year	Frequency
1819	2	1877	2	1960	5
1822	2	1906	2	1985	4
1835	3	1918	4	1995	2
1837	2	1922	2	2010	3
1868	2	1943	3		

3.2 Tendency judgment using quaternary commensurability

The parameters for the calculation using quaternary commensurability are as follows: $X_1 = 1819$, $X_2 = 1822$, $X_3 = 1835$, $X_4 = 1837$, $X_5 = 1868$, $X_6 = 1877$, $X_7 = 1906$, $X_8 = 1918$, $X_9 = 1922$, $X_{10} = 1943$, $X_{11} = 1960$, $X_{12} = 1985$, $X_{13} = 1995$, and $X_{14} = 2010$, where X_{15} is to be determined.

The calculation results yielded 10 groups for 2011, 11 groups for 2012, 8 groups for 2013, 13 groups for 2014, 13 groups for 2015, 9 groups for 2016, 5 groups for 2017, 13 groups for 2018, 8 groups for 2019, and 8 groups for 2020. The signal for 2014 is the strongest.

3.3 Tendency judgment using quinary commensurability

The parameters for the calculation using quinary commensurability are as follows: $X_1 = 1819$, $X_2 = 1822$, $X_3 = 1835$, $X_4 = 1837$, $X_5 = 1868$, $X_6 = 1877$, $X_7 = 1906$, $X_8 = 1918$, $X_9 = 1922$, $X_{10} = 1943$, $X_{11} = 1960$, $X_{12} = 1985$, $X_{13} = 1995$, and $X_{14} = 2010$, where X_{15} is to be determined.

The calculation results yielded 21 groups for 2011, 18 groups for 2012, 14 groups for 2013, 29 groups for 2014, 21 groups for 2015, 17 groups for 2016, 17 groups for 2017, 29 groups for 2018, 17 groups for 2019, and 16 groups for 2020. The signal for 2014 is the strongest.

3.4 Future tendency judgment using commensurability

By using the parameters $X_1 = 1819$, $X_2 = 1822$, $X_3 = 1835$, $X_4 = 1837$, $X_5 = 1868$, $X_6 = 1877$, $X_7 = 1906$, $X_8 = 1918$, $X_9 = 1922$, $X_{10} = 1943$, $X_{11} = 1960$, $X_{12} = 1985$, $X_{13} = 1995$, and $X_{14} = 2010$, the future tendency judgment of $Ms \geqslant 8.8$ strong earthquakes occurring in

Chile is judged as follows: $X_{15} = 2014$ (using ternary commensurability), $X_{15} = 2014$ (using quaternary commensurability), and $X_{15} = 2014$ (using quinary commensurability).

These results show that there is a relatively strong signal indicating that an $Ms \geq 8.0$ strong earthquake will occur in Chile in 2014.

3.5 Tendency judgment using symmetric butterfly structure diagram[10]

Based on the commensurability information, we plotted a butterfly structure diagram, as shown in figure 1, which indicates that the $Ms \geq 8.0$ strong earthquakes in Chile exhibit a temporal symmetry. For example, there are three periods related to 2014, i.e., 54, 92, and 108 years; there is a difference of 1 year between 55 and 54 years, which is within the acceptable error range.

The random probability of the butterfly structure is calculated using $T = M/N$, where T is the probability of occurrence in the predicted year, N is the number of total disaster events used for prediction, and M is the number of disaster events involved in the actual prediction (number of years related to the main period); here, $N = 14$ and $M_{2014} = 10$, so the random probability of an $Ms \geq 8.0$ strong earthquake occurring in Chile in 2014 is 71.43%.

3.6 Tendency analysis using commensurability structure system

It can be seen from figure 1 that the quasi-time intervals relatively significantly related to 2014 are 54, 92, and 108 years; the corresponding occurrence frequencies are 4, 3, and 3, respectively. This shows that the quasi-time periods related to 2014 have a relatively strong commensurability.

To obtain a commensurability structure system, numbers of X_i are added to or subtracted from each other for an integer set $\{X_i\}$[2]. A commensurability structure system diagram for $Ms \geq 8.0$ strong earthquakes, as shown in figure 2, was constructed by analyzing the distribution of intervalue differences. Using the ternary, quaternary, and quinary commensurability methods and the time series butterfly structure diagram demonstrate conclusively that the year with a relatively strong signal indicating occurrence of an $Ms \geq 8.0$ strong earthquake in 2014.

Through analysis of the distribution law and possible future development trends when $Ms \geq 8.0$ strong earthquakes occurred in Chile since the 19th century in figure 2, it can be concluded that the years when $Ms \geq 8.0$ strong earthquakes occurred in Chile are separated by certain intervals and obey a very strong law, being basically distributed in a parallelogram. 1877 and 1985 are 108 years apart, and 1877 and 1906 are 29 years apart; if the development obeys a parallelogram law, then 1906 will have a following interval of 108 years and 1985 will have a following interval of 29 years; thus, the years when a strong earthquake will occur in the future are just the same year (2014). Similarly, 1868 and 1960 have a following interval of 92 years, and 1868 and 1922 have a following interval of 54 years; if the development obeys a parallelogram law, then 1922 will have a following interval of 92 years and 1960 will have a following interval of 54 years; thus,

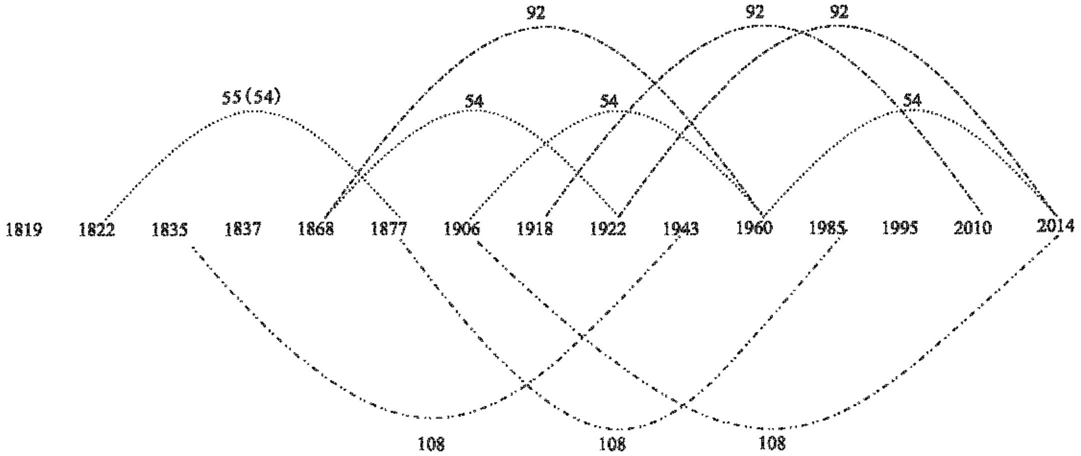


Figure 1 Butterfly structure diagram of $Ms \geq 8.0$ strong earthquake time series in Chile

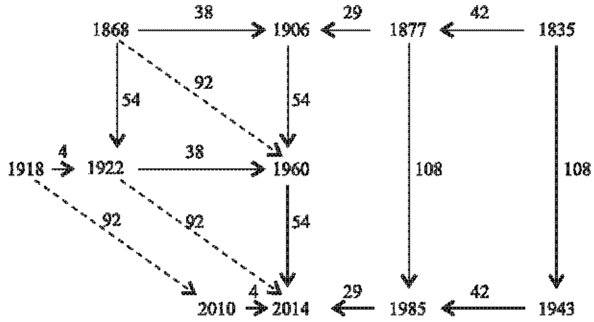


Figure 2 Commensurable structure of $Ms \geqslant 8.0$ strong earthquake time series in Chile

the years when a strong earthquake will occur in the future are just the same year (2014). Moreover, from the relationships among 1918, 1922, and 2010, it can be similarly concluded that the year when a strong earthquake will occur in the future is 2014.

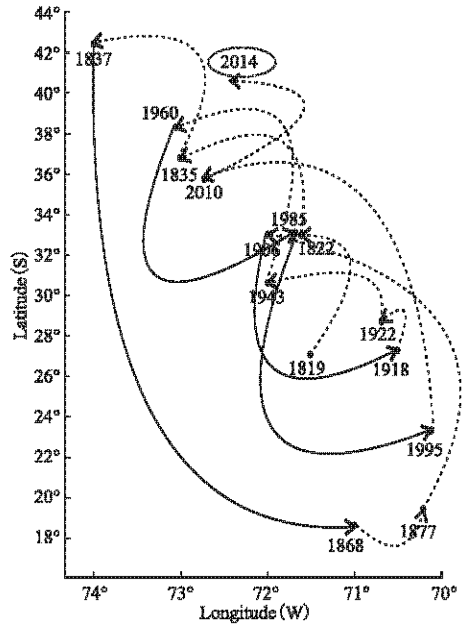
Therefore, it can be judged that an $Ms \geqslant 8.0$ strong earthquake is likely to occur in Chile in 2014. This conclusion is also obtained in the reference 11.

3.7 Spatial distribution of regional strong earthquakes

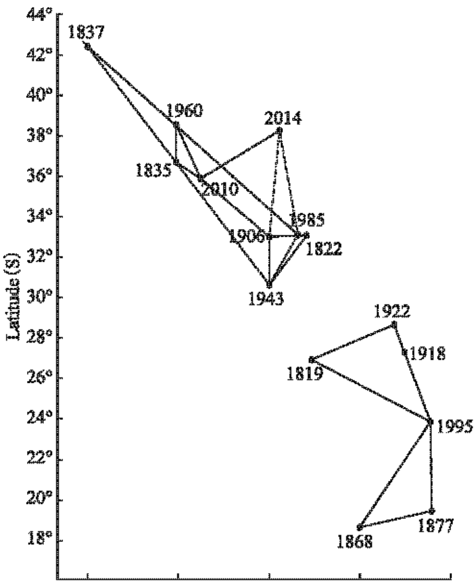
3.7.1 Epicenter migration of strong earthquakes[12,13]

Figure 3 shows that the epicenters of the $Ms \geqslant 8.0$ strong earthquakes occurring in Chile since the 19 th century exhibit an evident migration, primarily obeying a south-north tortuous migration law. Except for the slight south-north migration in 1819 and 1822, and the small-amplitude southwest-northeast migration in 1868 and 1877, there are five large migrations from southeast to northwest and four large migrations from northwest to southeast, exhibiting a regular spatial symmetry.

The spatial distribution of the epicenters of the $Ms \geqslant 8.0$ strong earthquakes in Chile indicates that all epicenters of the strong earthquakes exhibit a relatively regular isosceles triangle distribution law; the epicenter of the strong earthquake in 1918 located at one edge of a triangle, and all the other epicenters of the strong earthquakes are primarily distributed at vertices of the triangle, exhibiting a relatively strong law.



(a) Strong earthquake ($Ms \geqslant 8.0$) occurring since the 19th century



(b) Spatial distribution of the epicenters ($Ms \geqslant 8.0$)

Figure 3 $Ms \geqslant 8.0$ strong earthquake migrations in Chile

3.7.2 Longitudinal and latitudinal epicenter migration characteristics of strong earthquakes

Figure 4 shows the longitudinal and latitudinal epicenter migrations of the $Ms \geqslant 8.0$ strong earthquakes in Chile. It can be seen from figure 4 that the longitudinal epicenter migration law is obviously synchronized with the latitudinal epicenter migration law. When the longitudinal

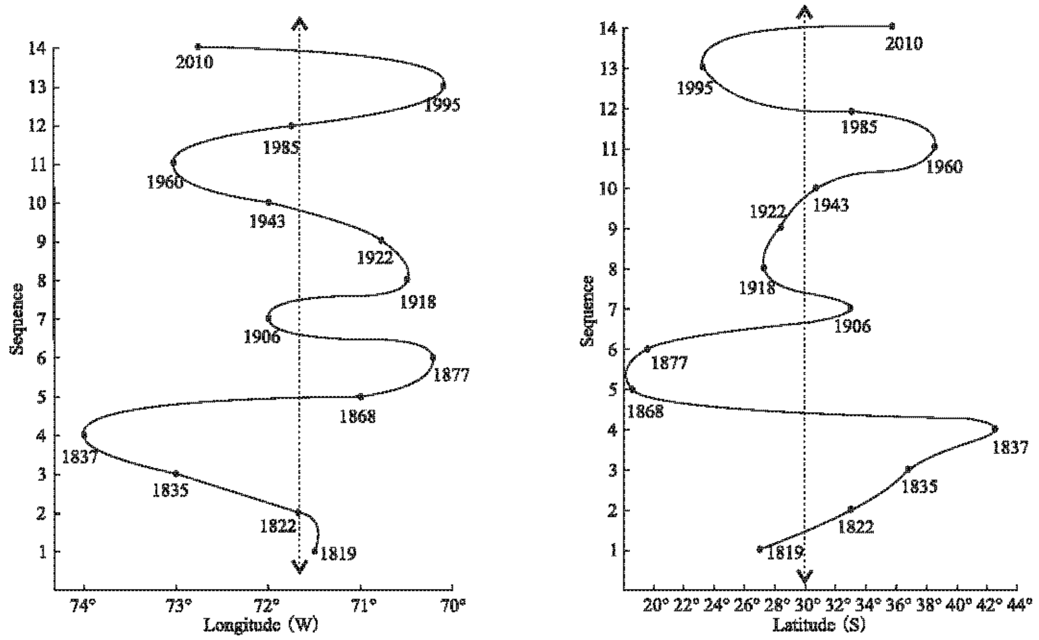


Figure 4 Latitudinal and longitudinal migrations of $Ms \geqslant 8.0$ strong earthquakes in Chile

epicenter migration of strong earthquakes proceeds westward, the latitudinal epicenter migration of strong earthquakes proceeds southward, and when the longitudinal epicenter migration proceeds eastward, the latitudinal epicenter migration proceeds northward.

The longitudinal epicenter migrations of the strong earthquakes in Chile have a symmetry axis at about 71.7°W, and the latitudinal epicenter migrations have a symmetry axis at about 30°S; these spatial symmetry axes are located at the subduction zone on the western margin of South America, where two major plates (the Nazca Plate and the South American Plate) converge. Assuming that the spatial distribution of strong earthquakes in the Chile region has a good symmetry, one can predict that the next strong earthquake in this region is likely to migrate northward, and will be in the area which locates east of 71.7°W and north of 30°S.

4 Conclusions and discussion

1) The tendency judgment using ternary, quaternary, and quinary commensurability shows that the signal indicating that an earthquake will occur in Chile in 2014 is relatively strong.

2) Using the commensurability information extraction method and the butterfly structure method, one can predict the strongest signal indicating that an $Ms \geqslant 8.0$ strong earthquake will occur in Chile in 2014 and that three groups of main periods are closely related to 2014.

3) A commensurability structure system was constructed to further explore the temporal symmetry law of the $Ms \geqslant 8.0$ strong earthquakes occurring in Chile since the 19th century. The years when $Ms \geqslant 8.0$ strong earthquakes occurred in Chile are separated by certain intervals, and the years with strong earthquakes obey a very strong law, being basically distributed in a parallelogram. From three groups of parallelogram structures with an evident law, it can be concluded that the year with a relatively strong signal indicating a strong earthquake in Chile in the future is 2014.

4) The epicenter migrations of the $Ms \geqslant 8.0$ strong earthquakes in Chile exhibit an evident symmetry and synchronism in longitudinal and latitudinal directions. The symmetry axis of the longitudinal epicenter migrations of the strong earthquakes is at about 71.7°W, and that of latitudinal epicenter migrations is at about 30°S. The spatial symmetry axes are located at the subduction zone on the western margin of South America, where two major plates (the Nazca Plate and the South American Plate) converge, and the earthquake epicenters are mainly distributed symmetrically in the northwest-southeast direction.

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