Attempts at using seismicity indicators for the prediction of large earthquakes by genetic algorithm-neural network method

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Abstract

In this paper the temporal variation of six indicators: T reciprocal of frequency, b value, $\bar{M}$ averaged magnitude, ΔM magnitude deficit, $\bar{E}$ rate of strain release or averaged energy, η deviation from Gutenberg-Richter relationship were calculated for 8 subregions in North China and 11 subregions in Southwest China from 1 January 1970 to 31 August 1998. The relation between the six indicators and the maximum magnitude of subsequent earthquakes within a certain period were analyzed by the method of categorical data analysis. A Genetic Algorithm based Neural Network method was further used to find a quantitative correlation between the indicators and the subsequent maximum earthquake. The GA-NN predicted results were evaluated by an R score criterion.

Introduction

Earthquake forecasting is one of the most challenging problems in the earth sciences. During the more than 30 years since Xingtai earthquake (M6.8, M7.2) in 1966 Chinese scientists have made great efforts to attempting to predict the next large event, using seismicity indicators among others (eg. geodetic, geophysical, geochemical.…..). Several tens of seismicity indicators and many different methods have been developed (Feng[3], Han[7], Li[11], Ma[12], Xu[23], Yin[24], Zhu[28]). While some earthquakes, such as the Haicheng earthquake, were foreseen and recognized as among the first successfully predicted cases the in the world (Chen[1], Ma[14], Zhang[26], Zhu[27]), the Tangshan devastating earthquake and many other events were not foreseen (Ma[13], Mei[18]). Hence a sharp contrast developed between the view that earthquakes cannot be predicted (Geller[4]) and the documented progress set out in Chinese articles (Han[6], Ma[17], Zhang[25]) and also in the articles (Harris[8], Keilis-Borok[10], Ma[15]) with their references.

How many and which seismicity indicators are independent, universal or important, how their fluctuations in time are related to the next principal earthquakes, are important questions which we have attempted to address in this work.

Six seismicity indicators

The six seismic indicators were calculated each month, from the data for the last 100 events before end of the month in question. The 8 subregions in North China and 11 subregions in Sorthwest China are divided by the seismic zones and distribution of active faults (Ma [16]). The events with $M \geq 2.0$ in North China and $M \geq 2.5$ in Southwest China are taken from the Chinese National Modern Catalogue in 1 January 1970 to 31 August 1998. The indicators are:

T value: The elapsed time covered by the last 100 events (reciprocal of frequency).

$$T = t - t_{100}, \quad \textbf{(1)}$$

where t is the end of the current period.

b value: Calculated by the least square method from the log-frequency plot[5] for the above 100 events, using data for each unit magnitude interval.

$$b = (k\sum M_i logN_i - \sum M_i \sum logN_i) / ((\sum M_i)^2 - k\sum M_i^2) \quad \textbf{(2)}$$

η value: The mean square deviation about the regression based on the Gutenberg-Richter relationship plot in (2)

$$\eta = \sqrt{\sum (logN_i - (a - bM_i))^2 / (k-1)} \quad \textbf{(3)}$$

M value: The mean magnitude of the last 100 events.DFSF

$$\bar{M} = \sum M_i / N \quad \textbf{(4)}$$

ΔM value: The magnitude deficit. The magnitude difference between the largest event M_{rmax} in the 100 and that expected M_{tmax} from the Gutenberg-Richter relationship.

$$\Delta M = M_{tmax} - M_{rmax} \quad \textbf{(5)}$$

E value: The rate of strain release or averaged root energy in the calculating window.

$$\bar{E}^{1/2} = \sum E_i^{1/2} / T \quad \textbf{(6)}$$

The relation between the six indicators and the maximum magnitude of subsequent earthquakes within a certain period were analyzed by the method of categorical data analysis, with the *AIC* value and weight (Sakamoto [19]), to select most significance indicators. They were then analyzed by Genetic Algorithm-Neural Network model. Only the latter will be described here.

Genetic algorithm-neural network

Although categorical data analysis could find out the better indicator subsets, what is the nonlinear relation between the indicators and the maximum magnitude of following earthquake? A Genetic Algorithm based Neural Network was used to find a quantitative correlation between the indicators and the subsequent maximum earthquake with errors. The Genetic Algorithm simulates biological body gene genetics and nutation characteristics, to build a kind of simple and effective searching method. This searching method is a global searching way, it is more effective than common searching method, and the speed of searching is very fast. The Genetic Algorithm is applied widely in the geophysics science.

Neural Network (Feng[2], Jiang[9], Wang [21]) is kind of algorithm which simulates human beings' memory and deduction characteristics; it has powerful learning ability. It can connect the explanatory variables with the response variable effectively by a nonlinear function within the learning period. In the learning process, the Back Propagate (BP) method has been adopted. BP method is made up of input forward and error back propagate. At the beginning, the network's connecting weights are given initial values, then it starts learning. Using the input explanatory variables, the network will output some results and compare these with the real values If the difference is greater or equal to a given error threshold, then the network will modify the connecting weights. Here the Genetic Algorithm is used to optimize the process of successively finding better connecting weights until the difference is small enough. Then the network has finished learning; the learning is a kind of simulating process.

Table 1 The Misfit of Magnitude for Learning Period Datasets of North China

	NC1	NC2	NC3	NC4	NC5	NC6	NC7	NC8
1	0.546651	0.517265	0.784164	0.311598	0.283033	0.967123	0.335506	0.500564
2	0.468005	0.573563	0.773244	0.165145	0.296030	0.893119	0.270186	0.549223
3	0.540910	0.465784	0.700435	0.213251	0.310576	0.694144	0.294021	0.765257
4	0.522857	0.583183	0.614063	0.188342	0.321575	0.281298	0.397040	0.871504
5	0.349970	0.647048	0.702027	0.172225	0.328698	0.277277	0.252919	0.897850
6	0.356214	0.614818	0.784833	0.163605	0.459201	0.192489	0.381671	0.734810
7	0.326088	0.549557	0.711951	0.183852	0.488535	0.203007	0.244105	0.734810
8	0.255836	0.567685	0.618032	0.202083	0.394160	0.274417	0.376030	0.660840
9	0.290113	0.604730	0.436563	0.193280	0.349718	0.252677	0.210558	0.521633
10	0.329075	0.538420	0.415863	0.239816	0.370832	0.288655	0.228742	0.572225
11	0.329075	0.495580	0.235664	0.254006	0.431761	0.317987	0.332046	0.635205
12	0.417009	0.430060	0.241302	0.238581	0.328151	0.334650	0.348455	0.725984
13	0.344877	0.490957	0.202713	0.243895	0.387019	0.253344	0.321330	0.746903
14	0.294801	0.376135	0.479051	0.230891	0.423081	0.337811	0.218629	0.634443
15	0.367121	0.526663		0.289259	0.456009	0.320038	0.339551	0.909146
16	0.268727			0.287992	0.456009	0.369439	0.401521	0.678547
17				0.191887		0.455345	0.527166	0.482447
18						0.458608	0.382738	0.345104
19						0.431822	0.363056	
20						0.448058	0.294189	
21						0.444534	0.464080	
22							0.425702	

A five-year period was used for the learning process, then the algorithm was used to predict the largest magnitude within the next one year. The whole process was then moved forward one year and repeated. Results were obtained for 8 subregions in North China and 11 subregions in Southwest China. The values in the Table 1 illustrate the output from the Neural Network algorithm for the learning period. Some regions seem more easy to model than others.

R score

To check the learning results of GA-NN, the results of a 1-year forward prediction were compared to the actual largest events occurring during that year, using the *R* score (Xu, [22]). Let *Sa* be the number of years in which an earthquake over a certain threshold occurred but was not predicted, *Sb* the number of years where an earthquake over the threshold was predicted did not occur, *Sc* the number of years where an earthquake over the threshold occurred and was predicted, *Sd* the number of years where such an earthquake was not predicted and did not occur. Then the *R* score is defined by

$$R=Sc/(Sa+Sc)-Sb/(Sb+Sd). \tag{7}$$

R_0 is 97.5% confidence level of *R*. The significance results can be got from the forward term of

Table 2 The *R* Score and R_0 of North China

	R					R_0				
M	4.0	4.5	5.0	5.5	6.0	4.0	4.5	5.0	5.5	6.0
NC1	0.25					0.20				
NC2		0.16	0.22				0.12	0.19		
NC3		0.02	0.20	0.55	0.55		0.10	0.16	0.33	0.33
NC4	0.62					0.35				
NC5	0.29	0.20				0.10	0.09			
NC6		0.04	0.09	0.15			0.08	0.08	0.17	
NC7		0.22	0.34				0.10	0.18		
NC8			0.03	0.07	0.13			0.07	0.07	0.11

Table 3 The *R* Score and R_0 of Southwest China

	R					R_0				
M	4.5	5.0	5.5	6.0	6.5	4.5	5.0	5.5	6.0	6.5
SW1	0.34	0.06	0.12	0.16		0.12	0.09	0.13	0.13	
SW2	0.30	0.51	0.60	0.37	0.17	0.10	0.18	0.38	0.34	0.22
SW3	0.27	0.27	0.07			0.12	0.18	0.11		
SW4	0.23	0.17	0.31			0.12	0.15	0.20		
SW5	0.17	0.23	0.25			0.13	0.14	0.15		
SW6	0.24	0.12				0.12	0.14			
SW7	0.15	0.07				0.10	0.12			
SW8	0.34	0.35	0.01			0.12	0.16	0.08		
SW9	0.26	0.45	0.28			0.10	0.17	0.19		
SW10		0.25	0.11				0.13	0.10		
SW11	0.18	0.16	0.08	0.09		0.08	0.10	0.11	0.10	

Genetic Algorithm-Neural Network with the higher *R* score than criterion R_0 in the all subregions. The *R* and R_0 scores are illustrated in Table 2 with the data from the 8 subregions in North China, and in Table 3 with the data from the 11 subregions in Southwest China.

Remarks and discussion

1) According to the Gutenberg-Richter Law and Chinese seismologists experiences, six seismicity indicators are selected to describe aspects of earthquake activity.
2) The categorical data analysis showed that the better indicator subsets for predicting the next bigger events are variable for the different subregions; ΔM is the indicator with the highest weight and lowest *AIC* value for most subregions of North China and Southwest China.
3) The training results of the Genetic Algorithm-Neural Network showed that the relation between 6 indicators and the magnitude of next bigger earthquake could be better represented by non-linear models in Southwest China than in North China.
4) Significant results can be got from the forward prediction term of the Genetic Algorithm-Neural Network, with the higher R score than criterion $R_{0,}$ in both North China and Southwest China.
5) This work shows that the GA-NN provides a possible method for forecasting the largest event in successive years. Further work (Vere-Jones [20]) should test the algorithm and associated software more comprehensively, for example by comparison with results for simulated and random catalogues.

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References

[1] Chen, L., Luo, P., Fu, H., Cai, J., et. al., 1996, *Medium-short term and impending predictions and precursory anomaly features for M7.3 earthquake Menglian Yunnan at the border area of China and Burma*, The Selected Papers of Earthquake Prediction in China, Seismological Press, 242-254.
[2] Feng, D., 1993, *Application of neural net in earthquake research*, Recent Developments in World Seismology, No.6, 1-5.(in Chinese).
[3] Feng, D., Chen, R., Lin, M., Jiang C., 1996, *Applications of Fuzzy sets in earthquake trend study*, The Selected Papers of Earthquake Prediction in China, Seismological Press, 63-69.
[4] Geller, R.J., Jackson, D.D., Kagan, Y.Y., Mulargia, F., 1997, *Earthquakes cannot be predicted*, Science, 275, 1616-1617.
[5] Gutenberg, B., Richter, C.F., 1956, *Earthquake magnitude, intensity, energy and acceleration*, Bulletin of the Seismological Society of America, 46, 1, 105-146.
[6] Han, W., Wang W., 1997, *New progress made in researches on seismological indexes for short-term prediction and synthetic prediction methods*, Journal of Earthquake Prediction Research 6, 181-196.
[7] Han, W., Xi, D., 1989, *The changes of b values in several zones of Sichuan Province and earthquake prediction*, in Collected Works of Practical Researches on Earth-

quake Prediction Methods, Seismology Volume, Seismological Press, 234-242(in Chinese).

[8] Harris, R.A., 1998, *Forecasts of the 1989 Loma Prieta, California, earthquake*, Bulletin of the Seismological Society of America, 88, 4, 898-916.

[9] Jiang, C., Feng, D., Wang, D., 1994, *Some application of Neural Network model in the earthquake prediction*, Earthquake Research in China, 10, 3, 262-269(in Chinese).

[10] Keilis-Borok, V.I., Kossobokov, V.G., 1990, *Premonitory activation of earthquake flow: algorithm M8*, Physics of the Earth and Planetary Interiors, 61, 73-83.

[11] Li, Z., Gao, X., 1996, *Seismic inhomogeneous degree and its application to medium-term earthquake prediction*, The Selected Papers of Earthquake Prediction in China, Seismological Press, 113-120.

[12] Ma, L., Bolt, B. A., 1988, *A comparison of seismicity C-value for Northern China and the central coast region of California*, Seismic Research, 11, 1.

[13] Ma, L., Chen, J., Chen, Q., and Liu, G., 1995, *Features of precursor fields before and after the Datong-Yanggao earthquake swarm*, Journal of Earthquake Prediction Research, 4, 1-30.

[14] Ma, L., Gao, X., 1996, *The state intensive monitoring and prediction at the Metropolitan area before Asia Game in 1990*, The Selected Papers of Earthquake Prediction in China, Seismological Press, 255-259.

[15] Ma, L., Vere-Jones, D., 1997, *Application of M8 and Lin-Lin algorithms to New Zealand earthquake data*, New Zealand Journal of Geology and Geophysics, 40, 77-89.

[16] Ma, X., 1986, *Lithospheric dynamics map of China and adjacent seas*, with Explanatory notes, Geological Publishing House.

[17] Ma, Z., et. al., 1989, *Earthquake prediction: nine major earthquakes in China (1966-1976)*, Seismological Press, Springer-Verlag.

[18] Mei, S., 1982, *Tangshan Earthquake in 1976*, Seismological Press(in Chinese).

[19] Sakamoto, Y., Ishiguro, M., Kitagawa, G., 1986, *Akaike Information Criterion Statistics*, KTK Scientific Publishers, Tokyo.

[20] Vere-Jones, D., 1995, *Forecasting earthquakes and earthquake risk*, J. of Forecasting, 11, 203-538.

[21] Wang, W., et. al., 1996, *A generation expert system for earthquake prediction based on Fuzzy Neural Networks and symbols*, The Selected Papers of Earthquake Prediction in China, Seismological Press, 222-228.

[22] Xu, S., 1989, *Ability evaluation for earthquake prediction, in Collected Works of Practical Researches on Earthquake Prediction Methods*, Seismology Volume, Science Book and Periodicals Press, 586-590(in Chinese).

[23] Xu, S., 1993, *Method of prediction of earthquake by using seismicity*, Acta Seismological Sinica, 15, 2, 517-533(in Chinese with English abstract).

[24] Yin, X., Aki, K., Ouyang, H., Chen, X., et. al., 1996, *A new approach to prediction for earthquakes and other geological disasters*, The Selected Papers of Earthquake Prediction in China, Seismological Press, 90-99.

[25] Zhang, G., Li, X., Li, L., 1996, *Research on earthquake prediction in China since the 1980s*, The Selected Papers of Earthquake Prediction in China, Seismological Press, 9-18.

[26] Zhang, X., Zeng, B., *Successful short-impending predictions of Gonghe medium-strong earthquakes*, The Selected Papers of Earthquake Prediction in China, Seismological Press, 231-241.
[27] Zhu, F., Wu, G., 1982, *Haicheng earthquake in 1975*, Seismological Press(in Chinese).
[28] Zhu, L., Zhou, S., Den, C., 1996, *The comprehensive forecasting model of projection pursuit regression*, The Selected Papers of Earthquake Prediction in China, Seismological Press, 213-221.