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MEDIUM-TIME EARTHQUAKE PREDICTION BASED ON TECTONIC FAULT ZONE DISPLACEMENT DATA

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Abstract: Extensometric measurements of deformations on a fault zone in SW Bulgaria were evaluated and an attempt was made to develop a method for quantitative assessment of relation between the fault displacements and seismic events. The relation is defined by using inverse probability method applied to variations in deformations. It has been concluded that a possibility of predicting earthquakes of a magnitude higher than $M > 5.0$, at medium time, i.e. by one to two months ahead, at a distance of 200 to 300 km in a sector S–SE and S–SW from the point of measurement in SW Bulgaria, is quite realistic.

Key words: earthquake prediction; tectonic fault; deformation field measurements

1. INTRODUCTION

During the last years serious attention has been paid to methods of medium-time earthquake prediction that would provide a chance for promulgating the state of alarm several months up to one year before the event occurs in a particular region. The possibility of such a prediction is now more real (Keilis-Borok *et al.*, 1988), and also social reactions of the population are more adequate.

The attempt of such a prediction, presented here, is based on data obtained by field measurements from SW Bulgaria. In 1982, the Institute of Geology and Geotechnics of the Czechoslovak Academy of Sciences together with the Geotechnical Laboratory of the Bulgarian Academy of Sciences installed three crack gauges (TM extensometers using Košťák's patent) to monitor active faults in the Kresna fault zone in SW Bulgaria. This region was known by its extreme seismic activity during the last century, and by the strongest earthquake in SE Europe with $M = 7.8$, which occurred on 4th of April, 1904.

The first published measurement results (Košťák and Avramova-Tacheva, 1988) show temporal variations of the three measured displacement components x, y, z (x – perpendicular to the fault direction, y – horizontal shear, z – vertical shear). The variations can be related to the earthquakes in this part of the Balkan peninsula. It has been shown that the most pronounced reaction of the three installed extensometers came from earthquakes with epicentres in Northern Greece and the Aegean Sea.

It has been attempted to develop a prognostic method based on quantitative analysis of a relation between the fault deformations and the Earth's crust stress resulting in strong earthquakes ($M > 5.0$). Such a relation can be used, under specific conditions, for medium-time earthquake prediction.

2. DEFORMATION RATES

The TM gauges are placed in the fault region as shown in Fig. 1. There are two faults here crossing each other. The longitudinal fault L representing the so-called Struma deep fault zone, and a crossfault T, well expressed in the terrain, a transverse fault of the known length of more than 200 km, are considered to be of primary importance with high influence on the seismic regime of this part of the Balkan peninsula.

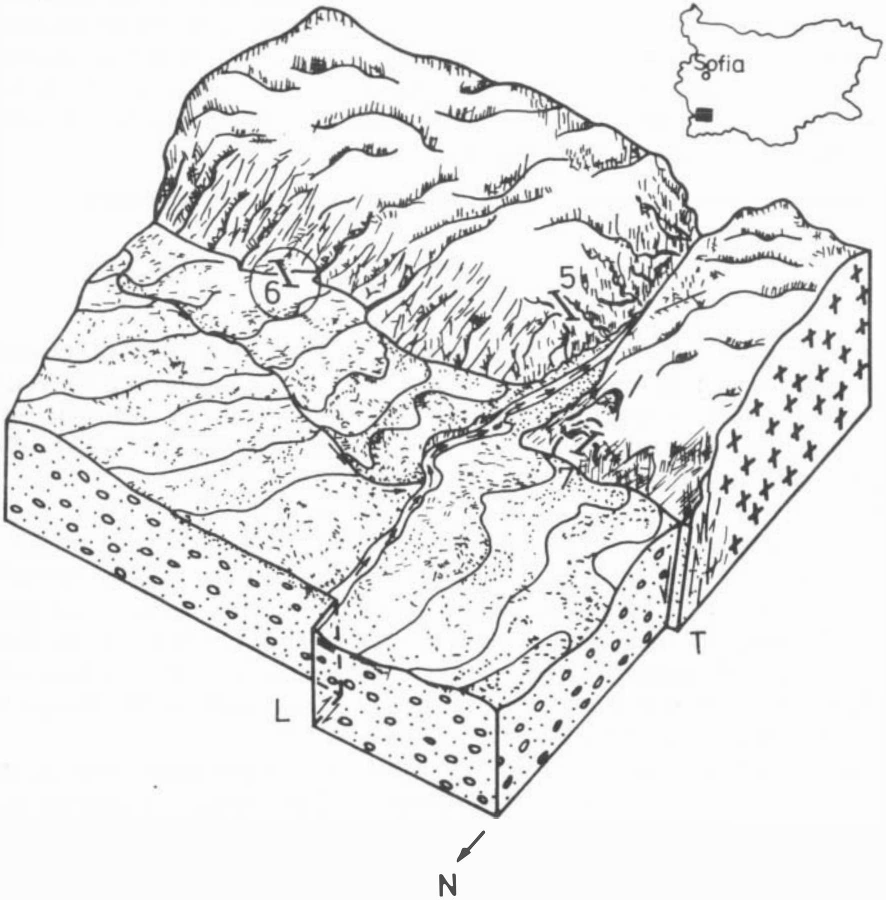

Fig. 1. The fault junction in SW Bulgaria and the location positioning of the observation points (after Košťák and Avramova-Tacheva, 1988). L – longitudinal fault zone (Struma); T – transverse fault (Kresna). Data analyzed from observation point No. 6 (encircled).

Careful study of the published data (Košťák and Avramova-Tacheva, 1988) may reveal instrument TM-71 as the most informative regarding the deformation rate observed in the fault region. The deformations detected in three components and drawn by x, y, z graphs can be converted into total deformation D using simple equation

$$D = \sqrt{x^2 + y^2 + z^2} \tag{1}$$

and plotted for about 2700 days of recording as shown in Fig. 2. The linear regression gives a very high correlation coefficient of 0.97 and reads

$$D = 2.277 + 0.00918\, d\,, \tag{2}$$

where D represents mm and d days. Hence, the average deformation rate approaches 0.00918 $\mathrm{mm\,.\,day^{-1}}$ or 3.35 $\mathrm{mm\,.\,yr^{-1}}$. However, the first impression does not imply that the deformation rate should be constant, the fluctuation in time is rather well expressed in the rate. It seems that the deformation rate exhibits alternating periods of the rate decrease and increase.

Fig. 2. Total deformation as observed at No. 6 observation point on the Kresna fault – linear regression (Košťák and Avramova-Tacheva, 1988).

A qualitative review of the rate fluctuation and the seismic activity in the region has shown that several months before earthquakes characterized by magnitude $M > 5.0$ and located up to 300--400 km from the observation point, the total deformation rate decrease is recorded, followed later by an increase. This fact has to be subjected to a more detailed quantitative analysis. A correlation between the seismic manifestations in the neighbouring seismic areas and the monthly No. 6 measurements has been carried out. A modification of the method of inverse probability can be applied in order to separate a comparatively weak, but efficient signal from the strong disturbing noise (if it exists at all).

This is a method which proved good seismoprognostic qualities. In Sofia, it has been applied recently to scanning the water level variations of the local thermal springs (Petrov *et al.*, 1989).

3. EVALUATION OF NOISE CORRELATION

When defining statistical parameters for noise correlation, attention must be paid to the selection of initial data, which should not contain anomalous observations. However, it is practically impossible to separate, in the observed variation, the anomalous from the normal by simple means. The absence of noise correlation could be most objectively determined by means of the autocorrelation function after Demidovich (1969):

$$R(\mu) = \frac{1}{m-\mu} \sum_{j}^{m-\mu} V(x_j)V(x_{j+\mu}) \tag{3}$$

where m is the number of observations, μ the interval between the first month and the month of comparison;

$$V(x_j) = \bar{V} - V_c(x_j)\,, \tag{4}$$

$V_c(x_j)$ is the calculated deformation rate for each month, $\bar{V}$ is the average value of the deformation rate:

$$\bar{V} = \frac{\sum_{j}^{m} V_c(x_j)}{m} \tag{5}$$

The ratio $R_H = R(\mu)/R(0)$ is the normalized autocorrelation function. The time interval, since which the correlation considerably increased (at $R_H(\mu) \approx 0.3$), is called radius of correlation. The radius of correlation between noises should be several times smaller than the duration of the expected anomaly preceding the earthquake.

The radius of correlation between the supposedly disturbing noises (for the deformation rates recorded by TM-71) is calculated for the whole recording period (November 1982–December 1989). For less than one month it lies at $R < 0.3$ (Fig. 3). This means that any anomaly of a period shorter than one month will be situated in the noise correlation zone.

In fact, the data were recorded at a month's interval, approximately, and thus the information can be significant only for one-month interval. Hence, the radius of noise correlation is below the measurement interval. This is the required prerequisite for the use of the method of inverse probability.

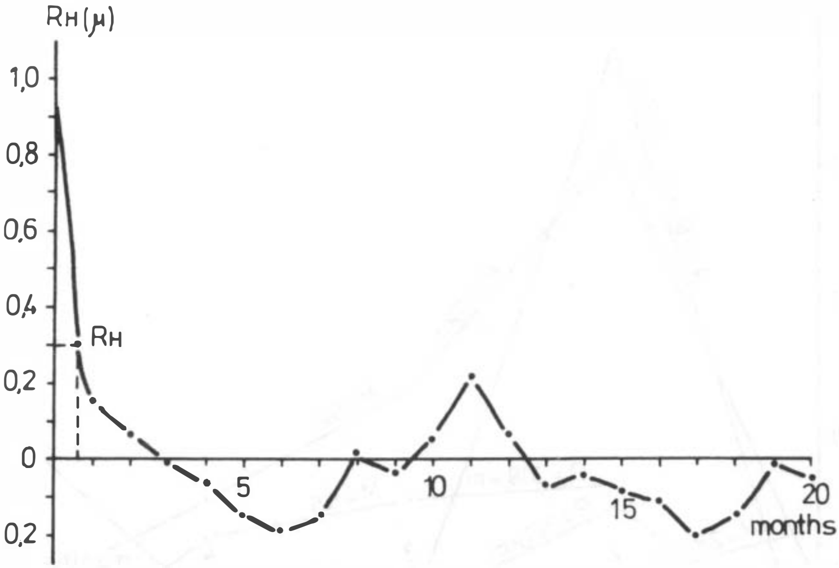

Fig. 3. Autocorrelation function of the noises for the period November 1982 to December 1989. R_H – radius of correlation for noises.

4. DEFINITION OF WARNING ANOMALY

Several terms are to be defined for the expected warning anomaly in the deformation rate variations if this investigation should be suitable for the medium-time prognosis of earthquake:

1. If the noise correlation radius is at minimum for one month, the expected anomaly should last for three months at least.

2. To be useful for a prognosis, it should have faded at least one month before the earthquake.

3. Using normalized data, the expected anomaly should have a dispersion of $\sigma^2 = 1$.

To define the model anomaly, we used the calculated normalized deformation rate preceding, by 5 months, all earthquakes of $M > 5.0$ within the radius of 400 km. The suggestion that the fault reacted to earthquakes from Greece and the Northern Aegean (Košťák and Avramova-Tačeva, 1988) has been confirmed. Fig. 4

summarizes plots of normalized deformation rates having preceded earthquakes in S, SW from the point of observation. No similar reaction was found for the earthquakes from N, NE and NW. Having made the appropriate calculations, the diagram of Fig. 5 was obtained. This represents the model anomaly of the normalized deformation rate 5 months before an earthquake of $M > 5.0$. The average anomaly value is 0, the dispersion is 1. It can be concluded that this model anomaly satisfies all the three terms stipulated for a warning anomaly.

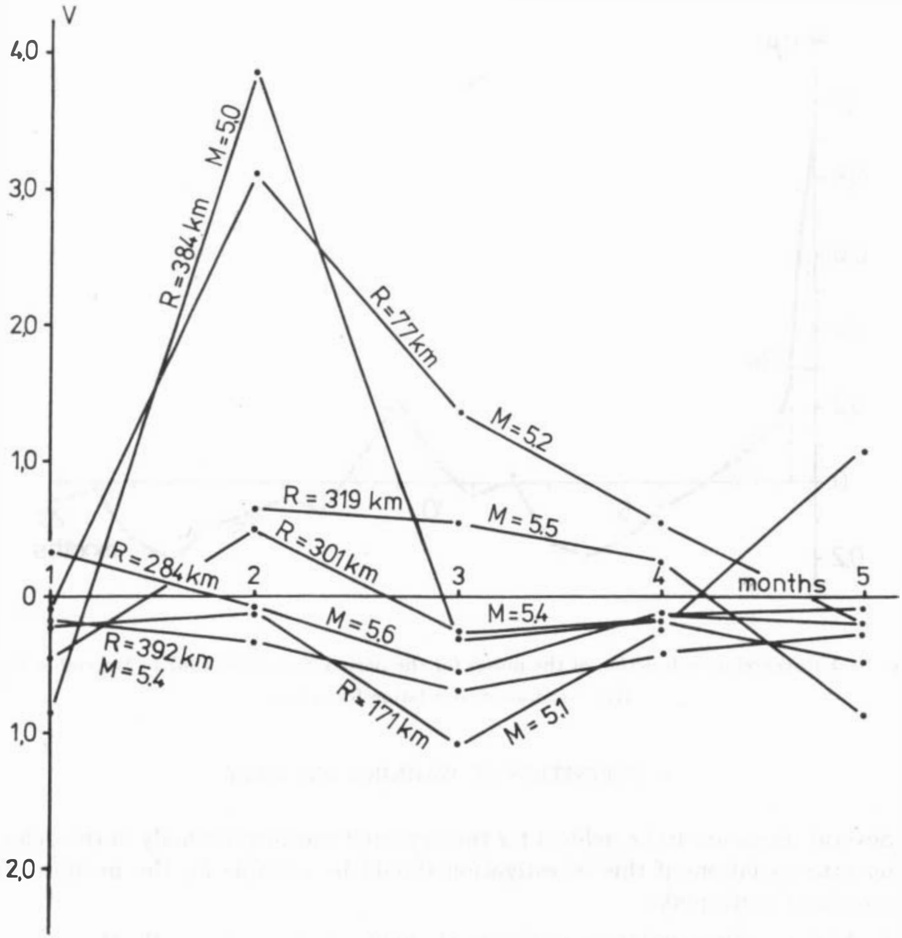

Fig. 4. Deformation rates 5 months before strong earthquakes in S–SW sector as observed at point No. 6 on the Kresna fault. Normalized.

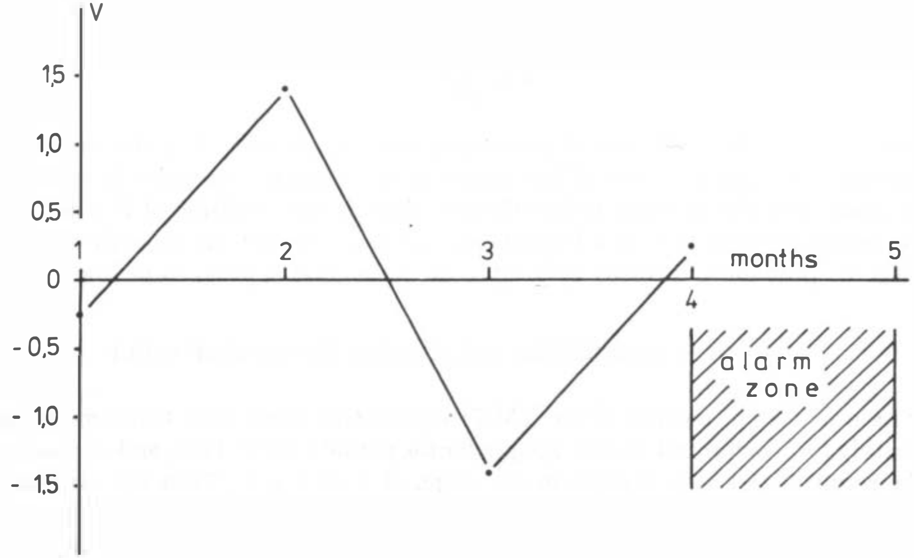

Fig. 5. Model warning anomaly 5 months before the earthquake. Normalized.

5. CALCULATION METHOD

The separation of weak signals on the background of noise calls for an optimum irreversible operation realized by mutual correlation between the input function and the effective signal. This task can be formulated as follows: A certain discrete distribution of values $F(x)$ of the observed event is given. Besides, it is supposed that, at a given interval of the measurements, a determinable anomaly $a(x)$ is present, interfered by noises $f(x)$ with certain statistical properties. It should be established whether an effective anomaly exists or not. The factual solution is based on Bayes' formula of inverse probability (Demidovich, 1969; Nikitin, 1979), taking into consideration the fact that the dispersion of the expected anomaly is equal to the noise dispersion. (It is considered that the data for an interval of, say, 5 months, have been normalized.)

The correlation is obtained by interval, constant step multiplication of the observed values $F(x)$ by m ordinates of the expected anomaly and by summarizing the products obtained:

$$KF = \sum_{j=1}^{m} F(x_j) \,.\, a(x_j) \tag{6}$$

For the purpose of our investigation this amount is attributed to the final measurement of the data interval. The curve plotted, using the values of cumulative function KF, will contain the entire information of effective anomalies. Maxima will define the intervals where it is likely to find an effective anomaly preceding an earthquake. The probability of an anomaly could be expressed as follows

$$p = \frac{e^{tk-r}}{e^{tk-r} - 1} \tag{7}$$

where e^{tk-r} is the coefficient of probability and, in our case, tk is the cumulative function KF, and r is half of the length of the expected anomaly ($r = 2.5$ for the case). For the anomaly to be effective, there is the condition of $P > 0.5$. Our investigations show that in a factual case, we may consider an anomaly any time when the probability exceeds 20%, since the noise level appears to be low.

6. RESULTS CONCERNING THE KRESNA TRANSVERSE FAULT

As a first step, records of the TM-71 observation point were transformed into monthly total deformation rate changes for the period 1982 to 1989, and normalized. The result of this step is given in the graph of V in Fig. 6. Then the diagram of cumulative function KF (Fig. 6) was drawn with the use of the anomaly model of Fig. 5, and probability P concerning the existence of such real anomalies was evaluated. The P-values exceeding the threshold of 20% were designated as alarm

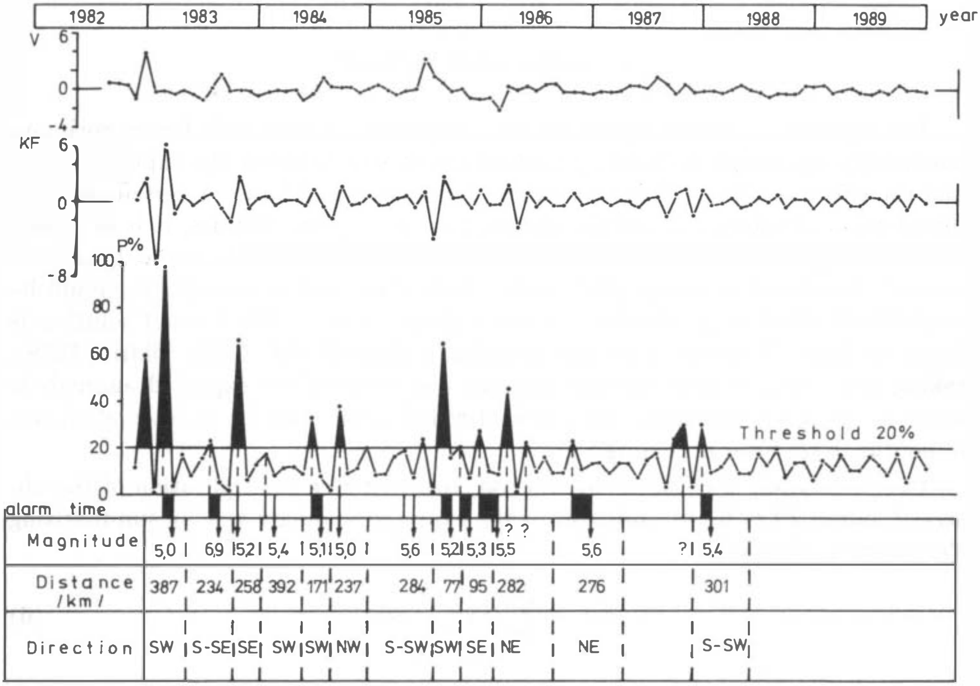

Fig. 6. Alarm indicators. Probability P of strong earthquake occurrence calculated from deformation rates V (normalized) and cumulative function KF. Observation at point No. 6 (Kresna fault) during 1982–1989. Earthquakes within the radius of 400 km, $M > 5.0$, as listed in catalogues (Košťák and Avramova-Tacheva, 1988).

indicators of expected earthquakes (Fig. 6). There were 15 indicators noticed in the given period as a result of this procedure.

At the same time, regional and global earthquake catalogues were checked for the occurrence of quakes with $M > 5.0$ within the radius of 400 km in given sectors. The success of the alarm indication was now analyzed. The result can be followed in Fig. 6.

There are 6 cases, when strong earthquakes occur one month after the alarm, and 2 cases with a 2 months' delay. These 8 cases clearly represent successful alarms.

There are 2 cases, when strong earthquakes occur a little too early. In one case it took place within the alarm month, in the other one the alarm indicator was found to follow the quake closely. Thus, only one of these two cases may be considered successful.

Among 12 strong earthquakes, recorded during that period, two were missed without any alarm ($M < 5.4$ and 5.6). A closer inspection of the diagram (Fig. 6) may reveal indicators of the two quakes, not reaching, however, the required probability.

Evidently, among 15 alarms five are false. This may be explained by the fact that earthquakes not reaching magnitude $M < 5.0$ were indicated, or the epicentre was situated outside the investigated sector.

Considering strictly successful alarms only, we come to the chance of 9 in 15, which means that the procedure will successfully report 60% of approaching earthquakes in the given sector. This seems to be sufficient probability to consider the method acceptable for the medium-time earthquake prediction.

All attempts to find empirical relations between the calculated parameters and magnitude or distance of epicentre produced very low coefficients of correlation and had to be abandoned. The best alarm indicators were obtained for the epicentres at the 200 to 300 km distance in SE–SW sector.

7. CONCLUSION

The applied unconventional approach proved to be quite successful and perspective for medium-time earthquake prognosis.

In order to improve its effectiveness, it may be recommended:

a) to improve the specification of the alarm anomaly on the basis of empirical data;

b) to find out, on the same basis, significant correlations between magnitude, epicentral distance and P;

c) to make comparative investigations and to use other data and other points of TM crack gauge displacement measurements on tectonically active fault zones.

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STŘEDNĚDOBÁ PŘEDPOVĚĎ ZEMĚTŘESENÍ NA ZÁKLADĚ ÚDAJŮ O POSUNECH V ZÓNĚ TEKTONICKÉHO ZLOMU

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Extenzometrická měření deformací na jedné z tektonických zón JZ Bulharska poskytla možnost vytvořit metodu kvantitativní analýzy vztahu mezi zjištěnými posuny a seismickými událostmi. Vztah je definován na základě metody inverzní pravděpodobnosti časových změn deformací. Bylo zjištěno, že v daném případě existuje reálná možnost předpovědi zemětřesení větších magnitud s $M > 5{,}0$ ve středním časovém předstihu, tj. jeden až dva měsíce předem, na vzdálenost 200 až 300 km v sektorech J–JV a J–JZ od bodu, v němž se konají zmíněná měření.