Bull. Nov. Comp. Center, Math. Model. in Geoph., 4 (1998), 1–13
© 1998 NCC Publisher

TangShang earthquake: analysis of the data of electromagnetic monitoring*

A.S. Alekseev, A.V. Avdeev,
E.V. Goruynov, and V.V. Skazka

An attempt is made to use the data of monitoring of electromagnetic precursors of earthquakes for reconstructing the time dynamics of some characteristics of the medium in the regions under observation. The results obtained show that, although the data are designed for statistical analysis, some parameters of the medium associated with the development of cracking can be estimated with a good accuracy.

1. Introduction

Seismologists in various seismically active regions of the Earth, as a rule, use the whole set of geophysical methods, taking into account the complex character of seismicity and for the preparation process of earthquake sources not to pass unnoticed. It is well-known that anomalous changes of different geophysical fields occurring before many strong earthquakes can apparently be considered as precursors of earthquakes. However, there are always contradictory data about the possibility of an earthquake and its parameters in the large set of such precursors.

One significant limitation of the algorithms of prediction available now based on studying the development of anomalies of various nature is basically the statistical character of these algorithms. They practically do not take into account the quantitative characteristics of the physical process of earthquake preparation itself.

Rich material on complex study of the process of seismicity [1–3] has been accumulated in the world in the last few decades. Some Russian institutes (Institute of Computational Mathematics and Mathematical Geophysics of SB RAS (former Computing Center), Institute of Geology and Geophysics of SB RAS, Institute of the Earth's Physics of RAS, and others) have contributed significantly to this problem. More than a thousand of anomalies which can be considered precursors of earthquakes have been detected in China by investigating approximately a hundred of large earthquakes [2, 4]. They form a data base of multidisciplinary investigations.

*Partially supported by the Russian Foundation for Basic Research under Grants 96–05–66058, 96–15–98542, and 98–05–65280.

The procedure of prediction of the magnitude, place and time of earthquakes has been developed by the Chinese scientists. Some real predictions have been successful. The Chinese scientists note, however, that these works are still at the initial stage and need theoretical development [5]. The theoretical foundations of the quantitative estimate of contradictory sets of precursors must be found.

The degree of cracking of rocks is one of the most important parameters, which influence various geophysical fields and rheological properties of the Earth's crust. A cracking zone occurs in a forming earthquake source. Some dynamic characteristics of this zone can serve as precursors of an approaching earthquake [1, 3, 6].

It is known that propagation of electromagnetic waves and currents is described by the Maxwell system of equations

$$\operatorname{rot} \boldsymbol{H} = \boldsymbol{J}, \qquad \frac{\partial \boldsymbol{B}}{\partial t} = -\operatorname{rot} \boldsymbol{E}, \qquad \operatorname{div} \boldsymbol{B} = 0, \tag{1}$$

where

$$\boldsymbol{B} = \mu(\boldsymbol{H}^0 + \boldsymbol{H}), \qquad \boldsymbol{J} = \sigma \boldsymbol{E}. \tag{2}$$

Here $\boldsymbol{E} = (E_1, E_2, E_3)$ is the vector of electric field strength, $\boldsymbol{H} = (H_1, H_2, H_3)$ is the vector of magnetic field strength, μ is the magnetic permeability, σ is the electric conductivity of the medium.

In practice simplified models (for specific cases) are used to solve various problems which describe the process of distribution of currents in media. Numerical calculations are carried out for these simplified models.

In our case, when the medium's structure is not known, we are forced to construct a medium's model, in which the apparent specific resistance is most similar to the resistance measured in the process of monitoring. An attempt of answering the question of a preparing earthquake using measurements of the cracking parameters can be made by analyzing time variations in the medium model obtained.

Such problems of reconstruction of the parameters of a medium by using recorded data have been investigated for a long time. These are the so-called **inverse problems**.

In the present paper we are interested in the variation of only one parameter of the medium under study, namely, cracking. This parameter influences other geophysical fields, for example, the gravitational field, the elastic wave field, the stress, strength and stability of the medium, etc. This makes necessary investigation of the multidisciplinary inverse problems (i. e., the problems of reconstruction of parameters of the medium using all available information of various physical nature). Solutions to these problems may allow more accurate reconstruction of the medium's parameters and, consequently, more accurate prediction of time of place of earthquakes [6].

Investigation of the multidisciplinary inverse problems has begun recently [1, 7]. Therefore, we do not dwell on the details of these problems in our paper.

2. An approach to quantitative interpretation of data of electromagnetic monitoring of earthquakes

An analysis of the data of electromagnetic monitoring made available to us by the Chinese specialists, allowed us to make the following preliminary conclusions:

- Routine observations are carried out with the help of the four-electrode unit (AB = 1000 m, MH = 300 m). The voltage difference in the line MH and the current strength in the line AB are measured every day. Using the results of these measurements, the apparent resistance is computed in a standard way, and the time series representing the variations of the observed signal are constructed.
- It follows from the data presented that the amplitude of variations of the apparent resistance relative to the normal noise background is small (1–2 per cent) and is comparable to the error of measurements.
- There are practically no data on geoelectric structure of the region. It is fair to note that the Chinese technology based on the statistical analysis of earthquake precursors does not need these data.
- The basic limitation of the data presented is the fact that it is difficult to use them for solving the inverse problems of geoelectrics, i. e., determining electric conductivity as a function of spatial coordinates.

In this connection, it is interesting to analyze a possibility of using the data of Chinese researchers for solving the "adapted" inverse problems of geoelectrics to attempt prediction of earthquakes. Besides, if the classically understood inverse problems are not solved satisfactorily, it would be interesting to try to get an answer to the question: what parameters of the medium can be reconstructed, or at least estimated with the help of the chosen cost functions on the basis of the optimization method using the material available?

The well-known Archie law [8, 9] relates the electric conductivity and cracking by the law

$$\sigma = a\sigma_\omega \phi^m,$$

where σ_ω is the electric conductivity of the fluid, ϕ is the porosity, m is the "cementation index".

In our investigations, we attempted to estimate variations in m and cracking versus time. As the data were not adapted to reconstruction of the geoelectric cross-section (the measurements were made not on the profile, but only between two points), we have chosen the simplest model as a basis. Namely, the whole half-space in the region under study was considered homogeneous. This means that the "averaged characteristics of the medium" in the vicinity of observation points were reconstructed [7].

In solving the inverse problem we use the minimization technique of data misfit functional of recorded and measured data.

Let us describe this approach in more detail.

It was assumed that the parameter m in the time interval (t_0, t_1) considered varies in accordance with the following law:

$$m = m_0 + \alpha t, \tag{3}$$

where t is the time.

The conductivity σ is sought as a function that depends on the time t in the following form:

$$\sigma(t) = A\sigma_\omega \left[\sum_{k=1}^{N} [\, a_k \sin(kLt) + b_k \cos(kLt)]\right]^{(m_0+\alpha t)}, \tag{4}$$

where the constants L and N are chosen from empirical analysis of the curve of the given apparent resistance (the dominant period of oscillations is taken into account).

The data misfit functional ("cost" function) has been chosen in the standard form for inverse problems of geoelectrics:

$$\Phi = \int_{t_0}^{t_1} |\rho(t) - \rho_{\mathrm{mod}}(t)|^2 dt, \tag{5}$$

where $\rho(t)$, $\rho_{\mathrm{mod}}(t)$ are the measured and calculated apparent resistance, respectively, at the given m_0 and α.

Using standard optimization programs, we find m_0 and α (as well as a_k and b_k), at which Φ reaches a minimum, at each fixed moment of time of real signal recording.

Then m_0 and α are found, at which Φ reaches a minimum.

The parameter α is most informative, because it shows the dynamics of the process. Moving the "window of observation", namely, the interval (t_0, t_1) along the whole data array of monitoring, we reconstruct "the evolution of the dynamics" of the parameter α.

Another form of the Archie law [9] is also known:

$$\sigma = A\sigma_\omega \,[S(t)\phi]^m . \tag{6}$$

Here the function $S(t)$ characterizes saturation of pores (or cracks) with water.

Numerical experiments on reconstruction of the parameter $\alpha(t)$ have been carried out. In these experiments, the data of variation in the ground water level made available to us by the Chinese specialists were taken as the function $S(t)$.

The following comparisons have been made:

- A series of test solutions of the direct problems has been carried out. The behavior of solutions at varying model parameters of cracking has been studied within the framework of the Archie law to understand what model adequately describes the variation of the observed data versus time.
- After a series of numerical experiments, the cost functions most suitable for solving the inverse problems have been chosen.
- Test calculations for solving the inverse problems using synthetic data have been carried out.
- It has been concluded, on the basis of the results of work using real data, that the available experimental material and the data on the medium under study are suitable for solving the inverse problems in "adapted" statements.
- The possibility of using the data made available by the Chinese side for solving the inverse problems in combined statements has been analyzed.

The map of the Hebei Province is shown in Figure 1. The place of TangShang earthquake is marked by $*$ symbol. The locations of resistivity stations are marked by $\circ$ symbols and location of the ground water level station is marked by ▪ symbols.

Figure 2 illustrates a plot of the reconstructed function $\alpha(t)$ using all available data in complex method.

Figures 3, 4, and 5 represent the data made available to us by the Chinese specialists: a plot of measured apparent resistance from stations D41ZX, D41KP, D41CL (the upper part of the figures), and a plot of the reconstructed function $\alpha(t)$, which characterizes variation in the medium's cracking (the lower part of the figures).

Figure 6 illustrates a plot of the reconstructed function $\alpha(t)$ using available data about saturation of pores with water from station SQ7279R (using formula (6)) and resistance from station D41BD in complex method.

The analysis and study of the real data have shown that the effective parameters of cracking can be reconstructed within the framework of the Archie law with some certainty. In any case, the obtained estimates of the effective parameters associated with the cracking of the medium correlate well with the time of earthquakes.

Interactive software has been created on the basis of the method described above.

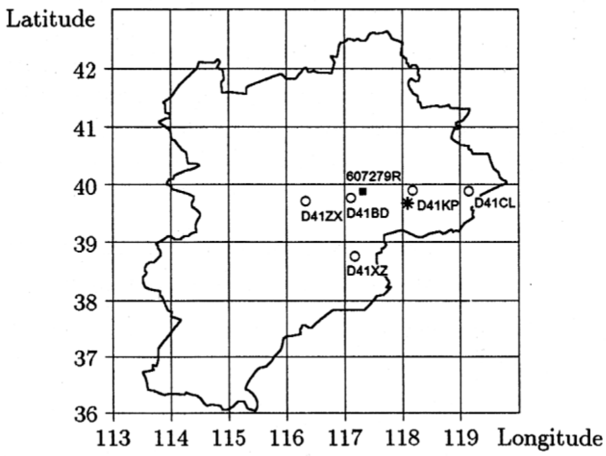

Figure 1

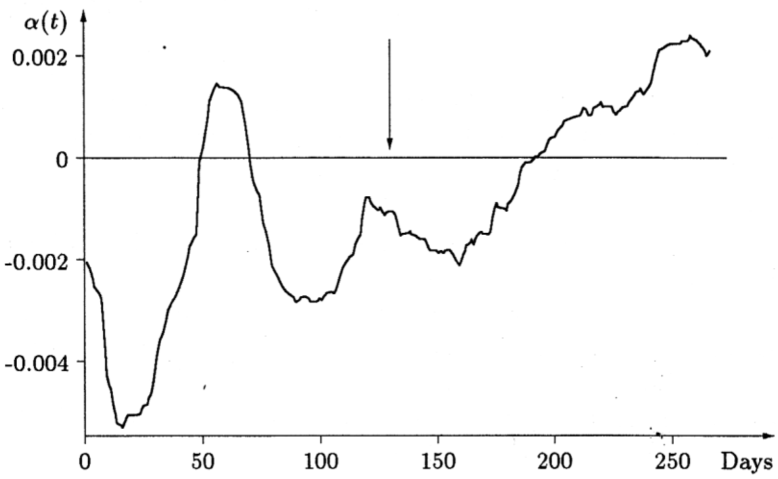

Figure 2

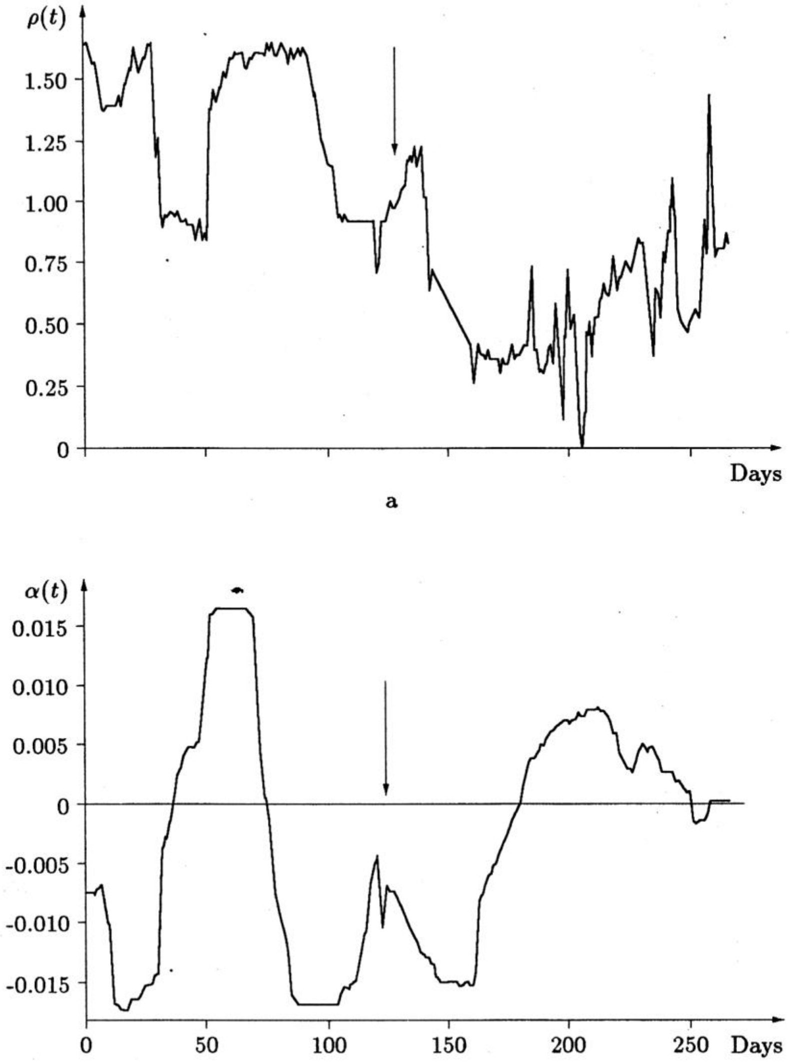
ρ(t)
1.50
1.25
1.00
0.75
0.50
0.25
0
Days
a
α(t)
0.015
0.010
0.005
0
-0.005
-0.010
-0.015
0
50
100
150
200
250
Days
b

Figure 3

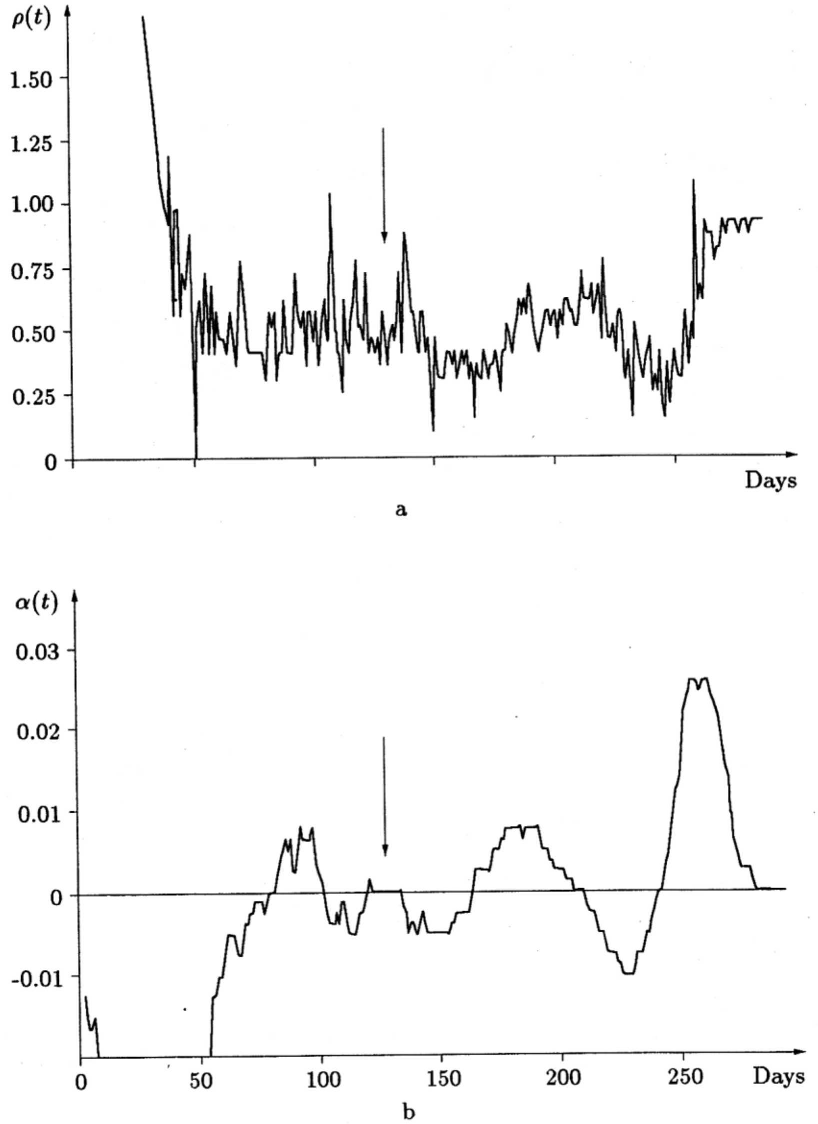
ρ(t)
1.50
1.25
1.00
0.75
0.50
0.25
0
Days
a
α(t)
0.03
0.02
0.01
0
-0.01
0
50
100
150
200
250
Days
b

Figure 4

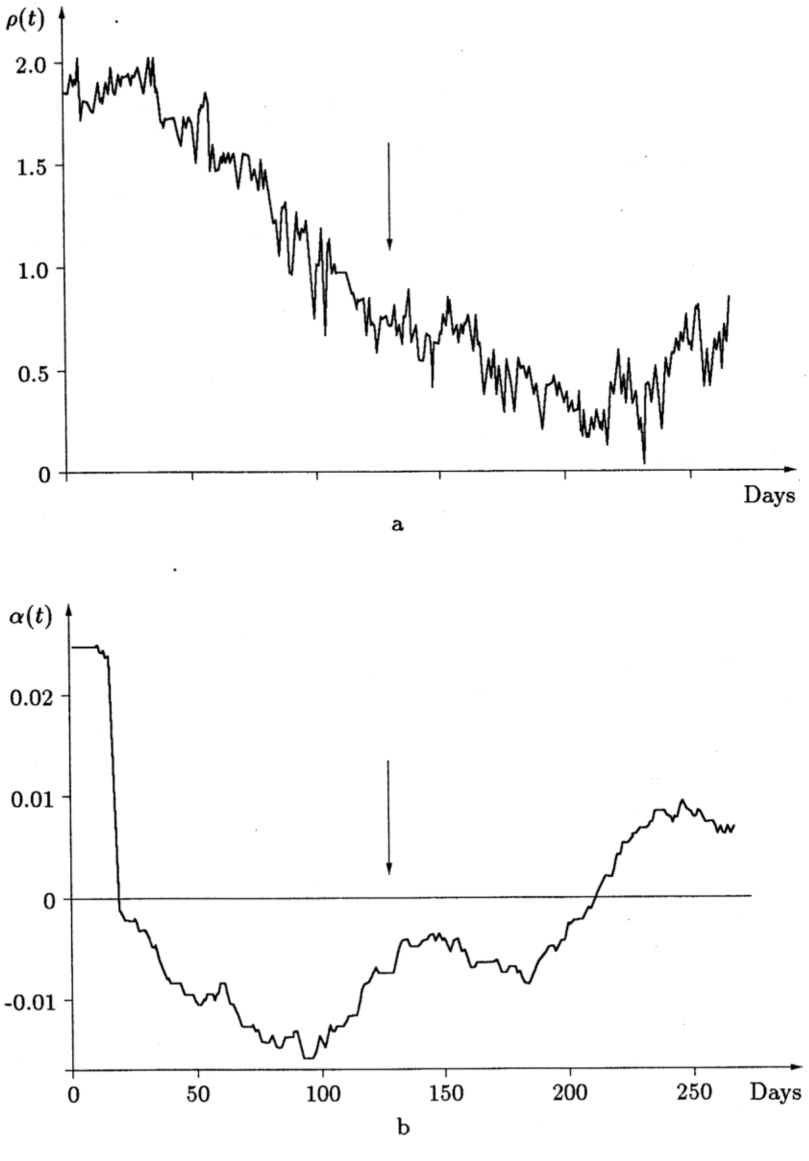

Figure 5

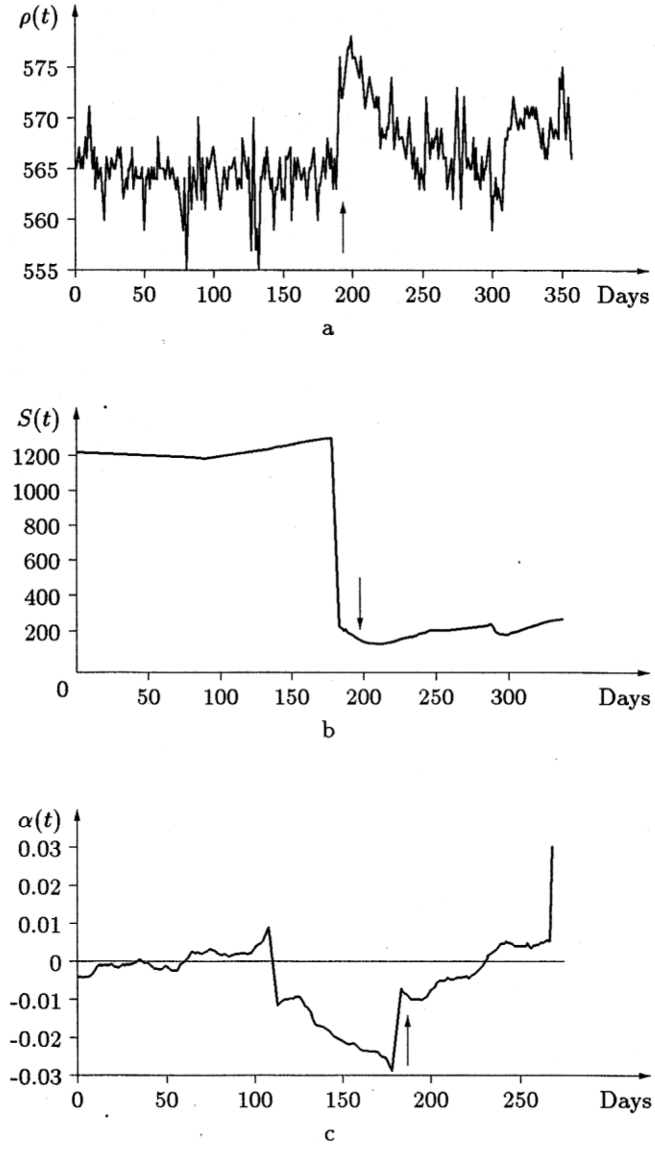
ρ(t)
575
570
565
560
555
0 50 100 150 200 250 300 350 Days
a
S(t)
1200
1000
800
600
400
200
0
50 100 150 200 250 300 Days
b
α(t)
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
0 50 100 150 200 250 Days
c

Figure 6

3. Description of interactive software

General description of the software

Interactive software realizes the approach proposed for processing of the data of monitoring of electromagnetic earthquake precursors to reconstruct the time dynamics of some characteristics of the medium in the regions under observation. Although the data are suitable for statistical analysis, some parameters of the medium which due to development of cracking can be estimated using interactive software.

In the interactive regime, the software developed makes it possible to:

- browse and reject the data of monitoring,
- choose an optimal size of time "window",
- choose optimal values of the parameters L and N using empirical analysis of the curve of the given apparent resistance (dominant period of oscillations),
- carry out the procedure of minimization of the data misfit functional in a chosen time interval,
- draw a plot of measured apparent resistance versus time and a plot of the reconstructed function $\alpha(t)$, which characterizes variation in the medium's cracking,
- draw a plot of variation in the ground water level.

The use of the ingenious methods and algorithms makes it possible to reduce considerably computer resources necessary for solving all the problems listed and to realize the process on personal computers (even on PC-486).

The software is of modular structure. This makes possible to update individual parts taking into account new demands and include them into any program packages for earthquake prediction.

Requirements to equipment and software environment of the system:

- IBM compatible computer,
- operating system Windows95,
- mathematical program package Mathematica (ver. 3.0 or higher),
- programming language Watcom C++.

Description of the structure and functional possibilities of the system

User interface with.software is via a system of control panels with hierarchical structure of access. The panels consist of menu options for control of individual stages of processing of input data. After start of software a user must select a menu option in the main control panel. Call of the functional panel for plotting a graph of data processing corresponds to each of four menu options.

The software is divided into five main parts (5 menu options of the main control panel):

- "Brief description of the method", it contains reference material with a description of the methods used and work with the package.
- "Input of data of monitoring", reading of files with data of monitoring.
- "Visualization of input data", plotting of graphs of input data.
- "Input of parameters", input (or reading) of parameter values typical of the given region.
- "Search for the minimum point of the functional", it realizes the procedure of minimization of the functional with simultaneous visualization of graphs of reconstructed parameters.

4. Further development of software

It is planned to develop the system in the following directions:

- increase in the number of mathematical models and numerical algorithms realized in the system software,
- creation of a data bank with the results of processing of data from various stations.

As for the first direction, combination of the developed method with other geophysical methods is planned.

As for the second direction, it is proposed to create data bases of various measured parameters for specific regions under study.

References

[1] Alekseev A.S. A multidisciplinary mathematical model of combined foreshock for earthquake prediction research // Journal of Earthquake Prediction Research. – 1993. – Vol. 2, № 2. – P. 137–150.

[2] Shirong Mei. Progress in earthquake prediction in China during the 80s // Journal of Earthquake Prediction. – 1992. – Vol. 1, № 1. – P. 43–57.

[3] Sobolev G.A. Earthquake prediction in the USSR: fundamental principles // Journal of Earthquake Prediction. – 1992. – № 1. – P. 21–42.

[4] Zhaocheng Z., Dalin Z., Yongsheng L., Qing J. Studies on earthquake precursors and the multidisciplinary earthquakes prediction in China Maindland // Journal of Earthquake Prediction Research. – 1992. – Vol. 1, № 2. – P. 191–205.

[5] Li Ma, Jianmin Chen, Qifu Chen, Guiping Liu. Features of precursor fields before and after the Datong–Yanggao earthquake swarm // Journal of Earthquake Prediction. – 1995. – Vol. 4, № 1. – P. 1–30.

[6] Alekseev A.S., Avdeev A.V., Skazka V.V. Combined inverse problems of geophysics for the earthquake prediction studies // Proceedings of Intern. Congress ECMI 96. – Kopenhagen, 1996. – P. 508–511.

[7] Alekseev A.S. On statement of combined inverse geophysics problems // Siberian Journal of Computer Mathematics. – 1992. – Vol. 1, № 1. – P. 47–58.

[8] Archie G.E. The electrical resistivity log as an aid in determining some reservoir characteristics // Trans. AIME. – 1942. – Vol. 146. – P. 54–62.

[9] Sen P.N., Scala C., Cohen M.H. A self-similar model for sedimentary rocks with application to the dielectric constant of fused glass beads // Geophysics. – 1981. – Vol. 46, № 5. – P. 781–795.