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Modeling earthquakes via computer programs

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Abstract

Modeling earthquakes plays an important role in investigation of different aspects of seismic risk. The paper continues previous studies and describes the user-friendly software destined for numerical simulation of lithosphere dynamics and seismicity by means of different modifications of the block model, which exploits the hierarchical block structure of the lithosphere. As a result, the model produces an earthquake catalog, and the programs give an opportunity to visualize it in different ways. The programs work in an interactive mode with a window interface. Numerical approximation of the Vrancea seismic region is considered as an example of application of the software. Parallel algorithms allowing to perform modeling dynamics of rather large structures are outlined.

Acknowledgments

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1. Introduction

The necessity of catastrophe modeling is stipulated both by the essential increase of losses due to recent natural and anthropogenic hazards and by a lack of real observation data. Proliferation of high-risk objects, clustering of population, comprehensive destabilization of large cities and industrial regions resulted in the forecast that the more frequent and larger damages of man-caused and ecological catastrophes can destroy the existing insurance system [1, 2]. This fact makes the problem of estimation of risks of natural catastrophes to be very important.

The present paper continues investigations started in [6] where the main attention was focused on earthquakes representing an example of local catastrophic events of great destructive force, statistical analysis of which is rather difficult due to incompleteness of reliable information. The problems of seismic risk were illustrated for the concrete seismic region, a brief overview of different approaches to mathematical modeling of lithosphere dynamics was presented, and the model of block structure dynamics and seismicity and its applications were described in detail. It was pointed out that the study of seismicity with the statistical and phenomenological analysis of the real earthquake catalogs has the disadvantage that the instrumental observation data cover, in general, a rather short time interval, in comparison with the duration of tectonic processes responsible of the seismic activity. This difficulty can be overcome by means of numerical modeling the seismic process. The synthetic earthquake catalog may cover arbitrary long time interval that allows to acquire a more reliable estimation of the parameters of an earthquake flow. In problems of risk estimation the numerical modeling plays the role of a generator of possible scenarios of catastrophic events [6]. Thus, the

importance of the software destined for numerical simulation of lithosphere dynamics and seismicity by means of different modifications of the block model is evident. In this study the emphasis is on the description of possibilities and main modes of work of the programs producing an earthquake catalog as a result and giving an opportunity to visualize it in different ways. In addition, the programs help us to analyze a catalog in order to find similarity between model and real data (the model should be adequate, if we use results of modeling as scenarios of possible catastrophes, and the programs serve as tools for checking whether it is so). As an example of application of the software, numerical approximation of the Vrancea seismic region is considered.

The paper has the following structure. First, we give a brief overview of two-dimensional (2D) and three-dimensional (3D) block models of lithosphere dynamics. Then we describe the possibilities and main modes of work of computer programs realizing these models. The conclusive section of the paper is devoted to discussion on necessity of application of numerical parallel algorithms for solving the problem of modeling dynamics of a real system of tectonic plates.

2. Block models: the brief description

Before passing to the description of possibilities of programs EARTH and EARTH-3, we give briefly main statements and notions of the models in question (2D model is explained in detail, for example, in [3, 6], 3D model – in [4, 5]) with emphasis on characteristics representing input data for the programs.

2.1. Block structure geometry

A layer with depth (thickness) H between two horizontal planes is considered. A block structure is a part of this layer limited and divided into blocks by planes intersecting the layer. Parts of these planes, which are inside the block structure or adjoin to it are called "faults". The block

structure geometry is defined by the description of intersection lines of faults (they will also be called faults below) with the upper plane and by angles of dip for the fault planes. The geometry on the lower plane is assumed to be similar to the one on the upper plane.

The notion "vertex" is used for the description of the system of faults. Three or more faults can not have a common point on the upper plane. Vertex is a common point of two faults. A fault is defined by indication of its initial and end vertices. The angle of dip for the fault plane is measured to the left of the fault. The fault direction is the direction from its initial point to its end point. The structure is separated by the faults into blocks. A common part of any block with the upper plane is a polygon. "Boundary blocks" are defined for the structure to introduce the movement of boundaries. A boundary block is a continuous part of the structure boundary between two vertices, which consists of some sides. It is defined by the indication of its initial and end vertices. A fault segment is a part of a fault plane limited by the upper and lower planes and lines, which connect positions on the upper and lower planes of two consecutive vertices of the fault. It is a trapezium.

2.2. Parameters and movements

Block parameters. The interaction between the block and the underlying medium at any point of the common part of the block and the lower plane (the block bottom) is described for 2D model by the equation

$$\frac{d\Delta\mathbf{u}}{dt} = W_u \mathbf{f}_u, \quad (1)$$

where the horizontal elastic force per unit area \mathbf{f}_u is defined by the formula

$$\mathbf{f}_u = K_u (\Delta\mathbf{r} - \Delta\mathbf{u}). \quad (2)$$

Here $\Delta \mathbf{r}$ is the vector of the total horizontal displacement between the block and the underlying medium at the point, $\Delta \mathbf{u}$ is the vector of the horizontal inelastic displacement at the point. K_u and W_u are parameters, which characterize the interaction between the block and the underlying medium. In 3D model the additional vertical elastic force \mathbf{f}_u^n is introduced. This force per unit area is found from the formula

$$\mathbf{f}_u^n = K_u^n \Delta z, \quad (3)$$

where Δz is the total vertical displacement between the block and the underlying medium at the point, K_u^n is a coefficient characterizing the elastic interaction in the vertical direction. The values of all the coefficients may be different for different blocks.

Fault parameters. The interaction between two adjacent blocks at any point of the fault plane separating them is described for 2D model by the equation

$$\frac{d\Delta w}{dt} = W \mathbf{f}, \quad (4)$$

where the elastic force per unit area \mathbf{f} in the fault plane is defined by the formula

$$\mathbf{f} = K (\Delta \mathbf{r} - \Delta \mathbf{w}). \quad (5)$$

Here $\Delta \mathbf{r}$ is the vector of the total fault plane displacement between the blocks at the point, $\Delta \mathbf{w}$ is the vector of the inelastic fault plane displacement at the point. K and W are parameters which characterize interaction between blocks in the fault plane. In 3D model the additional inelastic displacement δ_n and elastic force f_n , which are normal to the fault plane are introduced. The equation

$$\frac{d\delta_n}{dt} = W^n f_n. \quad (6)$$

describes the evolution of δ_n . The elastic force per unit area f_n is found from the formula

$$f_n = K^n (\Delta_n - \delta_n), \quad (7)$$

where Δ_n is the total normal displacement between the blocks at the point, W^n and K^n are coefficients. The values of all the coefficients may be different for different faults.

Another group of the fault parameters define a failure rise. Denote

$$\kappa = \frac{|\mathbf{f}|}{P - p_0} \quad (8)$$

where P is the parameter which may be interpreted as the difference between lithostatic and hydrostatic pressure, p_0 is the block reaction force per unit area which is normal to the fault plane at the point (for 3D model it is valid $p_0 = f_n$). The value of P is the same for all faults. When the value of κ in any part of a fault reaches the level B a failure occurs. After that the components of the vector $\Delta \mathbf{w}$ (and δ_n for 3D model) are changed sharply to reduce the value of κ to the level H_f ($H_f < B$). Parts of the faults for which the failure occurred are in creep state. It means that in equation (4) (and in (6) for 3D model) the parameter W_s , $W_s \geq W$ (W_s^n , $W_s^n \geq W^n$) is used instead of W (W^n). Creep continues while the value of κ is higher than the level H_s ($H_s < H_f$). When $\kappa \leq H_s$ the cell returns to the ordinary state and henceforth the parameter W (W^n) is used in equation (4) (equation (6)) for this cell. Values of the parameters B , H_f , H_s , W_s , and W_s^n may be different for different faults.

Movements. The movement of the block structure is caused by the movement of its boundaries (boundary blocks) and the underlying medium.

In 2D model a boundary block is supposed to move progressively in the horizontal plane with a constant velocity (with components V_x , V_y) and to rotate around the coordinate origin with a constant angle velocity U . The medium underlying a block is supposed to move progressively in the horizontal plane with a constant velocity (with components V_x , V_y) and to rotate around the geometrical center of the block bottom with a constant angle velocity U .

In 3D model the displacement of a boundary block is determined by a constant translation velocity with three components V_x, V_y, V_z and by three angle velocities U_1, U_2, U_3 of special rotation around the coordinate origin. The displacement of the medium underlying a block is determined by a constant translation velocity with three components V_x, V_y, V_z and by three angle velocities U_1, U_2, U_3 of special rotation around the geometrical center of the block bottom.

In the both models the system of equations which describes the movement of the block structure is a linear one and has the following form

$$A\mathbf{z} = \mathbf{b} \tag{9}$$

where the components of the unknown vector $\mathbf{z} = (z_1, z_2, \dots, z_k)$ are the components of the translation vectors of the blocks and the angles of their rotation around the geometrical centers of the bottoms ($k = 3n$ and $k = 6n$ for 2D model and 3D model respectively, n is the number of blocks). It should be noted that the matrix A does not depend on time and may be calculated a priori.

2.3. Discretization

Time discretization is defined by a time step Δt and the states of the structure are calculated for the discrete time moments $t_i = t_0 + i\Delta t$ ($i = 1, 2, \dots$), where t_0 is the initial moment.

Space discretization is defined by a space step ε and applied to the surfaces of the fault segments and to the block bottoms. The discretization of a fault segment is performed as follows. Each fault segment is a trapezium, which is divided into rows and then into small trapeziums (cells) within every row so that side lengths are less than ε for all cells. The bottom of a block is a polygon, which is divided into trapeziums (triangles) by segments passing through its vertices and parallel to axis Y . Discretization of these figures is performed in the same way as in the case of the fault segments. The small trapeziums (triangles) are also called cells. The values of coordinates, displacements and forces are not distinguished for different

points of the same cell. Thus, after the space discretization the cells are considered instead of points. Failure occurs for a whole cell.

The parameters of the earthquake are defined by the following way: the origin time is t_i (failure occurrence time); the epicentral coordinates and the source depth are the weighted sums of the coordinates and depths of the failed cells (the weights of the cells are given by their squares divided by the sum of squares of these cells); the magnitude is calculated from the formula:

$$M = (\log_{10} S + 4.01) / 1.02, \quad (10)$$

where S is the total area (in km^2) of cells involved in the earthquake.

3. Programs EARTH and EARTH 3: destination and possibilities

Programs EARTH and EARTH-3 are destined for the numerical simulation of block structure dynamics (by means of 2D and 3D models respectively). The input data for modeling are the following: a block structure geometry, values of parameters, which define features of interaction between elements of the structure, equations describing movements of the underlying medium and the boundaries. The output data represent different forms of visualization of sequences of model earthquakes.

Both programs are based on the same ideas and principles. They have the same structure, work in the interactive mode and include the similar calculation and service procedures united by the system of hierarchical menus. All data of the programs are defined by the window interface, the output is realized in the graphic form. The programs are supplied by the help information.

3.1. Modes of work

Both programs EARTH and EARTH-3 have the following main modes of work.

I. Dynamics of block structure. This is the base mode. If this mode is selected then the numerical simulation of dynamics (according to 2D or 3D model respectively) of the block structure and earthquake failure sequences caused by it is performed. The simulation can be started with zero initial conditions or from some intermediate state saved in a disk file of the special structure. If necessary the file, in which the parameters of the final or the current (for the moment of the process interruption) state will be written, may be indicated. Besides, it is possible to create a file for catalog preparation.

II. Calculation of maximum stress. If this mode is selected then the programs calculate for the fault segments the maximum (among the cells of the segment) value of κ (8) in percents of the value of the level B . This operation is carried out for the current time moment or for some intermediate state saved in a disk file of the special structure. The information about the maximum value of stress is imaged on the screen.

III. Image of earthquake flow. If this mode is selected then the programs image on the screen the sequence of cell failures for the fault segments. In this mode the programs use the file with the information for earthquake catalog preparation. There is a possibility to screen the plots of dependence of the number of earthquakes on the number of cells failed in an earthquake.

IV. Creation of catalog. If this mode is selected then the programs create an earthquake catalog using the file with the information for earthquake catalog preparation. The catalog may be produced by two ways: with unification of all segments of the same fault, and with distinguishing of such segments. After the catalog creation the plots of dependence of the number of earthquakes on the number of cells failed in an earthquake and the plot of dependence of the accumulated number of earthquakes on the magnitude are imaged on the screen.

3.2. Catalog

Programs EARTH and EARTH-3 create an earthquake catalog stored as a non-text file in the standard "20 bytes format". The specification of the records in a file of catalog is the following. The first record consists of 20 bytes; the first 4 bytes contain an integer, which is the total number of records in the file (it is the number of earthquakes plus 1). All other records have the following structure:

| Positions of records | Content | Type |
|----------------------|--|-----------|
| 1-4 | time of the earthquake in minutes A.D. | integer*4 |
| 5-6 | latitude*100 | integer*2 |
| 7-8 | longitude*100 | integer*2 |
| 9-10 | depth (km) | integer*2 |
| 11-12 | magnitude*100 | integer*2 |
| 13-20 | are not used (reserved) | |

In addition, the following information has to be indicated: the latitude and the longitude of the coordinate origin, the initial year of the catalog (00h 00m of the 1st January of this year is assigned to $t = 0$), the number of days to be assigned to the unit of time used in the equations describing dynamics of the block structure.

3.3. Dialog

The programs use the window interface represented in the form of hierarchical menus allowing to specify different parameters and to choose different options. Below we list the most important opportunities afforded by the programs.

3.3.1. Regions of seismoactivity

This mode gives an opportunity to specify seismoactive regions on the model map of the world (see Fig. 1). The aim of this specification is in using some real parameters connected with the region in the simulation process (the scheme of lineaments, real geographical coordinates, different coefficients and velocities and so on). These parameters are stored in special database files. If some region is chosen, the data from corresponding file are used.

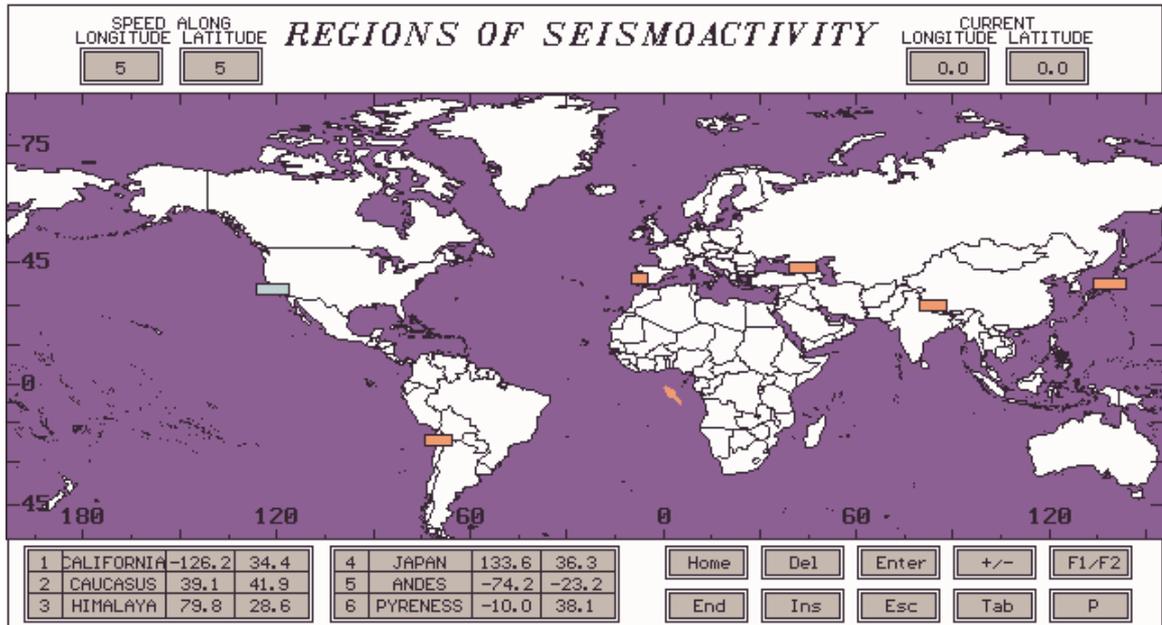


Figure 1. The regions of seismoactivity by default

3.3.2. Geometry of block structure

This mode gives an opportunity to specify the geometry of a block structure, which is defined by the description of intersection lines of the faults with the upper plane and by angles of dip for the fault planes. The faults and vertices are defined directly on the coordinate plane with real geographical coordinates.

There are the following restrictions on the geometric parameters of a block structure (the maximum values are listed):

Table 1. Restrictions on geometric parameters

| | 2D model, EARTH | 3D model, EARTH-3 |
|-------------------------------|-----------------|-------------------|
| Vertices | 100 | 90 |
| Faults | 75 | 50 |
| Segments | 150 | 120 |
| Blocks | 30 | 30 |
| Boundary blocks | 20 | 20 |
| Cells per a segment row | 250 | 450 |
| Rows per a segment | 40 | 50 |
| Cells per a bottom trapezium | 1100 | 1500 |
| Trapeziums per a block bottom | 10 | 10 |

When specification of the block structure geometry is finished, the verification procedure is performed. It should be noted that the block structure is inadmissible in the following cases:

- a) there is an intersection of more than two faults at one vertex;
- b) there is a vertex belonging to only one fault or not belonging to any fault;
- c) there is a multiply connected block structure;
- d) there is a segment which does not occur in any block;
- e) there is a segment which has intersection of its sides.

If the structure is recognized as an admissible one (otherwise the procedure marks the illegal part of the structure), its blocks and segments are determined automatically. After this action the boundary blocks, dip angles and other numerical parameters of faults, blocks and boundary blocks are defined in the special menu system. Namely, the user can specify for a fault:

- a dip angle for the fault plane (in degrees),

- parameters K and K^n (in bars/cm, see (5), (7)), W and W^n (in cm/bars, see (4), (6)), W_s and W_s^n (in cm/bars) which is used in (4) and (6) for the creep state,
- levels B, H_f, H_s ($B > H_f > H_s$);

for a block:

- parameters K_u and K_u^n (in bars/cm, see (2), (3)), W_u (in cm/bars, see (1)),
- velocities of the progressive movement of the underlying medium along axes X and Y (in cm), and angle velocity of the underlying medium rotation around the geometrical center of the block bottom (in 10^{-6} of a radian);

for a boundary block:

- velocities of the progressive movement of the block along axes X and Y (in cm), and angle velocity of the block rotation around the coordinate origin (in 10^{-6} of a radian).

Other numerical parameters of the simulation process (discretization steps, depth of the layer, time parameters and so on) are specified in separate menus. The ranges of changing of all parameters mentioned above are defined in programs and are checked immediately after specification of some value.

We illustrate how to pass from geometric parameters of a real seismic region to its program approximation considering the Vrancea seismic region as an example. The main structural elements of this region, directions of the movement of the various plates are presented in [6]. In that work, the block structure, which can be treated as a rough approximation of the region, and the values of model parameters are specified ([6], Figs. 4, 5). The program approximation of this structure is presented in Fig.2. The number of all elements of the structure, real longitude and latitude, list of functional keys, and the menu item for specification of marked block parameters are screened.

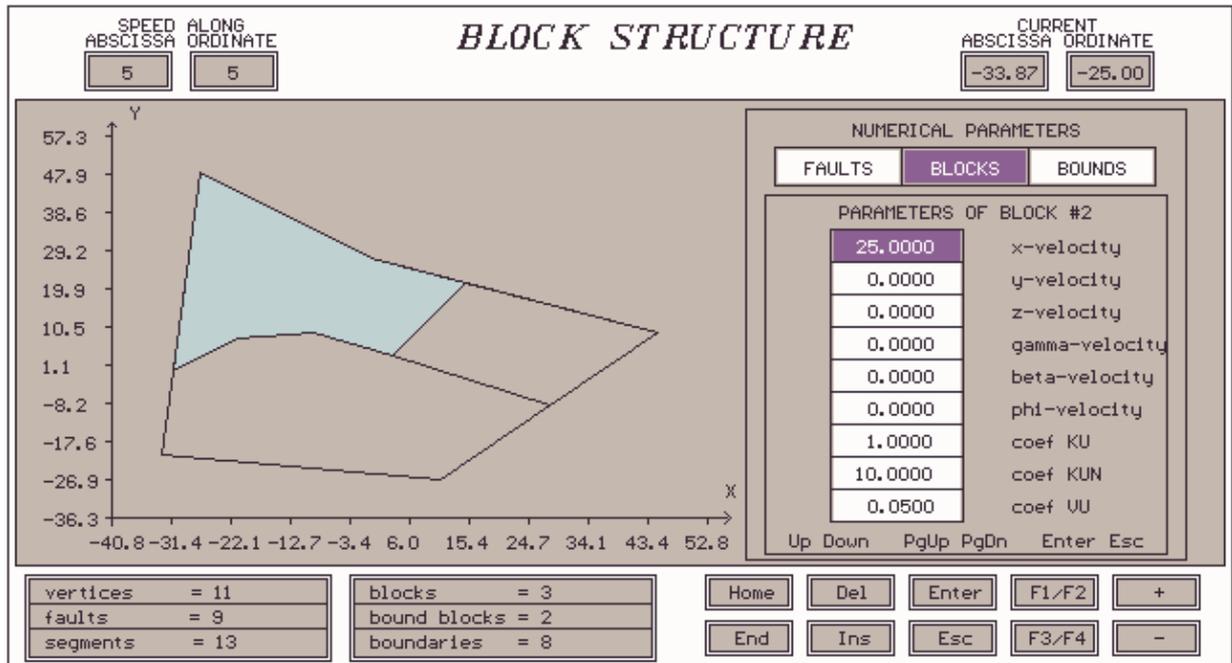


Figure 2. The program approximation of the Vrancea seismic region

3.3.3. Simulation of block dynamics

This mode gives an opportunity to visualize results of numerical simulation of dynamics of the block structure. At every time moment the displacements and rotation angles of the blocks are recalculated, the state of the structure is analyzed, arising failures are processed. The programs image on the screen the moments of earthquakes by vertical lines of the lengths proportional to the magnitudes and the information on the current maximum value of κ (8) in percents of the level B (maximum stress) for the structure, see Fig.3. So, we can see the distribution of events in time for the whole structure or for separate segment and can compare model earthquake flow with real one. It should be noted that non-dimensional time is used in the model, so we need to set correspondence between the model unit and real time unit (year, as a rule), for example, by using the seismic cycle or recurrence of the strongest events.

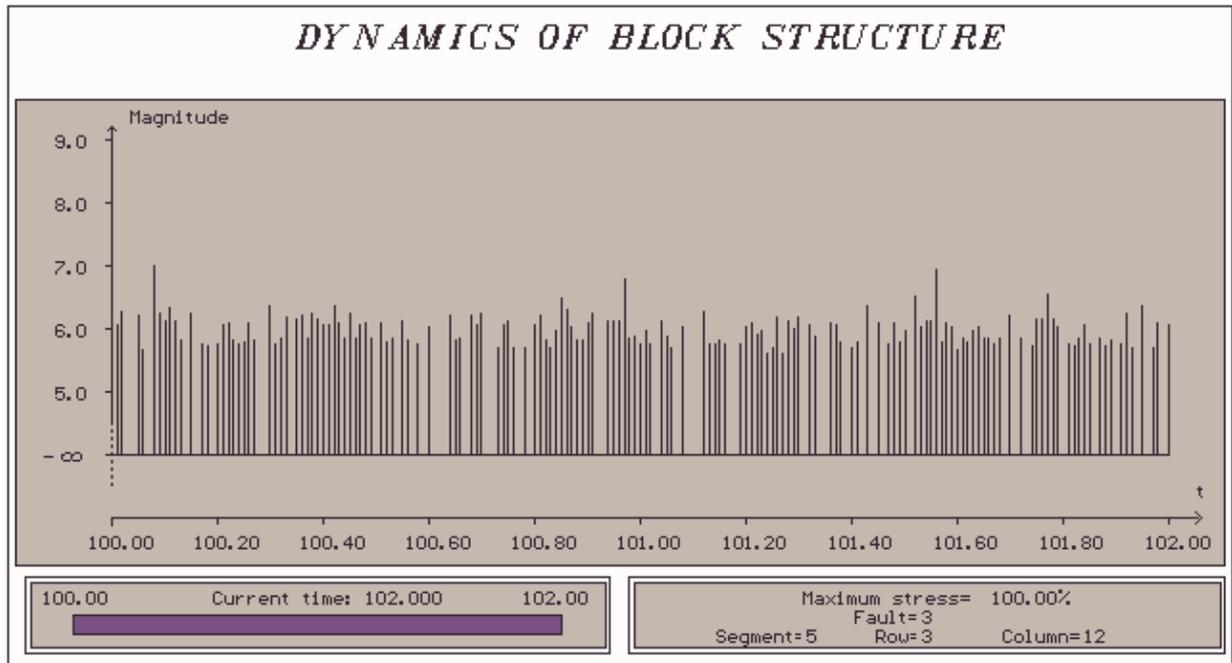


Figure 3. Dependence of model magnitude on time for the structure from Fig.2

3.3.4. Calculation of maximum stress

This mode gives an opportunity to image on the screen for fault segments the maximum (among the cells of the segment) value of κ (8) in percents of the value of the level B . This operation is carried out for the current time moment (if the simulation has been interrupted) or for some intermediate state saved in a disk file of the special structure.

Information on the selected segment is displayed in the special window and contains the current time moment, the parameters of the fault, which this segment belongs to, the coordinates of the cell with maximum stress for this segment, the percentage and the additional remark if the stress reaches the maximum value for the whole structure, see Fig.4. This mode helps us to find the most active boundaries of the structure and to observe how the stress spreads through the structure.

3.3.5. Image of earthquake flow

This mode gives an opportunity to image on the screen the sequence of cell failures for the selected segment (the form of a cell depends on its state (normal, creep or earthquake)), see Fig.5, and to output the frequency-of-occurrence relations in the graphic form. The distribution of cell failures in time is the important information for studying the phenomenon of migration of earthquakes along the faults and for investigation of mechanisms of arising and spreading earthquakes.

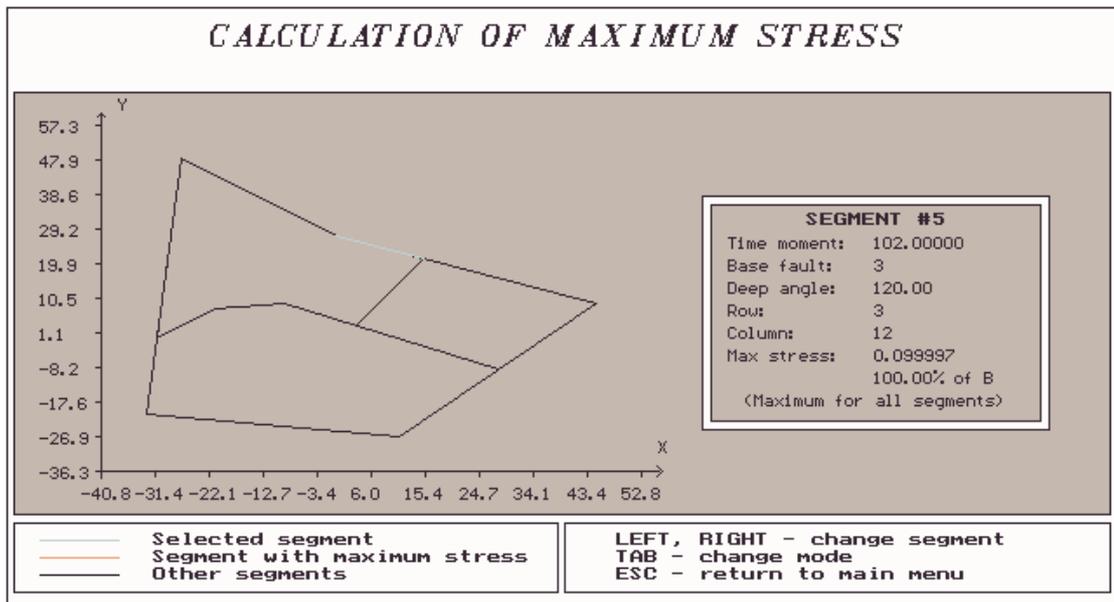


Figure 4. Maximum stress for the structure from Fig.2

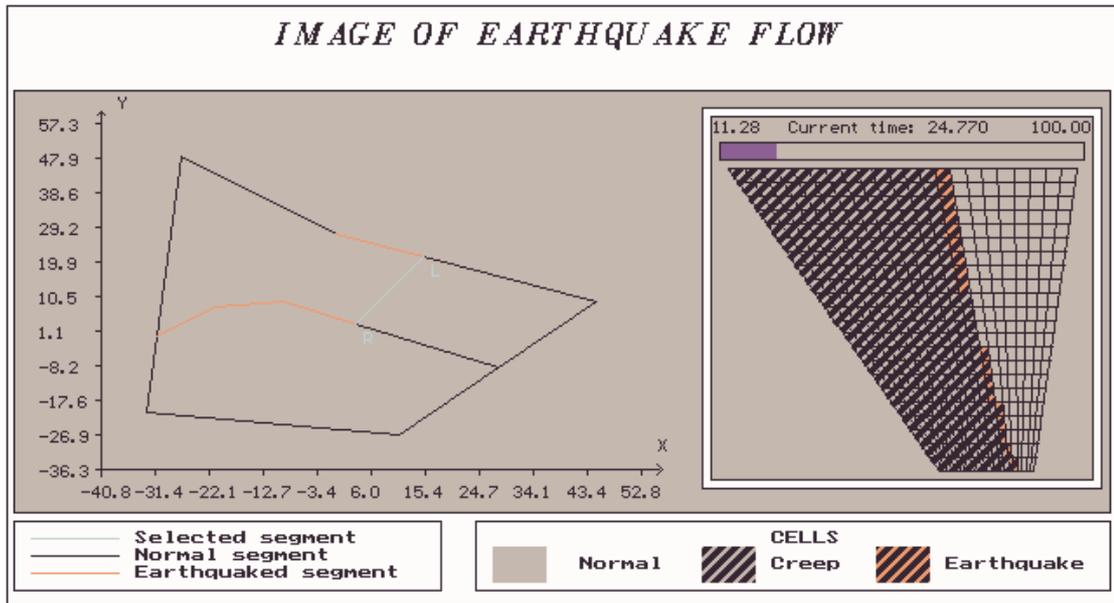


Figure 5. Image of earthquake flow for the structure from Fig.2

3.3.6. Creation of catalog

This mode gives an opportunity to create an earthquake catalog in the standard “20 bytes format” with unification of all simultaneously quaked cells of the conjugated segments belonging to the same fault into one earthquake and with distinguishing all simultaneously quaked cells of the different segments.

The plot of dependence of the number of earthquakes on the number of quaked cells forming one earthquake, the plot of dependence of the accumulated number of earthquakes on the magnitude and the information on the total number of earthquakes, on the minimum and maximum magnitudes, on the maximum number of cells involved in one earthquake are screened after successful creation of a catalog, see Fig.6. The synthetic catalog obtained may be processed by any standard program destined for operations with earthquake catalogs.

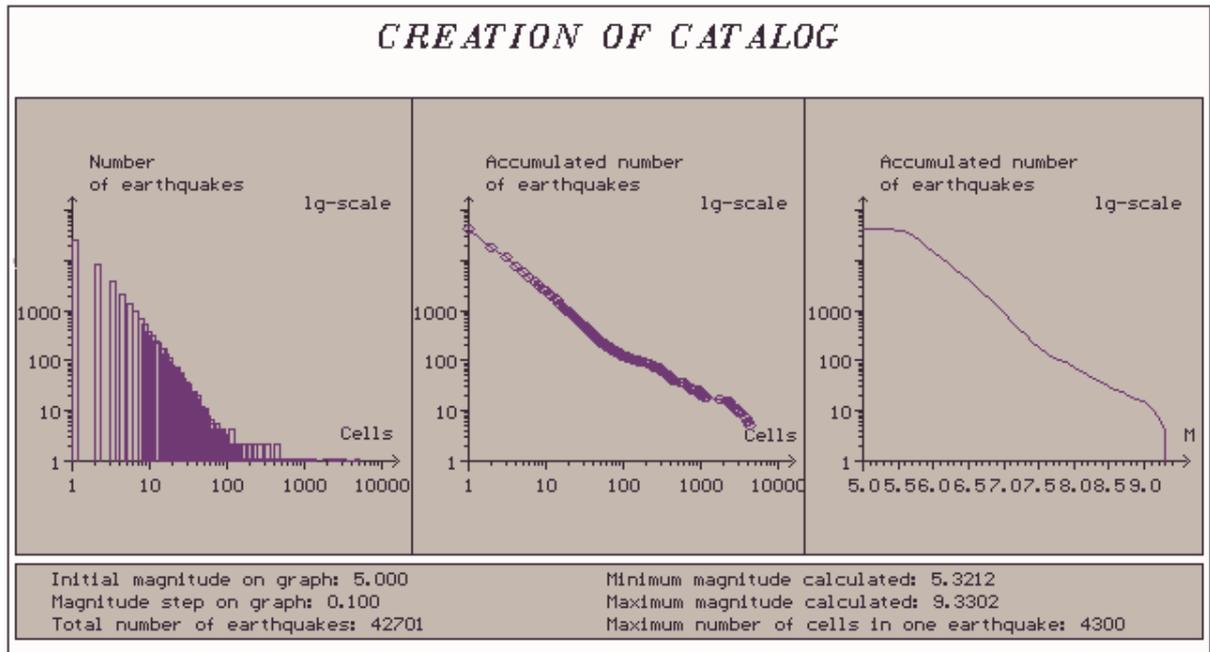


Figure 6. Plots of dependencies for the structure from Fig.2

It should be noted that all data may be saved in and may be loaded from disk files of the special structure at every time moment during the simulation process.

4. Parallel algorithm for numerical simulation

Computational experiments with programs EARTH and EARTH-3 show that the block models of lithosphere dynamics during performing on sequential computers require considerable expenditures of memory and time of a processor, and it does not allow to simulate dynamics of complicated structures and to use sufficiently small steps of time and space discretization.

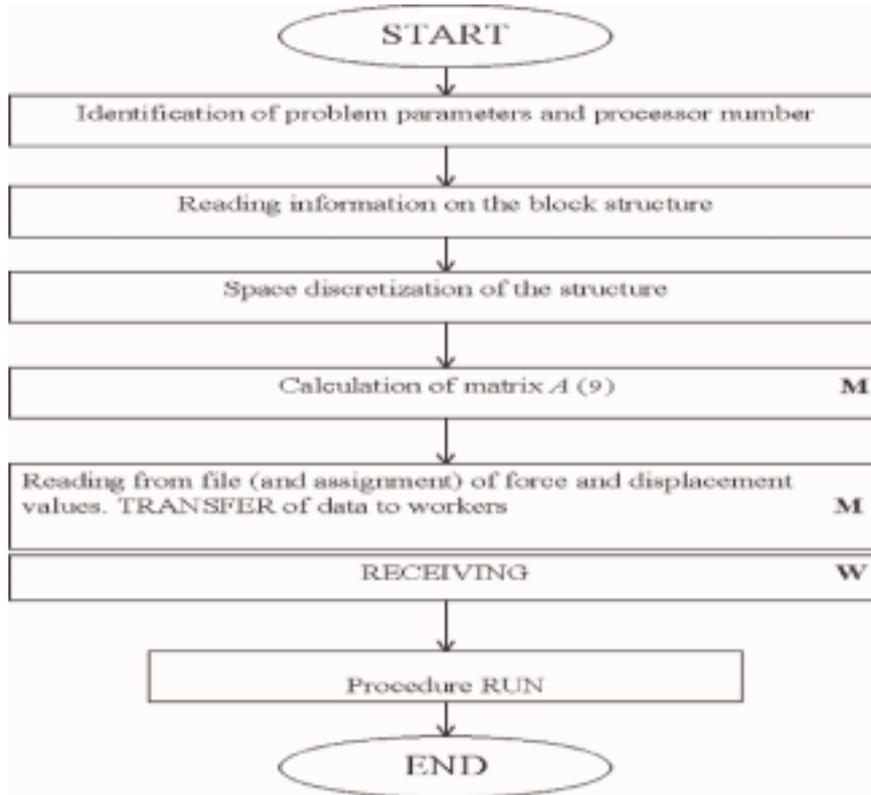


Figure 7. Scheme of parallelization of the block model. Notation: operations carried out only by master are marked by “M”, only by workers – by “W”

However, the approach applied to modeling admits effective parallelization of calculations on a multiprocessor machine, and it makes possible the use of real geophysical and seismic data in the process of simulation of dynamics of different block structures. The principal features of the parallel software created are the following: 1) multiprocessor machines are applied to numerical calculations; 2) personal computers are used to form input data and to visualize output data.

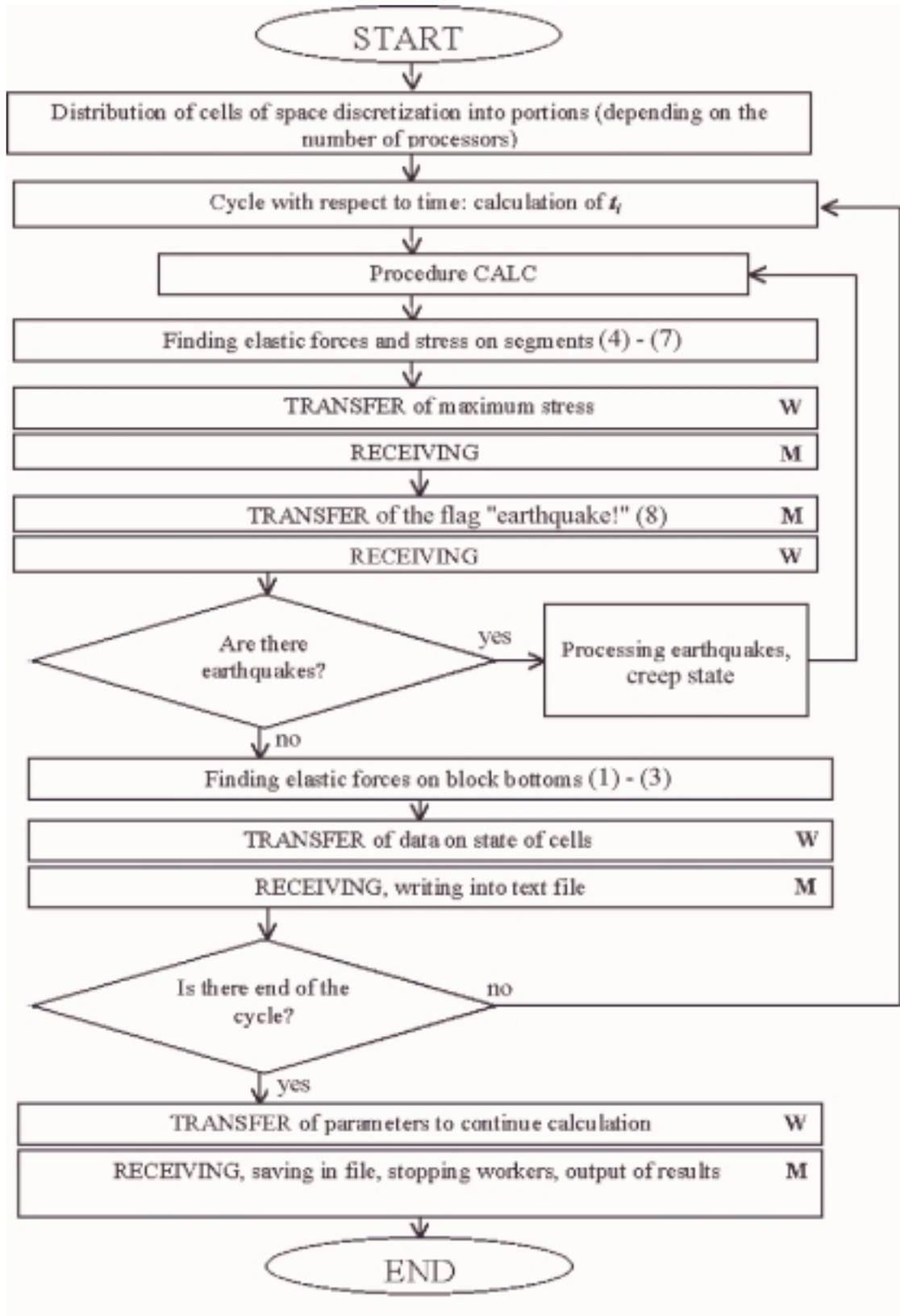


Figure 8. Procedure *RUN*

The variant of parallel program was realized on working stations basing on microprocessors Alpha-21164 (533MHz, 256Mb) at the Institute of Mathematics and Mechanics, Ural Branch of the Russian Academy of Sciences (Ekaterinburg, Russia) by the scheme “master–worker” (“processor farm”). The demands of compatibility with different platforms (in the sense of fast transition, ideally, by means of simple recompiling) were made to the program code. For this purpose, the special library MPI (“Message Passing Interface”) was used, and the parallel algorithm was designed in such a way that the unique loading module was formed for all processors. The block-scheme of this algorithm is presented in Fig. 7-9. Let us give necessary explanations.

In the beginning of the work the number of processor, which the program has loaded to, is detected (zero processor becomes the master). After this process, the information on a block structure is read, and auxiliary calculations (before the main cycle) are performed. It is important that a part of calculations performed only by the master (due to finding block and underlying medium displacements according to (9)) requires insignificant time expenditures. At every time step the most time-consumable procedure is calculation of values of forces and inelastic displacements in all cells of space discretization of block bottoms and fault segments. Since these calculations may be performed independently from each other, they are shared between all processors, each of which processes own portion of cells. The exchange of information between processors at every time step is realized according to the following scheme. The master calculates new values of block, boundary block and underlying medium displacements, then necessary parameters are transferred to the workers. Recalculated values of the right-hand part of system (9) are returned to the master, then the next time step is carried out. For processing the situation treated as an earthquake, the scheme is slightly complicated, since in this case the master should ask all the workers until cells of segments in the critical state exist. The time of calculations on each processor is much more than the time of exchange. Therefore rather high useful loading of each processor is achieved.

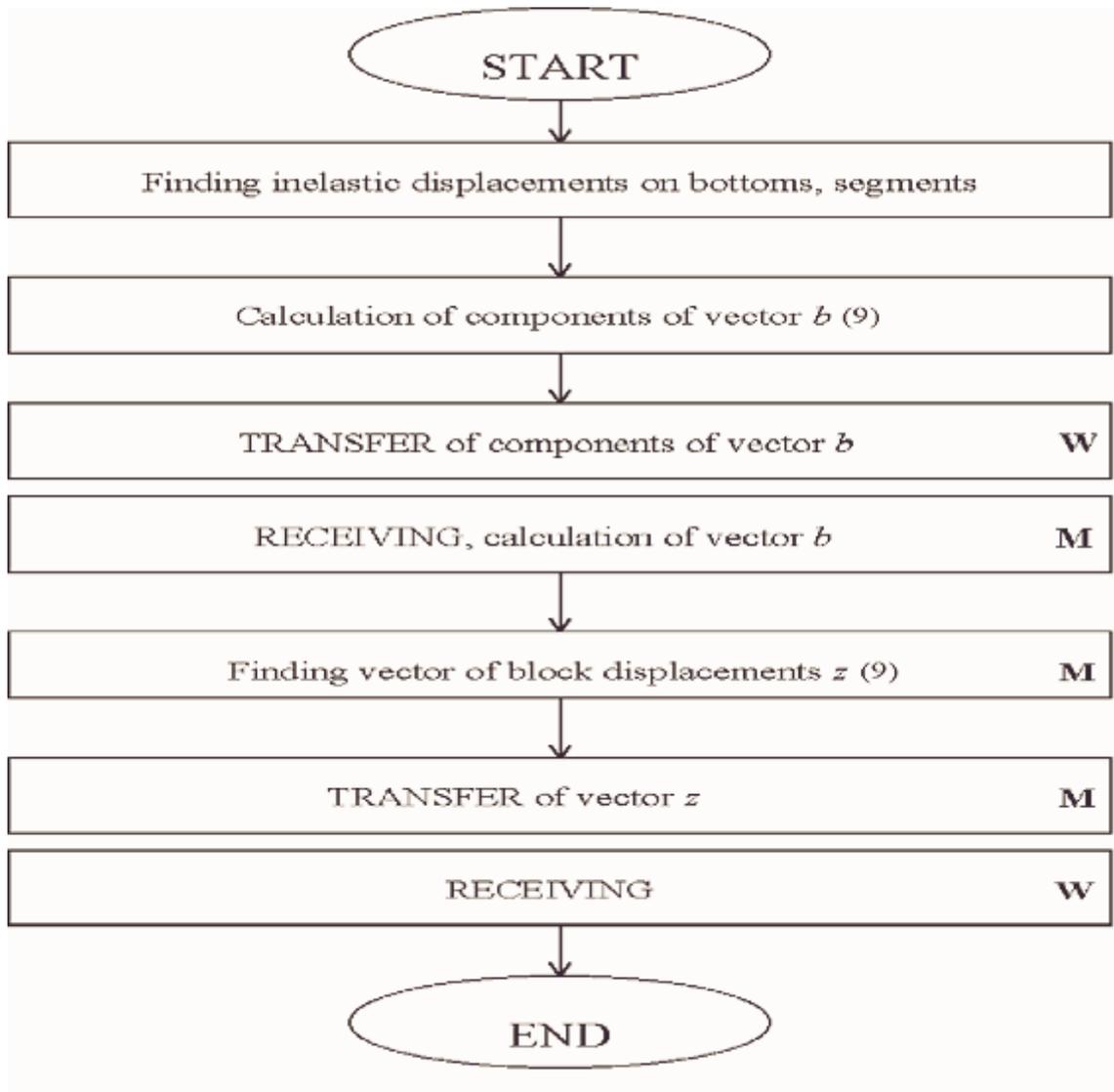


Figure 9. Procedure *CALC*

For testing the dependence of time of solving the problem on the number of processors and comparing with sequential algorithm, the following values were analyzed: acceleration coefficient $S_r = T_1/T_r$ and effectiveness coefficient $E_r = S_r / r$, where T_r is the time of program performance on multiprocessor computer with r processors, T_1 is the corresponding time for sequential algorithm. Note that T_r is the sum of pure time of calculations and expenditures for necessary exchanges. It is appeared that S_r is slightly less than r , consequently, E_r is close to 1, and the parallelization effectiveness is rather high and it insignificantly decreases with

increasing the number of processors in action (in correspondence with the parallelization scheme).

The scheme described in this section was applied to simulation of dynamics of different block structures: both model and approximations of real regions. Some results of modeling for the Vrancea seismic region and their analysis were presented in [6].

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