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Modelling of Block Structure Dynamics and Seismicity

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ABSTRACT

A model of block-and-fault system dynamics (or simpler "block model") considers a seismic region as a system of perfectly rigid blocks divided by infinitely thin plane faults. The blocks interact between themselves and with the underlying medium. The system of blocks moves as a consequence of prescribed motion of the boundary blocks and of the underlying medium. As the blocks are perfectly rigid, all deformation takes place in the fault zones and at the block base in contact with the underlying medium. Relative block displacements take place along the fault planes. This assumption is justified by the fact that for the lithosphere the effective elastic moduli of the fault zones are significantly smaller than those within the blocks. Block motion is defined so that the system is in a quasi-static equilibrium state. The interaction of blocks along the fault planes is viscous-elastic ("normal state") while the ratio of the stress to the pressure remains below a certain strength level. When the critical level is exceeded in some part of a fault plane, a stress-drop ("failure") occurs (in accordance with the dry friction model), possibly causing failure in other parts of the fault planes. These failures produce earthquakes. Immediately after the earthquake and for some time after, the affected parts of the fault planes are in a state of creep. This state differs from the normal state because of a faster growth of inelastic displacements, lasting until the stress falls below some other level. Numerical simulation of this process yields synthetic earthquake catalogues.

1. Introduction

A model of block-and-fault system dynamics (or simpler “block model”) of the lithosphere was developed to analyse features of seismicity in a particular region. A structure, which consists of perfectly rigid blocks divided by infinitely thin plane faults, is considered in the model. Displacements of all blocks are supposed to be infinitely small relative to their size. The blocks interact with each other and with the underlying medium. The system of blocks moves owing to prescribed motions of the boundary blocks and the underlying medium. The detailed description of the model is given below.

The model exploits the hierarchical block structure of the lithosphere proposed by *Alekseevskaya et al.* (1977). The basic principles of the model were developed by *Gabrielov et al.* (1986, 1990) on the basis of the proposition that blocks of the lithosphere are separated by comparatively thin, weak and less consolidated fault zones, such as lineaments and tectonic faults, and major deformation and most earthquakes occur in such fault zones. The model takes advantage of the simple fact that the integral rigidity of the fault zones is smaller that the blocks (at least in the time scale smaller than say 100 years or less). Accordingly, blocks are presumed perfectly rigid; hence deformation takes place only in fault zones and at block bottoms in contact with the underlying medium. Relative block displacements take place along fault zones.

Later on the model was improved to create possibility of approximating in it a block structure of a real seismoactive region under consideration (*Soloviev 1995*), and now it is region-specific and allows to set up specific driving tectonic forces, the realistic geometry of blocks and a fault network, and the rheology of fault zones. The model generates stick-slip movement of blocks, comprising seismicity and slow movements.

The model reproduces the whole ensemble: tectonic driving forces => geodetic movements => creep => earthquakes.

The block model as other numerical models of the processes generating seismicity (e.g., *Shaw et al. 1992*; *Gabrielov and Newman 1994*; *Allègre et al. 1995*; *Newman et al. 1995*; *Turcotte 1997*; *Narteau et al. 2000*) provides a straightforward tool for a broad range of problems: (i) connection of seismicity and geodynamics; (ii) dependence of seismicity on general properties of fault networks; that is, fragmentation of structure, rotation of blocks, direction of driving forces etc; (iii) study of the earthquake preparation process and earthquake prediction (e.g., *Gabrielov and Newman 1994*), moreover such models can be used to suggest new premonitory patterns that might exist in real catalogues (e.g., *Gabrielov et al. 2000*; *Shebalin et al. 2000*).

The block model reproduces some basic features of the observed seismicity: Gutenberg-Richter law, clustering of earthquakes, dependence of the occurrence of large earthquakes on fragmentation of the block structure and on rotation of blocks etc. It enables to study relations between geometry of faults, block movements and earthquake flow, and to reproduce regional features of seismicity. From simplest observation – territorial distribution of seismicity – the model enables to reconstruct tectonic driving forces (and to evaluate competing geodynamic hypotheses).

In the absence of seismicity the block model enables to study dependence between motions of boundary blocks specified at lateral boundaries of the structure, motions of the underlying medium specified at the block bottoms and motions of the blocks constituting the structure. One may consider the direct problem: to determine motions of the blocks constituting the structure (and their relative motions along the faults) when motions of the underlying medium and the boundaries are specified. The inverse problem may be considered as well: to determine motions of the underlying medium and the boundaries, which supply the best approximation of the specified motions of the blocks of the structure or their relative motions along the faults.

The detailed description of the block model and examples of its application are given by *Soloviev and Ismail-Zadeh* (2003). The model was used to analyze clustering of earthquakes (*Maksimov and Soloviev,* 1999), the dependence of the occurrence of large earthquakes on structure fragmentation and on rotation of blocks (*Keilis-Borok et al.*, 1997), long-range interaction between synthetic earthquakes (*Vorobieva and Soloviev*, 2005), transformation of frequency-magnitude relation prior to large earthquakes (*Soloviev*, 2008), seismicity of an arc subduction zone (*Rundquist and Soloviev*, 1999), the lithospheric motion and seismic flow in the Vrancea earthquake-prone region of the south-eastern Carpathians (*Panza et al.,* 1997; *Soloviev et al.,* 1999; *Ismail-Zadeh et al.,* 1999), in the Western Alps (*Soloviev and Ismail-Zadeh,* 2003), in the Sunda Arc (*Soloviev and Ismail-Zadeh,* 2003), in the Tibet-Himalayan region (*Ismail-Zadeh et al.,* 2007), and in Italy and its surroundings (*Peresan et al.*, 2007).

2. Block Structure Geometry

A block structure is illustrated in Fig. 1. A layer of thickness H is confined between two horizontal planes; a block structure covers a limited and simply connected part of this layer. Each lateral boundary of a block is part of a plane that intersects the layer. These planes divide the structure into blocks. The parts of these planes located inside the block structure and its lateral faces are called fault planes.

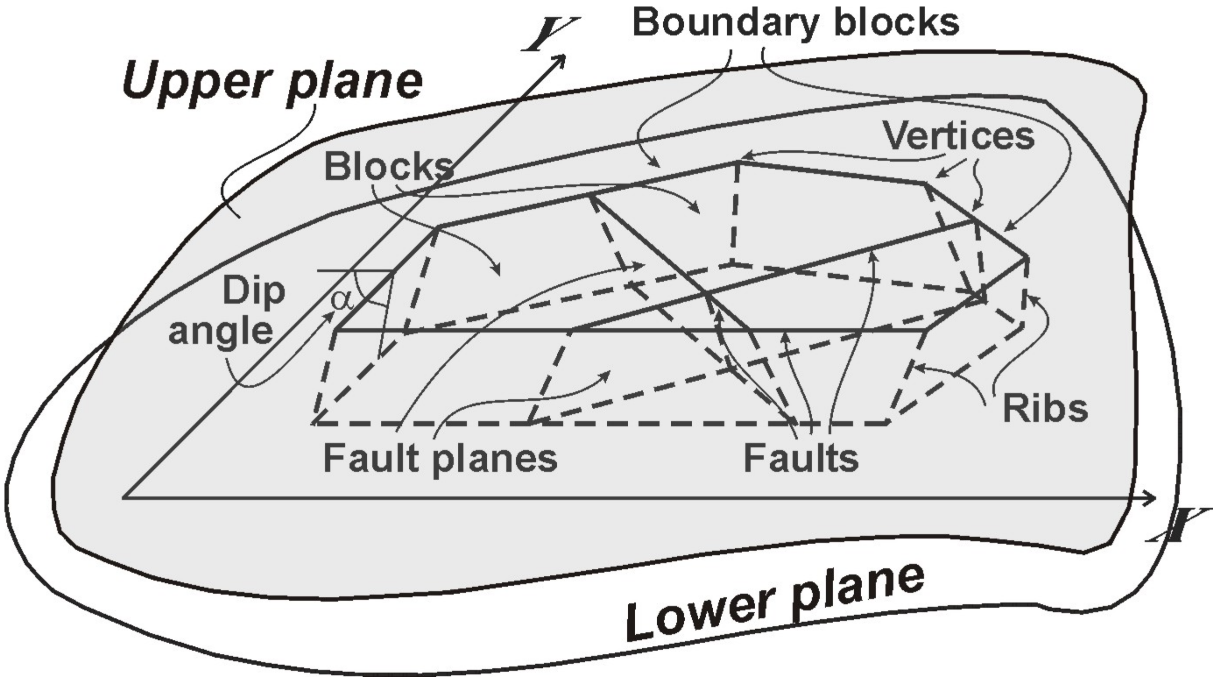

FIGURE 1 A sketch of the block-and-fault dynamics model.

The geometry of the block structure is described by the lines where fault planes intersect the upper plane limiting the layer (these lines are called faults) and by the dip angle of each fault plane. Three or more faults cannot have a common point on the upper plane, and a common point of two faults is called a vertex. The direction is specified for each fault and the dip angle of the fault plane is measured on the left of the fault. The positions of a vertex on the upper and the lower plane, limiting the layer, are connected by a segment (rib) of the line of intersection of the corresponding fault planes. The part of a fault plane between two ribs corresponding to successive vertices on the fault is called a fault segment. Any fault segment is a trapezoid. The common parts of the block with the upper and lower planes are polygons; the common part of a block with the lower plane is called a block bottom.

It is assumed that the block structure is bordered by a confining medium, whose motion is prescribed on its continuous parts comprised between two ribs of the block structure boundary. These parts of the confining medium are called boundary blocks.

3. Block Movement

The blocks are assumed to be rigid and all their relative displacements take place along the bounding fault planes. The interaction of the blocks with the underlying medium takes place along the lower plane, any kind of slip being possible.

The movements of the boundaries of the block structure (the boundary blocks) and the medium underlying the blocks are assumed to be an external force on the structure. The rates of these movements are considered to be horizontal and known.

Dimensionless time is used in the model; therefore, all quantities that contain time in their dimensions are measured per unit of dimensionless time, so that time does not enter their dimensions. For example, in the model, velocities are measured in units of length and a velocity of 5 cm means 5 cm for one unit of dimensionless time. When necessary, one assigns a realistic value to one unit of dimensionless time. For example, if one unit of dimensionless time is one year, then the velocity of 5 cm, specified for the model, means 5 cm/year.

At each time the displacements of the blocks are defined so that the structure is in a quasi-static equilibrium, and all displacements are supposed to be infinitely small, compared with the typical block size. Therefore the geometry of a block structure does not change during the simulation and the structure does not move as a whole.

4. Interaction between Blocks and the Underlying Medium

The elastic force, which is due to the relative displacement of the block and the underlying medium, at some point of the block bottom, is assumed to be proportional to the difference between the total relative displacement vector and the vector of slippage (inelastic displacement) at the point.

The elastic force per unit area $\mathbf{f}^{\mathrm{u}} = (f_{\mathrm{x}}^{\mathrm{u}}, f_{\mathrm{y}}^{\mathrm{u}})$ applied to the point with coordinates (X,Y), at some time t, is defined by

$$\begin{aligned} f_{\mathrm{x}}^{\mathrm{u}} &= K_{\mathrm{u}}(x - x_{\mathrm{u}} - (Y - Y_{\mathrm{c}})(\varphi - \varphi_{\mathrm{u}}) - x_{\mathrm{a}}), \\ f_{\mathrm{y}}^{\mathrm{u}} &= K_{\mathrm{u}}(y - y_{\mathrm{u}} + (X - X_{\mathrm{c}})(\varphi - \varphi_{\mathrm{u}}) - y_{\mathrm{a}}) \end{aligned} \qquad (1)$$

where X_{c} and Y_{c} are the coordinates of the geometrical centre of the block bottom; $(x_{\mathrm{u}}, y_{\mathrm{u}})$ and φ_{u} are the translation vector and the angle of rotation (following the general convention, the positive direction of rotation is anticlockwise), about the geometrical centre of the block bottom, for the underlying medium at time t; (x,y) and φ are the translation vector of the block and the angle of its rotation about the geometrical centre of its bottom at time t; $(x_{\mathrm{a}}, y_{\mathrm{a}})$ is the inelastic displacement vector at the point (X,Y) at time t.

The evolution of the inelastic displacement at the point (X,Y) is described by the equations

$$\frac{dx_a}{dt} = W_{\mathrm{u}} f_{\mathrm{x}}^{\mathrm{u}}, \quad \frac{dy_a}{dt} = W_{\mathrm{u}} f_{\mathrm{y}}^{\mathrm{u}}. \qquad (2)$$

The coefficients K_{u} and W_{u} in (1) and (2) may be different for different blocks.

5. Interaction between Blocks along Fault Planes

At the time t, in some point (X,Y) of the fault plane separating the blocks numbered i and j (the block numbered i is on the left and that numbered j is on the right of the fault) the components Δx, Δy of the relative displacement of the blocks are defined by

$$\Delta x = x_{\mathrm{i}} - x_{\mathrm{j}} - (Y - Y_{\mathrm{c}}^{\mathrm{i}})\varphi_{\mathrm{i}} + (Y - Y_{\mathrm{c}}^{\mathrm{j}})\varphi_{\mathrm{j}},$$

$$\Delta y = y_{\mathrm{i}} - y_{\mathrm{j}} + (X - X_{\mathrm{c}}^{\mathrm{i}})\varphi_{\mathrm{i}} - (X - X_{\mathrm{c}}^{\mathrm{j}})\varphi_{\mathrm{j}} \qquad (3)$$

where $X_{\mathrm{c}}^{\mathrm{i}}$, $Y_{\mathrm{c}}^{\mathrm{i}}$, $X_{\mathrm{c}}^{\mathrm{j}}$, $Y_{\mathrm{c}}^{\mathrm{j}}$ are the coordinates of the geometrical centres of the block bottoms, $(x_{\mathrm{i}}, y_{\mathrm{i}})$, and $(x_{\mathrm{j}}, y_{\mathrm{j}})$ are the translation vectors of the blocks, and φ_{i}, φ_{j} are the angles of rotation of the blocks about the geometrical centres of their bottoms, at time t.

Relative block displacements, it was assumed, take place only along fault planes; therefore, the displacements along the fault and horizontal planes are related by

$$\Delta_{\mathrm{t}} = e_{\mathrm{x}}\Delta x + e_{\mathrm{y}}\Delta y,$$

$$\Delta_{\mathrm{l}} = \Delta_{\mathrm{n}}/\cos\alpha, \text{ where } \Delta_{\mathrm{n}} = e_{\mathrm{x}}\Delta y - e_{\mathrm{y}}\Delta x. \qquad (4)$$

Here Δ_{t} and Δ_{l} are the displacements along the fault plane parallel (Δ_{t}) and normal (Δ_{l}) to the fault line on the upper plane; $(e_{\mathrm{x}}, e_{\mathrm{y}})$ is the unit vector along the fault line on the upper plane (Fig. 2); α is the dip angle of the fault plane; and Δ_{n} is the horizontal displacement, normal to the fault line on the upper plane. It follows from (4) that Δ_{n} is the projection of Δ_{l} on the horizontal plane (Fig. 3*a*).

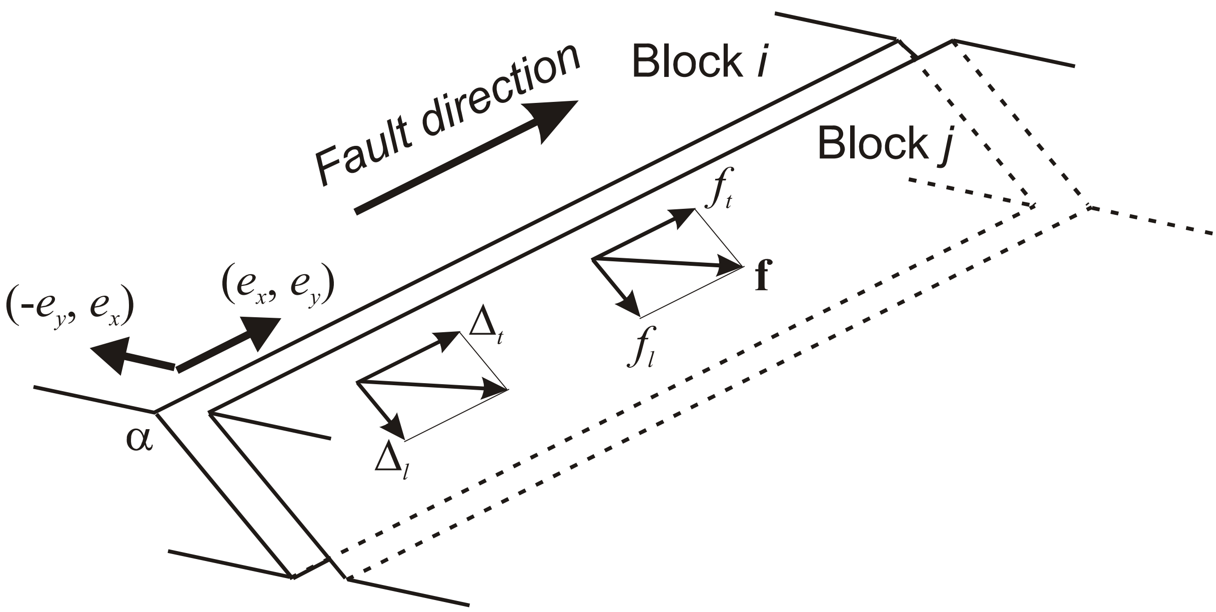

FIGURE 2 Displacements and forces along a fault plane

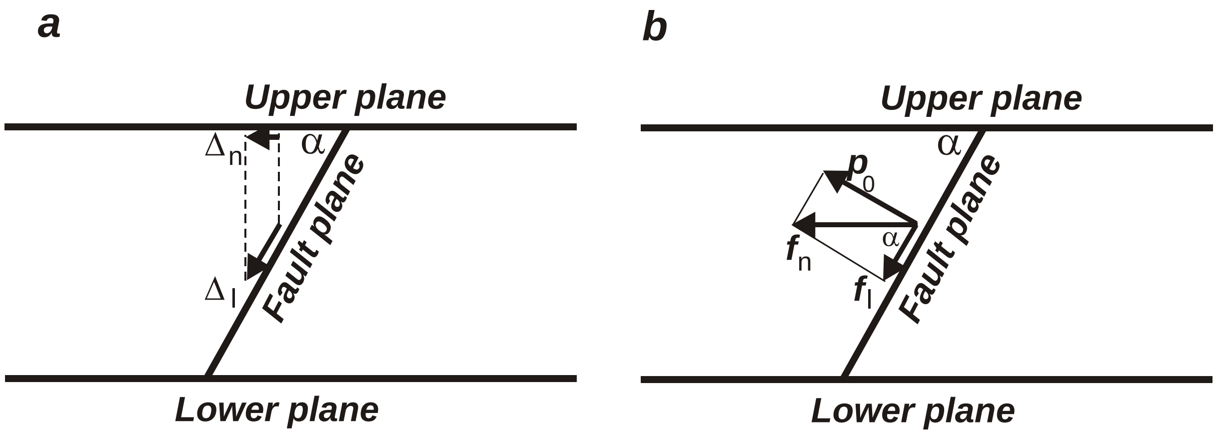

FIGURE 3 Vertical section of a block structure orthogonal to a fault. Relative displacements of blocks Δ_n and Δ_l (*a*) and forces p_0, f_l, and f_n (*b*).

The elastic force per unit area $\mathbf{f} = (f_t, f_l)$ acting along the fault plane at the point (X, Y) is defined by

$$f_t = K(\Delta_t - \delta_t),$$
$$f_l = K(\Delta_l - \delta_l). \tag{5}$$

Here δ_t, δ_l are inelastic displacements along the fault plane at the point (X,Y) at time t, parallel (δ_t) and normal (δ_l) to the fault line on the upper plane.

The evolution of the inelastic displacement at the point (X,Y) is described by the equations

$$\frac{d\delta_t}{dt} = Wf_t, \quad \frac{d\delta_l}{dt} = Wf_l. \tag{6}$$

The coefficients K and W in (5) and (6) may be different for different faults. The coefficient K can be considered as the shear modulus of the fault plane.

Equations (5-6) correspond to visco-elastic (Maxwell) rheological law that describes the relation of **f** to the strain ζ

$$\left(\frac{d}{dt} + \frac{1}{\tau}\right)\mathbf{f} = \mu\frac{d\zeta}{dt} \tag{7}$$

where τ is the relaxation time ($\tau = \eta / \mu$), μ is the shear modulus, and η is the viscosity. Coefficients in (5-7) are connected by formulas: $K = \mu/a$, $W = a/\eta$, a is the actual width of the fault zone; and $\tau = 1/(KW)$.

In addition to the elastic force, there is the reaction force which is normal to the fault plane; the work done by this force is zero, because all relative movements are tangent to the fault plane. The elastic energy per unit area at the point (X,Y) is equal to

$$e = (f_t(\Delta_t - \delta_t) + f_l(\Delta_l - \delta_l))/2. \tag{8}$$

From (4) and (8) the horizontal component of the elastic force per unit area, normal to the fault line on the upper plane, f_n can be written as:

$$f_n = \frac{\partial æ}{\partial \Delta_n} = \frac{f_l}{\cos\alpha} \ . \tag{9}$$

It follows from (9) that the total force acting at the point of the fault plane is horizontal if there is a reaction force, which is normal to the fault plane (Fig. 3*b*). The reaction force per unit area is equal to

$$p_0 = f_l \mathrm{tg}\alpha. \tag{10}$$

The reaction force (10) is introduced and therefore there are not vertical components of forces acting on the blocks and there are not vertical displacements of blocks.

Formulas (3) are also valid for boundary faults. In this case, one of the blocks separated by the fault is a boundary block. The movement of boundary blocks is prescribed by their translation and rotation about the coordinate origin. Therefore the coordinates of the geometrical centre of the block bottom in (3) are set to zero for any boundary block. For example, if the block numbered j is a boundary block, then $X_c^j = Y_c^j = 0$ in (3).

6. Equations of Equilibrium

The components of the translation vectors of the blocks and the angles of their rotation about the geometrical centres of the bottoms are found from the condition that the total force and the total moment of forces acting on each block are equal to zero. This is the condition of quasi-static equilibrium of the system and at the same time the condition of minimum energy. The equilibrium equations include only forces caused by specified movements of the underlying medium and the boundaries of the block structure are considered only in the equilibrium equations. In fact, it is assumed that the action of all other forces (gravity, etc.) on the block structure is ruled out and does not cause displacements of blocks.

In accordance with formulas (1), (3-5), (9), and (10) the dependence of the forces, acting on the blocks, on the translation vectors of the blocks and the angles of their rotations is linear. Therefore the system of equations which describes the equilibrium is linear one and has the following form

$$A\mathbf{z} = \mathbf{b} \tag{11}$$

where the components of the unknown vector $\mathbf{z} = (z_1, z_2, ..., z_{3n})$ are the components of the translation vectors of the blocks and the angles of their rotation about the geometrical centres of the bottoms (n is the number of blocks), i.e. $z_{3m-2} = x_m$, $z_{3m-1} = y_m$, $z_{3m} = \varphi_m$ (m is the number of the block, $m = 1, 2, ..., n$).

Matrix A does not depend on time and its elements are defined from formulas (1), (3-5), (9), and (10). The moment of the forces acting on a block is calculated relative to the geometrical centre of its bottom. Expressions for the elements of matrix A contain integrals over fault segments and block bottoms. Each integral is replaced by a finite sum, in accordance with the space discretization described in Section 7.

The components of the vector **b** are also defined from formulas (1), (3-5), (9), and (10) as well. They depend on time, explicitly, because of the movements of the underlying medium and of the block structure boundaries and, implicitly, because of the inelastic displacements.

7. Discretization

Time is discretized with a step Δt. The state of the block structure is considered at discrete values of time $t_i = t_0 + i\Delta t$ (i = 1, 2, ...), where t_0 is the initial time. The transition from the state at t_i to the state at t_{i+1} proceeds as follows:

(i) new values of the inelastic displacements x_a, y_a, δ_t, δ_l are calculated from equations (2) and (6);

(ii) translational vectors and rotational angles at t_{i+1} are obtained for boundary blocks and the underlying medium;

(iii) the components of **b** in equations (11) are found, and these equations are used to define the translational vectors and the angles of rotation for the blocks. The elements of A in (11) are independent of time; hence matrix A and the associated inverse matrix are calculated only once, at the beginning of the modeling.

Formulas (1-6, 8-10) describe forces, relative displacements, and inelastic displacements at points of fault segments and of block bottoms. Therefore, the discretization of these surfaces is required for the numerical simulation. The space discretization is defined by the parameter ε, and it is 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 trapezoid with bases a and b and height $h = H/\sin\alpha$, where H is the thickness of the layer, and α is the dip angle of the fault plane. The values

$n_1 = \mathrm{ENTIRE}(h/\varepsilon) + 1$, and $n_2 = \mathrm{ENTIRE}(\max(a,b)/\varepsilon) + 1$,

are determined, and the trapezoid is divided into $n_1 n_2$ small trapezoids by two groups of segments inside it; there are n_1-1 segments parallel to the trapezoid bases and spaced at intervals h/n_1, and n_2-1 segments connecting the points spaced by intervals of a/n_2 and b/n_2, respectively, on the two bases. The small trapezoids obtained in such a way are called cells. The coordinates X, Y in (3) and the inelastic displacements δ_t, δ_l in (5) are supposed to be the same for all points of a cell and are considered average values over the cell. When introduced in formulas (3-5), (9), and (10) they yield the average (over the cell) of the elastic and reaction forces per unit area. The forces acting on a cell are obtained by multiplying the average forces per unit area by the area of the cell.

The bottom of a block is a polygon. Prior discretization, it is divided into trapezoids (triangles) by segments passing through its vertices and parallel to the Y axis. The discretization of these trapezoids (triangles) is performed in the same way as for fault segments. Small trapezoids (triangles) so obtained are also called cells. Coordinates X, Y and inelastic displacements x_a, y_a in (1) are assumed to be the same for all points of a cell.

8. Earthquake and Creep

Let us introduce the quantity

$$\kappa = \frac{|\mathbf{f}|}{P - p_0} \tag{12}$$

where $\mathbf{f} = (f_t, f_l)$ is the vector of the elastic force per unit area given by (5), P is assumed the same for all fault planes and can be interpreted as the difference between the lithostatic and the hydrostatic pressure; p_0 given by (10) is the reaction force per unit area.

Three following values of κ are assigned to each fault plane:

$B > H_f \geq H_s$.

Let us assume that the initial conditions of the model satisfy the inequality $\kappa < B$ for all the cells of fault segments. If, at some time t_i, the value of κ in any cell of a fault segment reaches the level B, a failure ("earthquake") occurs. The failure is considered slippage during which the inelastic displacements δ_t, δ_l in this cell change abruptly to reduce the value of κ to the level H_f. Thus, the earthquakes occur in accordance with the dry friction model.

The new values of inelastic displacements in the cell are calculated from

$$\delta_t^e = \delta_t + \gamma f_t, \quad \delta_l^e = \delta_l + \gamma f_l \tag{13}$$

where δ_t, δ_l, f_t, f_l are the inelastic displacements and the components of the elastic force vector per unit area just before the failure. The coefficient γ is given by

$$\gamma = 1/K - PH_f/(K(|\mathbf{f}| + H_f f_l \mathrm{tg}\alpha)). \tag{14}$$

It follows from (5), (10), and (12-14) that on obtaining the new values of the inelastic displacements the value of κ in the cell becomes equal to H_f.

After calculating new values of inelastic displacements for all failed cells, new components of the vector **b** are found, and the translational vectors and the angles of rotation for all blocks are obtained from the system of equations in (11). If κ still exceeds B for some cell(s) of the fault segments, the procedure given above is repeated for this cell (or cells). Otherwise the state of the block structure at time t_{i+1} is determined as follows: translational vectors, rotational angles (at t_{i+1}) for boundary blocks and for the underlying medium, and the components of **b** in equations (11) are calculated, and then equations in (11) are solved.

The cells of the same fault plane, where failure occurs simultaneously, form a single earthquake. The parameters of the earthquake are defined as follows:

(i) the origin time is t_i;

(ii) the epicentral coordinates and the source depth are the weighted sums of the coordinates and the depths of cells included in the earthquake (the weight of each cell is given by its area divided by the total sum of areas of all cells included in the earthquake);

(iii) the magnitude is calculated from

$$M = 0.98 \lg S + 3.93, \tag{15}$$

where S is the total area of cells (in km^2) included in the earthquake and the values of coefficients are specified in accordance with *Utsu and Seki* (1954). *Wells and Coppersmith* (1994) updated the relationship between magnitude and rupture area and estimated the absolute term in (15) to be 4.07. Hence, if the updated relationship is employed in the model, earthquake magnitudes could be slightly higher.

It is assumed that the cells, in which a failure has occurred, are in the creep state immediately after the earthquake. It means that the parameter W_s ($W_s > W$) is used instead of W for these cells in (6) to describe the evolution of inelastic displacements; W_s may be different for different fault planes. After each earthquake, a cell is in the creep state as long as $\kappa > H_s$, whereas when $\kappa \leq H_s$, the cell returns to the normal state, and henceforth the parameter W is used in (6) for this cell.

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