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Block models of lithosphere dynamics and seismicity

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Contents

Abstract

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 reliable real observation data. This paper focuses on risks of earthquakes. The region of Italy is considered as an example. A brief overview of different approaches in mathematical modeling of the lithosphere dynamics is presented. A model of the block structure dynamics and seismicity is described in detail and used for the analysis of the Vrancea (Romania) seismoactive region. The corresponding synthetic earthquake catalog is viewed as a basis for a possible generator of catastrophic events for estimating the seismic risks in the region.

Acknowledgments

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1. Introduction

The vulnerability of the human civilization to natural dangers is critically growing due to proliferation of high-risk objects, clustering of population, and destabilization of large cities. Today a single earthquake may take up to a million lives; cause material damage up to US$1,000,000,000,000, with chain reaction expanding to worldwide economic depression; trigger major ecological catastrophe (e.g. several Chernobyl-type calamities at once); paralyze national defense. In many developing countries the damage from earthquakes consumes all the increase in the GDP. Critically vulnerable became low seismicity regions, e.g., European and Indian platforms, Eastern US, etc. It is discussed that more frequent and more intense anthropogenic and natural catastrophes may destroy the existing insurance system [19, 20]. In this context, problems of estimating risks of natural catastrophes are becoming highly important. In the last third of the 20th century, a number of concepts of risks of natural catastrophes have been suggested and a number of international projects on safety and risk management have been conducted. Serious difficulties in decision making in these fields are concerned with strong uncertainties in data and limitations in using mathematical tools for carrying out the historical analysis and forecasting [44].

Seismic risk is a measure of possible damage from earthquakes. Estimation of seismic risk may facilitate a proper choice in a wide variety of seismic safety measures, ranging from building codes and insurance to establishment of rescue-and-relief resources. Different representations of seismic risk require different safety measures. Most of the practical problems require to estimate seismic risk for a territory as a whole, and within this territory – separately for the objects of each type: areas, lifelines, sites of vulnerable constructions, etc. The choice of the territory and of the objects is determined by the jurisdiction and responsibility of a decision-maker.

Each concrete representation of seismic risk is derived from the ***primary models:*** of the occurrence of earthquakes; of strong motions caused by a single earthquake; of the territorial distribution of population, property, and vulnerable objects; and of the damage caused by an episode of strong motion.

In this study we focus on models of earthquake occurrence. Earthquakes are governed by non-linear hierarchical systems, which have a number of degrees of freedom and, therefore, cannot be understood by studying them piece by piece. Since an adequate theoretical base has yet not been well elaborated, theoretical estimation of statistical parameters of earthquake flows is still a highly complex problem.

Studying seismicity using the statistical and phenomenological analysis of real earthquake catalogues has a disadvantage that instrumental observation data cover, usually, too short time intervals, in comparison with the duration of the tectonic processes responsible for seismic activity. The patterns of earthquake occurrence identifiable in a real catalogue may be apparent and may not be repeated in the future. Moreover, the historical data on seismicity are usually incomplete and do not cover uniformly a region under consideration.

Numerical modeling of seismogenic processes allows to overcome these difficulties. Synthetic earthquake catalogues formed via numerical simulations may cover very long time intervals and, therefore, provide a basis for reliable estimates of the parameters of the earthquake flows.

The paper is organized as follows. In section 2 we characterize damages due to earthquakes (taking Italy as an example) and give a brief overview of mathematical models of lithosphere dynamics. In section 3 we describe a model of the block structure dynamics and seismicity. Section 4 presents results of numerical simulations of the dynamics of a block structure modeling the tectonic structure of the Vrancea region. In this highly seismically active region of Romania, several strongest European earthquakes of the 20th century occurred.

2. Damage from earthquakes in Italy

Table 1 shows a time history of major earthquake events in Italy in the 20th century, involving more than 100 casualties. Earthquakes of comparable intensities but resulting in smaller human losses have not been included. The number of deaths in 1908 Calabria/Messina (Sicily) is impressive: the event was followed by a sea-surge.

The dimensions of the earthquake risk can be summarized as follows:

- human lives: larger than 120,000 deaths in the 20th century;
- losses:~120000 billion lire (~63 billions ECU) in the last 20 years;
- ~64% of the buildings constructed before the seismic classification of the country;
- 23 million people exposed;
- cultural heritage threatened.

The 1980 Irpinia event was a landmark in raising awareness and developing a policy for preparedness and mitigation. The extension of the involved territory was almost equivalent to a country such as Belgium. The severity of losses appeared to be no longer acceptable with respect to the technological status of the country.

The rather recent Umbria-Marche earthquake, which started with a first shake on 26/9/97, is characteristic for losses in the Apennines mountain region of Italy, for the urban structure is typical here. Many cities are located in the seismically hazardous regions of central and southern Italy. Two-thirds of the buildings were built in traditional masonry (mainly stonework) more than 60 years ago. Furthermore, this region has a high cultural heritage.

Table 1. Major earthquakes in Italy in the twentieth century [5]

Year	Area	MCS Intensity	Deaths	Injuries
1906	Calabria	X	557	~2,000
1907	Calabria	IX	167	~90
1908	Calabria Messina	XI	85,926	14,138
1910	Irpinia	IX	~50	Many
1914	Etna (Vulcan)	X	~69	115
1915	Fucino	XI	32,610	Many
1919	Mugello	IX	~100	~400
1920	Lunigiana/	X	171	~650

	Carfagnana			
1930	Irpinia	X	1,778	4,264
1968	Belice	X	231	623
1976	Friuli	IX-X	965	~3,000
1980	Irpinia/ Basilicata	IX-X	2,914	10,000

The data on the Umbria–Marche event presented in Table 2 were provided by the Civil Protection Department (DPC) 4 months later the occurrence of the first event, which has been followed by a series of shakes of significant strength. In the quoted period 3,300 shakes followed the first one: ten of these had intensities larger than VI (MCS). 10,100 rescue operators were involved. The number of people assisted ranged from 13,500 (the first day) to 38,000 (after the violent shakes in mid October).

Table 2. Damages and losses from the Umbria–Marche Earthquake [5]

	Umbria	Marche	Total
Number of damaged public and historical buildings	1,178	948	2,126
Number of damaged private buildings and activities	16,082	10,617	26,699
Number of homeless people	18,276	7,194	25,470
Private buildings + activities. Losses in MECU	1490	2010	3500
Further activities and agriculture	180	390	570
Public buildings	150	590	740
State buildings and roads			130
Cultural heritage	140	410	550
Total losses in MECU	1960	3400	5490

Even if the number of victims had been relatively small, the cultural heritage and public infrastructures suffered seriously. The collapse of part of the cupola of the San Francesco Basilica in Assisi raised the problem of employing modern technologies for the restoration of old monuments: wood (subjected to fire risk) was substituted with reinforced concrete in the roof.

3. Review on models of seismic processes

3.1. Modeling approaches and their significance

The seismic observations show that features of a seismic flow are different for different active regions [30, 41]. It is reasonable to suggest that this difference is (among other factors) due to contrasts in the tectonic structure of the regions and the main tectonic movements determining the lithosphere dynamics in the regions. Laboratory studies show specifically that this difference is controlled mainly by the rate of fracturing and heterogeneity of the medium and also by the type of predominant tectonic movements [48, 66].

If a single factor is considered, it is difficult to detect its impact on features of a seismic flow by using real seismic observations because the seismic flow is effected by an assemblage of factors, some of which could be stronger than the one under consideration. It is extremely difficult, if not impossible, to identify the impacts of particular factors, basing on the analysis of real seismic observations. Numerical modeling of seismicity-generating processes and studying the corresponding synthetic earthquake catalogs (see, e.g., [4, 24, 52, 64, 74]) provides a methodological basis for such identification. Moreover, studying seismicity using the statistical and phenomenological analysis of real earthquake catalogues has a disadvantage that instrumental observation data cover, usually, too short time intervals, in comparison with the duration of the tectonic processes responsible for seismic activity. The patterns of earthquake occurrence identifiable in a real catalogue may be apparent and may not be repeated in the future, thus excluding reliable statistical tests. Numerical modeling of seismogenic processes allows to overcome these difficulties. Synthetic earthquake catalogues formed via numerical simulations may cover very long time intervals and, therefore, provide a basis for reliable estimates of the parameters of the earthquake flows.

An adequate model should incorporate the following principal features of the lithosphere:

- interaction of the processes of different physical origin, and of different spatial and temporal scales;
- hierarchical block or possibly «fractal» structure; and
- self-similarity in space, time, and energy.

The traditional approach to modeling is based on one specific tectonic fault and, often, one strong earthquake in order to reproduce certain seismic phenomena (relevant to this specific earthquake). In contrast, the class of the slider-block and cellular automata models treats the seismotectonic process in the most abstract way, in order to reproduce general universal properties of seismicity, first of all, the Gutenberg–Richter frequency-magnitude law, migration of events, sequence of aftershocks, seismic cycle and so on [33].

The specific and general approaches have their respective advantages and disadvantages. The first approach, which takes into account detailed information on the local geotectonic environment, usually misses universal properties of a series of events in a system of interacting faults. The second approach may be treated as a zero-order approximation to reality. However, the importance of this approach and, in general, the importance of the application of the methods of theoretical physics and nonlinear science to the earthquake prediction problem lies in the possibility of establishing generic analogs with problems in other sciences, and to elaborate a new language for the description of seismicity patterns on the basis of the well-developed lexicon of nonlinear science.

Mathematical models of lithosphere dynamics developed according to a general approach are also tools for the study of the earthquake preparation process and useful in earthquake prediction studies [24]. An adequate model should indicate the physical basis of premonitory patterns determined empirically before large events. Note one more time that the available data often do not constrain the statistical significance of the premonitory patterns. The model can be used also to suggest new premonitory patterns that might exist in real catalogs.

Although there is no adequate theory of the seismotectonic process, various properties of the lithosphere, such as spatial heterogeneity, hierarchical block structure, different types of non-linear rheology, gravitational and thermodynamic processes, physicochemical and phase transitions, fluid migration and stress corrosion, are probably relevant to the properties of earthquake sequences. The qualitative stability of these properties in different seismic regions suggests that the lithosphere can be modelled as a large dissipative system that does not essentially depend on the particular details of the specific processes active in a geological system.

An adequate model of seismicity should incorporate the universal features of self-organized nonlinear systems, as well as the specific geometry of interacting tectonic faults. Below we review some of the most important approaches to modeling seismic process [23].

3.2. Elastic rebound theory

One important ingredient in the modeling of seismicity is based on the so-called elastic rebound theory [58], which emerged in the aftermath of the great San Francisco earthquake of 1906. According to this theory, elastic stress in a seismically active region accumulates due to some external sources, e.g. movement of tectonic plates, and is released when the stress exceeds the strength of the medium. In the simplest case (constant rate of stress accumulation, fixed strength and residual stress) this model produces a periodic sequence of earthquakes of equal magnitude. This links the elastic rebound theory with the concepts of the seismic cycle and of characteristic earthquakes.

If only strength or residual stress is fixed in this model, we have the so-called "time-predictable" model (the time interval until the next earthquake is defined by the magnitude of the previous one) and the "slip-predictable" model (the magnitude of an expected earthquake increases with the elapsed time). But real sequences of strong earthquakes are fundamentally more complicated [69]. In particular, the elastic rebound model suggests that a strong earthquake should be followed by a period of quiescence, whereas in reality a strong earthquake is followed by a period of activation and sometimes by another earthquake of comparable magnitude. Simple deterministic nonlinear models for repetitive seismicity containing some of the attributes of «chaos» were developed by Knopoff and Neumann [39, 50].

3.3. Rate-dependent and state-dependent friction

A model with a rate-dependent and state-dependent friction law, based on laboratory experiments using rock samples, was introduced by Dieterich [17] and further developed and studied by Ruina [61], Tse and Rice [73], and others. The model defines the special dependence of the friction coefficient on the slip velocity and state variable. Instability appears when the stiffness is below a critical value, see [27]. The model gives an adequate description of preseismic, coseismic and postseismic slip on a fault, especially when, as in [73], transition from velocity weakening to velocity strengthening with depth is included.

The principal problem in this modeling is the applicability of the complicated friction law, derived from laboratory experiments on flat surfaces of homogeneous rock samples, to real fault zones that are neither homogeneous nor flat. The parameters in this friction law are empirical, and it is not clear how to scale them properly for real faults. The behavior of the system with this friction law is very sensitive to small variation in the values of the parameters— in the presence of noise, it may become unpredictable.

3.4. Spatial heterogeneity

Another direction in the modeling of complex earthquake sequences takes into account the spatial inhomogeneity of the strength distribution in the fault plane. The key concepts here are barriers, asperities, and characteristic earthquakes [1]. Asperities and barriers represent strong patches in the fault plane, while the difference is in their relation to the earthquake source. Asperities are strong patches on the stress-free background (due to preslip and foreshocks) and break during the earthquake [34]. Barriers appear as strong patches that do not allow further propagation of a fracture [16]. The interpretation of barriers in terms of the geometry of tectonic faults was suggested by King and Nabelek [37, 38]. In particular, King [38] suggested the existence of «soft» barriers where a seismic rupture terminates due to the absence of accumulated stress. Both asperities and barriers suggest the possible recurrence of earthquakes with a preferred source size, i.e. characteristic earthquakes [63].

3.5. Slider-block models and self-organized criticality

In contrast with the models mentioned above, a number of models composed of «masses and springs» or of cellular automata suggest the possibility of apparently chaotic earthquake sequences with a power law distribution of sizes in a spatially homogeneous medium due to self-organizing processes in a system of interacting elements (blocks, faults, etc.). The first class of these models, the slider-block models originally proposed by Burridge and Knopoff [10], have been studied by Cao and Aki [11], Carlson et al. [12, 13, 14], and others. In these models a linear system of rigid blocks connected by springs to adjacent blocks and to a driving slab and interacting with a stable surface according to a specified friction law.

In [10] the model was shown to reproduce such important properties of seismicity as the Gutenberg—Richter law, and with the inclusion of additional viscous elements, aftershock activity. Cao and Aki [11] considered a system of blocks with a rate-dependent and state-dependent friction law in order to reproduce premonitory patterns. Carlson and Langer [12] found a bimodal population of earthquakes in their model. While the small earthquakes obey a power law distribution, the strongest (runaway) events appear much more often than the extrapolation of the power law established for the small earthquakes would suggest. They associated this phenomenon with the concept of characteristic earthquakes. Shaw et al. [64] reproduced activation and concentration patterns for small events before a strong earthquake in their model catalog. Carlson [13] and Narkounskaia et al. [49] considered a two-dimensional variant of the slider-block model.

Bak et al. [7, 8] suggested a simple cellular automaton-type («sandpile») model represented by a lattice of threshold elements with random loading and a simple deterministic rule of stress release and nearest-neighbor redistribution. A sequence of consecutive breaks in the stress redistribution phase of the model was called an *avalanche.* The model is mathematically equivalent to a variant of the slider-block model in the limit of zero-mass blocks, and the avalanches can be interpreted as the earthquakes in the Burridge-Knopoff model. The sandpile model demonstrates an important property of *self-organized criticality:* from any initial state it evolves to a critical state characterized by a power law distribution of the avalanche sizes and two-point correlations. The applications of this model and its different variations and modifications can be found in [8, 9, 31, 43] and others. See Ito [32] for a review.

These models are concerned, in particular, with the power law distribution of earthquake sizes and, in general, with the chaotic character of a simple, homogeneous, and often deterministic, system. Different macroscopic effects due to changes in the local interaction rules, and phase transition phenomena according to variation of parameters were also investigated.

Although these models are rather abstract and oversimplified, some important features of seismicity can be understood in these models, and the influence of different types of interaction on the model catalog can be easily verified. It is important also as possibility to establish analogies between the problems of predictability in solid Earth geophysics and other sciences.

3.6. Hierarchical and fractal structures

Models of crack nucleation based on the hierarchical block structure of the Earth's lithosphere were suggested in [3, 39, 67]. All of these models explicitly introduce fractures of several scales and apply renormalization group methods to study interrelations between different scales. The condition for failure sometimes appears in these models as a critical phenomenon. In [51, 67], this approach explains the apparent low strength of fault zones— however, a critical point for failure does not emerge.

3.7. Interaction of tectonic faults

There are a few models of seismicity where the interaction of tectonic faults is taken into account. One is the fluctuation model due to [62] where earthquakes are treated as small thermodynamic fluctuations in the steady tectonic loading process in an elastic medium with embedded faults patches. Another is the block model of lithosphere dynamics, which exploits the hierarchical block structure of the lithosphere proposed by Alekseevskaya et al. [2]. The basic principles of the model are developed by Gabrielov, et al. [22]. Accordingly with this model, the blocks of the lithosphere are separated by comparatively thin, weak, less consolidated fault zones, such as lineaments and tectonic faults. In the seismotectonic process major deformation and most earthquakes occur in such fault zones.

A seismic region is modeled by a system of perfectly rigid blocks divided by infinitely thin plane faults. Relative displacement of all blocks is supposed to be infinitely small relative to their geometric size. 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 zones.

In the model the strains are accumulated in fault zones. This reflects strain accumulation due to deformations of plate boundaries. Of course considerable simplifications are made in the model, but simplifications are necessary to understand the dependence of earthquake flow on main tectonic movements in a region and its lithosphere structure. This assumption is justified by the fact that for the lithosphere the effective elastic modules in the fault zones are significantly smaller than those within the blocks.

The blocks are in viscous-elastic interaction with the underlying medium. The corresponding stresses depend on the value of relative displacement. This dependence is assumed to be linear elastic. The motion of the medium underlying different blocks may be different. Block motion is defined so that the system is in a quasi-static state of equilibrium.

The interaction of the blocks along fault zones is viscous-elastic ("normal state") so far as 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 zone, a stress-drop ("failure") occurs (in accordance with the dry friction model), possibly causing failure in other parts of the fault zones. These failures produce earthquakes. Immediately after the earthquake and for some time after, the affected parts of the fault zones are in a creep state. This state differs from the normal one because of a faster growth of inelastic displacements, lasting until the ratio of the stress to the pressure falls below some other level. The process of numerical simulation produces a synthetic earthquake catalog as a result.

On the base of idea outlined above a family of block models taking into account real geometry of tectonic regions was developed. The key point for further modifications is so-called two-dimensional plane model the detailed description of which is given below. The paper [60] is devoted to investigation of three-dimensional block movements. In [18, 47] the model is transferred into the sphere in order to simulate global tectonic plates dynamics.

4. Detailed description of the block model

The main principles of the block model are described taking as an example the two-dimensional model [26, 35, 57, 68], which is more studied than others.

4.1. Block structure geometry

A layer with thickness *H* limited by two horizontal planes is considered (Fig. 1), and a block structure is defined as a limited and simply connected part of this layer. Each lateral boundary of the block structure is defined by portions of the parts of planes intersecting the layer. The subdivision of the structure into blocks is performed by planes intersecting the layer. The parts of these planes, which are inside the block structure and its lateral faces, are called "fault zones".

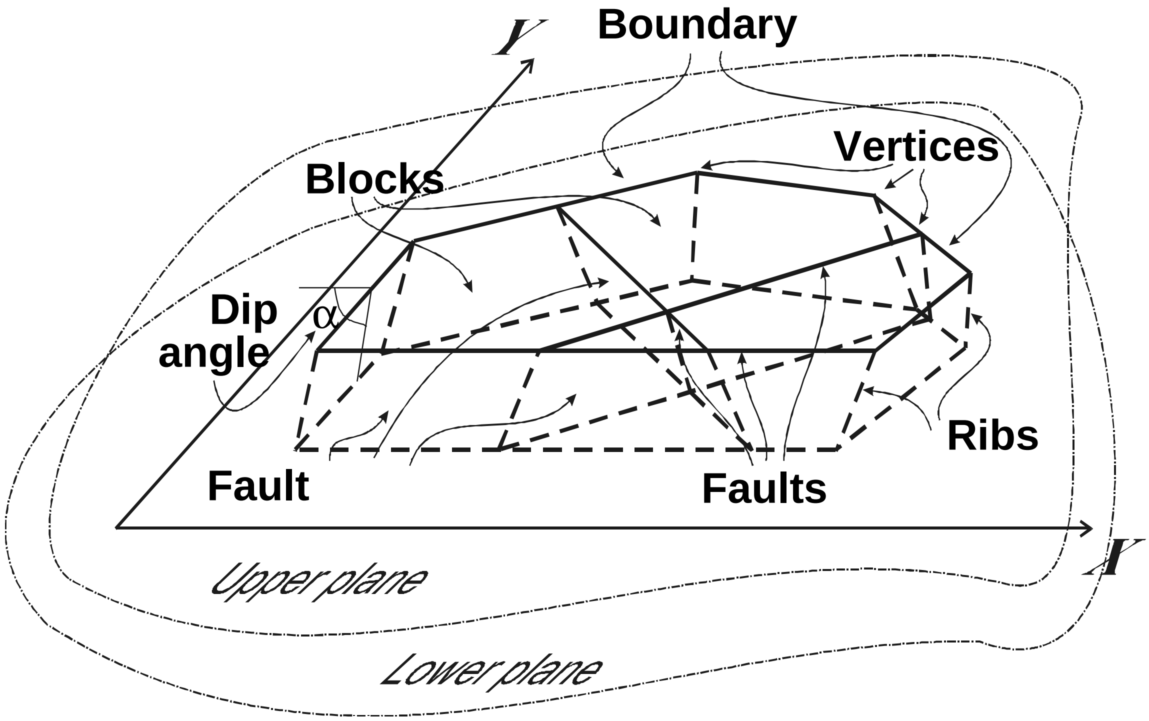

Figure 1.

The geometry of the block structure is defined by the lines of intersection between the fault zones and the upper plane limiting the layer (these lines are called "faults"), and by the angles of dip of each fault zone. Three or more faults cannot have a common point on the upper plane, and a common point of two faults is called "vertex". The direction is specified for each fault and the angle of dip of the fault zone 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 zones. The part of a fault zone between two ribs corresponding to successive vertices on the fault is called "segment". The shape of the segment is a trapezium. The common parts of the block with the upper and lower planes are polygons, and the common part of the block with the lower plane is called "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".

4.2. Block movement

The blocks are assumed to be rigid and all their relative displacements take place along the bounding fault zones. 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 referred to one unit of the dimensionless time, and their dimensions do not contain time. For example, in the model, velocities are measured in units of length and the velocity of 5 cm means 5 cm for one unit of the dimensionless time. When interpreting the results a realistic value is given to one unit of the dimensionless time. For example if one unit of the 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 quasistatic equilibrium, and all displacements are supposed to be infinitely small, compared with the block size. Therefore the geometry of the block structure does not change during the simulation and the structure does not move as a whole.

4.3. Interaction between the 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 $\mathbf{f}^u = (f_x^{\,u}, f_y^{\,u})$ applied to the point with co-ordinates (X,Y), at some time t, is defined by

$$f_x^{\,u} = K_u(x - x_u - (Y - Y_c)(\varphi - \varphi_u) - x_a),$$

$$f_y^{\,u} = K_u(y - y_u + (X - X_c)(\varphi - \varphi_u) - y_a). \tag{1}$$

where X_c, Y_c are the co-ordinates of the geometrical center of the block bottom; (x_u, y_u) and φ_u are the translation vector and the angle of rotation (following the general convention, the positive direction of rotation is anticlockwise), around the geometrical center 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 around the geometrical center of its bottom at time t; (x_a, y_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

$$\frac{dx_a}{dt} = W_u f_x^{\,u}, \ \frac{dy_a}{dt} = W_u f_y^{\,u}. \tag{2}$$

The coefficients K_u and W_u in (1) and (2) may be different for different blocks.

4.4. Interaction between the blocks along the fault zones

At the time t, in some point (X,Y) of the fault zone 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

$$\Delta x = x_i - x_j - (Y - Y_c^i)\varphi_i + (Y - Y_c^j)\varphi_j,$$

$$\Delta y = y_i - y_j + (X - X_c^i)\varphi_i - (X - X_c^j)\varphi_j. \tag{3}$$

where X_c^i, Y_c^i, X_c^j, Y_c^j are the co-ordinates of the geometrical centers of the block bottoms, (x_i, y_i), and (x_j, y_j) are the translation vectors of the blocks, and φ_i, φ_j are the angles of rotation of the blocks around the geometrical centers of their bottoms, at time t.

In accordance with the assumption that the relative block displacements take place only along the fault zones, the displacements along the fault zone are connected with the horizontal relative displacement by

$$\Delta_t = e_x\Delta x + e_y\Delta y,$$

$$\Delta_l = \Delta_n/\cos\alpha, \quad \text{where} \quad \Delta_n = e_x\Delta y - e_y\Delta x. \tag{4}$$

Here Δ_t and Δ_l are the displacements along the fault zone parallel (Δ_t) and normal (Δ_l) to the fault line on the upper plane; (e_x, e_y) is the unit vector along the fault line on the upper plane; α is the dip angle of the fault zone; 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. 2A).

The elastic force per unit area $\mathbf{f} = (f_t, f_l)$ acting along the fault zone 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 zone 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 zone.

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

$$e = (f_t(\Delta_t - \delta_t) + f_l(\Delta_l - \delta_l))/2. \tag{7}$$

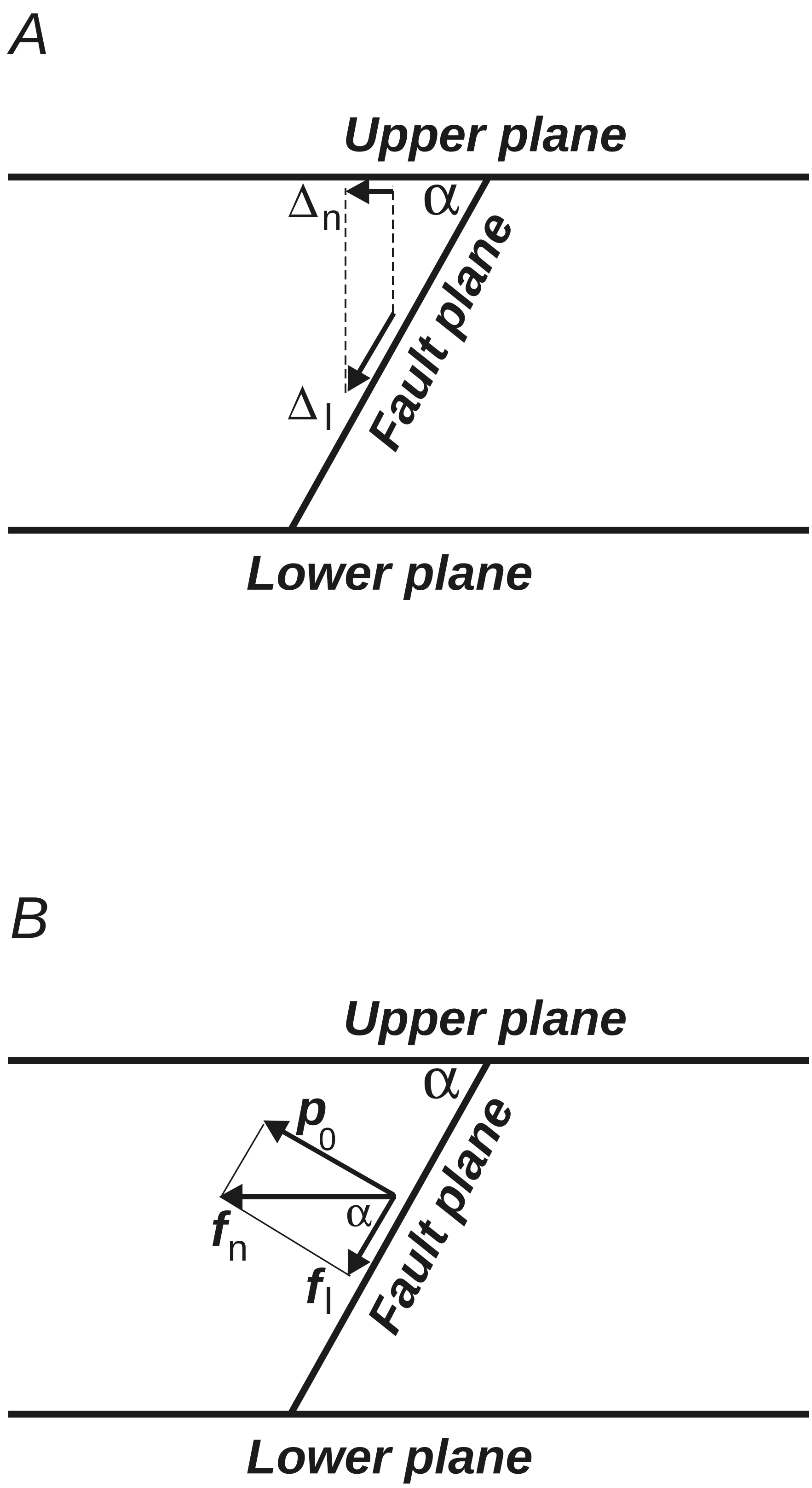
A
Upper plane
Δ_n
α
Fault plane
Δ_l
Lower plane
B
Upper plane
α
p_0
f_n
α
f_l
Fault plane
Lower plane

Figure 2.

From (4) and (7) 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:

$$f_n = \frac{\partial e}{\partial \Delta_n} = \frac{f_l}{\cos\alpha} \quad . \tag{8}$$

It follows from (8) that the total force acting at the point of the fault zone is horizontal if there is the reaction force, which is normal to the fault zone (Fig. 2B). The reaction force per unit area is equal to

$$p_0 = f_l \mathrm{tg}\alpha. \tag{9}$$

The reaction force (9) 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 valid for the boundary faults too. In this case one of the blocks separated by the fault is the boundary block. The movement of these blocks is described by their translation and rotation around the origin of co-ordinates. Therefore the co-ordinates of the geometrical center of the block bottom in (3) are zero for the boundary block. For example, if the block numbered j is a boundary block, then $X_c^j = Y_c^j = 0$ in (3).

4.5 Equilibrium equations

The components of the translation vectors of the blocks and the angles of their rotation around the geometrical centers 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 forces arising from the specified movements of the underlying medium and of 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 balanced and does not cause displacements of the blocks.

In accordance with formulas (1), (3-5), (8), and (9) 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

$$A\mathbf{z}=\mathbf{b} \tag{10}$$

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 around the geometrical centers 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, $m = 1, 2, ..., n$).

The matrix A does not depend on time and its elements are defined from formulas (1), (3-5), (8), and (9). The moment of the forces acting on a block is calculated relative to the geometrical center of its bottom. The expressions for the elements of the matrix A contain integrals over the surfaces of the fault segments and of the block bottoms. Each integral is replaced by a finite sum, in accordance with the space discretization described in the next section.

The components of the vector $\mathbf{b}$ are defined from formulas (1), (3-5), (8), and (9) 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.

4.6. Discretization

Time discretization is performed by introducing a time 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} is made 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) the translation vectors and the rotation angles at t_{i+1} are calculated for the boundary blocks and the underlying medium; (iii) the components of **b** in equations (10) are calculated, and these equations are used to define the translation vectors and the angles of rotation for the blocks. Since the elements of A in (10) are not functions of time, the matrix A and the associated inverse matrix can be calculated only once, at the beginning of the calculation.

Formulas (1-9) describe the forces, the relative displacements, and the inelastic displacements at points of the fault segments and of the block bottoms. Therefore the discretization of these surfaces (partition into «cells») is required for the numerical simulation. It is made according to the special rule, and the co-ordinates X, Y and the corresponding inelastic displacements are supposed to be the same for all the points of a cell.

4.7. Earthquake and creep

Let us introduce the quantity

$$\kappa = \frac{|\mathbf{f}\,|}{P - p_0} \tag{11}$$

where $\mathbf{f} = (f_t, f_l)$ is the vector of the elastic force per unit area given by (5), P is assumed equal for all the faults and can be interpreted as the difference between the lithostatic and the hydrostatic pressure, p_0, given by (9), is the reaction force per unit area. For each fault the following three values of κ are considered $B > H_f \geq H_s$.

Let us assume that the initial conditions for the numerical simulation of block structure dynamics satisfy the inequality $\kappa < B$ for all the cells of the 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 meant as slippage during which the inelastic displacements δ_t, δ_l in the 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 the inelastic displacements in the cell are calculated from

$$\delta_t^e = \delta_t + \gamma f_t, \quad \delta_l^e = \delta_l + \gamma f_l \qquad (12)$$

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

$$\gamma = 1/K - PH_f/(K(|\mathbf{f}| + H_f f_l \mathrm{tg}\alpha)) \qquad (13)$$

It follows from (5), (9), (11-13) that after the calculation of the new values of the inelastic displacements the value of κ in the cell is equal to H_f.

After calculating the new values of the inelastic displacements for all the failed cells, the new components of the vector **b** are calculated, and from the system of equations (10) the translation vectors and the angles of rotation for the blocks are found. If for some cell(s) of the fault segments $\kappa > B$, the procedure given above is repeated for this cell (or cells). Otherwise the state of the block structure at the time t_{i+1} is determined as follows: the translation vectors, the rotation angles (at t_{i+1}) for the boundary blocks and for the underlying medium, and the components of **b** in equations (10) are calculated, and then equations (10) are solved.

Different times could be attributed to the failures occurring on different steps of the procedure described above: if the procedure consists of p steps the time $t_i + (j - 1)\delta t$ can be attributed to the failures occurring on the jth step, and the value of δt is selected to satisfy the condition $p\delta t < \Delta t$.

The cells of the same fault zone in which failure occurs at the same time form a single earthquake. The parameters of the earthquake are defined as follows: (i) the origin time is $t_i + (j - 1)\delta t$; (ii) the epicentral co-ordinates and the source depth are the weighted sums of the co-ordinates and depths of the cells included in the earthquake (the weight of each cell is given by its square divided by the sum of squares of all the cells included in the earthquake); (iii) the magnitude is calculated from the formula:

$$M = D \lg S + E, \qquad (14)$$

where D and E are constants and S is the sum of the squares of the cells (in km^2) included in the earthquake.

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

5. Model of block-and-fault dynamic of the Vrancea region (the south-eastern Carpathians)

5.1. Introduction to seismicity and geodynamics of the region

The earthquake-prone Vrancea region is situated at a bend of the Eastern Carpathians and bounded on the north and north-east by the Eastern European platform, on the east and south by the Moesian platform, and on the west by the Transylvanian and Pannonian basins. The epicenters of mantle earthquakes in the Vrancea region are concentrated within a very small area (about 40 km × 80 km, Fig. 3A), and the distribution of the epicenters is much denser than that of intermediate-depth events in other intracontinental regions. The projection of the foci on the NW-SE vertical plane across the bend of the Eastern Carpathians (Fig. 3B) shows a seismogenic body in the form of a parallelepiped about 100 km long, about 40 km wide, and extending to a depth of about 180 km. Beyond this depth the seismicity ends suddenly: a seismic event represents an exception beneath 180 km [56, 71, 72].

In the middle of the twentieth century, Gutenberg and Richter [28, 29] drew attention to the remarkable source of shocks in the depth range of 100 km to 150 km in the Vrancea region. According to a historical data, there have been 16 large intermediate-depth shocks with magnitudes $M_S > 6.5$ occurring three to five times per century [40]. In the twentieth century, large events in the depth range of 70 to 170 km occurred in 1940 with moment magnitude M_W=7.7, in 1977 M_W=7.4, in 1986 M_W=7.1, and in 1990 M_W= 6.9 [56]. Using numerous fault-plane solutions for intermediate-depth shocks, Nikolaev and Shchyukin [53], and

Oncescu and Trifu [55] show that the compressional axes are almost horizontal and directed SE-NW, and that the tensional axes are nearly vertical, suggesting that the slip is caused by gravitational forces.

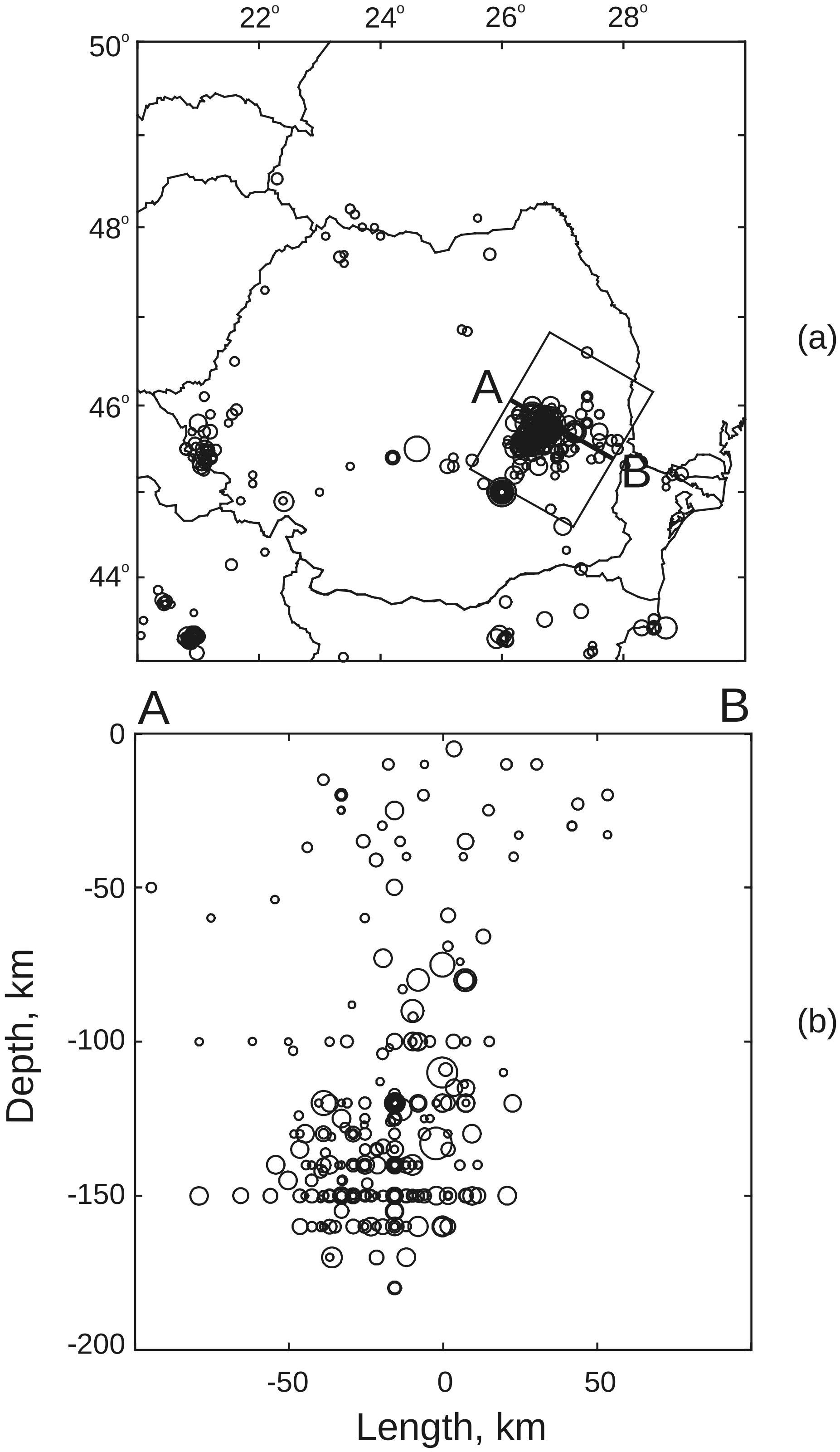
22°
24°
26°
28°
50°
48°
46°
44°
A
B
(a)
A
B
0
-50
-100
-150
-200
Depth, km
-50
0
50
Length, km
(b)

Figure 3.

There are several geodynamic models for the Vrancea region (e.g., [45, 46, 21, 59, 65, 15, 54, 70, 36, 42, 25]). McKenzie [45, 46] suggested that large events in the Vrancea region occur in a vertical relic slab sinking within the mantle and now overlain by continental crust. He believed that the origin of this slab is the rapid south-east motion of the plate containing the Carpathians and the surrounding regions toward the Black Sea plate. The overriding plate pushing from north-west has formed the Carpathian orogen, whereas the plate dipping from south-east has evolved the Pre-Carpathian foredeep [59]. Shchyukin and Dobrev [65] suggested that the mantle earthquakes in the Vrancea region are to be related to a deep-seated fault going steeply down. The Vrancea region was also considered [21] as a place where an oceanic slab detached from the continental crust is sinking gravitationally. Oncescu [54] proposed a double subduction model for Vrancea on the basis of the interpretation of a 3D seismic tomographic image. In their opinion, the intermediate-depth seismic events are generated in a vertical zone that separates the sinking slab from the immobile part of it rather than in the sinking slab itself. Trifu and Radulian [70] proposed a model of seismic cycle based on the existence of two active zones in the descending lithosphere beneath the Vrancea between 80 and 110 km depth and between 120 and 170 km depth. These zones are marked by a distribution of local stress inhomogeneities and are capable of generating large earthquakes in the region. Khain and Lobkovsky [36] suggested that the lithosphere in the Vrancea region is delaminated from the continental crust during the continental collision and sinks in the mantle. Linzer [42] proposed that the nearly vertical position of the Vrancea slab represents the final rollback stage of a small fragment of oceanic lithosphere. On the basis of the ages and locations of the eruption centers of the volcanic chain and also the thrust directions, Linzer [42] reconstructed a migration path of the retreating slab between the Moesian and East-European platforms. Most recently Girbacea and Frisch [25] suggested a model of subduction beneath the suture followed by delamination. The model can explain the location of earthquake hypocenters and of calc-alkaline volcanics, surface structure and accretionary wedge.

According to these models, the cold (hence denser and more rigid than the surrounding mantle) relic slab beneath the Vrancea region sinks due to gravity. The active subduction ceased about 10 Ma ago; thereafter only some slight horizontal shortening was observed in the sedimentary cover [76]. The hydrostatic buoyancy forces help the slab to subduct, but viscous and frictional forces resist the descent. At intermediate depths these forces produce an internal stress with one principal axis directed downward. Earthquakes occur in response to this stress. These forces are not the only source of stress that leads to seismic activity in Vrancea; the process of slab descent may cause the seismogenic stress by means of mineralogical phase changes and dehydration of rocks, which possibly leads to fluid-assisted faulting.

5.2. Block structure of the Vrancea region

In accordance with [6] the main structural elements of the Vrancea region are: (i) the East-European plate; (ii) the Moesian, (iii) the Black Sea, and (iv) the Intra-Alpine (Pannonian-Carpathian) subplates (Fig. 4). The fault separating the East-European plate from the Intra-Alpine and Black Sea subplates and the fault separating the Intra-Alpine and Black Sea subplates have the dip angle significantly different from 90^o. The main directions of the movement of the various plates are shown in Fig. 4. This information is sufficient to define the block structure, which can be considered as a rough approximation of the Vrancea region, and the movements, which can be used for the numerical simulation of the dynamics of this block structure.

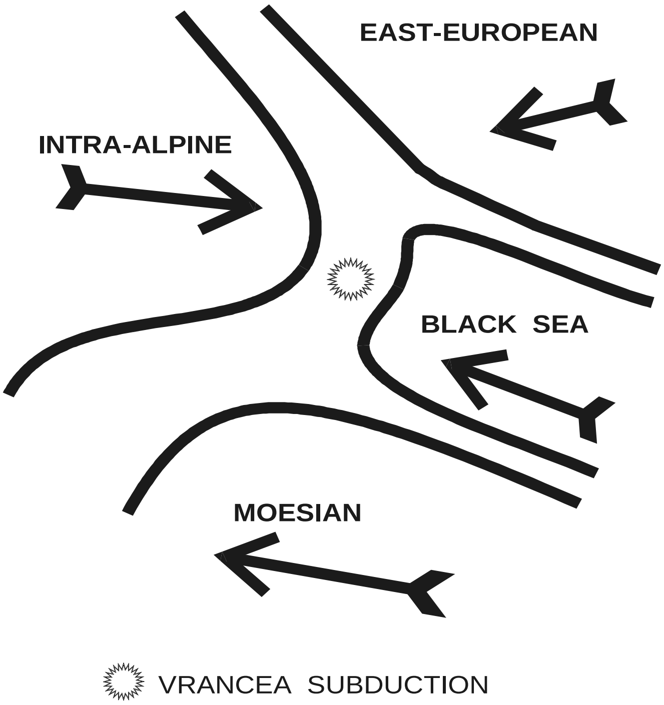

Figure 4.

The configuration of the faults on the upper plane of the block structure used to model the Vrancea region is presented in Fig. 5. The point with the geographic co-ordinates 44.2^{o}N and 26.1^{o}E is chosen as the origin of the reference co-ordinate system. The *X* axis is the east-oriented parallel passing through the origin of the co-ordinate system. The *Y* axis is the north-oriented meridian passing through the origin of the co-ordinate system.

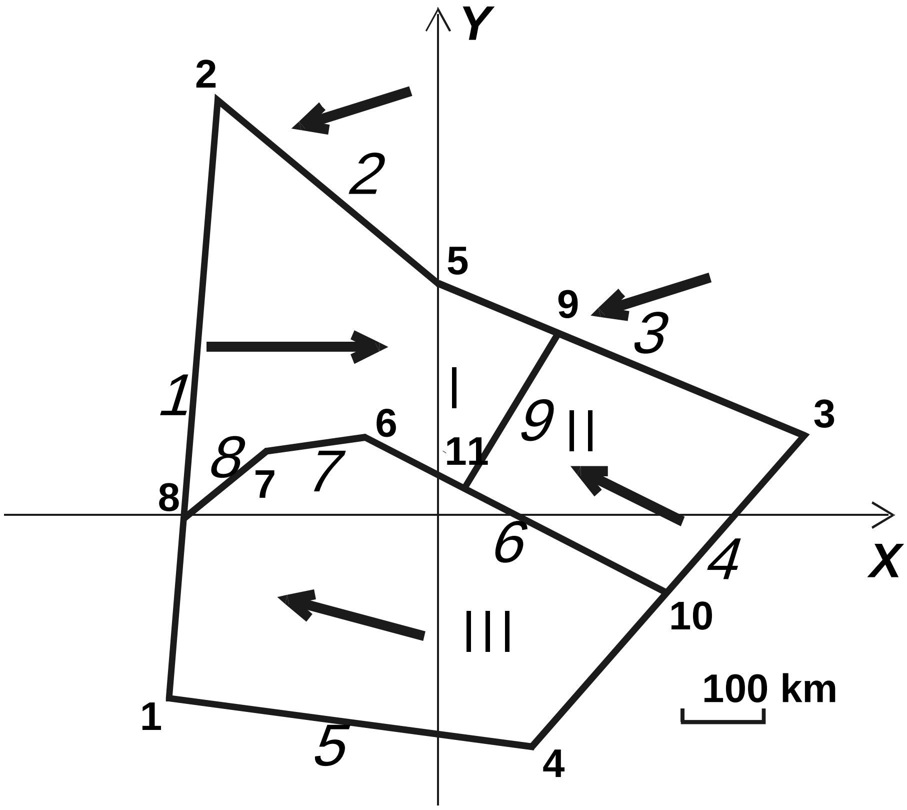

Figure 5.

The thickness of the layer is H = 200 km, which corresponds the depth of the deeper earthquakes in the Vrancea region. The vertices of the block structure with the numbers 1-7 have the following co-ordinates (in km): (-330; -210), (-270; 480), (450; 90), (110; -270), (0; 270), (-90; 90), (-210; 75). The vertices 8-11 have the following relative positions on the faults to which they belong: 0.3, 0.33, 0.5, 0.667. The relative position of each vertex is the ratio of its distance from the initial point of the fault, to the length of the fault. The vertices 1, 5, 3, and 10 are considered to be initial points for the faults. The structure contains 9 faults. The values of the parameters for these faults are given in Table 3, and the values of the parameters for the 3 blocks forming the structure are given in Table 4.

Table 3. Parameters of faults

Fault #	Vertices of fault	Dip angle	K, Bars/cm	W, cm/bars	W_s, cm/bars	Levels of κ		
						B	H_f	H_s
1	1, 8, 2	45^o	0	0	0	0.1	0.085	0.07
2	2, 5	120^o	1	0.5	1	0.1	0.085	0.07
3	5, 9, 3	120^o	1	0.05	0.1	0.1	0.085	0.07
4	3, 10, 4	45^o	0	0	0	0.1	0.085	0.07
5	4, 1	45^o	0	0	0	0.1	0.085	0.07
6	10, 11, 6	100^o	1	0.05	0.1	0.1	0.085	0.07
7	6, 7	100^o	1	0.05	0.1	0.1	0.085	0.07
8	7, 8	100^o	1	0.05	0.1	0.1	0.085	0.07
9	11, 9	70^o	1	0.02	0.04	0.1	0.085	0.07

Table 4. Parameters of blocks

Block #	Vertices of block	K_u, bars/cm (see (1))	W_u, cm/bars (see (2))	V_x, cm	V_y, cm
1	2, 8, 7, 6, 11, 9, 5	1	0.05	25	0
2	3, 9, 11, 10	1	0.05	-15	7
3	4, 10, 11, 6, 7, 8, 1	1	0.05	-20	5

The movement of the underlying medium is specified to be progressive. The components of the velocity (V_x, V_y) of this movement are specified for the blocks in accordance with the directions of the main movements of the Vrancea region, shown in Fig. 4 and are given in Table 4. In the numerical simulation the dimensionless time is used and the values of W and W_s in Table 3 as well as the values of W_u and velocities below (V_x, V_y) correspond to the dimensionless time.

The boundary, which consists of the faults 2 and 3, moves progressively with the same velocity: V_x = -16 cm, V_y = -5 cm. The boundary faults 1, 4, and 5 do not correspond to any real geological structure of the Vrancea region and are introduced only to limit the block structure. These faults do not move and $K = 0$ for them (Table 3). Therefore, in accordance with (5) and (8), all forces in these faults are equal to zero.

The value of P in (11) is 2 Kbar. Magnitude of synthetic earthquakes is calculated accordingly to formula (14) with the values of coefficients $D = 0.98$ and $E = 3.93$, which are specified in accordance with [75]. The values of the parameters for the discretization, in time and space, are respectively: $\Delta t = 0.001$, $\varepsilon = 7.5$ km.

Thus, the geometry of the block structure approximating the Vrancea seismoactive region and the values of model parameters are specified. Some results of modeling are given in the next section.

5.3. Synthetic earthquake catalog and its comparison with the observed one

The synthetic earthquake catalogue is obtained as the result of the block structure dynamics simulation, for the period of 200 units of dimensionless time, starting from the initial zero condition (zero displacement of boundary blocks and the underlying medium and zero inelastic displacements for all cells). The synthetic catalogue contains 9439 events with magnitudes between 5.0 and 7.6. The maximum value of magnitude in the synthetic catalogue is 7.6. In the twentieth century 4 catastrophic earthquakes with magnitude 7 or more occurred in the Vrancea region (Table 5). Note that the maximum value of magnitude (7.6) in the synthetic catalogue is close to one ($M = 7.4$) observed in reality (Table 5).

Table 5. Large earthquakes of Vrancea, 1900–2000

Date	Time	Hypocenter			Magnitude
		latitude	longitude	depth (km)	
1940/11/10	1 h 39 m	45.80°N	26.70°E	133	7.4
1977/03/04	19 h 21 m	45.78°N	26.80°E	110	7.2
1986/08/30	21 h 28 m	45.51°N	26.47°E	150	7.0
1990/05/30	10 h 40 m	45.83°N	26.74°E	110	7.0

The observed seismicity of the region for the period 1900-1995 is presented in Fig. 6, while the map with the distribution of epicenters contained in the synthetic catalogue is given in Fig. 7. Most of the synthetic events occur on fault 9 (the cluster *A* in Fig. 7), which corresponds to the subduction zone of Vrancea, where most of the observed seismicity is concentrated (the cluster *A* in Fig. 6). All large earthquakes (M > 6.7) of the synthetic catalogue are concentrated here, and the same phenomenon is seen in the distribution of the observed seismicity.

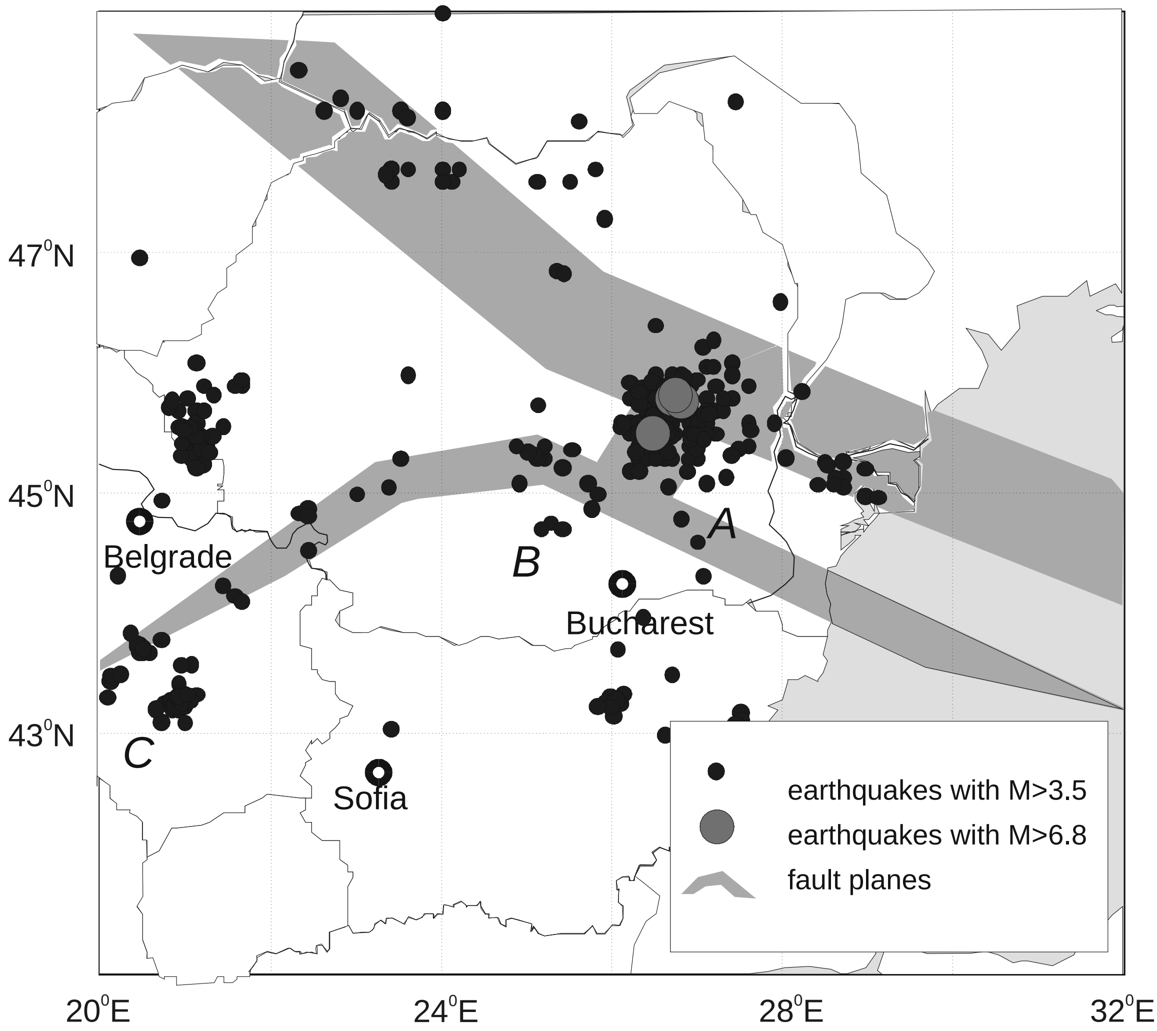

Figure 6.

Some events occur on fault plane 6, and they appear as a cluster of epicenters (cluster *B* in Fig. 7) located to the south-west of the main seismicity area and separated from it by a non-seismic zone. An analogous cluster of epicenters can be seen on the map of the observed seismicity (cluster *B* in Fig. 6). The third cluster of events (cluster *C* in Fig. 7) groups on fault plane 8 and corresponds to the cluster *C* of the observed seismicity in Fig. 6.

The modeling starts from the initial zero condition and some time is needed for the quasi-stabilisation of the stresses. Analysis of the synthetic catalog shows that starting from 60 units of the dimensionless time, the distribution of the number of events versus magnitude and time looks stable. Only the stable part of the synthetic catalogue from 60 to 200 units of the dimensionless time is considered in the following analysis.

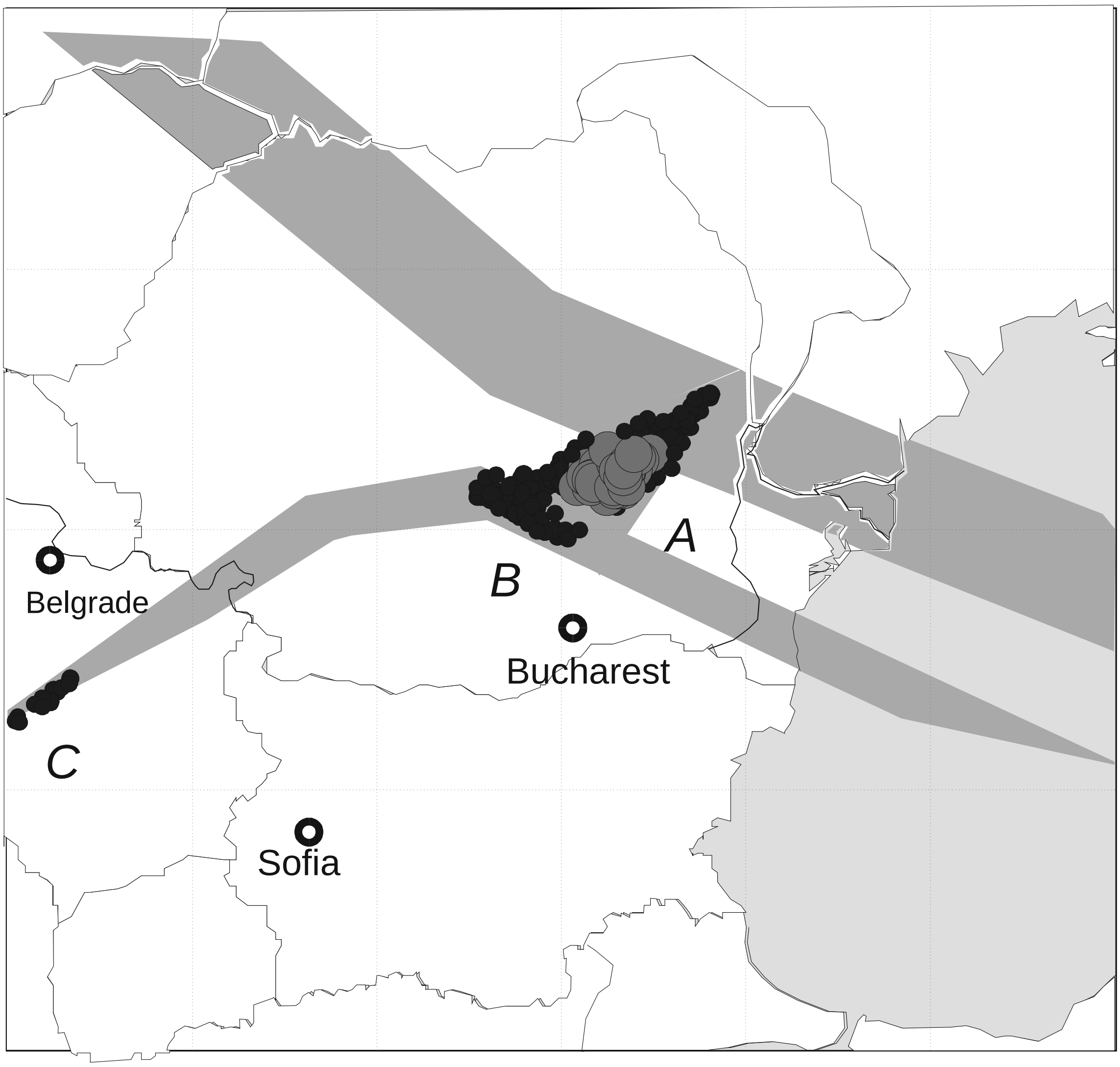

Figure 7.

The frequency-magnitude plots for the observed seismicity of Vrancea and for the synthetic catalogue are presented in Fig. 8. The curve constructed from the synthetic catalogue (dashed line) is almost linear, and it has approximately the same slope as the curve constructed from the observed seismicity (solid line).

Using the frequency-magnitude plots and the duration of the real catalogue (95 years) the correspondence of the dimensionless time with the real one can be estimated: 140 units of the dimensionless time correspond approximately to 7000

years, or equivalently 1 unit of dimensionless time corresponds to about 50 years. From this estimate it follows that the value of the velocity of the tectonic movement is about 5 mm per year.

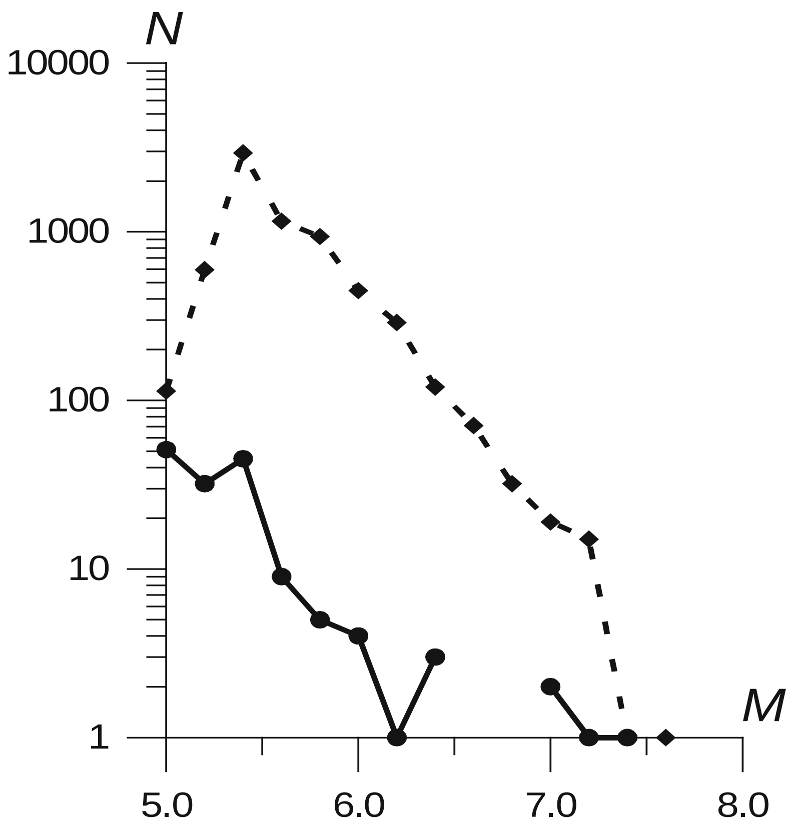

Figure 8.

The temporal distribution of large (*M* > 6.8) synthetic earthquakes in the period from 60 to 200 units of dimensionless time (7000 years) is presented in Fig. 9. One can see strong irregularity of the flow of these events. For example, in the interval from 70 to 120 units of the dimensionless time, the periodic occurrence of groups of large earthquakes, with return period of about 6–7 units, which corresponds to 300–350 years, is observed. For the interval from 120 to 140 units of the dimensionless time the periodic occurrence of a single large earthquake with the return period of about 2 units, or 100 years, is typical. For the remaining parts of the synthetic catalogue there is not any periodicity in the occurrence of the large earthquakes. These results show that it is necessary to be careful when using seismic cycle for prediction of the occurrence of a future large earthquake because the available observations cover only a very short time interval, in comparison with the time scale of the tectonic processes.

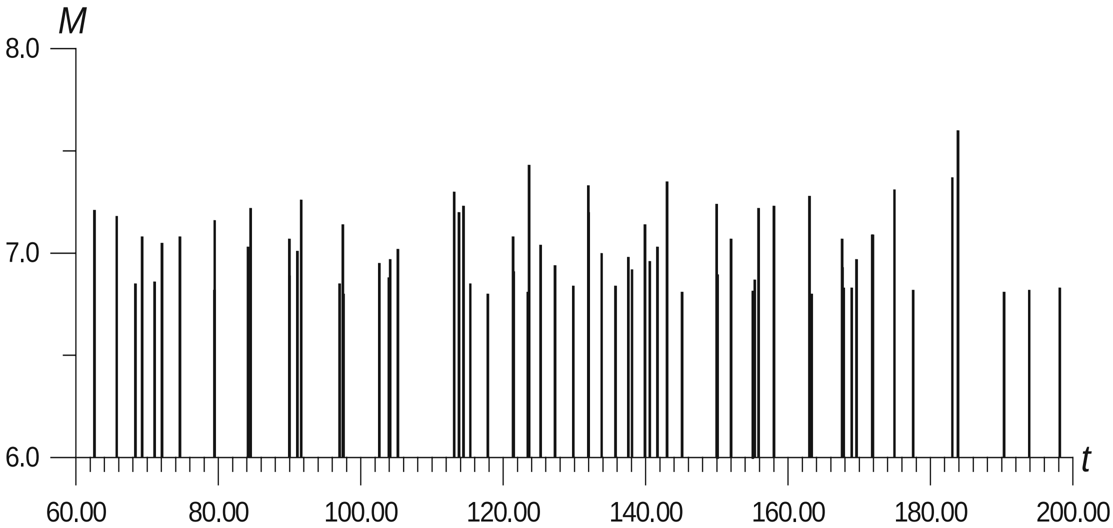

Figure 9.

6. Concluding remarks

The dramatic increase of losses due to natural and anthropogenic hazards in recent time entails the necessity of catastrophe modeling. Among other reasons it is explained by a lack of reliable observation data on catastrophic phenomena. The problems of risks connected with catastrophic events are considered with the using of earthquakes as an example. A brief overview of different approaches to mathematical modeling of lithosphere dynamics is presented, and the block model is described in details. The block structure approximating the tectonic structure of the Vrancea (Romania) region to develop the two-dimensional block model is constructed. The results of modeling show that, it is possible to generate in the Vrancea region a synthetic earthquake catalog that has features similar to those of the real earthquake catalog. This synthetic catalog or its relevant segment could be used to predict the future behavior of the seismicity in the region and therefore for seismic risk estimation.

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