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INTERACTION MECHANISM OF ROCK WITH DEEP WATER

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Relevance. Prediction of earthquakes is one of the most difficult actual problems of mankind. The complexity of the forecast is in the fact that, firstly, the processes in earthquake origin are stochastic and do not allow to give a deterministic evaluation. Secondly, the mechanism for generating the earthquake origin is not completely revealed. It is established that stress accumulation in the fault (at the boundaries of tectonic plates) is associated with the variation of local stress fields, the change in frictional coefficient in the fault, the variation in fluid processes, and so on. Consequently, the study of the mechanism of saturation of tiny fracture and the mechanism of rock interaction in the earthquake origin with juvenile water, which leads to earthquakes, is a very urgent task.

Purpose of the work. Determination of the mechanism of rock interaction with deep water and the development of mathematical models of rock performance when subjected to loadings taking into account the nonlinear effect of the load diagram and rock fold diagram.

Methodology of the study. The work gives the analysis of issues for determining the mechanism of earthquakes. A new approach to determination of this mechanism is proposed. It is shown that deep water is one of the determining factors in the beginning and development of earthquake origin.

Results. A method for determining the mechanism of earthquakes beginning is proposed, as well as some mathematical models that approximate the experimental data of rock performance when subjected to loadings in the process of filtration of deep water into tiny fractures of rock in the earthquake origin taking into account the nonlinear effect.

Conclusions. The current state of the earthquake prediction problem is analyzed. It is shown that the geodetic information for forecasting the location and strength of earthquakes is more accurate. The way of rock fragmentation under general compression is shown. The nature of stress accumulation in the earthquake origin is described. The mathematical models are proposed; they sufficiently (with an average relative error of 2.13%) describe the experimental data obtained while loading rock samples taking into account the mode of dilatancy.

Keywords: rock, water, earthquake, fracture, tectonic mixing, seismogenic fault.

Introduction

A number of works of literature about the prediction of earthquakes [1–7] give a general idea of the conditions that have been applied for many years in the hope of preventing the most terrible consequences of disastrous earthquakes. The success in this area was promoted by the fact that in recent years the efforts on forecasting was strongly stimulated [1, 4, 6–10]. In particular, the work [8] shows a fundamental way of solving the problem of earthquake prediction based on the idea of G. A. Gamburtsev, the academician and the founder of a scientifically based program for solving the earthquake prediction problem. In this program, G. A. Gamburtsev has pointed out ways to solve the problem of earthquake prediction based on the study of premonitory symptoms of the earthquake origin (EO), – crustal movements and earth's crustal deformation (EC) in seismic belt [7]. It is believed that the crustal seismic intensity is a consequence of earth's tectonism generated by deep endogenous processes that appear on the surface of the earth in its continuous movement. The energy of these processes creates mountains and valleys, moving continents and huge sections of the ocean bed. They split the earth crust into a number of blocks and force these blocks to move relative to each other along the deep separating faults. The reasons that generate stress raisers in the fault can be the following ones: variations of local and regional stress fields; change in the value of the frictional coefficient in the fault; influence of temperature and pressure; variation of fluid processes; mechanical "hooks" of blocks due to unevenness of their contiguous surfaces, etc. [7]. It is also shown in this paper that the precondition for EO development is the presence of a mechanically strong consolidated environment in the fracture zone with elastic properties, so that it is capable of accumulating potential elastic energy. And the reason for the crust seismic intensity generated by the mutual orogenic displacement of the blocks (plates) of the earth's crust is the complete (or partial) delay of these displacements in this or that part of the seismogenic fault. It should be noted that the seismic energy released during earthquakes is a very small fraction (~ 0.1%) of the tectonic energy expended on the orogenic displacement of the block systems (plates) along the faults.

The value of this work is also the fact that a direct geodetic method is used to predict the location and strength of the earthquake, which allows determining the type of deformation of the earth's surface in the investigated area, i.e., to establish the form of elastic bending of the rock in case of EO development process. In order to predict the time of an earthquake, it is recommended to start with a study of the mechanism of the beginning and development of EO.

The authors of [10] have shown that the stress prediction allows taking into account the critical geometry of the tiny fractures accompanying earthquakes. It is proposed to use signals on shear waves splitting and their delay in fluid-saturated tiny fractures, as premonitory symptoms; they equalize stress and reflect stress changes (Fig. 1). It is revealed that changes in the shear waves splitting (SWS) are accumulation and relaxation (attenuation due to coalescence of tiny fractures) of stresses before a strong earthquake, which is retrospectively observed in the rock mass. It should be noted that a magnitude-5 earthquake in SW Iceland was successfully stress-forecast 3 days before it occurred in 1998 [10]. Similar characteristic behaviour of shear-wave splitting has been observed retrospectively before – 17 other earthquakes. It is established that retrospective stress-forecast takes into account similarity of the rock mass behavior before earthquakes. Such performance confirms the compliance of geophysics of the Earth's tiny fractures.

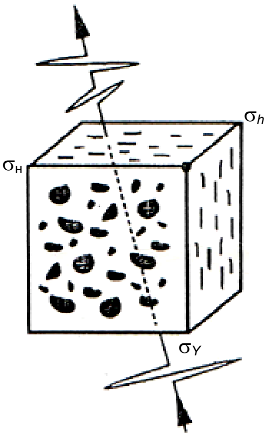

Figure 1. Stress-aligned shear-wave splitting observed in the shear-wave window.
Рисунок 1. Стресс, выравнивающий расщепление поперечных волн и наблюдаемый в окне поперечных волн.

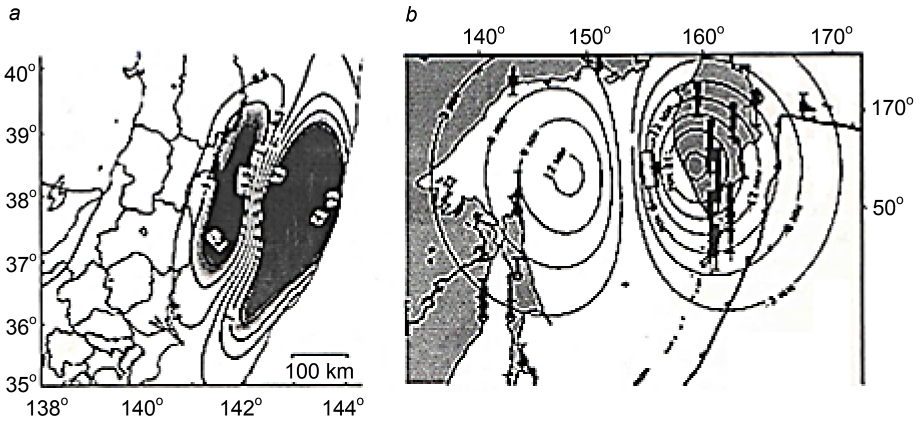

Figure 2. Bifocal structure of the earthquake focus in measurements of rise of sea level ("The Great Japanese earthquake" in Tōhoku – *a* and in the Sea of Okhotsk, focal depth is 630 km) – *b*.
Рисунок 2. Бифокальное строение очага землетрясения в измерениях подъема уровня моря «Великой Японской катастрофы» в Тохоку – *a* и в Охотском море (глубина гипоцентра 630 км) – *b*.

The authors of [11–15], as a result of world-known observations, have shown that rock of the upper and lower crust and upper mantle is covered by vertically oriented and fluid-saturated tiny fractures. As a result, the observation of anisotropism of the shear wave velocity shows that the tiny fractures are closely located at the edges of the fault [7].

It was established in [10] that the criticality level of the tiny fractures geometry and the application of these properties make it possible to predict earthquakes and volcanic eruptions according to stress. It is shown that earthquakes occur in defective places of the mountain massif with the accumulation of sufficient energy for this. The stress buildup is mitigated by the geometry of the stress equalizer, the fluid of a saturated tiny fracture, in which SWS spread in almost all the rocks through the upper and lower crust.

The works [9, 16] show that deep fluids participate in the process of preparation for strong earthquakes. Decreasing in the effective shift is related to the increase in the deep fluid activity.

It is shown that the decrease in the average depth of earthquakes is associated with the activity of the fluid moving in tiny fractures of the earth's crust.

A possible effect of increasing the reaction – increasing the permeability of the middle and lower crust [17–19] – and it was proved that fluid distribution is more typical in the case of its participation in the metamorphic reaction occurring in the deep crust. This illustrates the similar way of wave propagation.

It follows from the foregoing that the deep fluid is one of the determining elements in the mechanism of the occurrence of strong earthquakes.

In [6], the factor of the internal time of evolution is determined exclusively by the flow of deep water. It is shown that, currently, the dilatancy effect, volumetric gain of a geomaterial with a destructive shift, is recognized and accepted in the mechanics of the rock. The resulting volumetric deformations (due to opening cracks and pores) lead to the displacement of the "excess" volume into the outside environment. It was the dilatancy that allowed the authors of the works [20 , 21] to quantify in due time the dimensions of the cavity of an underground nuclear explosion with the study of elastic waves.

Active tectonics

As noted in [2, 3, 5–7, 9, 10], the stress in the earth is the result of interaction of the boundaries of tectonic plates.

In this case, the earth's crust is broken by faults that arise from the excess volume of the tectonic deformation chain "compaction-dislodgement" (Fig. 2); it is estimated based on the growth and fall of the pore-water pressure (Fig. 3) [22]. These faults extend far beyond the boundaries of the origin. Adjustment movement – the relative displacement of the fault sides is also accom-

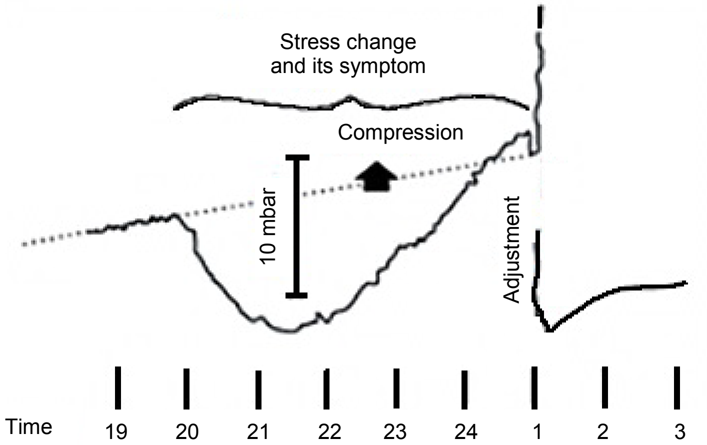

Figure 3. Dislodgement of the rock fault under general compression.
Рисунок 3. Разрыхление разлома горных пород при общем сжатии.

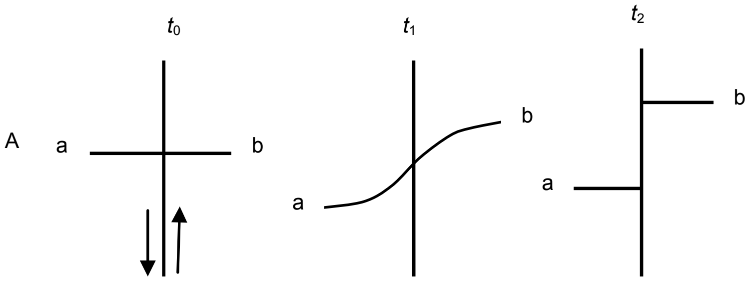

Figure 4. Explanation to the phenomenon of exponential distribution of station points in epicentral zones of strong crustal earthquakes.
Рисунок 4. Объяснение явления экспоненциального распределения смещений геодезических пунктов в эпицентральных зонах сильных коровых землетрясений.

panied by its lateral expansion [23], and, consequently, compaction of associate massifs in which elastic compressing energy is thereby accumulated. The earthquake focus has a bifocal structure of dislodgement and compaction (Fig. 2).

In the work [24], as a result of monitoring tectonic stresses in the rocky mountains of the United States (based on the liquid pressure in a flask inserted in the fracture near the fault), it is shown that there is a massif's dislodgement and then its compaction with the final blow against the background of regional linear growth of the compression of the massif (Fig. 3, dotted line) before an earthquake.

The earthquake occurs in defective places of the mountain massif with the accumulation of sufficient energy for this [10].

Fig. 3 shows a monotonous increase in pressure in the hydraulic sensor placed inside the cracks of the massif, which reflects the external tectonic loading. However, since May 20, 1974, a regime change occurred for crack opening (the pressure in the sensor has fallen), i.e., dilatancy began to develop, an increase in the volume of cracks in the massif. Medium-term symptoms of a shock are associated with this stage (with its preconditioning). Before the shock itself, the pressure in the sensor exceeded the level determined by the external tectonic loading (the so-called "overlapping"). According to Nikolayevsky [6], short-term symptoms of the shock correspond to it.

Movement in the geologic environment deforms blocks of crust in a quasistatic manner, including both monotonic stress change [5–7] and relatively slow periodic changes of tectonic waves. Moreover, as established [7], shifting (movement) of the rock is maximally near the fault and decreases very rapidly (exponentially) with distance from it. This fact convinces us that shifting of station points generated during strong earthquakes contain information on a consolidated tool for these earthquakes. It is also extremely important that this mechanism, as stated in [7], is universal for different continents but requires verification.

The reason for these regularities is shown in Fig. 4 , where the same segment of the seismogenic fault (vertical line) is shown at times t_0, t_1, t_2, corresponding to different stress state of rocks. The directions of orogenic displacements on the fault are shown with arrows. Moment t_0– there are no seismogenic stresses in the rock, which is shown on the right line *ab.* At the moment t_1, the rock is extremely elastically stressed (elastic bending) – the curve *ab.* The moment t_2 – the position of the rock after the earthquake, at which the following events occurred: the main failure of rocks in the origin; rock fold along this failure and, as a result, the fault of the previously accumulated flexural seismogenic deformations – straight jogs *a* and *b* [7].

Our studies have shown that to predict the time of an earthquake, we can mathematically approximate the curve *ab* at the time t_1 by the following formula [24, 25]:

$$\delta(t) = \delta_p - \left(\delta_p - \delta(0)\right)\exp\left[-m(t)^{n+1}\right],$$

where m, n – constants determined experimentally by geodetic data; δ(0), δ(τ) – initial and current values of stress in rocks; σ_p – the failure stress of rocks.

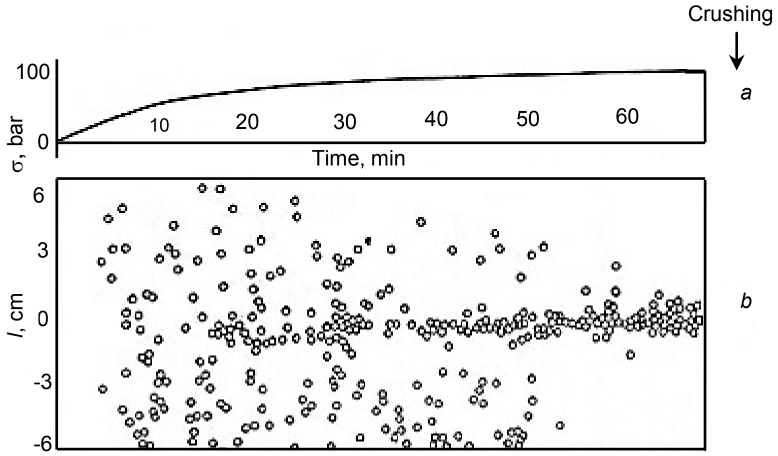

Figure 5. Temporal changes in the distribution of foci of acoustic emission while bending of a granite sample and the formation of fissures in it: *a* – temporary changes in stress; *b* – temporary changes in the one-dimensional distribution.
Рисунок 5. Временные изменения в распределении очагов акустической эмиссии при изгибе гранитного образца и образовании в нем трещин: *a* – временные изменения напряжения; *b* – временные изменения в одномерном распределении.

In the same way, it is necessary to approximate the experimental data on the accumulation of stress in the monoclinal fold leading to the formation of main fissures and, consequently, to an earthquake. Similar data are given in [5], whose geometrical interpretations are presented in Fig. 5.

However, this does not take into account the defining role of deep water in the mechanism of formation and development of OST [5]. Some fundamental studies [6, 9, 10] have unambiguously established that stresses of equalizing tiny fractures filled with deep water are everywhere observed in the earth crust.

In the work [6], the internal time factor of the evolution of EO is exclusively determined by the crossflow of inland water. Water entrance into the freshly opened fractures facilitates their further spontaneous crushing according to Rehbinder effect [26, 27]. The resulting time estimate explains the time gap (several days) between urgent symptoms and the shock itself. The authors of [6] have also showed that water filling rate of the origin is from 1 to 10 days, which is comparable with the overlapping stage. In this case, a deep-earth openness is 0.01–0.1 Darcy (10^{-12} m^2). In the work [9], it is proved that abyssal fluids participate in the process of preparation of strong earthquakes.

It follows from the above that water is one of the determining factors characterizing the process of preparation and development of the earthquake source; a study of interaction mechanism of rocks with deep water is an urgent task, which is the subject of this work.

Nonlinear effects of rock performance under loading and approximation of experimental data

In the works [8, 28, 29], typical load diagrams of rock samples under failure in the dilatancy mode are considered and the interpretation of some nonlinear features of their performance is given. A version of elasto-plastic strain model is presented and the procedure for determining its parameters is shown. Ratios are proposed that allow taking into account the nonlinear features of failure of the corresponding stage of failure localization and the formation of main fractures. A number of examples of numerical simulation that illustrate the effect of nonlinear effects in the propagation of elastic waves is given (as well as while unloading a sample of different degrees of failure). It is shown that the existing models of elasto-static failures and destruction of rock do not take into account some nonlinear features of the samples performance. At the same time, in [28], it was confirmed on the basis of experimental data that at the initial stage of failure in the load diagram, there is almost pitching segment (instead of the main quasilinear elastic one, Fig. 6). This area of failure is explained by the features of the loading of the hold-down arrangement with non-perfect form and state of the faces of the sample, as well as the presence of fissures in the rock. After the initial pressure application, most of these fissures close and the rock performs as a solid body (Fig. 7). However, in certain circumstances, ignoring the initial nonlinearity does not allow us to take into account and describe sufficiently important processes, including the sensitivity of the elastic properties of rocks to the stressed state; in cases when there is a high-stress zone in the environment, for example, in the area of fissures (Fig. 7) or in the area of increased pore-water pressure (when liquids extruded from the sediments while their compaction cannot freely migrate to the surface), abnormally high pressures arise.

In this case, anomalously high pressures can have any values, up to a value determined by the total weight of the rocks. Testing of rocks samples was carried out on installations providing an independent triaxial stress, where the cylindrical samples are placed in an elastic casing, the axial stress is created by the piston, the overburden stress is developed by liquid surrounding the casing [28]. The required pore-water pressure can be created in the sample.

In [8, 28, 29], a geometric interpretation of the load diagram was also given when the sample was unloaded at the stage of pseudoplastic failure (Fig. 7), where the following parameters were used: $\delta = \delta_1 - \delta_c$ – applied stress; δ_c = const – edging draft; ε^* – rate of the total volumetric strain; τ – maximum value of tangential stress; ε^d – dilatancy value; ; $\Delta V/V$ – volumetric strain.

For the purpose of predicting the moment of destruction of the rock sample, a mathematical model in the form of a differential equation of second order is proposed to approximate properly the experimental data from the load diagram shown in Fig. 6.

$$\varepsilon_1\varepsilon_2\frac{d^2(\delta)}{d\varepsilon^2}+(\varepsilon_1+\varepsilon_2)\frac{d(\delta)}{d\varepsilon}+\delta=\Delta\delta; \qquad (1)$$

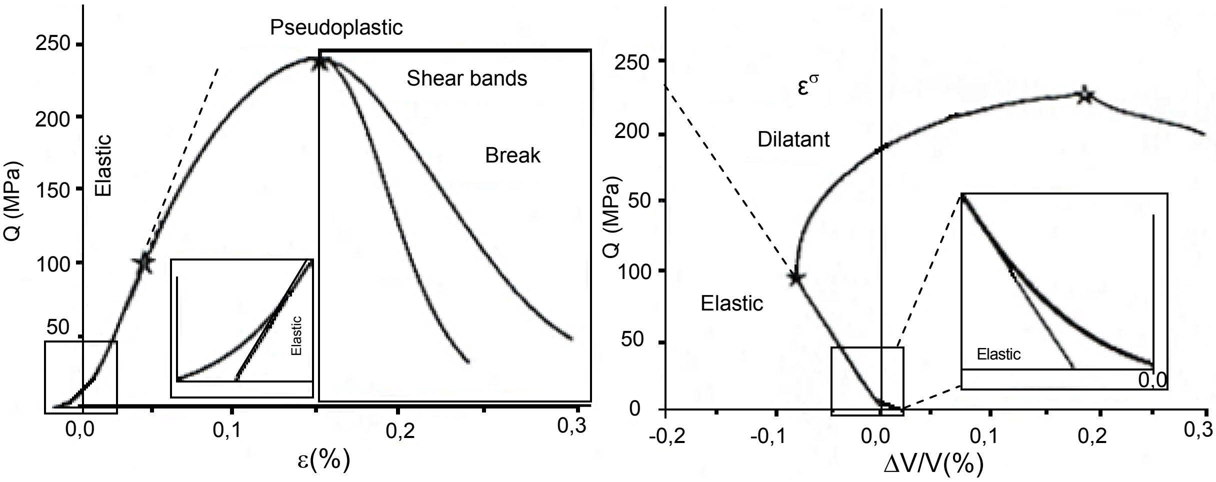

Figure 6. A characteristic type of load diagrams of rock samples under the dilatancy failure mode.
Рисунок 6. Характерный вид диаграмм нагружения образцов горных пород при дилатанционном режиме деформации.

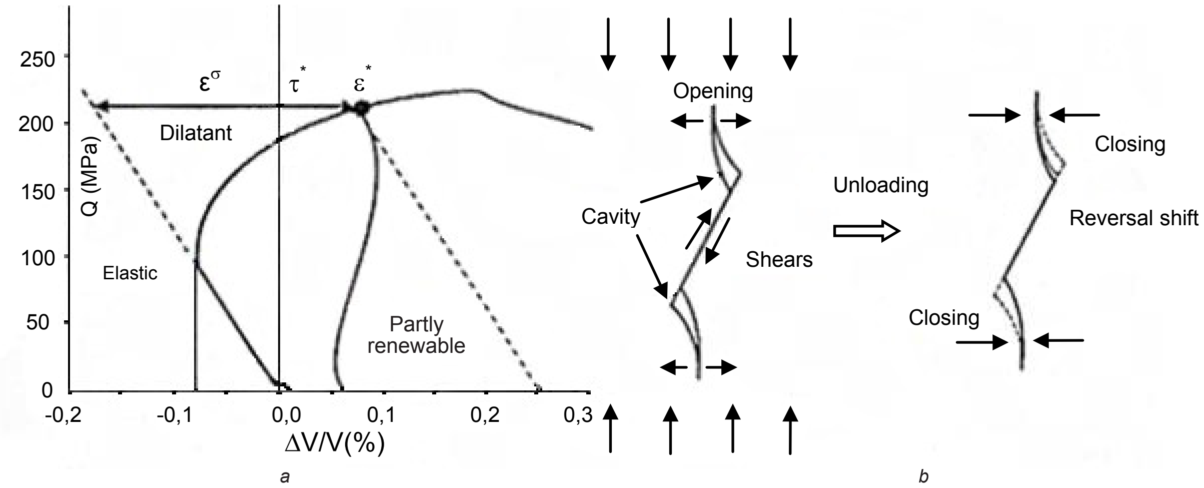

Figure 7. Type of load diagram for unloading the sample at the stage of pseudoplastic failure (*a*) and the scheme of fracture closure after removal of the load (*b*).
Рисунок 7. Вид диаграммы нагружения при разгрузке образца на стадии псевдопластической деформации (*a*) и схема закрытия мезотрещин после снятия нагрузки (*b*).

where $\Delta\delta = \delta_k - \delta_n$ – stress change when loading the rock; δ_n, δ_k – respectively the initial and final stress of the rock while loading; ε_1, ε_2 – characteristic strain parameters (constant coefficients).

Using Laplace transformation, we obtain the solution of equation (1) in the following form:

$$\delta = \Delta\delta\left(1 - \frac{\varepsilon_1}{\varepsilon_1 - \varepsilon_2}\exp\left(-\varepsilon/\varepsilon_1\right) + \frac{\varepsilon_2}{\varepsilon_1 - \varepsilon_2}\exp\left(-\varepsilon_2/\varepsilon\right)\right). \tag{2}$$

In order to identify or find the quantitative values of characteristic parameters ε_1, ε_2 taking into account the experimental data given in [4], we have formulated the following expression:

$$\left(\frac{\varepsilon_2}{\varepsilon_1 + \varepsilon_2}\right)^2 = a\left(\frac{\varepsilon_a}{\varepsilon_1 + \varepsilon_2}\right)^2 + b, \tag{3}$$

where $a = 0.3454$; $b = -0.3422$, and the values of ε_a и $\varepsilon_1 + \varepsilon_2$ determined using the maximum-slope method to the loading branch (Fig. 8). As you can see from Fig. 8, $\varepsilon_1 + \varepsilon_2 = 0.06$; $\varepsilon_a = 0.08$; $\delta_k = 237$.

Substituting these values into expression (3) and solving the quadratic equation obtained, we have $\varepsilon_1 = 0.37$; $\varepsilon_2 = 0.23$ and, therefore, we finally get:

$$\delta = 237\left(1 - 2{,}64\exp\left(-\varepsilon/0{,}037\right) + 1{,}64\exp\left(-\varepsilon/0{,}023\right)\right). \tag{4}$$

The obtained expression is the identification of the mathematical model (2). It describes the change in the rock stress as a function of failure with a higher accuracy (mean relative error of 2.13%); it can be successfully applied to the earthquake prediction by stress using geodetic data.

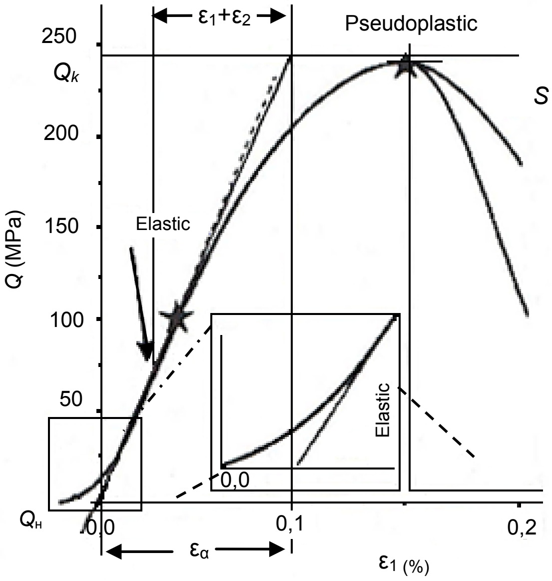

Figure 8. Interpretation of the maximum-slope method for estimating parameters ε_α and $\varepsilon_1 + \varepsilon_2$.
Рисунок 8. Интерпретация метода касательной для оценки параметров ε_α и $\varepsilon_1 + \varepsilon_2$.

Conclusion

The modern state of earthquake prediction is analyzed. It is shown that geodetic information for forecasting the location and strength of an earthquake is more accurate. Mathematical models of rock performance under loading are developed taking into account the nonlinear effect of the load diagram and rock fold diagram.

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МЕХАНИЗМ ВЗАИМОДЕЙСТВИЯ ГОРНОЙ ПОРОДЫ С ГЛУБИННОЙ ВОДОЙ

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Актуальность. Предсказание землетрясений является одной из сложных актуальных задач человечества. Сложность прогноза заключается в том, что, во-первых, процессы, происходящие в очаге землетрясений, являются стохастическими и не позволяют дать детерминированной оценки. Во вторых, механизм возникновения и развития очага землетрясений до конца не раскрыт. Установлено, что накопление напряжений в разломе (на границах тектонических плит) связано с вариацией локальных полей напряжений, изменением величины коэффициента трения в разломе, вариацией флюидных процессов и т. д. Следовательно, изучение механизма насыщения микротрещин и механизма взаимодействия горной породы в очаге землетрясения с глубинной водой, приводящей к возникновению землетрясений, является весьма актуальной задачей, чему посвящена данная статья.
Цель работы. Определение механизма взаимодействия горной породы с глубинной водой и разработка математических моделей поведения горных пород при нагружении с учетом нелинейного эффекта диаграммы нагружения-смешения.
Методология исследования. В работе анализируются существующие состояния проблем определения механизма возникновения землетрясения. Предложен новый подход к определению этого механизма. Показано, что глубинная вода является одним из определяющих факторов при возникновении и развитии очага землетрясений.
Результаты. Предложены способ определения механизма возникновения землетрясений и математические модели, адекватно аппроксимирующие экспериментальные данные поведения горных пород при нагружении в процессе фильтрации глубинной воды в микротрешины горной породы в очаге землетрясения с учетом нелинейного эффекта.
Выводы. Проанализировано современное состояние проблемы прогнозирования землетрясения. Показано, что геодезическая информация для прогноза места и силы землетрясений является более точной. Показано, как происходит разрыхление разлома горной породы при общем сжатии. Описан характер накопления напряжений в очаге землетрясения. Предложены математические модели, адекватно (средней относительной погрешностью 2,13 %) описывающие экспериментальные данные, полученные при нагружении образцов горных пород с учетом дилатанционного режима деформации.

Ключевые слова: горная порода, вода, землетрясение, трещина, тектоническое смешение, сейсмогенный разлом.

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