J. Appl. Comput. Mech., 7(SI) (2021) 1232-1241
DOI: 10.22055/JACM.2020.32385.2007

ISSN: 2383-4536
jacm.scu.ac.ir

Shahid Chamran University of Ahvaz

Journal of Applied and Computational Mechanics

Research Paper

About Earthquakes in Subduction Zones with the Potential to Cause a Tsunami

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Received January 25 2020; Revised August 11 2020; Accepted for publication August 12 2020.
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Abstract. The problem of occurrence of starting earthquakes in subduction zones is considered. Subduction is the phenomenon of movement of the oceanic lithospheric plate under the continental one. The oceanic lithospheric plate at a certain depth melts from below and can slide. The paper considers the occurrence of starting earthquakes under the assumption that lithospheric plates have different contact conditions, being on a rigid base in the subduction zone. A molten lithospheric plate has no tangential contact stresses, while the other, oceanic, is rigidly connected to the base. The block element method is used to study the occurrence of the starting earthquake and the peculiarity of its consequences. The conditions to generate of tsunamis as a result of such earthquakes are being studied. Solutions to boundary value problems that are constructed precisely, rather than approximatively, allow us to reveal the mechanisms of destruction of the environment that were not previously known. In particular, the results obtained allowed us to detect a new type of crack that was not previously described. They destroy the environment in a different way than Griffiths cracks, which is demonstrated in this paper and is important in engineering practice.

Keywords: Block element, Earthquakes, Subduction, Tsunamis, Cracks.

1. Introduction

Models for describing fragments of the Earth's crust using block structures, in particular, the possibility of using Kirchhoff plates, are discussed in [1,2]. The importance of studying earthquakes and their forecasts goes beyond the interests of the Earth alone [3-5]. Studies of contact problems for describing the behavior of contact stresses on the edge of a deformable model of contact plates are devoted to [6-11].

Various issues of earthquake prediction and protection of buildings and structures are studied in [12-25]. Special attention should be paid to the development of knowledge-intensive systems for assessing the seismic vulnerability of structures [12, 13]. Investigation of the possibility of predicting earthquakes by removing potential energy stored in lithospheric plates, the development of monitoring tools are important studies of protection against seismic impacts. Various theoretical and experimental questions of the behavior of deformable bodies, the destruction of the medium by cracks, are studied and discussed in [26-36]. Of particular interest are experimental approaches, in particular, the development of intelligent structures and systems for monitoring buildings and structures [27-28]. The problem of studying the process of destruction of the environment, structures and structures is of great importance. The object of research is cracks and faults. For a long time, research for strength assessment in engineering practice these were the Griffiths cracks that he had described a hundred years ago. There is a huge amount of research and publications related to the study and application of Griffith cracks [37-41]. A good example of research in this area that can make a long-term forecast of the development of cracks, in connection with the application of the probabilistic approach, is the work [38, 39]. Recently, a new type of cracks has been discovered that complement the Griffiths cracks [40.41]. These cracks have a different mechanism of destruction of the medium. They are formed as a result of the convergence of lithospheric plates located on a deformable base. In the previous work of the authors [1, 2], as a result of applying a mechanical approach, the possibility of starting earthquakes during the convergence of lithospheric plates at the Conrad boundary is shown. The reason for the destruction of the medium in the convergence zone is the occurrence of a singular concentration of vertical and horizontal components of contact stresses. The studied earthquakes are named as starting ones, since they occur before the interaction of lithospheric plates with each other. In this paper, this method is used to study the possibility of starting earthquakes in the conditions of subduction of lithospheric plates. Subduction is the phenomenon of movement of one lithospheric plate under another, arising in connection with the diversity of both geometric and physical parameters of approaching each other met lithospheric plates [29]. These phenomena can occur in areas of the ocean and in coastal areas. These phenomena are divided

Published online: August 29 2020

into two types - subduction and collision. Collision processes are characteristic of the interaction of continental lithospheric land plates and lead mainly to the twisting and generation of new mountains, while subduction zones tend to cause earthquakes.

During subduction, part of the ocean floor is submerged under the land plate. At a great depth, this part melts and, thanks to spreading, spreads and forms new crust, both under land and under the ocean. A subduction zone was discovered and described by seismologist Benioff. Earthquakes are most common in these areas. The Benioff called them seismic focal zones, now they are called zones of Benioff, Fig. 1.

There are attempts to explain the reasons for such properties of Benioff's zones, but they are not based on strict mechanical and mathematical approaches and are not convincing in the subduction zone. Taking into account these properties of lithospheric plates and the detection of starting earthquakes and their precursors [1, 2], it was possible to strictly mathematically study earthquakes in subduction zones. As the oceanic lithospheric plate moves under the continental plate, the plate can break and acquire faults. Then, moving deeper, it heats up and melts from below [30, 31]. As a result, the tangential stresses under the slab become small and can be ignored. A fragment of a lithospheric plate that has not yet fused, in contact with the compacted layer described by Beniof, has both tangential and normal stresses in the contact zone. Thus, the fault separates two lithospheric plates that have different properties in the contact zone. Fragments of the lithospheric plate, after the fracture, are close and only a fault separates them. Then the melted fragment of the lithospheric plate can move away from the neighboring one due to sliding Fig. 2, Fig. 3. Taking into account this statement of the problem, a boundary value problem is formed.

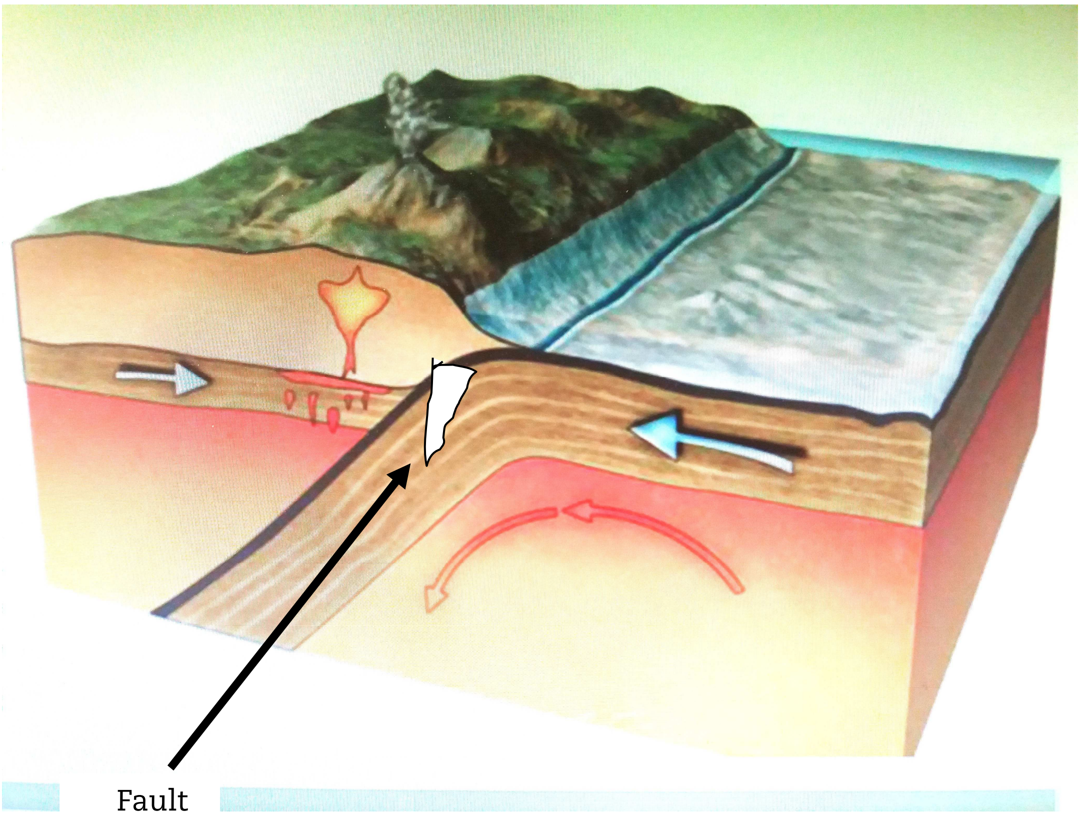

Fig. 1. Diagram of the subduction process. The fault divides the lithospheric plate into two fragments.

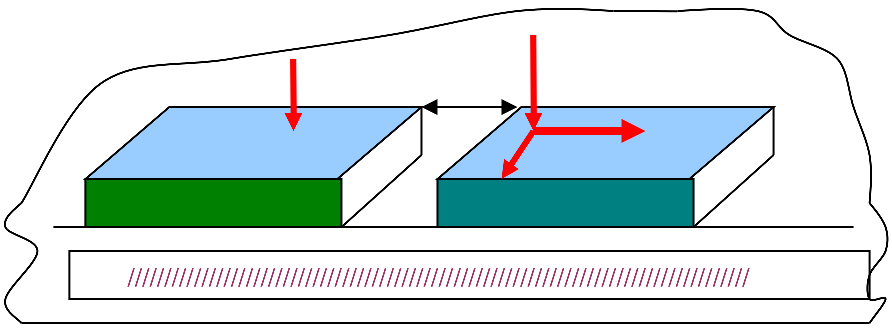

Fig. 2. Diagram of the location of lithospheric plates before interaction. The red arrows show the direction of the components of the contact stress vectors on the lower base of the lithospheric plates

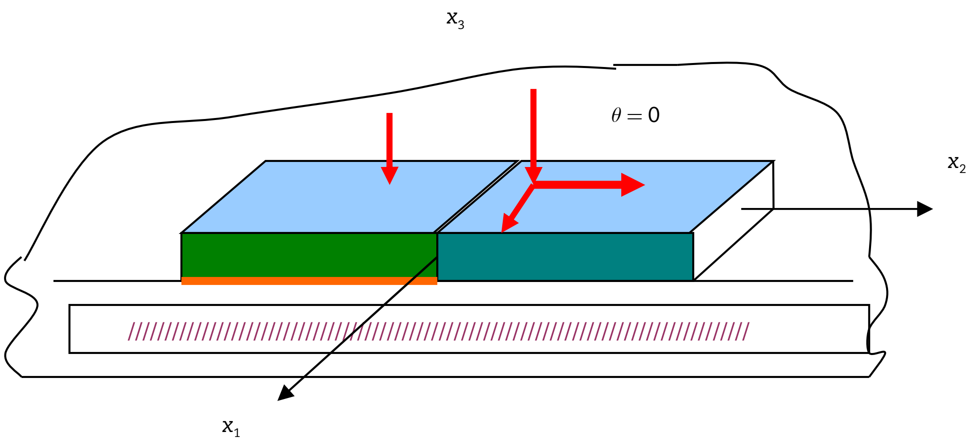

Fig. 3. Converging lithospheric plates. The red arrows show the direction of the components of the contact stress vectors on the lower base of the lithospheric plates.

2. Problem Statement

We believe that the lithospheric plates lie on a deformable base. It is represented by semi-infinite Kirchhoff plates in the form of half-planes whose borders are parallel and at a distance 2θ, $\theta \geq 0$ from each other. Each lithospheric plate has individual mechanical properties. The coordinate axes x_1ox_2 lie in the plane of the plates, and the x_3 axis is directed along the external normal to the base. We consider the case of static effects on the surface of plates, of which the left one, which has an index $b=\lambda$, contacts the base without friction, and the right one , which has an index $b=r$, is rigidly connected to the base.

We believe that lithospheric plates lie on a deformable base and are semi-infinite Kirchhoff plates in the form of half-planes, whose borders are parallel and at a distance 2θ, $\theta \geq 0$ from each other, and each has individual mechanical properties. Assume that the x_1ox_2 coordinate axes lie in the plane of the plate, and the x_3 axis is directed along the outer normal to the base. Consider the case of static effects on the surface of plates, of which the left, which has an index $b=\lambda$, contacts the base without friction, and the right, which has an index $b=r$, is rigidly connected to the base. We made the notation

$$\mathbf{s}_b(x_1,x_2)=\begin{Vmatrix} -\varepsilon_{5b}s_{1b}(x_1,x_2) & 0 & 0 \\ 0 & -\varepsilon_{5b}s_{2b}(x_1,x_2) & 0 \\ 0 & 0 & \varepsilon_{53b}s_{3b}(x_1,x_2) \end{Vmatrix}, \quad s_{nb}(x_1,x_2)=(t_{nb}+g_{nb}), \tag{1}$$

$$\mathbf{R}_b(\partial x_1,\partial x_2)\mathbf{u}_b=\begin{Vmatrix} \left(\frac{\partial^2}{\partial x_1^2}+\varepsilon_{1b}\frac{\partial^2}{\partial x_2^2}\right)u_{1b} & \left(\varepsilon_{2b}\frac{\partial^2}{\partial x_1\partial x_2}\right)u_{2b} & 0 \\ \left(\varepsilon_{2b}\frac{\partial^2}{\partial x_1\partial x_2}\right)u_{1b} & \left(\frac{\partial^2}{\partial x_2^2}+\varepsilon_{1b}\frac{\partial^2}{\partial x_1^2}\right)u_{2b} & 0 \\ 0 & 0 & \left(\frac{\partial^4}{\partial x_1^4}+2\frac{\partial^2}{\partial x_1^2}\frac{\partial^2}{\partial x_2^2}+\frac{\partial^4}{\partial x_2^4}\right)u_{3b} \end{Vmatrix}. \tag{2}$$

The equations of boundary value problems for plates are have the form

$$\mathbf{R}_b(\partial x_1,\partial x_2)\mathbf{u}_b-\mathbf{s}_b(x_1,x_2)=0, \quad b=\lambda,r \tag{3}$$

The $\mathbf{u_b}=\{u_{1b},u_{2b},u_{3b}\}$ is the vector of displacement the points of the plate along the horizontal u_{1b},u_{2b}, and vertical u_{3b} directions of the median plane.

There are no contact tangential stresses under the left plate so it is accepted $s_{nb}(x_1,x_2)=0,\ u_{nb}=0,\ n=1,2$. Applying the Fourier transform to the system of equations (2), we get

$$\mathbf{R}_b(-i\alpha_1,-i\alpha_2)\mathbf{U}_b=-\begin{Vmatrix} (\alpha_1^2+\varepsilon_{1b}\alpha_2^2)U_{1b} & \varepsilon_{2b}\alpha_1\alpha_2U_{2b} & 0 \\ \varepsilon_{2b}\alpha_1\alpha_2U_{1b} & (\alpha_2^2+\varepsilon_{1b}\alpha_1^2)U_{2b} & 0 \\ 0 & 0 & -(\alpha_1^2+\alpha_2^2)^2U_{3b} \end{Vmatrix}$$

$$\mathbf{U}_b=\mathbf{F}\mathbf{u}_b, \quad \mathbf{G}_b=\mathbf{F}\mathbf{g}_b \quad \mathbf{T}_b=\mathbf{F}\mathbf{t}_b$$

$$\mathbf{u}_b=\{u_{1b},u_{2b},u_{3b}\}, \quad \mathbf{g}_b=\{g_{1b},g_{2b},g_{3b}\}, \quad \mathbf{t}_b=\{t_{1b},t_{2b},t_{3b}\}$$

There are the normal stresses t_{3b}, $b=\lambda,r$ to act on the plate at the top and g_{3b}, $b=\lambda,r$ at the bottom. Similarly, the stresses act in the tangent plane, and - in the direction of the normal to the ends of the lithospheric plates.

There are the following designations: - μ_b shear modulus, ν_b - Poisson's ratio, E_b - young's modulus, h_b - thickness of lithospheric plates, H - thickness of the base layer, $\mathbf{g}_b$ $\mathbf{t}_b$ vectors of contact stresses and external horizontal, g_{1b}, g_{2b} t_{1b}, t_{2b}, influences, respectively, acting tangentially to the base boundary and along the normal to it in the areas Ω_b. $\mathbf{F}_2 \equiv \mathbf{F}_2(\alpha_1,\alpha_2)$, $\mathbf{F}_1 \equiv \mathbf{F}_1(\alpha_1)$ - two-dimensional and one-dimensional Fourier transform operators, respectively. The boundary conditions described in [2] are preserved here. Expressions for the normal N_{x_2} and tangent $T_{x_1x_2}$ components of the stresses to the median plane at the ends of the plates are given by the relations, respectively

$$T_{x_1x_2} = \varepsilon_{7b}\left(\frac{\partial u_{2r}}{\partial x_1} + \frac{\partial u_{1r}}{\partial x_2}\right), \quad N_{x_2} = \varepsilon_{8b}\left(\frac{\partial u_{2r}}{\partial x_2} + \nu_b \frac{\partial u_{1r}}{\partial x_1}\right),$$
$$\varepsilon_{7r} = \frac{E_r}{2(1+\nu_r)H}, \quad \varepsilon_{8r} = \frac{E_r}{(1-\nu_r{}^2)H}$$

For a deformable base described by the boundary value problem, various models given by the ratios are applicable

$$\mathbf{u}(x_1,x_2) = \varepsilon_6^{-1}\frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int \mathbf{K}(\alpha_1,\alpha_2)\mathbf{G}(\alpha_1,\alpha_2)e^{-i\langle\alpha,x\rangle}\,d\alpha_1 d\alpha_2,$$
$$x\in\Omega_\lambda, \quad x\in\Omega_r, \quad x\in\Omega_\theta, \quad \langle\alpha,x\rangle = \alpha_1x_1+\alpha_2x_2$$
$$\Omega_\lambda(|x_1|\le\infty; \quad x_2\le-\theta), \quad \Omega_r(|x_1|\le\infty; \quad \theta\le x_2), \quad \Omega_\theta(|x_1|\le\infty; \quad -\theta\le x_2\le\theta)$$
$$\mathbf{K} = \|K_{mn}\|, \quad m,n=1,2,3, \quad \mathbf{K}(\alpha_1,\alpha_2) = O(A^{-1}), \quad A=\sqrt{\alpha_1^2+\alpha_2^2}\to\infty$$
$$\varepsilon_6^{-1} = \frac{(1-\nu)H}{\mu}, \quad \mathbf{G}(\alpha_1,\alpha_2) = \mathbf{F}_2(\alpha_1,\alpha_2)\mathbf{g}$$

$\mathbf{g}$ - vector of tangent and normal stresses under the plates at the base boundary. Some types of matrix-functions $\mathbf{K}(\alpha_1,\alpha_2)$ of bases, called the symbol of the system of integral equations, are given in [42]. For example, for an elastic layer with a fixed lower face, in the static case, it looks like

$$\mathbf{K}(\alpha_1,\alpha_2) = \begin{Vmatrix} \alpha_1^2M+\alpha_2^2N & \alpha_1\alpha_2(M-N) & i\alpha_1P \\ \alpha_1\alpha_2(M-N) & \alpha_1^2N+\alpha_2^2M & i\alpha_2P \\ -i\alpha_1P & -i\alpha_2P & K \end{Vmatrix}$$

$$M(u) = \frac{(1-\nu)(3-4\nu)(sh4u+4u)}{u^2\Delta}, \quad N(u) = \frac{2sh2u}{u^3ch2u},$$

$$P(u) = -\frac{(1-2\nu)(3-4\nu)sh^2 2u - 4u^2}{u\,\Delta(u)}, \quad K(u) = \frac{(1-\nu)(3-4\nu)(sh4u-4u)}{\Delta(u)},$$
$$\Delta(u) = u\left[(3-4\nu)sh^2 2u + 4u^2 + 4(1-\nu)^2\right], \quad u=\sqrt{\alpha_1^2+\alpha_2^2}$$

The matrix (2) of the boundary value problem is a block – diagonal matrix consisting of a second-order matrix located on the diagonal, representing a matrix operator or vector operator, and a separate scalar operator on the diagonal. Since the operators are independent, this greatly facilitates the study of the boundary value problem at the stage of external analysis, allowing you to use the results obtained in the works [1, 2].

3. External Analysis of the Boundary Value Problem

Three stages are required for solving boundary value problems for differential equations using the block element method: external algebra, external analysis, and factor topology. The solution is sought in topological spaces of slowly growing generalized functions. Such solutions can describe functions that numerical methods cannot describe-Delta functions, singularities, and other singularities. The external algebra stage ensures that the block structure is divided into separate blocks endowed with interblock boundary conditions and each block is considered individually.

The boundary value problem of a block is immersed in a topological space and is considered as a manifold with an edge. The boundary is tangentially delaminated, which allows the introduction of external forms. After this, the boundary value problem is reduced to a functional equation using the Stokes integral. One scalar equation or matrix equation is obtained, which has a system of equations. The phase of the external analysis involves a mathematical analysis and transformation of external forms, participating in the functional equation. Differential factorization of the coefficient of the functional equation is performed. If it is a function, it is factorized into parts containing certain zeros of the function. If it is a matrix function, then factorization includes representation as a product of two matrix functions. After factorization, the calculation of Leray form-residues on polar sets in the right part ensures the automorphism of the boundary problem on the block element. This ensures both that the boundary conditions are met and that the boundary problem carrier is limited only to the area of the block element. The resulting pseudo-differential equations contain all types of boundary conditions allowed by the boundary problem. Therefore, when solving them, the ones that are required by the task are selected.

Solutions of pseudodifferential equations are introduced into external forms, which allows us to construct a solution of the boundary value problem for a block element from the functional equation. At this stage of external analysis is completed. Below, the block element method is implemented in scalar and vector cases.

The functional equations of the scalar operator for functions U_{3b}, $b=\lambda,r$ have the form [1,2]

$$R_{3b}(-i\alpha_1,-i\alpha_2)U_{3b} \equiv (\alpha_1^2+\alpha_2^2)^2 U_{3b} = -\int_{\partial\Omega_b} \omega_{3b} + S_{3b}(\alpha_1,\alpha_2)$$
$$S_{3b}(\alpha_1,\alpha_2) = \varepsilon_{53b}\mathbf{F}_2(\alpha_1,\alpha_2)(t_{3b}+g_{3b}), \quad b=\lambda,r \tag{4}$$

Here ω_{3b} are the external forms participating in the representation, which have an expression for the left λ and right r lithospheric plate

$$\omega_{3\lambda} = e^{i\langle\alpha,x\rangle}\{\ -[\ \frac{\partial^3 u_{3\lambda}}{\partial x_2^3} - i\alpha_2\frac{\partial^2 u_{3\lambda}}{\partial x_2^2} - \alpha_2^2\frac{\partial u_{3\lambda}}{\partial x_2} + i\alpha_2^3 u_{3\lambda} + 2\frac{\partial^3 u_{3\lambda}}{\partial x_1^2\partial x_2} - 2i\alpha_2\frac{\partial^2 u_{3\lambda}}{\partial x_1^2}\ ]dx_1 + [\ \frac{\partial^3 u_{3\lambda}}{\partial x_1^3} - i\alpha_1\frac{\partial^2 u_{3\lambda}}{\partial x_1^2} - \alpha_1^2\frac{\partial u_{3\lambda}}{\partial x_1} + i\alpha_1^3 u_{3\lambda}\ ]dx_2\ \},$$

$$\omega_{3r} = -e^{i\langle\alpha,x\rangle}\{\ -[\ \frac{\partial^3 u_{3r}}{\partial x_2^3} - i\alpha_2\frac{\partial^2 u_{3r}}{\partial x_2^2} - \alpha_2^2\frac{\partial u_{3r}}{\partial x_2} + i\alpha_2^3 u_{3r} + 2\frac{\partial^3 u_{3r}}{\partial x_1^2\partial x_2} - 2i\alpha_2\frac{\partial^2 u_{3r}}{\partial x_1^2}\ ]dx_1 + [\ \frac{\partial^3 u_{3r}}{\partial x_1^3} - i\alpha_1\frac{\partial^2 u_{3r}}{\partial x_1^2} - \alpha_1^2\frac{\partial u_{3r}}{\partial x_1} + i\alpha_1^3 u_{3r}\ ]dx_2\ \}$$

To construct pseudodifferential equations in the scalar case, Lehrer deduction forms are calculated, including two-fold ones. Pseudodifferential equations of the boundary value problem, taking into account the accepted designations, can be represented for plates $b=\lambda, r$ in the form

$$\mathbf{F}_1^{-1}(\xi_1^\lambda)\langle\ -\int_{\partial\Omega_\lambda}\{\ i\alpha_{2-}D_{\lambda 1}{}^{-1}M_\lambda - D_{\lambda 2}{}^{-1}Q_\lambda - (\alpha_{2-}^2+\nu_\lambda\alpha_1^2)\frac{\partial u_{3\lambda}}{\partial x_2} + i\alpha_{2-}[\ \alpha_{2-}^2+(2-\nu_\lambda)\alpha_1^2\ ]u_{3\lambda}\ \}e^{i\alpha_1 x_1}dx_1 + \varepsilon_{53\lambda}S_{3\lambda}(\alpha_1,\alpha_{2-})\ \rangle = 0,$$
$$\alpha_{2-} = -i\sqrt{\alpha_1^2}, \qquad \xi_1^\lambda \in \partial\Omega_\lambda$$

$$\mathbf{F}_1^{-1}(\xi_1^\lambda)\langle\ -\int_{\partial\Omega_\lambda}\left\{ iD_{\lambda 1}{}^{-1}M_\lambda - 2\alpha_{2-}\frac{\partial u_{3\lambda}}{\partial x_2} + i[\ 3\alpha_{2-}^2+(2-\nu_\lambda)\alpha_1^2\ ]u_{3\lambda}\right\}e^{i\alpha_1 x_1}dx_1 + \varepsilon_{53\lambda}S'_{3\lambda}(\alpha_1,\alpha_{2-})\ \rangle = 0,$$
$$\xi_1^\lambda \in \partial\Omega_\lambda, \qquad \partial\Omega_\lambda = \{-\infty \le x_1 \le \infty, \quad x_2 = -\theta\}$$

Respectively for the right plate

$$\mathbf{F}_1^{-1}(\xi_1^r)\langle\ -\int_{\partial\Omega_r}\{\ i\alpha_{2+}D_{r1}{}^{-1}M_r - D_{r2}{}^{-1}Q_r - (\alpha_{2+}^2+\nu_r\alpha_1^2)\frac{\partial u_{3r}}{\partial x_2} + + i\alpha_{2+}[\ \alpha_{2+}^2+(2-\nu_r)\alpha_1^2\ ]u_{3r}\ \}e^{i\alpha_1 x_1}dx_1 + \varepsilon_{53r}S_{3r}(\alpha_1,\alpha_{2+})\ \rangle = 0,$$
$$\alpha_{2+} = i\sqrt{\alpha_1^2}, \quad \xi_1^r \in \partial\Omega_r$$

$$\mathbf{F}_1^{-1}(\xi_1^r)\langle\ -\int_{\partial\Omega_r}\left\{ iD_{r1}{}^{-1}M_r - 2\alpha_{2+}\frac{\partial u_{3r}}{\partial x_2} + i[\ 3\alpha_{2+}^2+(2-\nu_r)\alpha_1^2\ ]u_{3r}\right\}e^{i\alpha_1 x_1}dx_1 + \varepsilon_{53r}S'_{3r}(\alpha_1,\alpha_{2+})\ \rangle = 0,$$
$$\xi_1^r \in \partial\Omega_r, \quad \partial\Omega_r = \{-\infty \le x_1 \le \infty, \quad x_2 = \theta\}$$

The functional equations of the boundary value problem for the vector case of the plate with rigit contact $b=r$ are matrix equations and have the form

$$\mathbf{R}_r(-i\alpha_1,-i\alpha_2)\mathbf{U}_r = -\int_{\partial\Omega_b}\boldsymbol{\omega}_r + \mathbf{S}_r(\alpha_1,\alpha_2), \quad \mathbf{U}_r = \{\ U_{1r}, U_{2r}\ \},$$

$$\boldsymbol{\omega}_r = \{\ \omega_{1r},\omega_{2r}\ \}, \quad \mathbf{S}_r(\alpha_1,\alpha_2) = -\varepsilon_{5r}\mathbf{F}_2(\alpha_1,\alpha_2)(\mathbf{g}_r+\mathbf{t}_r),$$

$$\mathbf{S}_r(\alpha_1,\alpha_2) = \{\ S_{1r}, S_{2r}\ \} \tag{5}$$

$$\mathbf{R}_r(-i\alpha_1,-i\alpha_2) = -\begin{Vmatrix}(\alpha_1^2+\varepsilon_{1r}\alpha_2^2) & \varepsilon_{2r}\alpha_1\alpha_2 \\ \varepsilon_{2r}\alpha_1\alpha_2 & (\alpha_2^2+\varepsilon_{1r}\alpha_1^2)\end{Vmatrix}$$

Here $\boldsymbol{\omega}_r$ is a vector of external forms that have components

$$\omega_{1r} = e^{i\langle\alpha,x\rangle}\{-(\varepsilon_{1r}\frac{\partial u_{1r}}{\partial x_2} + \varepsilon_{2r}\frac{\partial u_{2r}}{\partial x_1} - i\varepsilon_{1r}\alpha_2 u_{1r})dx_1 + (\frac{\partial u_{1r}}{\partial x_1} - i\alpha_1 u_{1r} - i\varepsilon_{2r}\alpha_2 u_{2r})dx_2\ \},$$
$$\omega_{2r} = e^{i\langle\alpha,x\rangle}\{-(\varepsilon_{2r}\frac{\partial u_{1r}}{\partial x_1} + \frac{\partial u_{2r}}{\partial x_2} - i\alpha_2 u_{2r})dx_1 + (\varepsilon_{1r}\frac{\partial u_{2r}}{\partial x_1} - i\varepsilon_{1r}\alpha_1 u_{2r} - i\varepsilon_{2r}\alpha_2 u_{1r})dx_2\ \}$$

To construct pseudo-differential equations, differential factorization of the matrix function $-\mathbf{R}_r(-i\alpha_1,-i\alpha_2)$ of the functional equation is performed [2]. Using an external analysis algorithm, a factorizing matrix-function is constructed. Taking into account that the determinant of the matrix-function $-\mathbf{R}_r(-i\alpha_1,-i\alpha_2)$ has two-fold roots $\alpha_{2\pm} = \pm i\sqrt{\alpha_1^2} \equiv \pm i|\alpha_1|$, we obtain factoring matrix-functions for the left and right plates in the form

$$\mathbf{D}_r(-i\alpha_1,-i\alpha_2) = \begin{Vmatrix}\dfrac{1}{(\alpha_2-\alpha_{2+})^2} & \dfrac{\alpha_{2+}}{(\alpha_2-\alpha_{2+})^2\alpha_1} - \dfrac{(1+\varepsilon_{1r})}{(\alpha_2-\alpha_{2+})\varepsilon_{2r}\alpha_1} \\ 0 & 1\end{Vmatrix}$$

After performing external analysis operations on these functional equations [1, 2], including differential factorization of the coefficient of the functional equation-matrix-function and calculating the Lehrer deduction forms, we construct pseudo-differential equations. They have the form

$$\mathbf{F}_1^{-1}(\xi_1^r)\langle -\int_{\partial\Omega_r}\{\varepsilon_{6r}(\mathrm{T}_{x_1x_2r}+\alpha_{2+}\alpha_1^{-1}\mathrm{N}_{x_2r})-2i\varepsilon_{1r}\alpha_{2+}u_{1r}+2i\varepsilon_{1r}\alpha_1u_{2r}\}e^{i\alpha_1x_1}dx_1-$$
$$-\varepsilon_{5r}[\ \mathrm{S}_{1r}(\alpha_1,\alpha_{2+})\ +\alpha_{2+}\alpha_1^{-1}\mathrm{S}_{2r}(\alpha_1,\alpha_{2+})\ ]\ \rangle=0,\quad \xi_1^r\in\partial\Omega_r$$

$$\mathbf{F}_1^{-1}(\xi_1^r)\langle\ \int_{\partial\Omega_r}\{\ (1+\varepsilon_{1r})\varepsilon_{6r}\mathrm{N}_{x_2r}-2i\varepsilon_{1r}^2\alpha_1u_{1r}-2i\varepsilon_{1r}\alpha_{2-}u_{2r}\ \}e^{i\alpha_1x_1}dx_1-$$
$$-\varepsilon_{5r}[\ -(1+\varepsilon_{1r})\mathrm{S}_{2r}(\alpha_1,\alpha_{2+})+\varepsilon_{2r}\alpha_1\mathrm{S'}_{1r}(\alpha_1,\alpha_{2+})+\varepsilon_{2r}\alpha_{2+}\mathrm{S'}_{2r}(\alpha_1,\alpha_{2+})\ ]\ \rangle=0,$$
$$\xi_1^r\in\partial\Omega_r$$

Here are the inverse operators to the one-dimensional Fourier transform. We apply the Fourier transform operator to these systems of equations and introduce the following notation system

$$\begin{gathered}\mathbf{Y}_{\lambda0}=\{y_{1\lambda0},y_{2\lambda0}\},\quad \mathbf{Z}_{\lambda0}=\{z_{1\lambda0},z_{2\lambda0}\},\quad \mathbf{Y}_{r0}=\{y_{1r0},y_{2r0}\},\quad \mathbf{Z}_{r0}=\{z_{1r0},z_{2r0}\},\\ \mathbf{F}_1g=\mathbf{F}_1(\alpha_1)g,\quad \mathbf{F}_2g=\mathbf{F}_2(\alpha_1,\alpha_2)g,\\ y_{1\lambda0}=D_\lambda^{-1}\mathbf{F}_1M_\lambda,\quad y_{2\lambda0}=D_\lambda^{-1}\mathbf{F}_1Q_\lambda,\quad y_{1r0}=D_r^{-1}\mathbf{F}_1M_r,\quad y_{2r0}=D_r^{-1}\mathbf{F}_1Q_r,\\ z_{1\lambda0}=\mathbf{F}_1\frac{\partial u_{3\lambda}}{\partial x_2^\lambda},\quad z_{2\lambda0}=\mathbf{F}_1u_{3\lambda},\quad z_{1r0}=\mathbf{F}_1\frac{\partial u_{3r}}{\partial x_2^r},\quad z_{2r0}=\mathbf{F}_1u_{3r},\end{gathered}\tag{6}$$

$$\begin{gathered}\mathbf{K}_{\lambda0}=\{k_{1\lambda0},k_{2\lambda0}\},\quad \mathbf{K}_{r0}=\{k_{1r0},k_{2r0}\},\quad k_{1\lambda0}=\varepsilon_{53\lambda}\mathbf{F}_2(\alpha_1,\alpha_{2-})(t_{3\lambda}+g_{3\lambda})=\varepsilon_{53\lambda}S_{3\lambda}(\alpha_1,\alpha_{2-}),\\ k_{2\lambda0}=\varepsilon_{53\lambda}S'_{3\lambda}(\alpha_1,\alpha_{2-}),\quad k_{1r0}=\varepsilon_{53r}\mathbf{F}_2(\alpha_1,\alpha_{2+})(t_{3r}+g_{3r})=\varepsilon_{53r}S_{3r}(\alpha_1,\alpha_{2+}),\\ k_{2r0}=\varepsilon_{53r}S'_{3r}(\alpha_1,\alpha_{2+})\end{gathered}$$

Similarly, for the vector,

$$\begin{gathered}\mathbf{Y}_\lambda=\{y_{1\lambda},y_{2\lambda}\},\quad \mathbf{Z}_\lambda=\{z_{1\lambda},z_{2\lambda}\},\quad \mathbf{Y}_r=\{y_{1r},y_{2r}\},\quad \mathbf{Z}_r=\{z_{1r},z_{2r}\},\\ \mathbf{F}_1g=\mathbf{F}_1(\alpha_1)g,\quad \mathbf{F}_2g=\mathbf{F}_2(\alpha_1,\alpha_2)g,\\ y_{1\lambda}=\mathbf{F}_1\mathrm{T}_{x_1x_2\lambda},\quad y_{2\lambda}=\mathbf{F}_1\mathrm{N}_{x_2\lambda},\quad y_{1r}=\mathbf{F}_1\mathrm{T}_{x_1x_2r},\quad y_{2r}=\mathbf{F}_1\mathrm{N}_{x_2r},\\ z_{1\lambda}=\mathbf{F}_1u_{1\lambda},\quad z_{2\lambda}=\mathbf{F}_1u_{2\lambda},\quad z_{1r}=\mathbf{F}_1u_{1r},\quad z_{2r}=\mathbf{F}_1u_{2r}\end{gathered}\tag{7}$$

In this case, the pseudo-differential equations are reduced to systems of algebraic equations. Solutions of these equations are introduced in the external forms of the functional equations in (4) and (5).

4. Solving the Boundary Value Problem.

To construct solutions to boundary problems, it is necessary to pair lithospheric plates with a three-dimensional base that has three-dimensional displacement and stress vectors on the border. To do this, it is necessary to present the parameters of the stress-strain state of lithospheric plates in the same form. To do this, enter the characteristics of both the left and right lithospheric plates into the vector representation.

$$\boldsymbol{\omega}_\lambda=\{0,0,\omega_{3\lambda}\},\quad \mathbf{S}_\lambda=\{0,0,S_{3\lambda}\},\quad \boldsymbol{\omega}_r=\{\omega_{1r},\omega_{2r},\omega_{3r}\},\quad \mathbf{S}_r=\{S_{1r},S_{2r},S_{3r}\}$$

Then the solutions in each plate can be represented as

$$\begin{gathered}\mathbf{u}_\lambda(x_1,x_2,0)=\mathbf{F}_2^{-1}(x_1,x_2)[\ \mathbf{R}_\lambda(-i\alpha_1,-i\alpha_2)\ ]^{-1}(\ -\int_{\partial\Omega_\lambda}\boldsymbol{\omega}_\lambda+\mathbf{S}_\lambda\ ),\\ \mathbf{u}_\lambda=(0,0,u_\lambda),\quad [\ \mathbf{R}_\lambda(-i\alpha_1,-i\alpha_2)\ ]^{-1}=\begin{Vmatrix}0&0&0\\0&0&0\\0&0&R_\lambda^{-1}(-i\alpha_1,-i\alpha_2)\end{Vmatrix}\end{gathered}\tag{8}$$

We perform the operation of building a factor topology-gluing block elements. All three components of the movement of lithospheric plates, both normal and tangent, are conjugated with the movements of the upper boundary of the base. We get relations of the form

$$\begin{gathered}\mathbf{P}_\lambda\mathbf{u}(x_1,x_2,0)+\mathbf{P}_\theta\mathbf{u}(x_1,x_2,0)+\mathbf{P}_r\mathbf{u}(x_1,x_2,0)=\varepsilon_6^{-1}\mathbf{F}_2^{-1}\mathbf{K}(\alpha_1,\alpha_2,0)[\ \mathbf{G}_\lambda(\alpha_1,\alpha_2)+\\ +\mathbf{G}_r(\alpha_1,\alpha_2)\ ],\quad \mathbf{G}_\lambda(\alpha_1,\alpha_2)=\mathbf{F}_2\mathbf{P}_\lambda\mathbf{g}(x_1,x_2),\quad \mathbf{G}_r(\alpha_1,\alpha_2)=\mathbf{F}_2\mathbf{P}_r\mathbf{g}(x_1,x_2)\\ \mathbf{P}_p\mathbf{u}=\mathbf{F}_2^{-1}[\ \mathbf{R}_p(-i\alpha_1,-i\alpha_2)\ ]^{-1}\langle\ -\int_{\partial\Omega_p}\boldsymbol{\omega}_p+\mathbf{S}_b(\alpha_1,\alpha_2)\ \rangle,\quad p=\lambda,r\end{gathered}\tag{9}$$

Here, $\mathbf{P}_\lambda$, $\mathbf{P}_r$ $\mathbf{P}_\theta$ - projectors on the left, right half-planes and on the middle interval, which are carriers of the corresponding plates and describing the interval $|x_2|\le\theta$. We add the relations (8) to the left parts of (9) and apply the Fourier transforms. Get the relations of the form

$$
\begin{aligned}
&[\ \mathbf{R}_\lambda(-\mathrm{i}\alpha_1,-\mathrm{i}\alpha_2)\ ]^{-1}\langle\ -\int_{\partial\Omega_\lambda}\boldsymbol{\omega}_\lambda+\mathbf{S}_\lambda\ \rangle+\mathbf{U}_\theta+\\
&+[\ \mathbf{R}_r(-\mathrm{i}\alpha_1,-\mathrm{i}\alpha_2)\ ]^{-1}\langle\ -\int_{\partial\Omega_r}\boldsymbol{\omega}_r+\mathbf{S}_r\ \rangle-\\
&-\mathbf{K}(\alpha_1,\alpha_2,0)[\ \mathbf{G}_\lambda(\alpha_1,\alpha_2)+\mathbf{G}_r(\alpha_1,\alpha_2)\ ]=0,\\
&\mathbf{U}_\theta=\mathbf{F}_2\mathbf{P}_\theta\mathbf{u}(x_1,x_2)
\end{aligned}
$$

Vector functions $\mathbf{G}_\lambda(\alpha_1,\alpha_2)$, $\mathbf{G}_r(\alpha_1,\alpha_2)$ that are Fourier transforms of functions with carriers in half-planes, there are regular functions of parameter α_2 with fixed α_1 in the lower and upper half-planes, respectively. In this regard, we can denote vector functions that are regular by parameter α_2 in the lower, minus sign, and in the upper, plus sign, half-planes by putting

$$\mathbf{G}_\lambda(\alpha_1,\alpha_2)=\mathbf{G}_-(\alpha_1,\alpha_2),\quad \mathbf{G}_r(\alpha_1,\alpha_2)=\mathbf{G}_+(\alpha_1,\alpha_2)$$

By adding these notations to the previous relation, we arrive at the Wiener – Hopf matrix functional equation.

$$
\begin{aligned}
&\mathbf{M}\mathbf{G}_+=\mathbf{G}_-+\mathbf{V}+\mathbf{K}_1^{-1}\mathbf{U}_\theta,\quad \mathbf{M}=\mathbf{K}_1^{-1}\mathbf{K}_2,\quad \mathbf{K}_2=\boldsymbol{\varepsilon}_r\mathbf{R}_r^{-1}-\varepsilon_6^{-1}\mathbf{K},\quad \mathbf{K}_1=\varepsilon_6^{-1}\mathbf{K}-\boldsymbol{\varepsilon}_\lambda\mathbf{R}_\lambda^{-1}\\
&\mathbf{V}=\mathbf{K}_1^{-1}(\mathbf{R}_\lambda^{-1}\int_{\partial\Omega_\lambda}\boldsymbol{\omega}_\lambda+\mathbf{R}_r^{-1}\int_{\partial\Omega_r}\boldsymbol{\omega}_r-\boldsymbol{\varepsilon}_\lambda\mathbf{R}_\lambda^{-1}\mathbf{T}_\lambda-\boldsymbol{\varepsilon}_r\mathbf{R}_r^{-1}\mathbf{T}_r),\quad \mathbf{U}_\theta=\mathbf{F}_2\mathbf{P}_\theta\mathbf{u}(x_1,x_2)
\end{aligned}
$$

Unknown functions in this equation are $\mathbf{G}_\pm(\alpha_1,\alpha_2)$, and their functionals of the form $\mathbf{G}_\pm(\alpha_1,\alpha_{2\pm})$. They need to be defined. This is achieved as follows. A system of Wiener-Hopf functional equations is solved. Its solutions have the following matrix structure.

$$
\begin{aligned}
&\mathbf{G}_\pm(\alpha_1,\alpha_2)=\mathbf{C}_{1\pm}(\alpha_1,\alpha_2)\mathbf{G}_+(\alpha_1,\alpha_{2+})+\mathbf{C}_{2\pm}(\alpha_1,\alpha_2)\mathbf{G}_-(\alpha_1,\alpha_{2-})+\\
&+\mathbf{C}_{3\pm}(\alpha_1,\alpha_2)\mathbf{G}'_+(\alpha_1,\alpha_{2+})+\mathbf{C}_{4\pm}(\alpha_1,\alpha_2)\mathbf{G}'_-(\alpha_1,\alpha_{2-})+\mathbf{C}_{5\pm}(\alpha_1,\alpha_2)
\end{aligned}
$$

Here the matrices $\mathbf{C}_{n+}(\alpha_1,\alpha_2),\mathbf{C}_{n-}(\alpha_1,\alpha_2)$ are known, and the vectors $\mathbf{G}_+(\alpha_1,\alpha_{2+})$, $\mathbf{G}_-(\alpha_1,\alpha_{2-})$, $\mathbf{G}'_+(\alpha_1,\alpha_{2+}),\mathbf{G}'_-(\alpha_1,\alpha_{2-})$ need to be defined. To determine them, we differentiate the first and second matrix equations by α_2. Put in the first matrix equation and in the differentiated equation $\alpha_2=\alpha_{2+}$, and in the second matrix and in the differentiated equation $\alpha_2=\alpha_{2-}$. We obtain an algebraic system of matrix equations for determining all of the above unknown vectors, solving which we find the desired functions. Adding the found solutions to the relations (6), (7) makes it possible to fully determine the stress-strain state of the block structure under consideration.

5. Result and Discussion

The factorization approach described in [42] was used to study the features of solving the functional equation. The study of the properties of solutions of this matrix functional equation has led to new results that were not met before.

When, $\theta>0$ that is, when the ends of the plates are removed by a distance 2θ, the contact stresses on the edges of the plates have a representation [42] of the form

$$
\begin{aligned}
&g_{3\lambda}(x_1,x_2)=\sigma_{1\lambda}(x_1,x_2)(-x_2-\theta)^{-0,5}+\sigma_{2\lambda}(x_1,x_2)(-x_2-\theta)^{-0,5},\quad x_2<-\theta\\
&\mathbf{g}_r(x_1,x_2)=\boldsymbol{\sigma}_{1r}(x_1,x_2)(x_2-\theta)^{-0,5+i\gamma}+\boldsymbol{\sigma}_{2r}(x_1,x_2)(x_2-\theta)^{-0,5-i\gamma},\quad x_2>\theta\quad \gamma>0
\end{aligned}
\tag{10}
$$

Functions $\boldsymbol{\sigma}_{n\lambda},n=1,2$ and vectors $\boldsymbol{\sigma}_{nr},n=1,2$ are continuous in both parameters. The parameter γ has representation $\gamma=\mathrm{arcth}[1-2\nu]/[2(1-\nu)]$ where ν is the Poisson ratio. When $\theta=0$, that is, when the ends of the plates are completely converged, both in the presence γ and without it, the contact stresses have the form

$$
\begin{aligned}
&g_{nr}(x_1,x_2)=\sigma_{nr}(x_1,x_2)x_2^{-0,5+i\gamma}\\
&\quad n=1,2\\
&g_{3\lambda}(x_1,x_2)\to\sigma_{3\lambda}(x_1,x_2)x_2^{-1}\\
&g_{3r}(x_1,x_2)\to\sigma_{3r}(x_1,x_2)x_2^{-1}
\end{aligned}
$$

All functions $\boldsymbol{\sigma}_{3\lambda}(x_1,x_2)$, $\boldsymbol{\sigma}_{3r}(x_1,x_2)$ and $\boldsymbol{\sigma}_{nr}(x_1,x_2)$, $n=1,2$ are continuous on both variables. All functions and are continuous over both variables. Knowing the stress concentrations obtained above, we can the movement of the surface of lithospheric plates in the fault zone can be calculated, as described in [1, 2]. The fault under consideration, located between the lithospheric plates, is a new type of crack [40, 41]. The result described in the article was obtained for the first time. It shows that a tsunami can occur if there is a vertical movement of the right and left lithospheric plates. This will happen if the pressure on the left and right fault plates is so loaded that stress concentrations are destructive under each plate. If, for example, they are weaker, then in this case, there will be no destruction. If the destructive load is realized only for the left plate, which arises from the pressure of the continental plate, then the destruction will occur to the left of the fault. Thus, the new type of cracks that occur in seismology in the form of faults can destroy the environment directionally, one or the other side. This is evidenced by the results of this article, obtained for the first time. Griffiths cracks destroy the environment in a straight line. Griffiths cracks are formed as a result of virtual compression from the sides of an elliptical cavity in the plate and have a smooth border Fig. 4.

The new type of cracks are obtained as a result of virtual compression from the sides of a rectangular cavity in the plate and have a piecewise smooth border Fig. 5. The laws of fracture crack of a new type may be useful in engineering practice.

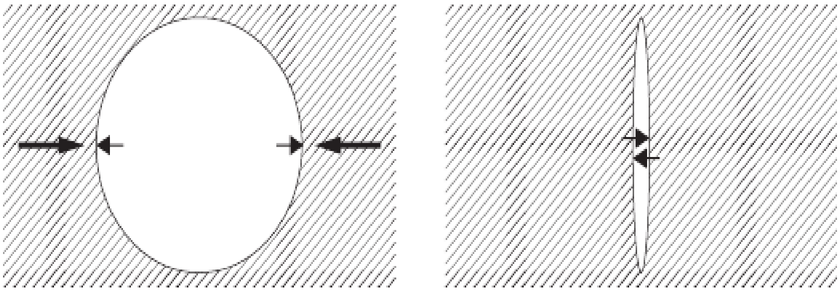

Fig. 4. Diagram of the formation of Griffiths cracks.

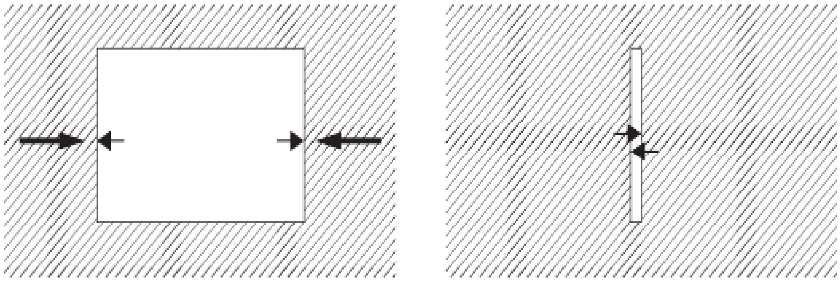

Fig. 5. Scheme of formation of cracks of a new type.

6. Conclusion

Comparing this result with those obtained in [1,2] , it can be noted that when conditions for starting earthquakes appear in a block structure consisting of two lithospheric plates on a rigid base, only singular vertical stress concentrations in the converging lithospheric plates will cause an earthquake. The concentrations of contact stresses under the right lithospheric plate under horizontal impacts are summable, with limited energy and are not capable of destroying the environment. If the vertical impacts on the lithospheric plates are sufficient for the occurrence of the initial earthquake, then an instantaneous vertical displacement of the fault banks will occur at the epicenter on the surface of the plates. It can cause a tsunami due to a sharp change in the level of the ocean over the banks of the fault. Horizontal displacements of the right lithospheric plate cannot cause a tsunami. The fault of converging lithospheric plates is a new type of crack. Its feature is the ability to destroy the environment not only in the direction of its continuation, but also in lateral directions. Destruction is carried out by concentrations of contact stresses that occur in the zones of contact of lithospheric plates with the base at the top of the crack.

Acknowledgments

The authors wish to express their cordial thanks to the Editors and Reviewers for their valuable suggestions and constructive comments which have served to improve the quality of this paper.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

Funding

This work was supported by the Russian Foundation for Basic Research, projects no. (19-41-230003), (19-41-230004), (19-48-230014), (18-08-00465), (18-01-00384), (18-05-80008), the GZ UNC RAS, project № 01201354241, (00-19-13), the Program no 7 and 20 of the Presidium of the Russian Academy of Sciences, projects (00-19-03), (00-19-10) and Ministry of the science Russian Federation, project (9.8753.2017/8.9) charged on 2020 year.

Nomenclature

t_{3b}, g_{3b}	Normal stresses $[kg/m^2]$	H	Thickness of the base layer $[m]$
g_{1b}, g_{2b}	Horizontal bottom stresses $[kg/m^2]$	h_b	Thickness of lithospheric plates $[m]$
t_{1b}, t_{2b}	Horizontal top stresses $[kg/m^2]$	$\mathbf{u_b} = \{u_{1b}, u_{2b}, u_{3b}\}$	Vector of displacement $[m]$
E_b	Young's modulus $[kg/m^2]$	$\mathbf{F}_1 \equiv \mathbf{F}_1(\alpha_1)$	One-dimensional Fourier transform operators
μ_b	Shear modulus $[kg/m^2]$	$\mathbf{F}_2 \equiv \mathbf{F}_2(\alpha_1, \alpha_2)$	Two-dimensional Fourier transform
ν_b	Poisson's ratio	α_1, α_2	Parameters of the Fourier transform
$\mathbf{t}_{3b}, \mathbf{g}_{3b}$	Vector normal stresses $[kg/m^2]$	$\mathbf{K}(\alpha_1, \alpha_2)$	Core of the integral equation
$\mathbf{g}_{1b}, \mathbf{g}_{2b}$	Vector horizontal stresses $[kg/m^2]$	ω_{3b}	Scalar external form
$\mathbf{t}_{1b}, \mathbf{t}_{2b}$	Vector horizontal stresses $[kg/m^2]$	$\boldsymbol{\omega}_r$	Vector external form
θ	Distance between lithospheric plates $[m]$		

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How to cite this article: Babeshko V.A., Evdokimova O.V., Babeshko O.M. About Earthquakes in Subduction Zones with the Potential to Cause a Tsunami, *J. Appl. Comput. Mech.*, 7(SI), 2021, 1232–1241. https://doi.org/10.22055/JACM.2020.32385.2007