***Supplement 1***

*Yu.L.Rebetsky, Y.Guo, K.Wang, R.S.Alekseev, and A.V.Marinin*, “Stress state and dangerous crustal faults West Sichuan, China,” Geotectonics. 2021. Vol.**55**. No. 6.

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**Rebetsky Method of Cataclastic Analysis of Discontinuous Displacements:**

The method of cataclastic analysis of discontinuous displacements has been developed since the mid-1990s and contains four stages of calculation of the parameters of the natural stress state [11,

12, 16, 18, 19]. The sequential application of the algorithms of each of these stages allows us to determine the absolute values of stresses, to estimate the values of the cohesion strength of rocks, the rocks friction coefficient and the fluid pressure in the fractured-pore space. In addition, the parameters of the ellipsoid of the increments of seismotectonic deformations corresponding to the obtained stress data are also determined. All these parameters are calculated on the averaging scale that corresponds to the volume within which the discontinuities with displacements (earthquakes) are distributed. This article presents only the parameters that determine the shape and directions of the principal axes of the stress ellipsoid, as well as the normalized stress values. Therefore this appendix contains only the algorithms of the first two stages of this method of tectonophysical inversion a.k.a. reconstruction of the natural stress state.

***Criteria for the formation of homogeneous sets of mechanisms of earthquake foci***

The method of cataclastic analysis of discontinuous displacements (MCA) presupposes that the calculation of the stress tensors components and increments of seismotectonic deformations is carried out based on the data taken from the homogeneous set of mechanisms of earthquake foci (MEF). The formation of the homogeneous sample in MCA is preceded by the creation of an initial set of MEF. With geological studies this issue is solved at the very initial stage of research by

creation of cracks sample according to the morphological type of structures found in a geological outcrop. In the case of the reconstruction of modern tectonic stresses based on seismological catalogs of focal mechanisms, this issue can be solved by the calculation process based on the involvement of physical laws that allow us to assess the possible compatibility of the foci mechanisms included in a homogeneous set.

The initial set of MEF based on spatial proximity cannot be considered as homogeneous, that characterizes the homogeneous phase of deformation of the rock massif under study. Within the framework of MCA, the creation of a homogeneous set of MEF is the first task that should be carried out before the reconstruction of stresses and deformations. The criteria for data selection for a homogeneous set are based on several energy propositions in the theory of plasticity.

***Drucker’s postulate***

The modern theory of plasticity based on the Drukker principle, which determines that for an elastic-plastic body with an associated flow law, the requirement of the positivity of the work of true stresses on the increments of plastic deformations is fulfilled [10]. By extending the requirement of the positivity of the work of the desired stresses to each act of quasi-plastic

deformation, i.e. to each event with the number from the initial sample set of MEF, we can write:

 *d*   0 , i = 1, 2, 3, (1)

*i ii*

where  *i*

are the principal stresses, and

*d*  are the increments of irreversible plastic

*ii*

deformations in the direction of the action of the principal stresses. Here and further, according to the rule adopted in continuum mechanics, the longitudinal tensile stresses are positive.

In [16] is shown that (1) follows

*d*   0

*11* ,

*d*   0

*33*

. (2)

Inequalities (2) for a wide class of materials determine the spectrum of possible values of the components of the tensor increments of plastic deformations formed in the direction of the principal

stress axes and following the principle of reduction of the internal elastic energy on the tensor of realized irreversible deformations.

According to (2) the contribution from each fault to the tensor increments of seismotectonic deformations should form/deliver elongation deformation at the stress tensor in the direction of the action of the axis of minimum compression, it should form/deliver shortening deformation at the

stress tensor in the direction of maximum deviatory compression

     0

     0

n1 s1

, n3 s3

. (3)

Here  

*ni*

and 

are the direction cosines of the poles of the nodal planes (MEF) in the



*si*

coordinate system that deals associated with the orientation of the principal axes of the desired stress tensor. Inequalities (2) and the following formulas (3) will be referred to as the criterion for reduction of the elastic energy on individual faults.

It is shown in [16] that a similar (2) system of inequalities can also be written for the deformation increments from each discontinuous displacement in the coordinate system that dealsassociated with the principal axes of the seismotectonic strain tensor that characterizes the fractured flow of the rock mass. Thus, the inequalities (3) also extend to the increment tensor of seismotectonic deformations.

***Principle of plastic deformation regularity***

We will require the implementation of the principle of monotonicity (orderliness) of elastic- plastic deformation for the faulting flow [5] on the tensor of the desired stresses in order to contribute seismotectonic deformations from each fault to the tensor of increments:

*d*   *d*   *d* 

11 22

33 . (4)

The inequalities (4) impose stricter restrictions on the orientation of the axes of the principal stresses than the inequalities (2). On one hand, they include restrictions of inequality (2), and on the other hand, they impose an additional restriction on the increments of deformations from each fault

in the direction of the action of the intermediate principal stress  2 . Both additional elongation and shortening deformations may occur in this direction. In this case, the amplitudes of the elongation

deformation should be lower than the deformations in the direction of the axis  1 , and the amplitudes of the shortening deformations should be lower than the deformation in the direction of

the axis  3 :

             

n1 s1

n2 s2

n3 s3 ; (5)

Here, as well as in (3),   and  

are the direction cosines of the poles of the nodal planes

*ni si*

of MEF in the coordinate system associated with the orientation of the principal axes of the desired stress tensor. The inequalities will be defined (5) as the criterion of monotonicity of deformation [13].

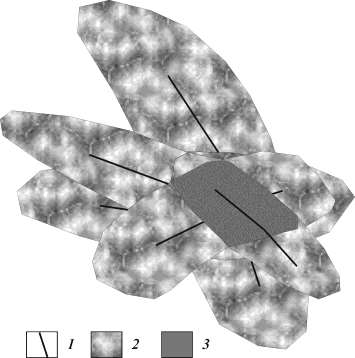
The fulfillment of inequalities (3) and (5) for the tensor of seismotectonic deformations and stresses, respectively, is a necessary condition for the inclusion of MEF in a homogeneous set.

***Algorithm for calculating the parameters of the increment ellipsoid of seismotectonic deformations***

Within the framework of MCA, the problem of calculation of the components of the increment tensor of seismotectonic deformations and stresses, as well as the creation of a homogeneous sample of MEF are interrelated tasks. They should be solved simultaneously during the reconstruction.

According to the principles of continuum mechanics, the residual deformations formed as a result of each act of sliding along the fault should be distributed only within the area of elastic unloading for a particular fault. Therefore, the summation of residual deformations should be performed only within the area of mutual intersection of elastic unloading areas for a set of earthquake foci, i.e. within their cumulative area. Figure 1 schematically shows in two-dimensional

space the cumulative elastic unloading areas formed as a result of several earthquakes. The summation of the deformations relieved during the process is within this area. The above statement is the first criterion of MCA, which is the basis for the formation of an initial, and then a homogeneous set of MEF. This criterion will be defined as the criterion of spatial proximity.



**Fig.1.** A diagram illustrating the method of calculating the increment tensor of seismotectonic deformations in the cumulative region.

*1* ‒ fault or earthquake source; *2* ‒ area of elastic unloading formed in the vicinity of the fault; *3* ‒ mutual intersection of elastic unloading areas

On the calculation of the strain increment tensor in the cumulative area. For a homogeneous sample set of MEF formed in accordance with the criterion of spatial proximity, the following formula for the increment tensor of seismotectonic deformations can be written:

*S*   *U*

*A*

 

 *n*  *s*   *n*  *s*   , ki,j. (6)

*ij*

 =1

*Ue*

2*V*   *i j*

*j i* 

where *U* 

is the amplitude of the shear displacement of the rupture sides, 

is the area of the

rupture, *V* 

is elastic influence zone of rupture, *n*  *s* 

and *n*  *s* 

respectively, the direction

*Ue i j i j*

cosines of the poles of the two nodal planes of MEF (is the number of rupture in a homogeneous sample set of MEF).

The MCA shows that (6) can be rewritten as:

*A*



      

   *A*  

*Sij*

0.5

*n s n s*

,   0.5

  *n*  *s* 

 *n* 

*s*   , (7)

*ns i j*

=1

*j i k*

 =1

*ns*  *i j*

*j i* 

where 



*ns*

is the average shear displacement for the elastic unloading area determined

according to the ratio of its dimensions and the characteristic dimensions of the focus *L* as

follows:

  *U*

  *U* 

*ns*  

*V*

*Ue*

 0.01  0.1

*L*

. (8)

This value can be defined as constant





 

*ns ns*

 ~

and it can be taken off the sum signs in

formulas (7) in cases when earthquakes from a homogeneous set of MEF characterize the quasi- homogeneous state of the volume under study under specific loading conditions.

***Normalization of the increment tensor of seismotectonic deformations***

Based on (7) and the conclusion made above, we can propose the following formulas for the increment tensor of seismotectonic deformations:

*Sij*

 *I S*

A

 *n* 



 =1  *i*

*s*   *n* 

*j j*

*s*  

*i* 

, (9)

where

*I s* is the normalizing factor determined on the condition of

0.5*Sij Sij*

 1 . Thus,

*Sij*

is a

normalized tensor of increments of seismotectonic deformations with a value of the shear intensity equal to one.

***Algorithm for calculating the parameters of the stress ellipsoid* – the 1st stage of MCA**

It was shown above that the inequalities (3) and (5) enable us to exclude the events from the initial sample of MEF, only leaving the events that have been tested by these criteria in [11,12]. It was proposed to use inequalities of the type (3) directly to determine the position of the axes of the

principal stresses [4]. That approach was based on the restriction defined in [7] that included the possible orientation of the axes of the principal stresses responsible for the movement in the earthquake source.

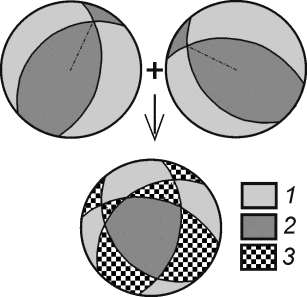
In MCA the inequalities (3) determine the geometric position of points in the intersecting quadrants that are formed on the lower or upper hemispheres by the nodal planes of MEF (Fig.2 ‒ inequalities are seen as permissible orientation of the axes of the algebraically maximum and

minimum increments of seismotectonic deformations).

**a b**

**c**

**Fig.2.** Summation of the possible exit areas of the axes of algebraically maximum and minimum increments of seismotectonic deformations on the lower surface of the hemisphere according to the inequalities (3): a, b –



compression and tension quadrants for two different MEF; c – the result of summation of these quadrants for two MEF.

*1‒3 ‒* area of summation of: *1* – solely compression quadrants, *2* – solely tension quadrants, *3* ‒ compression and tension quadrants

***The graphic method of fulfilling the principle of monotonicity of elastic-plastic deformation***

Inequalities (5) let us localize the areas of the permissible exit of the principal axes of the tectonic stress tensor on the hemispheres in a manner similar to the one discussed above. As can be seen in Figure 3b, summation of two events from a homogeneous set leads to the fact that the area

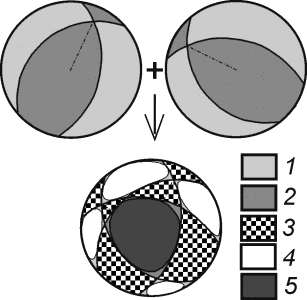
of the permissible position of the axes of the principal stresses, determined by the inequalities (5),

will be slightly smaller than after using the inequalities (3).

**a b**

**c**

**Fig.3.** Summation of the areas of possible output of the axes of algebraically maximum and minimum principal stresses on the lower surface of the hemisphere according to the inequalities (5): a, b – compression and tension quadrants for two different MEF; c – the result of summing the quadrants for two MEF.



*1‒2* – areas of summation of solely the compression and stretching quadrants according to the inequalities (3), *3* – area where the compression and tension quadrants were summed according to the inequalities (3), *4‒5* – areas of inequality fulfillment (5) inside the compression and tension quadrants of the focal mechanisms

When summing MEF from a homogeneous set, the axes of the principal stresses of the greatest and least compression will always be located inside the corresponding regions (Fig.3), determined according to the inequalities (5).

The regions that, according to the inequalities (5) and (3), are allocated on the lower hemispheres in MCA, are referred to as the areas of the permissible output of the algebraically maximum and minimum axes of the principal stresses and increments of seismotectonic deformations, respectively.

Finding the unique orientation of the principal axes of the desired stress tensor

To find the only possible (consistent) orientations of the principal axes of the stress tensor in the region highlighted by the inequalities (5), we should use data on the tensor of increments of seismotectonic deformations and the position on the maximum of elastic energy dissipation (Mises principle in the theory of plasticity).

The Mises principle determines that of all the possible states, the desired one is the one for which the maximum decrease in the internal energy accumulated in elastic deformations is achieved

on a known tensor of increments of plastic deformations

~

 

*ij*



*ij ij*

*d* *p*  0

. (10)

Here  *ij*

and ~

are, respectively, the desired (consistent) and possible stress tensors. We

*ij*

will define ~

*ij*

a tensor whose axes can have an orientation allowed by the inequalities (5) for a

homogeneous sample of MEF, and we can also use the assumption made above about the similarity

of tensors *d* *p* and

*ij*

*Sij* . In this case, the inequality

~

 



*S*

 0

*ij ij ij*

(11)

allows to select the orientation of the principal axes of the stress tensor in the areas of the permissible output to the hemisphere of the principal axes of maximum deviatory tension and

compression, as well as to select the value of the Lode–Nadai coefficient, the entire range of

changes of which is given by the inequality 

 1 .

The formula (11) in the application to the calculated characteristics of the stress-strain state

determines the finding of the maximum of the expression:

*E*   *ij Sij*



(12)

при  *ij*



  *p*  

2

 3



  *ij*



  1  

1*i*

1 *j*

 1  

 3*i*  3 *j* ,

*Sii*  0

by discrete search with a certain step of the “Euler” angles that determine the values of the direction cosines (k = 1, 3) of the desired principal stress axes in the topo-centric coordinate system, and varying of the values from +1 to -1 with a small step.

We interpret the finding of the maximum of the formula (12) as a requirement for the maximum reduction of the elastic strain energy for a set of discontinuous displacements from a homogeneous set, achieved on the tensor of the desired stresses. Note that in case when the axes of the principal deformations of the seismotectonic deformations of maximum elongation and shortening fall into the region of the permissible position of the axes of the principal stresses, allocated according to the inequalities (5), the requirement (12) is fulfilled automatically if the parameters of the ellipsoid of the increments of seismotectonic deformations and stresses coincide.

***The algorithm for calculating the normalized values of stresses – the2nd stage of MCA***

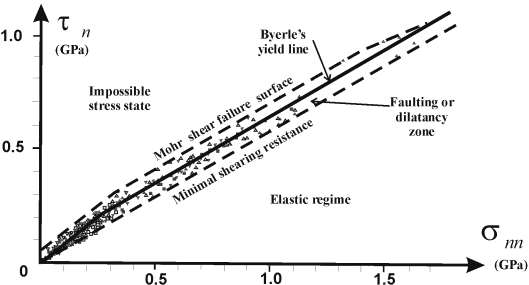
The algorithm of the first stage of MCA is formulated above for calculating four of the six components of the stress tensor (the orientations of the principle axes of the tensor determined by the three Euler angles, and the coefficient of the type of the stress tensor or the Lode–Nadai coefficient). After performing these calculations, two parameters of the stress tensor remain unknown, especially important from the point of view of studying geodynamic processes and seismic zoning, the isotropic pressure and the modulus of the maximum shear stress. The results

obtained in accordance with the above approach will be interpreted as the results of the first stage of stress calculation [14].

***Experiments on the destruction of fractured rock samples***

The principles of determining the ratio between the spherical and deviatory components of the stress tensor are based on the results of experiments on the brittle fracture of samples of various rocks, both initially continuous and containing sections or prepared surfaces of reduced strength,

performed within the framework of engineering (industrial and civil), as well as special geophysical studies [1‒3, 6, 8, 9, 20, 21]. These experiments made it possible to identify two characteristic lines on Mohr diagrams that determine the limit of internal friction strength of undisturbed rock samples and the minimum shear resistance due to friction at the boundaries of existing cracks – further, the minimum friction strength (Fig. 4). In a number of experiments, it was shown that the line of minimum friction strength comes to the origin [6, 20, 21].



**Fig.4.** Results of laboratory experiments on the study of the law of friction in the destruction of rock samples at high pressure – a solid broken line is passing through the middle of the cloud of experimental points (after [3]), with additions in the form of lines of internal strength and minimum resistance of surface friction (dashed lines bounding the cloud of points).The compressive normal stresses are shown horizontally to the right.

Note that Byerle's experiments were carried out for samples under dry conditions, i.e. without the addition of fluid. In reality, fluid pressure ( *p fl* ) in the fractured-pore space of rocks facilitates

the formation of shear cracks, since it reduces the pressure on the shifting sides of the crack,

therefore, speaking of effective normal stresses ( \*

*nn*

  *nn*

 *p fl* ), which determine the level of

friction. The equations of these lines, taking into account the softening effect of fluid pressure [22], can be presented in the following form:

    *k*  \*   ,

*n f nn f*

*С*

\*

*n s nn*

 *k* 



 0 . (13)

Here  *C*

are Coulomb stresses determined by the level of shear ( *n* ) and effective normal (  *nn* )

stresses acting on the plane of the formed or activated chip. The strength parameters *k f*

\*

and *k s* ,

respectively, the coefficients of internal and surface friction, and  *f*

is the value of internal

cohesion or the shear strength of undisturbed rock samples. According to the experimental results,

*k f* and  *f*

are functions of \* .

It is important to note that there is an extended section for which the upper bounding line is

*nn*

approximately parallel to the lower line. In this section, we can assume that *k f*

 *ks* ,  *f*

 const .

The experimental results showed that such an interpretation is possible for the section of the horizontal axis, where the normal pressures at the rupture sites range from 0.3 to 1.5 GPa. The zone enclosed in the Mohr diagram between the line of the limit of brittle strength of rocks and the line

of the minimum friction resistance within the MCA is defined as the brittle fracture band [15]. This interpretation of the experimental results is the basis of the method for calculating the values of the stress tensor.

***Minimum friction strength of existing faults***

We will assume that for critical states corresponding to the activation process on partially healed cracks, sliding along their shores is realized with dry friction according to Coulomb's law at

a constant value of the surface friction coefficient ( *k s*

 const ). In this case, the value of surface

cohesion for newly activated faults (  ) can vary from a minimum (zero) value to a maximum

*s*

value equal to the value of the internal cohesion of undisturbed arrays ( 

*s*

  *f* ). Thus, for faults

with the same value on their banks, the difference in the limit states lies in the different values of the coupling values (ordinal number of faults in a homogeneous set). All possible limiting states on the shores of newly formed or activated faults can be represented in the following form:

      *k*  

  

    0

*C n s nn*

*s* при

0  *s*

  *f* и

*nn* (14)

where  

*n*

, 

 and  

are shear stress, effective normal stress and surface cohesive strength

on the seismic faults number  from homogenous MEF accordingly.

*s*

*nn*

***Representation of stress at faults on Mohr diagram***

Using the limit condition (14), we evaluate the possibility of solving the problem that we formulated at the beginning of this section. To do this, we will draw on Mohr diagram the areas for

which the activation of faults is possible with variations in cohesion on its sides 0   

*s*

  *f* . Figure

5 shows that the size and type of the area of permissible solutions (permissible orientation of

activated faults) depends not only on the slope of the limit lines that determine the range of possible

conditions at the break, but also on the type of stress state (values of Lode–Nadai coefficient

 ),

which determines the location on the horizontal coordinate axis of the point of the intermediate principal stress between the points of two other principal stresses. The center of the great Mohr circle (Fig.5, point O) will correspond to the value of the compressive effective normal stress (  \* )

*O*

acting on the sites of maximum shear stresses:

  

 \*  0.5 \*   \*   *p* \*     

for

*p*\*  *p*  *p*

, (15)

*O* 1 3 *fl*

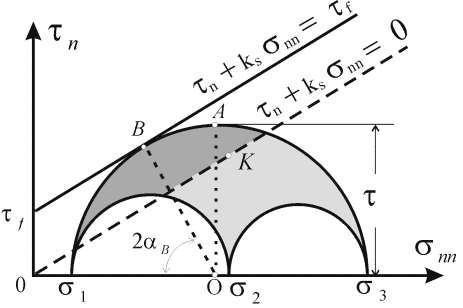
3

 

where  is the maximum shear stress,

*p*\* is the effective pressure,

*p fl* is the fluid pressure.



**Fig.5.** Circular Mohr diagram and lines of the minimum dry friction resistance on existing faults (dotted line) and the internal strength limit (solid line) for the general case of a stressed state. The area of the permissible position of the planes of faults with a variation of coupling is painted in dark gray ( 0   *i*   ); other areas of possible states on arbitrary sites are painted in light gray.

*s f*

A and B are points of stresses for planes of maximal shear stress and maximum of Coulomb stress. The compressive

normal stresses are shown horizontally to the right.

To assess the influence of stress values on the nature of the distribution of plane of faults, we will analyze Mohr diagram shown in Figure 5. Shear ( ) and normal (  \* ) stresses acting on fault

*n nn*

planes of maximum Coulomb stress are determined according to the formulas:

*B*   sin 2 ;  *B*   *p* \*



*B nn*

*n*



 (cos 2 *B* 

3

) , (16)

where  *B*

is the angle between the axis  1 and the normal **n** to the fault plane.

***Reduced stresses***

We will build a calculation algorithm for the general case of a stressed state under the assumption of the possibility of the formation of faults of arbitrary orientation in accordance with the criterion (14). We will assume that the set of data on the totality of earthquake foci, on the basis of which the orientation of the principal stresses and the value of Lode–Nadai coefficient were calculated at the first stage, is quite representative and contains definitions of MEF for the entire

spectrum of their orientation occurring in the studied volume of the medium, which includes faults

with the value of surface cohesion *s*  0 . In this case, to draw a line of minimum strength, you should choose a point on Mohr diagram that characterizes the stress state on the surface of one of

the chips, for which the length of the perpendicular drawn from the center of the circle will be

minimal (Fig. 5, point K). The stress values on the crack surface can be represented as

*i i* ~*i*

*i* ~*i*

 *nn*   *o*  *nn* ;  *n*   *n* , (17)

where ~*i*  ~*i*

and ~*i*

are the reduced stresses and

*n nt nn*

~*i i i i i*

σ*nj*  1   1*n*1 *j*  1    3*n* 3 *j*

 *nj* , j = n, t, (18)

in which *i*

*kn*

and *i*

are the guiding cosines, respectively, of the normal vector n to the cleavage

plane with a number *i* from a homogeneous sample and the action vector of the maximum shear stresses **t** on this plane in the coordinate system associated with the principal stress axes (k = 1, 2,

*kt*

3). Here and further, the superscript at stresses identifies a point on Mohr diagram.

The introduced definition of reduced stresses is very important, since it allows for homogeneous sets of MEF, without having data on the values of pressure and maximum shear stress, to construct Mohr diagrams characterizing the limit states on the surfaces of discontinuities.

***Calculation of the normalized values of the effective pressure and the maximum shear stress***

Using the formulae (14) and (17), it is possible to determine the ratio of the magnitude of the isotropic pressure to the modulus of the maximum shear stress. To this end, we assign the minimum possible value of surface cohesion to the fault with the minimum length of the perpendicular drawn

from the center of the circle (Fig. 5, point K), i.e.:

*p*  1 ~ *K*  *k* ~ *K*   / 3

\*

 *ks*

*n*

*s nn*



. (19)

For the point B, at which the line of maximum strength of rocks (the limit of internal friction)

touches the Mohr circle, the limit ratio (14), written for the maximum value of cohesion  *B*

*s*

  *f* , is

true . On its basis, using (17) and (19), we obtain:

 1 *p*\*

 ~ *K*  *k* ~ *K*  *k*  3

 ~ *K*

~ *K* 

 *n s*

*nn s* 

~ *K* ~ *K*

*s nn*

 *f* cos ec2 *B*   *n*

 *ks* *nn* ;  *f*

*ks* cos ec2 *B*   *n*

 *k*  

, (20)

1 1

where  *B*  arctan .

2 *ks*

\*

The formulae allow us to calculate the relative values of the effective pressure

*p* /  *f*

and

the maximum shear stress modulus

 /  *f*

based on the results of the first stage of calculation and

data on the values of the surface friction coefficient.

Next, we will use the selection with triangular brackets for the normalized values of the effective pressure and maximum shear stresses.

***Selection of the plane of the rupture in the earthquake source***

The necessary condition for using the formulas obtained above (18) is knowledge of the orientation of the plane of rupture. When reconstructing stresses from seismological data, two nodal planes (shown in the form of a double dipole for the mechanism source) represent two variants of the position of such a plane. Only for earthquakes whose focus has reached the surface, or for sufficiently strong earthquakes in the aftershock region where special seismological observations were made, there is data on the position of the plane of the discontinuity of the medium. We

propose a new criterion for selecting the realized plane.

We assume that the fault in the earthquake source corresponds to the nodal plane with the normal n, for which the relation is fulfilled

   *k*       *k*  

 0 , (21)

*n s nn*

*m s mm*

where   ,  

и   ,  

is the shear stress and effective normal stress for two nodal planes **n** and

*n nn*

*m mm*

**m**.

So, when we are to choose from two nodal planes of the MEF the one that will be the earthquake focus, we select the plane for which the Coulomb stresses are greater [15].

According to (19), nodal planes that have located points to the upper-left part of the total Mohr diagram are more preferable in the selection of the plane of rupture in the earthquake source. The criterion (21) works formally when nodal planes are close to the planes of action of maximum shear stresses, since the points of the nodal planes on the Mohr diagram are located near the vertical axis.

According to the criterion (21) the plane selected as a realized plane in the earthquake source will be the one that will correspond to the greater value of cohesion. As it is shown further, this means that the value of the stress drop for the selected plane will also be greater.

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