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INVESTIGATION OF DILATANCY IN BLOCK-STRUCTURED GEOLOGICAL MEDIUM ON THE BASE OF MOVABLE CELLULAR AUTOMATON METHOD

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Summary. The peculiarities of dilatancy processes in block-structured media that experience nonequiaxial compression under shear deformation are investigated using movable cellular automaton (MCA) method. For a characteristic of compression nonequiaxiality (also termed the degree of constraint) a dimensionless parameter – the lateral to normal pressure ratio in the deformation plane – used. The main objective of the work is to trace the sequence in which various dilatancy mechanisms are involved in deformation depending on the level of shear stress and degree of constraint. It is shown that in the block-structured medium an increase in the degree of constraint causes the dominating dilatation mechanism to change from slip of discontinuity surfaces to opening and expansion of pores. The dominating dilatancy mechanism changing because increasing the degree of constraint increases the threshold shear stress at which the slip is activated. Beginning with certain lateral pressures, the slip is impeded giving way to expansion of the pore space; however, the latter fails to provide so considerable volume change as the slip of contact surfaces does, and this decrease critical dilatation characteristics of the medium and, in particular, its dilatation coefficient and volume changing.

1 INTRODUCTION

It is well known fact that fragments of the Earth's crust are in complex stress-strain state. In particular, there are areas characterized as relatively high and low levels of stress, as well as various relations between the pressure and intensity of shear stresses. So, even on a sufficiently large depth, where pressure is high, the stress distribution is strongly nonuniform [1,2]. This heterogeneity is manifested at all scales and is associated with a block structure of rocks.

One of the most important characteristics of the stress-strain state of the rock massif is the constraint, which greatly affects the intensity and the sequence of involving the mechanisms of deformation and fracture regime of the medium [3-7]. So one of the most important directions of investigation of regularities of the mechanical response of rocks is to identify the role of constraint conditions.

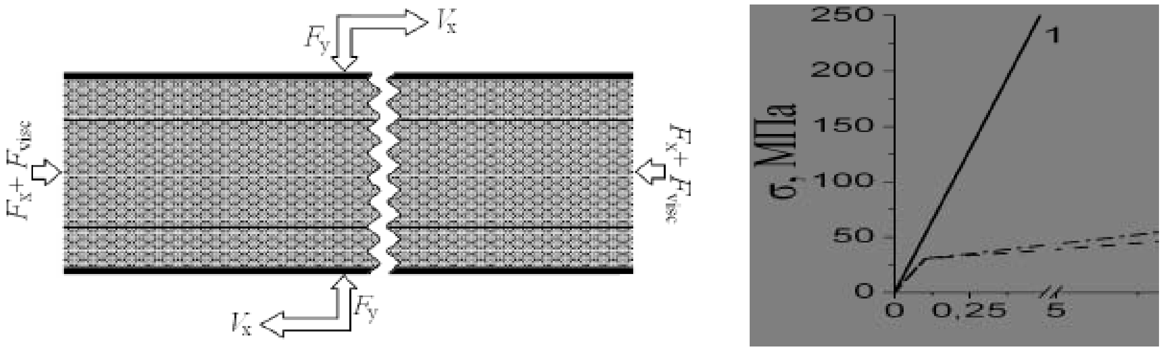
Specific areas of rocks, which include areas of active faults and cracks, along with a compression undergo a significant shear deformation. Moreover, due to nonuniform distribution of the stress state in a medium value of compression of the system in different directions may vary considerably. Thus, the deformation of the shear zones, both at considerable depths, and near the surface occurs in conditions of nonequiaxial compression. Therefore, the actual problem is to study the influence of the ratio of stresses acting on the shear zone in the normal and lateral with respect to its line direction (hereinafter such a parameter called the degree of constraint of the shear zone) on the main parameters of the mechanical response of the medium [8,9].

An important factor which determines the behavior of geomedium is the change of its volume during shear deformation (dilatancy) due to the repackaging of individual fragments, as well as the formation of new or closing of existing cracks. The result of dilatancy are changing the structure of the block geomedium her wave and mechanical properties [1]. Dilatancy plays a great role in the deformation processes taking in the crust and, in particular, for earthquakes. Since it is associated with the processes of softening and hardening of rocks, it contributes to the spread of fluids in the crust, etc. [1]. In this regard, important to analyze the effect of the degree of constraint of the shear zone at its dilatation characteristics. In this case, interest is not only the phenomenon of dilatancy, but also the dependence of the involvement of different dilatancy mechanisms on the level of shear stress and the extent of damage in the medium [10].

Carrying out of full scale studies of dilatancy processes in real natural systems is extremely complex, although the problem under consideration. Therefore, important information about the behavior of fragments of rocks could be obtained based on the physical and computer-aided simulation. Note that when conducting such studies on geological materials must take into account the main features associated with multiscale hierarchical organization of the block structure [2,9,11]. In particular, the interface between structural elements in geomedium possess lower compared with blocks of mechanical properties. Therefore, the main deformation processes in rock massifs localized at interblock interfaces. Consequently, taking into account of the block structure of the medium and related geomechanical processes, in particular, the formation of discontinuities and growth of cracks at the interfaces is a prerequisite for studying the behavior of rocks in different deformation conditions. This work is devoted to theoretical investigation of the influence of a block medium degree of constraint on the dilatancy effects during shear deformation. The study was based on computer-aided simulation by movable cellular automaton method (MCA) [12,13]. This method is a type of particle-based method and a number of years been successfully applied to study the characteristics of deformation and fracture of consolidated, granular and loosely coupled geological media.

2 PROBLEM STATEMENT OF COMPUTER EXPERIMENT

As was mentioned in the introduction, to construct models of block-structured geological media must take into account the hierarchical organization of their structure. In other words, on any considered scale level it is necessary to take into account the deformation processes at smaller scales [9]. Under such a formulation of the problem of special interest to study the general peculiarities of the mechanical response of a block medium with the so-called one-ranged structure, i.e. a medium consisting of structural elements of the same scale. Therefore, in this paper to study dilatancy process was carried out using a model system with blocks of the same size, separated by the interface region (boundaries) (fig. 1 a) [9,14]. In this case, as in [9], taking into account the higher (compared with the blocks) the extent of damage and porosity of the inter-block interfaces was carried out by setting them lower strength and deformation characteristics. Used a structural model of block medium was realized in the two-dimensional version of the method of movable cellular automata [9,12]. Calculation of stress-strain state was carried out in an approximation similar to the approximation of plane-strain state. The choice of this approach stems from the fact that it is most correctly reflects the stress-strain state of the medium at considerable depths.



a) b)

Figure. 1. a) structure and loading scheme of simulated specimen; b) reponse functions of automata of blocks (1), interfaces in inner part of specimen (2) and on surface layers (3). Wavy line in the figure (a) schematically indicated by a conventional line break.

In analogy with [9] for the automata modeling blocks, determined by linear response function, corresponding to high-strength materials deforms elastically (curve 1 in fig. 1 b). Response functions of the automata that simulate the interface areas were characterized by a long section, corresponding to the accumulation of irreversible deformation (curves 2 and 3 in fig. 1 b). This section of the curves simulates the effect of the processes of "destructive degradation" of the material interface (hereinafter called simply "degradation") [9]. Mechanical characteristics of blocks and interfaces (fig. 1 b) is qualitatively consistent with granite and brecciated rocks.

Higher degree of degradation of the structure and mechanical properties of the medium in the central part (core) of the shear zone took into account by assignment of low strength characteristics of inter-block interfaces in the central zone of the model sample (curve 2 in fig. 1 b) compared to the interfaces in the layers near upper and lower surfaces (curve 3 in fig. 1 b). In fig. 1 a central zone bounded by thin solid schematically by horizontal lines.

Presented model corresponds to the so-called "granular" representation of the concept of zones of active faults [15]. As noted in [9] using of this approach in conjunction with prescribed response functions of automata of blocks and interfaces allows to take into account deformation and fracture processes occurring in the medium at least on three spatial-structural levels, which can be roughly defined as micro- meso- and macroscale. This classification also applies to defects and damage in a simulated medium, which corresponds to the concept of structural levels of deformation and fracture of solids [16]. Thus, "microdamages" can be identified as damages whose typical size is considerably smaller than the width of the interface region (which in this case corresponds to the size of a cellular automaton). The presence/occurrence of such damage is implicitly taken into account by the response function. Under the "mezodamages" in this model are the damages whose size is equal to the width of the interface zone. The presence in the original structure of interfaces of such damages took into account the assignment of pairs of unlinked automata. The formation of new "mezodamages" in the process of deformation of the samples simulated by broken of interautomata bonds in accordance with criteria similar Mises criterion. "Macrodamages" can be defined as injuries that are larger than the size of the typical structural element (in this case - the block). It should be noted that due to significant differences in the strength characteristics of structural blocks and interfaces in this model destruction process was localized in the interfacial zones. This feature corresponds to the peculiarities of the destruction of a block-structured geological media at low strain rates and moderate pressures.

Ratio of linear dimensions of the simulated region (fig. 1 a) was $L/H=5$, where L - length (size in the horizontal direction), H - width of the sample (size in the vertical direction). The initial stress state of the sample was set by nonequiaxial compression with forces F_x and F_y (fig. 1 a). The value of F_y in all calculations was the same, and its specific value (σ_y) was 40% of the yield stress (σ_{yield}) of response function of the material of interfaces (curve 2 in *F*ig. 1b). Constrained sample was subjected to shear deformation with a small constant velocity V_x (fig. 1 a). To account for inertial and dissipative properties of the simulated environment of a fragment of a block medium in the lateral surface of the sample, in addition to compressive forces F_x, viscous forces $F_{\text{visc}}=-\alpha V_{\text{x}}$ were acting, where V_x - X component of the velocity of the respective automaton of lateral surface.

The degree of constraint (which determines the degree of nonequiaxialty of compression) of the specimen was characterized by the dimensionless parameter C_σ, which is defined as the ratio of the specific value compresses in the horizontal direction force F_x (denote it as σ_x) to the specific value of the vertical compressive force F_y (denote it as σ_y): $C_\sigma=\sigma_x/\sigma_{\text{y}}$ [9]. Parameter C_σ characterizes the relative magnitude of compression of system in the direction of the shear. In the paper value of C_σ ranged from 0 to 1.

3 RESULTS OF COMPUTER-AIDED SIMULATION

As noted in the introduction, an important characteristic of the response of fragments of block-structured geological media is a change in their geometric dimensions during the deformation process, which manifests itself in particular through the dilatancy. Dilatancy of the medium depends on several factors: stress state, physical and mechanical characteristics of structural elements, regime of deformation, etc. According to [10] dependence of dilatancy strain ΔV on the shear stress τ can be expressed by a power law:

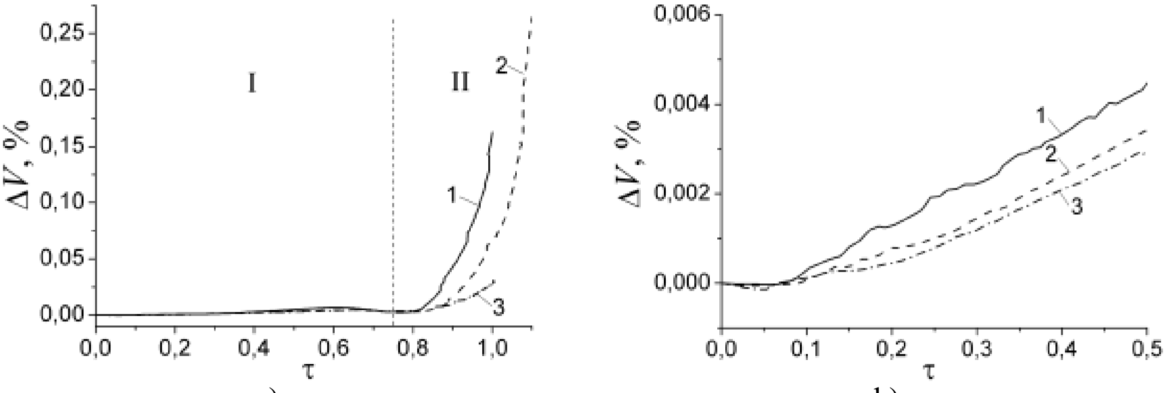
$$\Delta V \approx \delta \tau^n \tag{1}$$

where δ - coefficient of proportionality, n - exponent, directly determines the mechanism of dilatancy. In particular, when $n<1$ is realized dilatational mechanism associated with the rotation of individual conglomerate of particles relative to each other, their relative displacement, and repackaging (i.e., this mechanism is associated with grainy/blocky structure of the environment called sand dialtancy). For $n>1$ dilatancy develops as a result of lightweight slip on the surfaces of existing or forming new cracks and pores. Following the terminology adopted in this mechanism (so-called microcrack dilatancy) is associated with behavior mesodamages at the interfaces of structural elements. "Borderline" value of $n=1$ corresponds to the mechanism by which shear deformation leads to a relative displacement of individual fragments of the medium on the weak borders or large cracks (joint crack dilatancy).

Change of volume of the simulated specimen under shear loading ΔV is due to two main mechanisms: the accumulation of irreversible strains on the block boundaries and the evolution of "mesoscopic" discontinuities [9]. Elastoplastic deformation of the interfaces could lead to a change in their width, as well as localized shear of blocks (due to the mechanism of joint crack dilatancy). Used in the calculation model of the response of movable cellular automata suggests that their forming is not accompanied by an irreversible change of volume. Therefore, extension of the model shear zone is associated mainly with mesodamages and is determined by action of two factors (hereinafter also called mechanisms): disclosure of discontinuities (increasing the "porosity") and lightweight slip along surface of damages on the block interfaces. Thus, using the developed model in our simulations make it possible to analyze the dilatancy effects associated with the block structure of the medium.

Figure 2 shows a graph of changes of the volume of the model system ΔV from the level of shear stress τ. The value of ΔV is defined as the relative change of volume of the specimen: $\Delta V=(V-V_0)/V_0$, where V_0 - volume of the simulated specimen at the beginning of shear deformation, V - the current value of the sample. Shear stress τ in figure 2 (defined as the specific resistance force to shear deformation of the modeled system) is given in dimensionless form, obtained by normalization of its absolute value on the shear strength of "not constrained in the horizontal direction specimen (at $C_\sigma=0$) The analysis of the $\Delta V(\tau)$ curves, corresponding to different degrees of constraint of the specimen (different values σ_x), showed that they have a two-stage character (fig. 2). The selected stages are largely associated with the major stages of the force response of the model system (quasyelastic (I) and quasiplastic (II) stages of the diagram of the shear loading in fig. 3). It should be noted that in figure 3, the shear deformation (shear angle γ) was defined as $\gamma=d_x/H$, where d_x - the relative displacement of the upper and lower surfaces of the sample in the horizontal direction (fig. 1 a), H - height of the specimen.

Comparison of figures 2 and 3 shows that at the stage of quasielastic response of the shear zone ($\tau<0{,}75$, stage I in fig. 3) curves $\Delta V(\tau)$ have almost a linear form (stage I in fig. 2 a). With further increase of shear stress τ, in the transition region to quasiplsatic response, character of the changes of ΔV became nonlinear (phase II in fig. 2 a). These peculiarities of system behavior reflect the sequential involvement of different strain (and dilatancy) mechanisms. At a low level of the shear stress evolution of constrained medium occurs mainly by means of the relative movement of block conglomerates on some weak interfaces. This is accompanied by a small (about 0,003 - 0,004%) linear increase of the volume of the specimen (fig. 2 b). The small deviations of the character of the dependences at this stage from linear form, are apparently associated with partial repackaging of fragments of the medium. Thus, at the initial stage of loading localized shear of blocks is dominant dilatancy mechanism (which corresponds to (1) with parameter *n* close to unity). The involvement of this mechanism at the early stages of deformation (in the region of the quasielastic response of the medium) is due to the fact that the sample is preloaded and the stress state of a number of inter-block interfaces is close to the yield stress to the moment of application of shear loading. Further increase of the level of shear stress (moving to the area of quasiplastic response for τ>0,75 ÷ 0,8, fig. 3) leads to an increase of the volume fraction of interfaces, whose stress state exceeds the elastic limit and, consequently, to intensifying of the process of localization of irreversible deformations in the most stressed parts of interfaces. As a result, the sample begin to accumulate mesodamages, which become an additional source of dilatancy, whose contribution increases with their number *N* (resulting in a ratio (1) the parameter *n* is greater than one). Thus, in the area of transition from quasielastic to quasiplastic response of the simulated block medium there is a change of the dominant dilatational mechanism from localized shear to the mechanism of evolution mesodamages. Figure 2 a also shows that the main contribution to the total volume changing makes mesodamages as deformation mechanisms of a relatively high scale level. This relates in particular to the fact that the quasielastic stage of shear loading irreversible deformation can accumulate on a relatively small number of interfaces. Consequently, the contribution from the mechanism associated with localized shear of blocks along the weak boundaries in the first stage of deformation to the total dilatancy is negligible.



a) b)

Figure 2. Graphs of dependences of relative changing of the volume of the specimen ΔV on shear stress level τ: 1 – C_σ =0; 2 – C_σ =0,5; 3 – C_σ =1. In figure (a) is shown extended range of shear stresses $\tau \in [0\ ,\ 1]$, in the figure (b) initial interval $\tau \in [0\ ,\ 0{,}5]$ Curves 1-3 in figure (a) are shown up to the moment of achievement of ultimate state of the system (maximum value of shear resistance force).

As can be seen from figure 2 a the change of volume to the moment of reaching of the ultimate state of shear zone (this characteristic is denoted as ΔV_c) is determined by the degree of constraint (by the parameter C_σ). Thus in Figure 4 a shows a dependence of ΔV_c on the degree of constraint. It is seen that the curve $\Delta V_c(C_\sigma)$ has a pronounced nonlinear threshold chracter. Thus, in the interval $0<C_\sigma<0.4$ ultimate magnitude of change of volume increases (with a maximum at 0.4). Further, with increasing of degree of constraint (C_σ>0.4) parameter ΔV_c begins to decrease monotonically.

In mathematical models of geomedia dilatancy characterized by a number of characteristics, the most common of which is the coefficient of dilatancy λ. In general, it is determined by the ratio of the rate of irreversible change of volume of the medium to the intensity of plastic deformation. By analogy with this parameter in the paper was introduced the "ultimate coefficient of dilatancy" λ^c, which was calculated by the ratio of the ultimate volume change ΔV^c to the angle of shear at the time of achieving of the maximum shear resistance force γ^c ($\lambda^c = \Delta V^c / \gamma^c$). As shown in figure 4 b the dependence of $\lambda^c(C_\sigma)$ is similar to the dependence $\Delta V^c(C_\sigma)$, with a peak at $C_\sigma \approx 0.4$. Note that the parameter λ^c can be interpreted as some effective rate of change in volume of the shear zone at a constant strain rate.

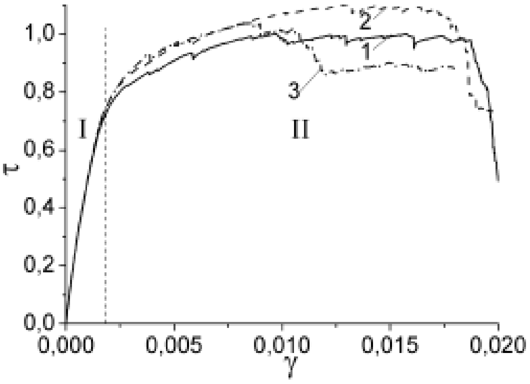
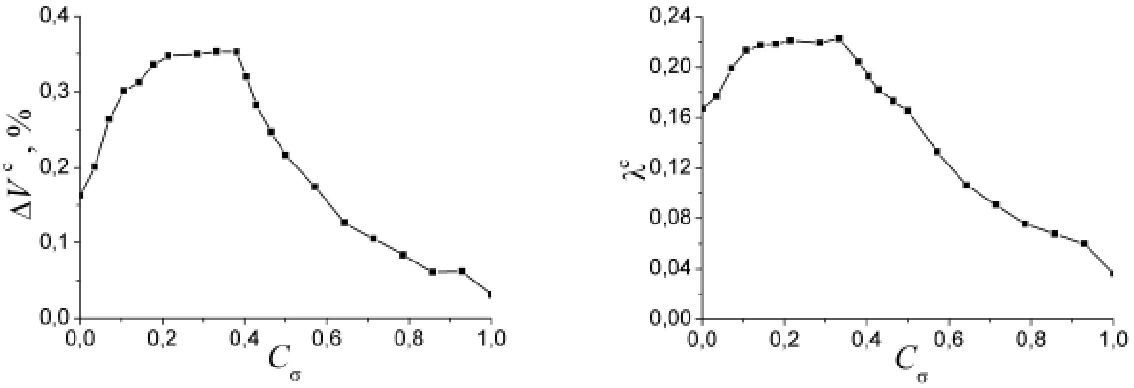


Figure 3. Graphs of dependences of shear resistance force of simulated system (τ) on value of shear strain (γ): 1 – C_σ=0; 2 – C_σ=0,5; 3 – C_σ=1. Roman numerals I and II denotes quasielastic and quasiplastic stages of loading diagrams.



a) b)

Figure 4. Graphs of dependences of relative changing of volume of the specimen ΔV^c (a) and dilatancy coefficient λ^c (b) to the moment of reaching of ultimate state of the system on parameter C_σ.

As was noted above, the main contribution to the change of the volume of the modeled system make the mechanism of dilatancy associated with evolution of existing and newly formed mesodamages at the interfaces of structural elements. Its effect on increasing of volume is due to the influence of two basic mechanisms described above (increases porosity and sliding of contact surfaces mesodamages). In the initial stress state the samples which are characterized by different values of C_σ, the amount of damages is almost identical, so the dependence of $\Delta V^c(C_\sigma)$ is determined mainly by the number and evolution of mesodamages formed during specimen deformation. Figure 5 shows a graph of the number of mesodamages N^c to the moment of achieving of the ultimate state of the specimen on the degree of constraint. It is seen that in the region $0<C_\sigma<0.4$ the value of N^c increases and then saturates. Consequently, the increase of volume of the model shear zone at small values of C_σ ($C_\sigma<0.4$) is associated with an increase of the number of mesodamages. At the same time, when $C_\sigma>0.4$, where the amount of accumulated damage, at least, not decreasing, dilatational characteristics ΔV^c and λ^c undergo reduction up to 5-7 times.

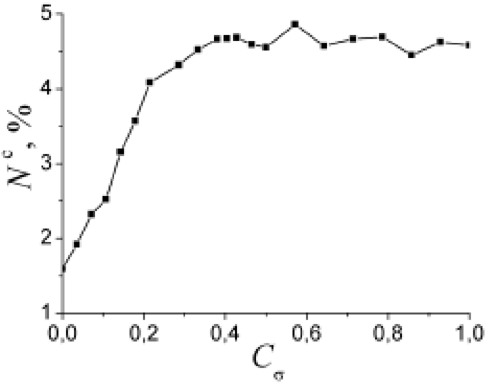
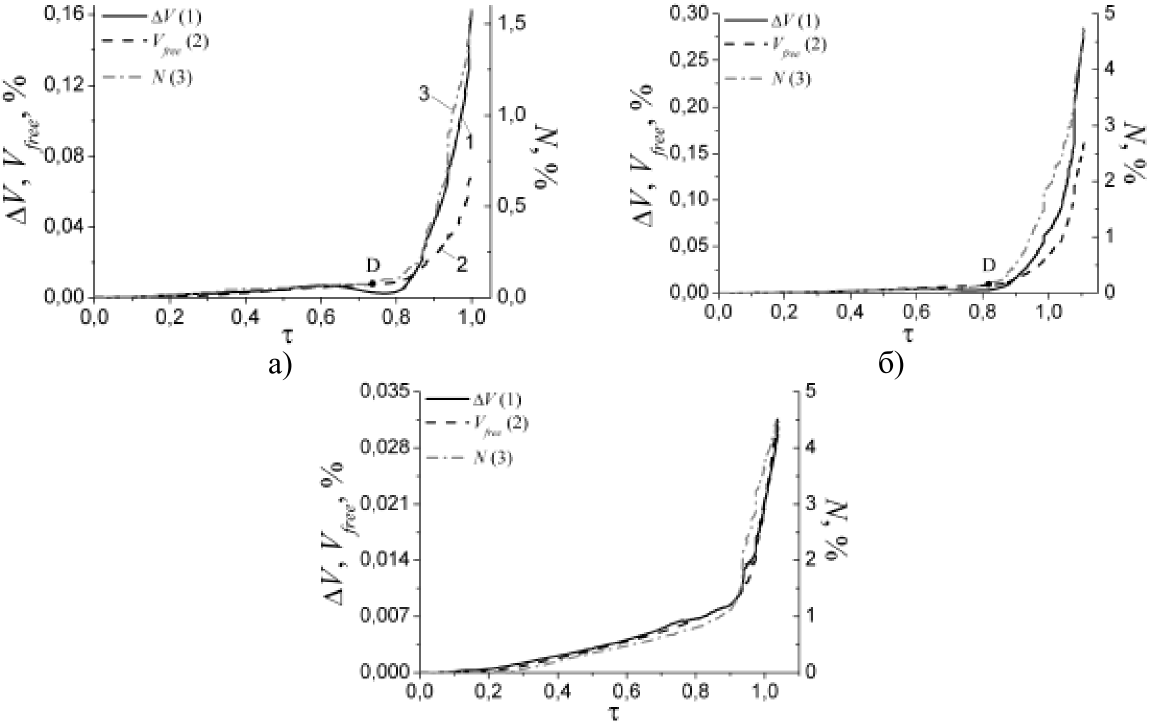


Figure 5. Graph of dependence of value of accumulated mesodamages N^c to the moment of achieving of ultimate state of the specimen on the parameter C_σ.

As shown by detailed studies, the effect of a significant decrease of dilatancy at $C_\sigma>0.4$ is associated with a change of the contributions of the elementary mechanisms of evolution of mesodamages. This can be illustrated by the graphs in figure 6, which shows the dependence of the total volume changes ΔV (curve 1), free volume V_{free} (curve 2) and the amount of accumulated mesodamages at block boundaries N (curve 3) on the shear stress level of the modeled system τ. In the calculations, the value of free volume V_{free} estimated through the volume of voids (pores). Based on the analysis of dependencies following conclusions could be made. Thus, the increase of the number of generated mesodamages accompanied by an increase of free volume value V_{free}. At relatively low values of τ increase of the specimen volume (ΔV) is achieved by the disclosure of damage (increase V_{free}), as evidenced by the coincidence of curves 1 and 2 in fig. 6. However, from a certain point (point D in fig. 6 a-b), curve 2 begins to fall behind the curve 1, and to the moment of reaching the ultimate state values ΔV and V_{free} may differ by several times. This means that at high shear stresses close to the shear strength of the medium, the main contribution to dilatancy makes slip along the surfaces of formed mesodamages. Formally, the threshold stress at which changing of the dominant mechanism of dilatancy takes place could be characterized as a stress of activation of mechanism of the shear slip. The difference between the total volume changing and the maximum free volume V_{dev} determines the contribution to the dilatancy of slippage. As can be seen from fig. 6 a-b, with increasing of degree of constraint there is a shift of D point toward larger values of shear stress, and the value of V_{dev} decreases. In the extreme case (for large values of C_σ) all the curves behave in consistently, and the values ΔV^c and V^c_{free} are the same (fig. 6 c). Thus, with increasing degree of constraint contribution of the mechanism of shear-slip along the surfaces of mesodamages decreases and at $C_\sigma \rightarrow 1$ becomes negligible. In these circumstances, the decisive role plays the increasing of the porosity of the medium.

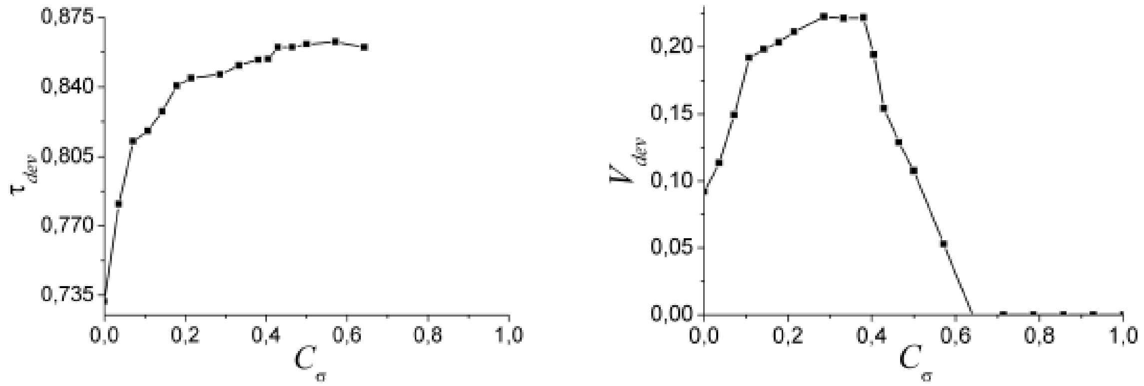


а) б) в)

Figure 6. Graphs of dependences of volume changing (ΔV), free volume (V_{free}) and number of mesodamages (N) on value of shear stress τ: а) – C_σ =0; б) – C_σ =0.4; в) – C_σ =1.

Figure 7 shows the dependence of the specific force of resistance shear deformation at the time of activation of the shear slip τ_{dev} and the magnitude of the difference between the ultimate values of the total change of the volume and free volume (V_{dev}) on the parameter C_σ. As seen from fig. 7 a, with increasing of degree of constraint threshold of activation of the mechanism of slipping shifted to higher values of shear stresses and reaching saturation at C_σ~0,4. The relative contribution of the slippage (defined, for example, in terms of the V_{dev}) grows and at C_σ~0.4 reaches a maximum (fig. 7 b). Note that in this range of C_σ observed increase of the total volume changing ΔV^c (fig. 4 a). Further, with increasing of parameter C_σ (C_σ >0.4) dependence $V_{dev}(C_\sigma)$ decreases sharply and at $C_\sigma \approx 0,65$ falls to zero. Thus, if $C_\sigma > 0.4$ the contribution of the slippage to the dilatancy of a block medium is reduced, and at high degrees of constraint change of volume of the simulated system is provided, mainly due to the disclosure of existing and newly formed mesodamages. This leads to decrease of dilatancy of the medium (fig. 4).

Thus, the increase of the magnitude of the dilatancy ΔV^c and the coefficient of dilatancy λ^c at low degrees of constraint (C_σ <0,4) is provided firstly by the increasing role of slip along the surfaces of mesodamages. With increasing of shear stress level realization of this mechanism becomes more and more difficult, and the primary role begins to play the expansion of damages and pores.



a) b)

Figure 7. Graphs of dependences of the specific force of resistance to shear deformation at the time of activation of the shear slip (a) and the value of the difference between the ultimate values of the total change of the volume and free volume (b) on the parameter C_σ.

4 CONCLUSIONS

The results of computer simulation of the shear deformation of the block-structured model specimens of the geological media in conditions of nonequiaxial compression showed that the main source of dilatancy of the medium is process of evolution of mesodamages originally existed, and the newly generated at the interfaces between structural elements. The change of volume of a block medium under shear loading is determined by the action of two elementary dilatancy mechanisms: the opening of discontinuities/pores and sliding along surfaces of mesodamages.

Analysis of the obtained results showed that the main dilatancy characteristics of the medium, in particular, the changing of volume at the time of reaching the ultimate state of the system and the corresponding coefficient of dilatancy, largely depend on the ratio of lateral and normal pressures acting on a fragment of the shear zone. At the same time dependence of these parameters on the degree of constraint have a pronounced nonlinear threshold character. This is due to the fact that with increasing of degree of constraint a changing of the dominant dilatational mechanism takes place.

Thus, with increasing of parameter C_σ from zero to a certain threshold value (in this case $C_\sigma \approx 0.4$), the contribution to dilatancy of the mechanism associated with the sliding along surfaces of the initial and formed mesodamages increases. This is accompanied by a significant (up to 2 times) increase of the values of the fundamental dilatancy parameters. Slip along surfaces of mesodamages is a deformation mechanism with a relatively high threshold stress of activation, and this threshold value significantly increases with increasing of C_σ (fig. 7). Because if $C_\sigma > 0.4$ a reduction of the shear strength of the medium [9] takes place, dilatational mechanism of slippage is involved in all the later stages of loading (this effect is obviously connected with the difficulty of the local shift in conditions of strong lateral compression). In this regard, contribution of this mechanism to the change of volume of the medium reduces and at the main dilatancy mechanism becomes the mechanism associated with the extension (opening) of discontinuities, which is characterized by a lower threshold of activation. However, the expansion of pores has not been providing such a large volume changing of geomedium, so that there is a dependencies $\Delta V^c(C_\sigma)$ and $\lambda^c(C_\sigma)$ decrease (fig. 4).

So, in the pursuit of stress state of the block-structured heterogeneous medium to the condition of equiaxial compression hampered the involvement of dilatational deformation mechanisms and high scale levels (mechanisms with a high threshold of activation), which ultimately leads to a decrease of basic dilatational characteristics of the medium.

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