Effect of compression nonequiaxiality on shear-induced dilatation in a block-structured medium

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

Keywords: block-structured medium, nonequiaxial compression, shear deformation, dilatation, dilatation mechanisms

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1. Introduction

Fragments of the Earth crust are known to experience various and, as a rule, complex stress-strain states. In particular, they differ in stress level, which can be rather high or low, and in pressure to tangential stress intensity ratio. Moreover, the stress distribution nonuniformity is considerable even at a sufficiently large depth where pressure is high [1, 2]. This stress nonuniformity shows up on all scales and owes to the block structure of rock massifs.

One of the major characteristics of the stress-strain state of a rock massif is its constraint, which strongly affects the rate and sequence of the processes involved in deformation and fracture of the medium [3–7]. Therefore, one of the main lines of research in the mechanical response of rocks is to ascertain the role of constrained conditions for which, in particular, much use is made of axial compression tests of specimens under lateral pressure [5, 7–10].

Individual regions of rock massifs, to which zones of active faults and powerful fractures are referred, experience considerable shear strains along with compressive strains. The compression of the medium can differ greatly in different directions due to nonuniform stress distribution in the system. Thus, deformation in shear zones both deep in the system and near the day surface proceeds under nonequiaxial compression. In this context, an urgent problem is to study the influence of the normal to lateral pressure (stress) ratio in a shear zone (we term it the degree of constraint of a shear zone) on the main mechanical response parameters of the medium [11, 12].

An important factor responsible for the behavior of a geological medium is its shear-induced dilatation or volume change (dilatancy) due to repacking of individual fragments and formation of new or closure of existing cracks. Dilatancy causes a change in the structure of a block-structured geological medium and in its wave and mechanical properties [3] and plays a peculiar role in deformation processes occurring in the Earth crust, in particular, in earthquakes. Dilatancy has associated with it softening and hardening of rocks, assists the propagation of fluids in the Earth crust,

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etc. [3, 13]. In this context, it would appear important to analyze in what way the degree of constraint of a shear zone affects its dilatation characteristics. Of interest here is not only dilatancy as such but also involvement of various dilatation mechanisms in deformation of a geological medium depending on the shear stress level and damage degree [14].

Full-scale investigation of dilatation processes in actual natural systems is an extremely hard, though solvable, problem. At the same time, important information on the behavior of fragments of rock massifs can be gained in physical [15–17] and computer simulation [6, 18]. Notice that in similar studies of geological materials, one should allow for basic peculiarities associated with hierarchical multiscale organization of their block structure [4, 12, 19]. In particular, interfaces of structural elements (blocks) in a geological medium display lower strength characteristics compared to those of blocks [1, 12, 20], and therefore main deformation processes in rock massifs are localized at block interfaces [1, 4, 12, 21]. Consequently, account of the block structure and its associated geomechanical processes, in particular nucleation of discontinuities and growth of cracks at interfaces of structural elements, is a necessary requirement in studying the behavioral peculiarities of rock massifs under various deformation conditions. The present paper is a theoretical study of the degree of constraint of a block-structured medium in relation to its dilatation under shear deformation. The study was performed by the movable cellular automaton method [22, 23], which is a variant of the particle method and is applied to advantage in studies of deformation and fracture of consolidated, loose and weakly bound geological media [5, 12, 21–24].

2. Problem statement for computer simulation

As noted in the introduction, models of block-structured geological media require account of hierarchical organization of their structure. In other words, deformation on any scale should be considered with regard to processes on lower scales [12]. In this problem statement, of particular interest is to study general mechanisms of mechanical response of a block-structured medium with the so-called "peer" structure, i.e., a block-structured medium consisting of structural elements of one scale. For this purpose, we studied dilatation processes on a model system containing blocks of the same size with interfaces in-between (Fig. 1(*a*)) [12, 25, 26]. Like in [12], the higher damage degree and porosity of the block interfaces compared to the blocks was allowed for by assigning them decreased strength and strain characteristics. The structural model of a block-structured medium was realized in the two-dimensional version of the movable cellular automaton method [12, 25]. The stress-strain state of the medium was calculated in an approximation similar to the plane strain approximation. This approximation was chosen because it most correctly reflects the stress-strain state of a medium at high depths.

By analogy with [12], the automata that model blocks were assigned a linear response function to suit an elastically deformed high-strength material (Fig. 1(*b*), curve *1*). The response functions of the automata that model interface regions were characterized by a long portion to meet irreversible strain accumulation (Fig. 1(*b*), curves *2* and *3*). This portion of the curves simulated the effect "destructive degradation" of the interface material (in what follows we term it simply degradation) [12]. The mechanical characteristics of the blocks and interface regions (Fig. 1(*b*)) qualitatively matched granite and breccia [27, 28].

The higher degree of degradation of the structure and mechanical properties of the medium in the central part of the shear zone [29, 30] was taken into account by specifying decreased strength characteristics of block interfaces in the central region of the model specimen (Fig. 1(*b*), curve *2*) compared to those of interfaces in layers near the upper and lower surfaces (Fig. 1(*b*), curve *3*). In Fig. 1(*a*), the central zone is schematically bounded by thin horizontal solid lines.

The described model fits in the so-called "granular" concept of active fault zones [30]. As pointed out in [12], this approach in combination with similar response functions of block and interface automata makes it possible to consider deformation and fracture in a model medium on at least three characteristic spatial-structural scales which can conventionally be defined as micro-, meso- and macroscales.

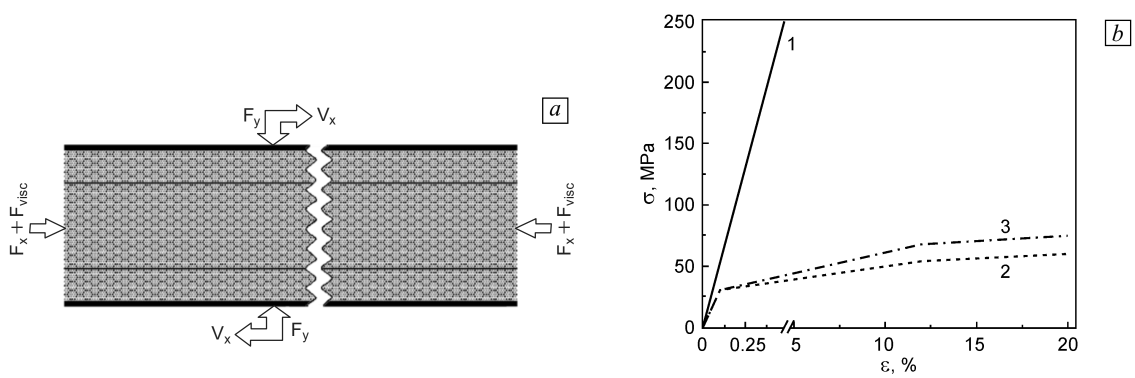

Fig. 1. Structure of the model specimen and loading pattern (*a*); response functions (*b*) of automata of blocks (*1*), interblock boundaries in the internal specimen region (*2*) and in near-surface layers (*3*). The wavy line in (*a*) is a conventional line of discontinuity

The above classification covers defects and damages in a model medium, and this fits in the concept of structural levels of deformation and fracture of solids [31]. So, microdamages can be identified as damages whose characteristic size is much smaller than the width of an interface region (which, in our case, corresponds to the size of a cellular automaton); the presence and nucleation of microdamages is implicitly taken into account by a response function. Mesodamages in the considered model are understood as damages whose size is commensurable with the width of an interface region. The presence of interfaces of mesodamages in the initial structure was taken into account by specifying unlinked pairs of automata. The formation of new mesodamages under deformation was modeled by interautomata link rupture according to a criterion similar to the Mises criterion. Macrodamages can be defined as damages of size larger than the size of a characteristic structural element (block). It is worthy of note that due to the considerable difference in the strength characteristics of structural blocks and interfaces in the model medium, fracture was localized in interface regions. This peculiarity fits in the fracture mechanisms of block geological media at small strain rates and moderate pressures.

The ratio of the linear dimensions of the model region (Fig. 1(*a*)) in the calculations was $L/H = 5$, where L is the specimen length (horizontal dimension) and H is the specimen width (vertical dimension). The initial stress state of the specimen was specified by nonequiaxial compression with forces F_x and F_y (Fig. 1(*a*)). The force F_y in all calculations was the same and its specific value σ_y was 40 % of the yield strength σ_{yield} of the response function of interblock boundaries (Fig. 1(*b*), curve *2*). The constrained specimen was subjected to shear deformation with a low constant rate V_x (Fig. 1(*a*)). Inertial and dissipative properties of the surroundings of the model block-structured medium fragment were taken into account by specifying, in addition to the compressive forces F_x, viscous forces on the lateral surfaces: $F_{\text{visc}} = -\alpha V_x$, where V_x is the X component of the velocity of an appropriate automaton of the lateral surface.

The degree of constraint (responsible for the degree of compression nonequiaxiality) of the specimen was characterized by a dimensionless parameter C_σ, which is defined as a ratio of the specific value of the horizontal force F_x (denoted as σ_x) to the specific value of the vertical compressive force F_y (denoted as σ_y): $C_\sigma = \sigma_x/\sigma_y$ [12]. The parameter C_σ characterizes the relative compression of the system in the shear direction. In the calculations, the parameter C_σ was varied from 0 to 1, i.e., in the limiting case, the horizontal stress σ_x is equal to the normal working stress σ_y.

3. Results of computer simulation

As noted in the introduction, an important response characteristic of fragments of block geological media is the change of their geometric dimensions under loading, showing up, in particular, through dilatancy. The dilatancy of a medium depends on many factors: stress state, physical and mechanical characteristics of structural elements, deformation mode, etc. According to [14], the dependence of dilatation strain (dilatancy-induced volumetric strain of a medium) ΔV on the shear stress τ can be expressed by the power law:

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

where δ is the proportionality factor, n is the power exponent which directly determines the operating dilatation mechanism. In particular, at $n < 1$ the operating dilatation mechanism is associated with rotation of individual particle conglomerates relative to each other, their relative displacement and repacking (i.e., the mechanism is associated with the granular or block structure of a medium and is termed in the foreign literature as sand dilatancy). At $n > 1$, dilatancy develops as a result of easy slip along the surfaces of existing or arising cracks or pores. This mechanism (microcrack dilatancy, according to the terminology accepted in [14]) is associated with the behavior of mesodamages at interfaces of structural elements. The boundary value $n = 1$ corresponds to the mechanism through which shear deformation causes relative displacement of individual fragments of the medium along weakened boundaries or large cracks (joint crack dilatancy).

The shear-induced volume change ΔV in the model specimen is governed by two main mechanisms: irreversible strain accumulation at interblock interfaces and evolution of mesoscale discontinuities (mesodamages and growing cracks) [12]. Elastoplastic deformation of interblock interfaces can lead to a change in their width (“crumpling” or expansion) and to localized shear of blocks (by the mechanism of joint crack dilatancy). The response model of movable cellular automata used in the calculations assumes that their form change does not involve irreversible volume changes. Therefore, expansion of the model shear zone is mainly due to mesodamages and is governed by the following two factors (below we term them mechanisms as well): opening of discontinuities (increase in porosity) and easy slip of damage surfaces at interblock boundaries. It should be emphasized that slip is understood hereinafter not as consolidated shear of one structural element relative to another but as local shear of mesodamage surfaces, i.e., unlinked contacting automata. Moreover, despite the relative smallness of these local shear strains, they can much contribute to overall dilatancy with increasing the damage degree of a medium. Thus, the developed model provides a possibility to analyze dilatancy effects associated with the block structure of the medium.

Figure 2 shows the volume change ΔV of the model system in relation to the working shear stress τ. The quantity ΔV was determined as a relative volume change of the specimen: $\Delta V = (V - V_0)/V_0$, where V_0 is the volume of the model specimen at the onset of shear deformation; V is the current volume of the specimen. The shear stress τ in Fig. 2

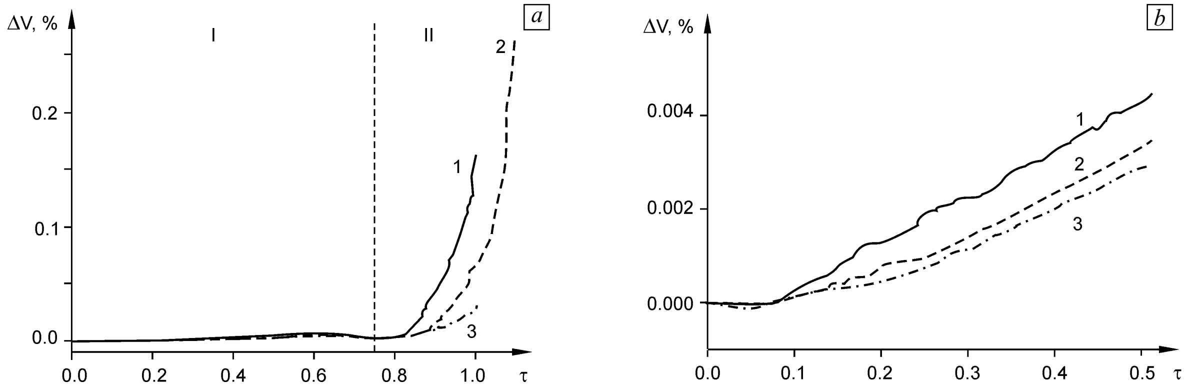

Fig. 2. Dependence of the relative volume change ΔV on the specific shear resistance force τ of the model specimen: $C_\sigma = 0$ (*1*), 0.5 (*2*), 1 (*3*). Curves *1–3* in (*a*) correspond to the time before the instant the system reaches its limiting state (maximum shear resistance force). Roman numerals I and II stand respectively for quasi-elastic and quasi-plastic stages of the stress-strain diagram

(defined as the specific shear resistance force of the model system) is represented in the dimensionless form obtained by normalizing its absolute value to the shear strength of the specimen free of horizontal constraint (at $C_\sigma = 0$). Analysis of the dependences $\Delta V(\tau)$ for different degrees of constraint of the specimen (for different σ_x), demonstrates their two-phase character (Fig. 2). The distinguished stages are largely associated with main stages of the force response of the model system (quasi-elastic I and quasi-plastic II portions of the shear strain diagram in Fig. 3). Notice that in Fig. 3 the shear strain (the displacement angle γ) was defined as $\gamma = d_x/H$, where d_x is the relative horizontal displacement of the upper and lower surfaces of the specimen; H is the specimen height.

Comparison of Figs. 2 and 3 suggests that at the stage of quasi-elastic response of the shear zone ($\tau < 0.75$, stage I in Fig. 3), the curves $\Delta V(\tau)$ are almost linear (stage I in Fig. 2). As the shear stress τ is further increased, the variation in ΔV in the transition region to quasi-plastic response becomes markedly nonlinear (stage II in Fig. 2(*a*)). These behavioral peculiarities of the system reflect successive involvement of various deformation (and dilatation) mechanisms. At a low shear stress level, the constrained medium evolves primarily through relative motion of block conglomerates along certain weakened interfaces. This is accompanied by a small (about 0.003–0.004 %) linear increase in specimen volume (Fig. 2(*b*)). The small deviations of the presented dependences from linearity at this stage are presumably related to partial repacking of fragments of the medium. Thus, early in the loading, localized shear of blocks dominates (which corresponds to relation (1) with n close to unity). The involvement of this mechanism even at early stages of deformation (in the range of quasi-elastic response of the medium) is due to the fact that the specimen is preliminary loaded and the state of certain block interfaces approximates the yield strength by the time the shear force is applied. Further increasing the shear stress level (transition to quasi-plastic flow at $\tau > 0.75$–0.8, Fig. 3) increases the volume fraction of interfaces whose stress state goes above the yield strength and, hence, the rate of irreversible strain localization on most stressed sites of interblock boundaries. As a result, the specimen starts accumulating mesodamages which become an additional dilatancy source whose contribution increases with an increase in their number N (causing the parameter n in (1) to become higher than unity). Thus, in the quasi-elastic to quasi-plastic response transition of the model block-structured medium ($\tau \sim 0.75$–0.80), the dominating dilatation mechanism changes from localized shear to evolution of mesodamages. It is also seen from Fig. 2(*a*) that the major contribution to the overall volume change of the model system is just the one made by mesodamages as strain mechanisms of rather high scale. This owes, in particular, to the fact that at the quasi-elastic stage of shear deformation, irreversible strains can be accumulated within a rather small number of interfaces. Hence, the contribution of the mechanism associated with localized shear of blocks along weakened boundaries to overall dilatancy at the first deformation stage is insignificant.

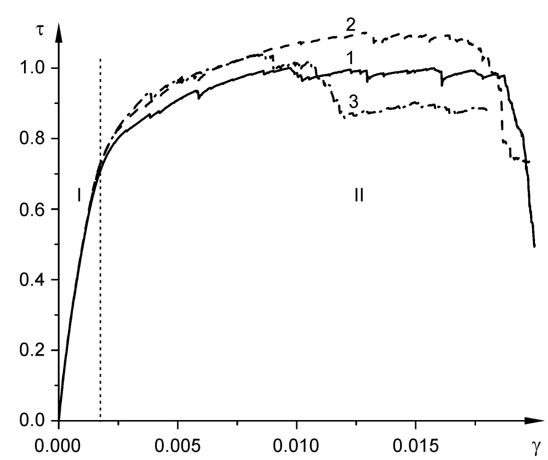

Fig. 3. Dependence of the specific shear resistance force τ on the shear strain γ of the model system: $C_\sigma = 0$ (*1*), 0.5 (*2*), 1 (*3*)

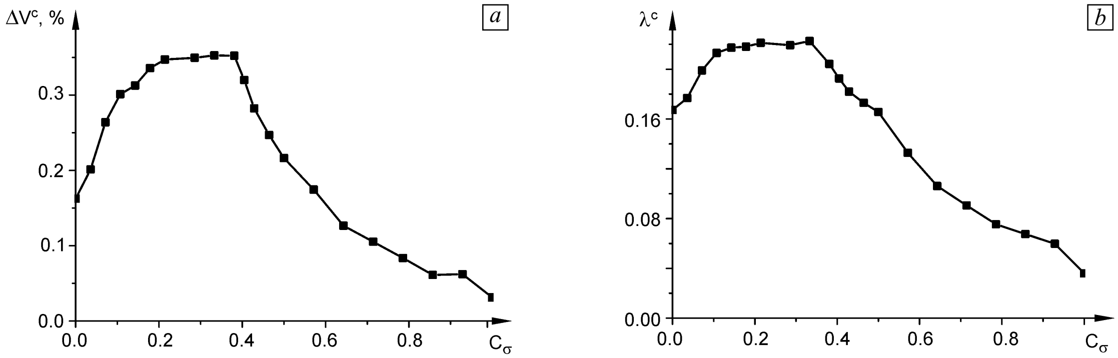

Fig. 4. Dependence of the relative volume change ΔV^c and dilatancy factor λ^c on the degree of constraint (parameter C_σ) by the instant the limiting state is reached (maximum shear resistance force)

As can be seen from Fig. 2(*a*), the volume change by the time the shear zone reaches the limiting state (this characteristic is denoted as ΔV^c) is determined by the degree of constraint (parameter C_σ). The dependence $\Delta V^c(C_\sigma)$ has a clearly defined nonlinear threshold character (Fig. 4(*a*)). On the interval $0 < C_\sigma < 0.4$, the volume change ΔV^c increases (with a maximum at 0.4). Next, as the degree of constraint increases ($C_\sigma > 0.4$), the parameter ΔV^c starts decreasing monotonically.

In mathematical models of geological media, dilatancy is described by a series of characteristics, the most widespread among which is the dilatancy factor λ. In the general case, the dilatancy factor is determined from the ratio of the rate of irreversible volume change to the plastic strain rate intensity of a medium [32–34]. By analogy with this parameter, we introduced a limiting dilatancy factor λ^c, which was calculated from the ratio of the volume change ΔV^c to the corresponding displacement angle at the instant the maximum shear resistance force is reached γ^c ($\lambda^c = \Delta V^c / \gamma^c$). The dependence $\lambda^c(C_\sigma)$ is similar to the dependence $\Delta V^c(C_\sigma)$, and has a maximum at $C_\sigma \approx 0.4$. Notice that the parameter λ^c can be interpreted as a certain effective rate of volume change of the shear region at a constant strain rate.

As already noted, the major contribution to the volume change in the model system is by dilatation associated with evolution of existing and newly formed mesodamages at interfaces of structural elements. Its effect on the increase in volume owes to two elementary mechanisms described above (increase in porosity and slip along contacting surfaces of mesodamages). In the initial stress-strain state characterized by varying C_σ, the amount of damages in the specimens is nearly the same; therefore, the dependence $\Delta V^c(C_\sigma)$ is determined mainly by the amount and peculiarities of mesodamages formed in the specimen in shear. Figure 5 shows the dependence of the number of mesodamages N^c accumulated by the instant the specimen reaches its limiting state on the degree of constraint. It is seen from the figure that in the range $0 < C_\sigma < 0.4$, the quantity N^c increases and further comes to saturation. Hence, the increase in the volume of the model shear zone at low values of C_σ ($C_\sigma < 0.4$) owes to the overall increase in the amount of mesodamages (main dilatancy carriers) at interblock boundaries. At the same time, in the range $C_\sigma >$ > 0.4 in which the number of accumulated damages fails at least to decrease, the dilatation characteristics ΔV^c and λ^c decrease five to seven-fold.

Detailed examinations demonstrate that the effect of considerable reduction of dilatancy at $C_\sigma > 0.4$ is associated with a change of contributions of elementary evolution mechanisms of mesodamages. This can be illustrated by Fig. 6 which shows dependences of the total volume change ΔV (curve *1*), free volume V_{free} (curve *2*), and number of accumulated mesodamages at interblock boundaries N (curve 3) on the specific shear resistance force τ of the model system. In these calculations, the free volume V_{free} was estimated from the volume of voids (pores) between by unlinked and non-interacting cellular automata. Analysis of the presented dependences allows the following conclusions on the contribution to dilatancy by each of the elementary mechanisms associated with evolution of arising mesodamages. The increase in the amount of mesodamages involves an increase in free volume V_{free}. At rather low

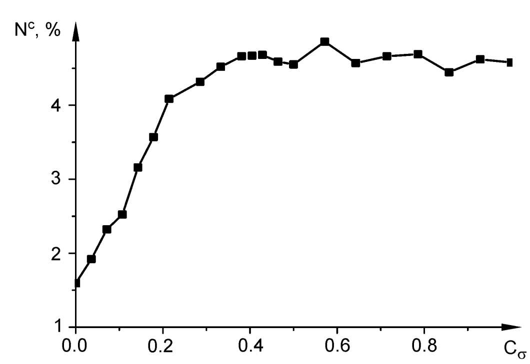

Fig. 5. Dependence of the amount of accumulated mesodamages N^c on the degree of constraint (parameter C_σ) by the instant the limiting state is reached (maximum shear resistance force)

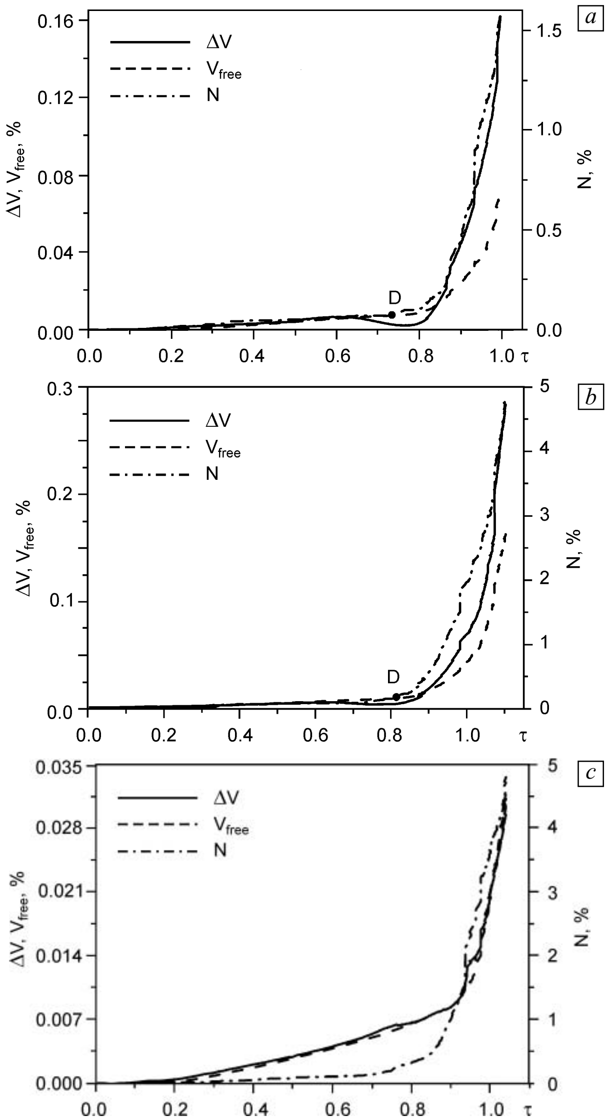

Fig. 6. Dependence of the volume change ΔV, free volume V_{free} and number of damages N on the specific shear resistance force τ of the model system: $C_\sigma = 0$ (*a*), 0.4 (*b*), 1 (*c*). The ends of the diagrams correspond to the limiting state of the system (maximum shear resistance force)

values of τ, the increase in specimen volume ΔV is ensured by opening of damages (by the increase in V_{free}), as evidenced by coincidence of the corresponding curves in Fig. 6. However, at a certain point (point *D* in Figs. 6(*a*, *b*)), the curve $V_{\text{free}}(\tau)$ starts lagging behind the curve $\Delta V(\tau)$ and by the instant the limiting state is reached, ΔV and V_{free} can differ several times. This means that at high shear stresses close to the shear strength of the medium, the decisive contribution to dilatancy is by surface slip of incipient mesodamages. Formally, the threshold stress at which the dominating dilatation mechanism of a block-structured medium is changed can be interpreted as the stress of shear slip activation. The difference between the total volume change and the maximum free volume determines the slip contribution to dilatancy. As can be seen from Figs. 6(*a*, *b*), increasing the degree of constraint causes the point *D* to shift toward the range of higher shear stress, and the difference $V_{\text{dev}} = \Delta V^{\text{c}} - V_{\text{free}}^{\text{c}}$ decreases (here, $V_{\text{free}}^{\text{c}}$ is the value of V_{free} at the instant the system reaches its limiting state). In the limiting case (at high C_σ), all curves under consideration behave consistently, and the quantities ΔV^{c} and $V_{\text{free}}^{\text{c}}$ coincide (Fig. 6(*c*)). Thus, as the degree of constraint increases, the role of shear slip along surfaces of mesodamage decreases and at $C_\sigma \to 1$ it becomes negligible. Under these conditions, the decisive role belongs to the increase in the porosity of the medium.

Figure 7 shows dependences of the specific shear resistance force at the instant of shear slip activation τ_{dev} and difference of the limiting volume change and free volume V_{dev} on the parameter C_σ. As the degree of constraint increases, the activation threshold of surface slip of mesoscopic discontinuities shifts toward the range of higher shear stress with saturation at $C_\sigma \sim 0.4$. The relative contribution of the slip mechanism (determined, e.g., from V_{dev}) increases and at $C_\sigma \sim 0.4$ it reaches its maximum (Fig. 7(*b*)). Notice that in this range of C_σ, the total volume change ΔV^{c} also increases (Fig. 4(*a*)).

Next, increasing the applied lateral stress ($C_\sigma > 0.4$) causes the dependence $V_{\text{dev}}(C_\sigma)$ to decrease rapidly and at

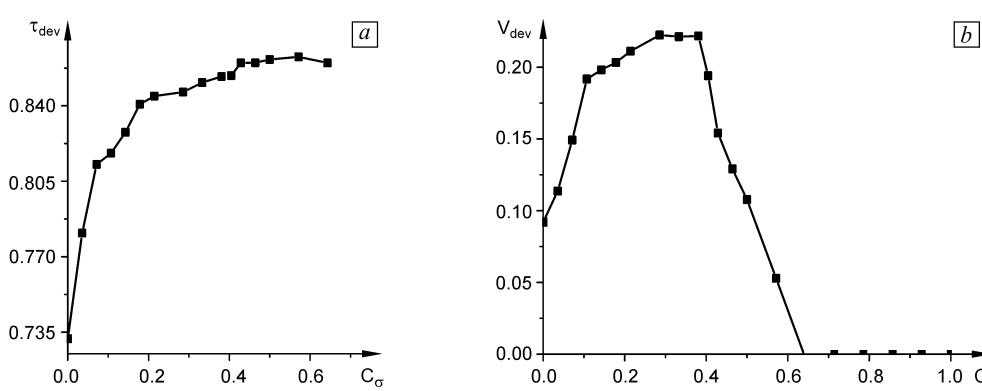

Fig. 7. Dependence of the specific shear resistance force τ_{dev} at the instant of shear slip activation (*a*) and difference of the total volume and free volume V_{dev} (*b*) on the degree of constraint (parameter C_σ)

$C_\sigma \approx 0.65$ it vanishes. Thus, at $C_\sigma > 0.4$, the contribution of the slip mechanism to dilatancy of the block-structured medium decreases, and at high degrees of constraint, the volume change of the model system is mainly by opening of existing and newly formed mesodamages to which corresponds a decrease in dilatancy in Fig. 4(*a*).

Thus, the increase in dilatancy ΔV^c and dilatancy factor λ^c at low degrees of constraint ($C_\sigma < 0.4$) is ensured primarily by the increasing role of surface slip of mesodamages. Increasing the stress level in the shear direction impedes the slip mechanism and the leading role passes on to pore expansion. However, despite the considerable increase in the amount of damages in the system at high C_σ (Fig. 5), this mechanism fails to provide the so noticeable volume change as the slip does and this eventually decreases the dependences $\Delta V^c(C_\sigma)$ and $\lambda^c(C_\sigma)$ (Fig. 4).

4. Conclusion

The results of computer simulation of shear deformation of the model specimens under nonequiaxial compression show that the main source of dilatancy in a geological medium is initially existing and newly formed mesodamages at interfaces of structural elements. The volume change of the block-structured medium in shear is governed by two elementary dilatation mechanisms: opening of discontinuities or pores and surface slip of mesodamages.

The analysis of the obtained data demonstrates that the main dilatation characteristics of the medium, in particular the volume change at the instant the system reaches its limiting state and the dilatancy factor, depend largely on the lateral to normal pressure ratio in a shear zone fragment. The dependence of the above parameters on the degree of constraint has a strongly pronounced nonlinear threshold character. This is associated with a change of the dominating dilatation mechanism in response to the increase in the degree of constraint.

As the parameter C_σ increases from zero to a certain threshold (in our case, $C_\sigma \approx 0.4$), the contribution to dilatancy by surface slip of initial and arising mesodamages grows. This involves a considerable (up to two-fold) increase in main dilatation parameters. Surface slip of mesodamages is a deformation mechanism with a rather high threshold stress of activation and the threshold increases greatly with an increase in C_σ (Fig. 7). Because the shear strength of the medium decreases at $C_\sigma > 0.4$ [12], slip is activated at increasingly later loading stages (which presumably owes to hindered local shear in severe lateral compression). As a result, by the time the limiting state is reached, the contribution of this mechanism to the volume change of the medium decreases giving way to dilatation by expansion (opening) of discontinuities for which the activation threshold is smaller. However, pore expansion fails to provide the so noticeable volume change of the geological medium as slip does and the dependences $\Delta V^c(C_\sigma)$ and $\lambda^c(C_\sigma)$ decrease (Fig. 4).

Thus, as the stress-strain state of the block-structured geological medum tends to equiaxial compression, the involvement of dilatation and deformation mechanisms of high scales (mechanisms with a high activation threshold) is impeded and this eventually leads to a decrease in the main dilatation characteristics of the medium. Notice that the change of the dominating deformation and dilatation mechanism as the medium tends to the equiaxial stress state (i.e., the initial tangential stress decreases) fit in the basic propositions of the concept of structural levels of plastic deformation and fracture of solids.

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