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THE INFLUENCE OF FLUID FILTRATION ON THE STRENGTH OF POROUS FLUID-SATURATED BRITTLE MATERIALS

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ABSTRACT

This paper is devoted to the study on dependence of the strength of fluid-saturated permeable brittle materials on the strain rate. The study has been carried out by means of a numerical modeling using a hybrid cellular automata method with the use of a coupled model, which takes into account the interplay of deformation of solid-phase skeleton, pore pressure change and fluid filtration. It is found that the influence of pore fluid on the material strength is determined by the competition of the processes of fluid pore pressure change (due to the volume deformation of solid-phase skeleton) and filtration. By means of a parametric study we obtained combinations of physical and mechanical characteristics of solid-phase skeleton and fluid, as well as of linear dimensions of the samples, that unquestionably determine the relationship between the strength of the deformed fluid-saturated sample and the strain rate. Results of uniaxial compressive strength and constrained shear tests have shown that the sort and level of influence of the fluid filtration on the sample strength is determined by the sign and amount of pore volume change during deformation. Under the loading involving a decrease in the filtration space volume and increase in the pore pressure, fluid redistribution allows to reduce the local maxima of pore pressure and thereby provides an increase in strength of the samples. Under the loading conditions causing an increase in the filtration space volume and decrease in the pore pressure, the filtration allows to maintain the fluid pressure and thereby reduces strength of the samples. Based on the simulation results, we have constructed basic logistic dependences of the sample strength of brittle materials on load rate, mechanical properties of liquid, solid-phase skeleton and sample dimensions. The results show that the non-stationary type of the related deformation and filtration processes determines significant changes in the sample strength of permeable materials even at low strain rates.

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1. Introduction

It is known that the presence of liquid phase in the pores of background medium has a significant influence on its physical and mechanical properties, including its strength. Meanwhile special attention is paid to the study of the influence of fluids on the behavior of brittle materials, primarily rock formations [1-12]. This interest is caused by a high content of different fluids in a free state in the brittle upper portion of the lithosphere [13, 14]. The level of influence of the fluid on the ultimate strength and deformation ability of the material is determined by a number of structural and physical-chemical factors. At the same time, the basic "macroscopic" factor which determines the influence of the liquid phase on the behavior of different permeable brittle materials is the pore pressure, the value of which is directly associated with the value of external mechanical stresses acting on the considered fluid-saturated volume (in other words, with the level of volume constraint).

It is well known that the strength of fragile materials increases with the typical value of mean stresses in the system going higher. The value of mean stresses determines fracture behavior as well. Upon reaching a certain threshold level of compressive mean stresses, the fracture behavior of porous materials changes from a typically brittle one (dynamic behavior localized in the form of one or several cracks) to a localized quasiplastic flow associated with the formation of an inelastic shear band and at even higher compressive stresses it changes to a cataclastic flow distributed in the sample volume [8, 15-19]. A distinction of the latter two sorts of destruction is a significant non-elastic volumetric strain (dilatancy) associated with the formation of new damages/cracks in the material and growth of existing ones. The limit (at the time of loss of sample integrity) value of dilatancy increases with compression stresses going higher. Integrated influence of pore fluid on the stress state of enclosing solid-phase skeleton is usually determined within Terzaghi's concept of effective stresses. This concept assumes that the mechanical behavior of a certain amount of porous material is determined not by applied external stresses $\sigma_{\alpha\beta}$, but by their superposition with the pore pressure of the fluid P_{pore} :

$\sigma_{\alpha\beta}^{eff} = \sigma_{\alpha\beta} + \delta_{\alpha\beta}\chi P_{pore}$, where $\delta_{\alpha\beta}$ are Kronecker symbols ($\alpha, \beta = x, y, z$), and $0 < \chi \leq 1$ is a material index. These are called effective stresses. Based on definition of effective stresses, in the area of positive or negative and small (in modulus) values of the mean applied pressure $\sigma_{mean} = (\sigma_{xx} + \sigma_{yy} + \sigma_{zz})/3$ corresponding to the brittle behavior of the material non-zero pore pressure results in a decrease in the material strength. Furthermore, during deformation followed by a directed increase σ_{mean} the pore pressure value increases at least in the same proportion as the mean pressure in the skeleton. This leads not only to an

increase in absolute contribution, but also to an increase in relative contribution P_{pore} to strength reduction. At the same time, at high in modulus negative values σ_{mean} which cause quasi-plastic fracture behavior the volume of fracture pore space available for the fluid (material dilatancy) goes higher at the stage of inelastic response of the material. As a result, pore pressure of the fluid drops drastically to zero, which leads to an increase (in modulus) of effective stresses in the skeleton and to a corresponding increase of the limits of plasticity and strength of the material up to the values corresponding to unwatered materials. The reason of such increase of strength properties of permeable materials is the increase of normal compressive stresses on surfaces of existing fractures and cracks. This effect is called dilatancy strengthening [8, 20, 21]. Therefore, type of the influence of the liquid phase on mechanical response of porous permeable brittle materials can vary significantly depending on the level of constraint and the ability of such materials to volumetric plastic deformation [22].

The change of pore pressure in the material volume is caused not only by deformation of the solid-phase skeleton, but also by fluid filtration the direction and intensity of which is determined by the dynamics of deformation processes and boundary conditions. Usually, the study of response of fluid-saturated permeable samples is carried out under one of two "limit" conditions: 1) under conditions of free outflow (or inflow) of liquid (drained condition) or 2) as a waterproof sample (undrained condition). Normally, under the first condition the influence of fluid on mechanical behavior of materials under quasi-statically changing loads is studied, when the typical rate of fluid redistribution in the solid-phase skeleton significantly exceeds the rate of external mechanical strain of this skeleton. In this case, the elastic and plastic change of pore space volume practically does not influence the value and distribution of pore pressure in the sample. The second limit condition simulates conditions when the strain rate is significantly higher than the filtration rate and fluid filtration transfer can be ignored at the time scale of loading. In this case, type of pore pressure change is determined by an absolute value and change of the mean applied stress σ_{mean} .

At the same time, much less attention is paid to the study of physical and mechanical properties (including strength properties) of brittle permeable materials in variation interval of load parameters which provides intermediate conditions between free outflow of liquid and waterproof sample. In this area, fluid distribution in the studied material volume can no longer be considered as equal even during elastic deformation. Furthermore, since plastic deformation which is followed by irreversible changes of the volume is localized, it leads to occurrence of high local gradients of the fluid pore pressure both in volume of the sample and at its boundaries. It results in an irregular and spatially uneven fluid filtration. It is obvious that evolution of a sample or medium fragment in volume of

which irregular filtration and deformation (inexorably associated with filtration) occur is determined by the ratio of fluid redistribution (filtration) rates and mechanical loading of the skeleton.

The influence of strain rates and fluid redistribution in pore volume of fluid-saturated brittle materials on their mechanical response has been discussed for more than half a century now [4, 5, 23-27]. Over the last years, researchers have begun to focus on the study of influence of an irregular filtration on localization of deformations (in particular, on sliding in the shear band) and material strength under constrained shear conditions. For instance, the works devoted to the study of response of water-saturated construction materials and rocks to dynamic shear loading, report on a significant influence of strain rate (and, consequently, of filtration intensity) on effective values of elastic moduli and strength of such materials [28, 29]. Meanwhile, level of influence of shear strain rate on the strength of a dilating water-saturated medium is in a great measure determined by boundary conditions (a waterproof sample or a sample in such environment that allows liquid exchange) [30, 31].

Growing interest in the study of peculiarities of mechanical response of brittle porous materials and media under conditions of irregular deformation and filtration is considerably determined by the relevance of application of the obtained results to the problem of earthquake origin and seismic cycle duration. For instance, one of the two generally accepted models for earthquake forerunners is the dilatancy-diffusion hypothesis [32, 33]. This model assumes that liquids play a key role in the processes of earthquake origin in active fault zones that consist of permeable materials. An important role is played not only by the pore pressure of liquid, but also by its redistribution in the fault zone and adjacent volumes of the neighboring blocks [34-36]. A number of works point out that presence of fluid has a significant influence on earthquakes associated with fault zones due to the fact that fluid pressure partially compensates normal pressure in the fault plane thereby reducing its shear strength [34, 37, 38]. It is also being noted that the influence of fluid on occurrence conditions and dynamics of earthquakes is considerably determined by the ratio of typical rates of pore pressure equalization and shear deformation in the fault zone [39]. For instance, at low values of medium permeability that limit the flow of fluid in dilatation area from the surrounding volume of blocks, dilatancy strengthening prevents strain localization and thereby increases shear strength and a "slow" seismically quiet slipping of blocks.

Despite a great number of works devoted to the study of strength properties of water-saturated elastic-plastic permeable media, there are still no comprehensive representations and functional estimates of the role of the relationship between deformation and filtration on deformation response and strength of such materials. Numerical modeling is an effective tool that allows to analyze the influence of physical and mechanical properties and their relations on strength properties of fluid-saturated

permeable media in more detail. This work is devoted to the study of this problem using numerical modeling by means of a hybrid cellular automata method [40, 41] with the use of a coupled macroscopic model of fluid-saturated fractured porous brittle materials [42, 43].

2. Model Description

By using the hybrid cellular automata (HCA) method a permeable rigid body is modeled by an ensemble of permeable discrete elements. Note that the term "discrete elements" includes a wide group of numerical methods based on representation of a solid-phase medium by an ensemble of particles of finite size and definite shape [44-46]. In this work, we use a version of discrete elements called distinct elements [45, 47, 48]. Their unique characteristic is approximation of real form of a discrete element by an equivalent disk (in a two-dimensional formulation of the problem) or a sphere while keeping the same mass and volume of the element. This approximation makes it possible to simplify formulation of motion equations for rotational degrees of freedom of elements and also allows to consider forces of normal and tangential interaction of elements as independent components of the total force vector. The main differences between the model of mechanical response of distinct elements used in this work and traditional models are the use of approximation of homogeneous deformation distribution in the element volume and multiparticle formulation of relations for interelement interaction forces [49-51].

Depending on characteristics of permeable material structure and simulated scale level, dimensions of the discrete element can significantly exceed linear dimensions of imperfections in the rigid body, be comparable to them or be smaller. The influence of imperfections in the element volume (normally their dimensions are smaller than the dimensions of the element) on its mechanical properties and stress-strain behavior is implicitly considered. The space around the rigid body (as well as internal "macroscopic" imperfections dimensions of which exceed those of the discrete element) is modeled by a fine grid "frozen" into laboratory coordinate system. This grid is used for calculation of spatial distribution of fluid in the space around the rigid body (and in internal "macroscopic" imperfections), as well as for calculation of the volume of these "macroscopic" areas [42, 43].

The HCA method allows to solve the coupled problem of deformation of a solid-phase skeleton modeled by discrete elements and fluid filtration through an intra-element fracture pore space by means of numerical integration of the Newton-Euler equations of motion and transfer of fluid density on the ensemble of automata [43]:

$$\begin{cases} m \frac{d^2 \vec{r}}{dt^2} = m \frac{d\vec{v}}{dt} = \sum_{n \in N_{nb}} (\vec{F}_n + \vec{F}_\tau), \\ J \frac{d\vec{\omega}}{dt} = \sum_{n \in N_{nb}} \vec{M}, \end{cases} \quad (1)$$

$$\phi \frac{\partial \rho}{\partial t} = K_{fl} \nabla \left[\frac{k}{\eta} \nabla \rho \right], \quad (2)$$

where $\vec{r}$, $\vec{v}$ and $\vec{\omega}$ are radius vector and vectors of linear and angular velocities of the movable cellular automaton; m and J are the mass of automaton and the moment of inertia of equivalent disk/sphere which corresponds to automaton; $\vec{F}_n$ and $\vec{F}_\tau$ are normal (central) and tangential forces of interaction of the automaton in question with the neighboring one; $\vec{M}$ is the moment of interaction forces; N_{nb} is the number of interacting neighbors of the automaton; ϕ and k are current values of porosity (determined by the ratio of the current filtration volume in the automaton to its current volume value [43]) and permeability of the material of the movable cellular automaton; ρ , η and K_{fl} are current values of density of the fluid, its viscosity and compression modulus.

The fluid transfer between permeable discrete elements and the external medium (pores and cavities dimensions of which exceed dimensions of the discrete element) is calculated by solving the transfer equation which is similar to equation (2). Numerical implementation of this calculation method is described in the work [43].

Within the used approximation of an evenly deformable element the functional type of relations which connect forces of normal and tangential interaction of a pair of discrete elements with their relative normal and tangential displacements is definitely determined by the functional type of the defining relations for the element material [49-51]. In this work we use macroscopic description of permeable rigid bodies assuming that dimensions of coupling imperfections that form the filtration volume are much smaller than dimensions of the discrete element. The influence of the fluid in fracture pore space of a discrete element on the stress-strain behavior of the element is described according to the Biot's model of poroelasticity [1-3]. In the approximation of isotropy of a discrete element material the linear Hooke law for a locally isotropic fluid-saturated medium is used as the defining relation in the elastic area. The said law is expressed in a hypoelastic form [3]:

$$\Delta \bar{\sigma}_{\alpha\beta} = 2G_i \left(\Delta \bar{\epsilon}_{\alpha\beta} - \delta_{\alpha\beta} \frac{\Delta P_{fluid}}{K} \right) + \delta_{\alpha\beta} (1 - 2G/K) \Delta \bar{\sigma}_{mean}, \quad (3)$$

where Δ means increment of the corresponding variable per a time step of the numerical scheme of integration of dynamics equations; $\bar{\sigma}_{\alpha\beta}$ and $\bar{\epsilon}_{\alpha\beta}$ are components of tensors of mean (evenly distributed) stresses and strains in the element volume; $\bar{\sigma}_{mean}$ is the mean stress, G and K are modules of shear and volume deformation of the element material, P_{fluid} means contribution of fluid pore pressure in the fracture pore space of the element to the value of effective stresses averaged on volume basis. According to the Biot's model, P_{fluid} value is linearly connected with the

average value of the fluid pore pressure P_{pore} in the fracture pore space of the element:

$$P_{fluid} = a P_{pore}, \quad (4)$$

where $a = 1 - K/K_s$. Where K_s is the module of volume deformation of a non-porous material (monolithic walls of a solid-phase skeleton).

The connection between density and pressure of the pore fluid is determined by the linear state equation used to describe weakly compressible liquids [52]:

$$\rho_{fl}(P_{pore}) = \rho_{fl}^0 \left(1 + (P_{pore} - P_{pore}^0) / K_{fl} \right), \quad (5)$$

where ρ_{fl}^0 and P_{pore}^0 are equilibrium values of density and pressure of the liquid under atmospheric conditions (without mechanical limitation of liquid volume).

Inelastic behavior of brittle penetrable material of the discrete element is described in accordance with the model of plastic flow with a non-associated law of flow and the Mises-Schleicher criterion of reaching the elastic limit (the Nikolaevskiy model) [53, 54]. In order to take into account the influence of the fluid pore pressure, the Mises-Schleicher criterion is formulated using the effective mean stress $\bar{\sigma}_{mean}^{eff}$:

$$\beta \bar{\sigma}_{mean}^{eff} + \frac{\bar{\sigma}_{eq}}{\sqrt{3}} = \beta \left(\bar{\sigma}_{mean} + b P_{pore} \right) + \frac{\bar{\sigma}_{eq}}{\sqrt{3}} = Y, \quad (6)$$

where $\bar{\sigma}_{eq}$ is the intensity of mean stresses in the element volume; b is the material index that effectively takes into account influence of the fluid pore pressure in the fracture pore space of the element on occurrence and development of new fractures (formation of which provides macroscopically inelastic behavior of brittle materials).

The Drucker-Prager criterion (which is a modified form of the Mises-Schleicher criterion) is used as a fracture criterion modeled in the discrete element methods by changing behavior of pairs of interacting elements from an associated behavior to a non-associated one [47]. The Drucker-Prager criterion is expressed as follows:

$$\sigma_{DP} = 0.5(\lambda + 1)\sigma_{eq} + 1.5(\lambda - 1)(\sigma_{mean} + b P_{pore}) = \sigma_c, \quad (7)$$

where $\lambda = \sigma_c / \sigma_t$ is the ratio between strength of "dry" material under uniaxial compression (σ_c) and tension (σ_t).

The described model is based on the assumption that influence of the fluid pore pressure on formation of cracks of different sizes is the same (the relations (6) and (7) use the same material index b). Terzaghi's concept $b \approx 1$ [6, 8] applies to the most of the permeable brittle materials. At the same time, characteristics of pore space and microscopic structure of the solid-phase skeleton can define a more complex connection between pore pressure and damage accumulation in which the value b is both bigger and significantly smaller than 1 and is a function of porosity parameters, ratio of applied and pore pressures, stress

intensity, etc. [6, 55-58]. Therefore, in this work the material index b is used as a variable model parameter to analyse dependence of the identified regularities of response of the fluid-saturated material on the level of influence of pore pressure on conditions of formation and development of fractures and cracks. The initial porosity value of the material ϕ_0 is considered as the lower limit of the parameter b [8].

3. General Equation for the Strength of Samples of Fluid-Saturated Brittle Materials under Uniaxial Compression

It is well known that under uniaxial loading and unconstrained shear that correspond to small (in modulus) values of mean stress most of the permeable brittle materials (granites, sandstones, ceramics, etc.) demonstrate elastic response up to fracturing. Under such conditions, pore pressure is only changed due to elastic change of pore space volume and possibility of fluid redistribution [42, 43]. Under uniaxial compression of the fluid-saturated sample of a brittle porous material mean stresses in the sample are negative and increase in modulus during deformation. It is followed by a decrease of pore space volume and, consequently, by an increase of pore pressure which leads to fluid outflow from the sample through side surfaces which decreases pore pressure. The sample strength under these conditions is determined by the ratio of axial compression and fluid filtration rates (resulting in fluid outflow from the sample). Our previous works [42, 43] show that strength of brittle samples of fluid-saturated materials under uniaxial compression is a single-valued function of the ratio between material permeability k and axial strain rate. The type of this dependence is nonlinear and described using a logistic function which is a consequence of competition of processes of pore pressure growth due to pore compression and fluid outflow. At the same time, in works [42, 43] we did not obtain expressions for indexes included in this dependence. Therefore, in this work we performed a detailed parametric study on influence of deformation rate on strength of liquid-saturated samples in order to find common patterns of competition between the processes of pore space compression and fluid filtration.

As in works [42, 43], the numerical modeling of uniaxial compression was carried out using a two-dimensional formulation in approximation of plane stress state on rectangular samples compressed with a constant rate V . The sample structure was assumed to be homogeneous without macroscopic pores and inclusions. The initial fluid pore pressure of was assumed to be equal to atmospheric pressure.: $P_{pore}^0 = 0.1$ MPa. The physical and mechanical properties of the permeable brittle material and fluid, as well as linear dimensions of samples varied over a wide range. As basic values of material properties the following values (that correspond to sandstone and water) were used: $G = 5.77$ GPa, $K = 37.5$ GPa, $K_s = 107$ GPa,

$$\sigma_c = 70 \text{ GPa}, \lambda = 3, \phi_0 = 0.1, b = 0.1, \rho_{fl}^0 = 1000 \text{ kg/m}^3, K_{fl} = 2.2 \text{ GPa}, \eta = 10^{-3} \text{ Pa}\cdot\text{s}.$$

3.1. Combination of Identifying Parameters

The analysis of equations that determine dynamics of the system behavior allows to identify combinations of parameters that determine the required strength value of fluid-saturated material. In this case, a combination of material parameters that determine velocities of competing processes can be obtained using the following analytical estimation. Ignoring non-linearity of the pore pressure gradient along the sample section, the balance of processes of the pore pressure growth due to axial compression of the sample and outflow (filtration) of liquid into external environment through the side surfaces can be described using the following differential equation:

$$\frac{dP_{pore}}{dt} = C_{solid} K_{fl} \dot{\epsilon} - \frac{P_{pore}(t)}{t_{filtr}}, \quad (8)$$

where t is the time; C_{solid} is the index that determines relation between volumetric pore deformation of the solid-phase skeleton and axial deformation of the sample under uniaxial loading; $\dot{\epsilon}$ is the rate of axial compression strain (defined as the ratio between applied compression rate V and the height of the sample H), t_{filtr} is the characteristic duration of liquid filtration through the side surfaces of the sample which can be estimated as follows:

$$t_{filtr} = \frac{\eta}{K_{fl}} \frac{\phi_0}{4k} W^2, \quad (9)$$

where W is the width of the sample (linear dimension crosswise to the axis of loading). This estimate can be easily obtained using the following replacements in equation (2): $\partial t \approx t_{filtr}$, $\partial x^2 \approx W^2$. Note that the estimate (9) of the characteristic duration of pore pressure equalization in the crosswise direction to the axis of loading implies constancy of the pressure gradient in this direction and is therefore understated. The differential equation (8) with zero initial conditions is solved as follows:

$$P_{pore}(t) = C_{solid} \frac{\eta \phi_0 W^2}{4k} \dot{\epsilon} \left(1 - e^{-t/t_{filtr}}\right), \quad (10)$$

According to the analytical estimation (10), with an increase of the width of the sample W liquid pore pressure on the sample axis increases proportionally W^2 under otherwise equal conditions. Indeed, as the sample width increases, the part of material adjacent to the side surface (which is to a greater extent subjected to liquid outflow) becomes smaller. Accordingly, the specific quantity and pressure of liquid in pore space of the sample at the same value of axial deformation increases with increase of the value W . So we can draw an unexpected conclusion: under otherwise equal conditions the strength of a wider fluid-

saturated sample is lower than the strength of a narrower sample. This conclusion is based on the results of numerical modeling [43].

According to the equation (10), the pore pressure in the sample and, therefore, the strength of the fluid-saturated sample under uniaxial compression are determined by the product of three multipliers $C_{solid}(\eta\phi_0 W^2/4k)\dot{\epsilon}$ demonstrating influence of various factors. The first one (C_{solid}) characterizes compressibility of pores and is associated with mechanical and structural properties of the solid-phase skeleton (including the initial porosity ϕ_0). The second $(\eta\phi_0 W^2/4k)$ and the third ($\dot{\epsilon}$) multipliers determine velocities of the competing processes of decrease of pore pressure as a result of liquid outflow from a sample and increase of P_{pore} due to the compressive axial strain.

3.2. Empirical Determination of Generalized Logistic Dependence

The obtained above combination of material and fluid parameters was used for empirical determination of generalized dependence of the sample strength σ_{comp} under uniaxial compression on loading parameters, sample geometry and physical and mechanical properties of hard-phase porous skeleton and fluid. This generalized dependence was determined by means of a numerical modeling of uniaxial compression of samples up to fracturing.

At the first stage, we analyzed influence of parameters that determine the balance of velocities of competing processes of solid-phase skeleton compression and filtration. In order to do so, we used a wide range of values $\dot{\epsilon}$, η , k and W , and the rest of characteristics of the two-phase system remained unchanged (to ensure constancy of the influence coefficient of properties of the solid-phase skeleton C_{solid}). The results of modeling confirmed the unique dependence of the sample strength σ_{comp} on combination of parameters $(\eta W^2/4k)\dot{\epsilon}$ at $C_{solid} = \text{const}$ and $\phi_0 = \text{const}$. This is a logistic dependence.

Figure 1 shows examples of dependencies $\sigma_{comp}((\eta W^2/4k)\dot{\epsilon})$ that were numerically obtained by varying four specified parameters. There are several rows of points that correspond to different strain rate values $\dot{\epsilon}$. Each row of points is obtained by varying the parameters η , k and W over a wide range at a constant value of $\dot{\epsilon}$. We can see that in the area of small values of the argument $(\eta W^2/4k)\dot{\epsilon} \rightarrow 0$ that corresponds to low strain rates, small sample width, low fluid viscosity and/or high material permeability, compressive strength of the fluid-saturated sample tends to the upper limit σ_{max} that corresponds to the compressive strength of "dry" sample. This effect is caused by a slow increase of pore pressure during deformation of

the sample due to the fact that filtration rate is higher than fluid compression rate. The increase of the argument $(\eta W^2/4k)\dot{\epsilon}$ which is associated with increase of strain rate, sample width, fluid viscosity, and/or decrease of permeability of the material is followed by a nonlinear decrease of the strength σ_{comp} . The reason for this is growth acceleration of pore pressure of the fluid due to the insufficiently rapid fluid filtration. In the area of high values of the argument the strength of the sample tends to the lower limit σ_{min} which corresponds to the strength of fluid-saturated samples in the absence of filtration. Such situation is possible, for instance, in nanoporous materials at relatively low pressures, when the system of nanoscale channels is almost impermeable, or under dynamic loading. An analytical estimate of σ_{min} for a brittle material under uniaxial compression can be obtained with the equation (3) and (7) [43]:

$$\sigma_{min} = \sigma_c / \left[1 + 1,5(\lambda - 1) \frac{bK_\beta}{\phi_0} \left(\frac{1}{K} - \frac{1}{K_s} \right) \right]. \quad (11)$$

According to the modeling results, tolerance for the analytical estimate does not exceed a few percent of the value of σ_{min} .

Fig. 1. Dependences between strength of fluid-saturated samples and values of parameters combinations $(\eta W^2/4k)\dot{\epsilon}$: (a):

$$b = \phi_0 = 0,1; (b): b = 1$$

At the second stage we determined the type of functional dependence of the material index C_{solid} which is able to provide uniqueness of the dependence $\sigma_{comp}(C_{solid}(\eta\phi_0 W^2/4k)\dot{\epsilon})$ for permeable materials with different elastic and strength properties and porosities. Figure 1 and equations (7) and (11) show that the lower tensile strength σ_{min} , and therefore the specific value of σ_{comp} at a given value of the argument $(\eta W^2/4k)\dot{\epsilon}$ is largely determined by the influence coefficient of pore pressure on the material strength b . Furthermore, due to irregularity of the filtration process, at least at the initial stage of deformation of the sample [42, 43], it is obvious that the specific value of σ_{comp} (in the range between σ_{max} and σ_{min}) should also depend on the value of σ_c . Since the parameters b and σ_c are not directly associated with the degree of deformation of the pore space during compression of the solid-phase skeleton, the functional form of the coefficient C_{solid} was analyzed under the assumption of separation of elastic and strength parameters: $C_{solid} = C_{solid}^{elast} C_{solid}^{strength}$, where C_{solid}^{elast} is determined by elastic constants and porosity of the skeleton, and $C_{solid}^{strength}$ is determined by parameters that define strength of the material. Determination of type of the parameter C_{solid}^{elast} was carried out by a variation of Young's moduli E and module of volumetric strain K of the solid-phase skeleton, module of uniform compression of the fluid K_f , initial porosity ϕ_0 and influence coefficient of pore pressure on elastic stresses a . The values of the compressive strength of "dry" material σ_c and the coefficient b that determine $C_{solid}^{strength}$, were considered to be constant. The modeling results have shown that strength values of fluid-saturated samples lie on a single logistic curve (for material with given values of σ_c and b), if $C_{solid}^{elast} = E\sqrt{a/K\phi_0^{2/3}}$. Similar studies (modeling of uniaxial compression at different values of σ_c and b) allowed us to determine the following type of the second material index: $C_{solid}^{strength} = \sqrt{b/\sigma_c}$.

The use of analytical estimates and numerical modeling allowed us to determine a combination of physical, mechanical and geometric parameters that uniquely determine the compressive strength of samples of fluid-saturated brittle materials:

$$A_{fluid} C_{solid} = \dot{\epsilon}(\eta\phi_0 W^2/4k) \left(E\sqrt{ab/K\phi_0^{2/3}}/\sigma_c \right). \quad (12)$$

According to the modeling results, the dependences $\sigma_{comp}(A_{fluid} C_{solid})$ that correspond to permeable brittle materials with different values of compressive strength σ_c and of coefficient b can be summarized on a single curve using the specified strength value $(\sigma_{comp} - \sigma_{min})/(\sigma_c - \sigma_{min})$ (see Fig. 2).

Fig. 2. Generalized dependence between strength of fluid-saturated samples of brittle materials and the parameter value $A_{fluid} C_{solid}$

As was mentioned above, processes behavior of which is determined by competition of some factors or phenomena (for example, the growth of biological populations, etc.) are often described by logistic functions [59]. A good approximation of a single strength curve of fluid-saturated samples of brittle materials (see Fig. 2) is provided by the following logistic function:

$$\sigma_{comp} = \sigma_{min} + \frac{\sigma_{max} - \sigma_{min}}{1 + \left((A_{fluid} C_{solid})/B_0 \right)^p}, \quad (13)$$

where σ_{max} is strength of the sample under uniaxial compression without liquid in pores, σ_{min} is strength of the water-saturated sample with liquid "blocked" in pores (can be estimated with the equation (11)), $B_0 = 1 \text{ Pa}^{1/2}$ is a normalization constant, $p \approx 1.8$ is an exponent. It should be noted that the dependence (13) is fair in the range of strain rates that allow to ignore the influence of deformation rate on the strength of the solid-phase skeleton. For the most of materials this corresponds to $\dot{\epsilon} < 10 \text{ s}^{-1}$.

Thereby, even with the loading parameters that correspond to elastic-brittle behavior of the material, complex competitive nature of relations between mechanical response of the solid-phase skeleton and liquid phase and the dynamics of fluid filtration redistribution in the coupled system of imperfections determines a significantly non-linear dependence of strength of the samples on the material properties and deformation rate.

4. Influence of Liquid Phase on the Strength of Elastic-plastic Layer under Constrained Shear Conditions

As mentioned in the Introduction to this paper, in the area of loading parameters that cause inelastic mechanical response of brittle permeable materials, influence of fluid on mechanical properties may qualitatively differ under conditions of elastic-brittle response. For the most part these differences are associated with the dilatancy nature of macroscopic inelastic deformation, mechanisms of which are formation of new fractures, growth and opening of

existing fractures. The increase of the pore space volume is followed by a sudden drop of local pore pressure. It is well known that inelastic deformation is usually localized and occurs in the form of narrow bands of localized shear (in geological environments such macroscopic bands are fault zones) [8, 15, 19, 36, 39]. Herewith, material areas or structural blocks of geological environment which are adjacent to the bands of localized shear are mainly subjected to elastic deformation. Dilatancy processes in such bands cause occurrence of sharp gradients of pore pressure crosswise to the shear band and, consequently, intensive fluid transfer in the material volume (as for the fault zones, this effect is called "absorption" of the liquid phase by the fault). It is evident that the ratio between shear deformation rate in localized shear band and rate of fluid filtration from adjacent elastically deformed areas/blocks will determine the shear strength of this band to a considerable extent, as well as deformation ability and dilatancy value at the beginning of shear weakening and transformation of shear displacements into dynamic ones.

Numerical study of dependence of the shear strength of localized shear band on the ratio of shear and filtration rates was based on the following simplified model system. It is an infinite homogeneous layer of elastic-plastic material with the width of L_0 modeling the interface zone between elastic blocks (see Fig. 3, a). Elastic blocks simulate areas adjacent to the interface zone which are characterized by low damage and therefore are in a state of an elastic response under the considered loading conditions. The elastic properties of materials of the interface zone and blocks are assumed to be the same and correspond to the "basic" properties of the model material specified in Section 2. Fig. 3, b shows diagrams of uniaxial loading of model materials of the interface zone and adjacent areas. For the elastic-plastic material of the interface zone we used values of internal-friction coefficients $\beta = 0.57$ and dilatancy $\Lambda = 0.36$, as well as the strength properties $\sigma_c = 70$ MPa, $\lambda = 3$ typical for consolidated sandstones. We assumed that the strength of adjacent volumes of the medium significantly exceeds the strength of localized shear bands, therefore material of elastic blocks in the model is considered to be indestructible.

The elastic-plastic interface and adjacent areas of elastic medium are permeable and saturated with liquid. The initial values (before loading) of permeability and porosity of the materials of interface and blocks were considered to be the same ($\phi_0 = 0.1$). The initial liquid pressure in the interface zone and blocks was considered to be equal to the atmospheric pressure. The upper and lower surfaces of the sample were considered to be impermeable ("waterproof" area around the interface zone was examined). Periodic boundary conditions were set on the side surfaces in the horizontal direction. The problem was solved in a two-dimensional formulation in plane strain approximation.

Constrained shear of the model sample in a horizontal plane was modeled (see Fig. 3, a). The loading was carried

out in two stages. At the first stage, normal pressure of σ_N was applied to the upper and lower surfaces of the sample, after that the sample was isolated until full attenuation of elastic waves. At the second stage, shear loading was applied to the precompressed sample by applying a constant tangential velocity V_x to the upper and lower surfaces. The vertical component of velocity vectors at the upper and lower boundaries was assumed to be equal to zero. The samples were being deformed up to the fracture moment in the interface zone. Note that the described two-dimensional system can also be interpreted as a simplified model of a horizontal cross-section of the interface zone of structural blocks of the geological environment (resistive fracture, part of the fracture, etc.) at the specific depth. The work [60] shows that the used loading scheme adequately reflects the main characteristics of stress state of active fault zones away from daylight surface.

Fig. 3. Schematic illustration of constrained shear implementation for a porous water-saturated material (a) and diagram of uniaxial compression of blocks' model materials and interface zone (b)

Fig. 4 shows a typical dependence of the shear strength of fluid-saturated interface zone on the value of compressive stresses σ_N when there is no liquid redistribution in the pore volume of blocks (in other words, at zero permeability of blocks). Two areas are clearly visible. The first one (area of relatively small compressive

normal loads and mean stresses) corresponds to elastic-brittle deformation of the interface and its destruction before reaching shear elastic limit. The second area shows that destruction of the interface is preceded by its plastic deformation followed by dilatancy. The rapid change of shear strength of the interface during transition to the area of mean stresses that cause inelastic deformation of the interface zone, is associated with the dilatancy strengthening. During dilatancy, increase of the pore space volume of the interface zone leads to a sudden drop of liquid pore pressure from the initial one determined by the value of compressive load σ_N to zero. Meanwhile, due to the fact that there is no fluid inflow from the volume of blocks, dilatancy strengthening of the interface occurs, i. e. its observed shear strength τ_c increases noticeably with an increase of the mean stress in medium (associated with σ_N). This area can be described using the following dependence:

$$\tau_c(k=0) \approx \tau_0 \left(1 + \left(\sigma_N / \sigma_N^0 \right)^{0.55} \right), \quad (14)$$

where τ_0 and σ_N^0 are parameters determined by physical and mechanical properties of the material. The results given below are obtained in the range of normal loads σ_N which result in destruction of the elastic-plastic interface after reaching the elastic limit (i. e. under conditions of plastic straining).

Fig. 4. Dependence between shear strength and normal loading for impermeable water-saturated interface. The approximating dependence is shown in red (14)

4.1. Influence of Fluid Filtration on the Shear Strength of Interface Zone

Based on the results obtained in Section 2, a combination of characteristics of shear strain and filtration rates $A'_{fluid} = (\eta L^2 / 4k) \dot{\epsilon}_{xy}$ was used as basic combination of parameters that determine shear strength of the interface, where $\dot{\epsilon}_{xy} = V_x / L$, L is the width of the sample (distance between the upper and lower surfaces shown in Fig. 3, a). The modeling results have shown that at constant values of mechanical properties of the solid-phase skeleton, applied

normal load σ_N and ratio of linear dimensions of interface and sample (L_0/L) dependencies of the shear strength of interface τ_c on the shear rate, fluid viscosity, medium permeability and sample width are summarized to a single function $\tau_c(A'_{fluid})$. Fig. 5, a shows an example of such curve.

a

b

Fig. 5. (a) Dependence between interface shear strength ($L_0/L = 0.052$, $\sigma_N = 41.7$ MPa) and parameter value A'_{fluid} at different values of shear-strain rate $\dot{\epsilon}_{xy}$; (b) distribution of pore pressure of fluid P_{pore} in a direction transverse to the interface line in samples, which are characterized with different values of parameter A'_{fluid} at different values of applied shear strain ϵ_{xy} : $0.82 \epsilon_c^{\min}$ (1); $0.89 \epsilon_c^{\min}$ (2); $0.96 \epsilon_c^{\min}$ (3). Here $\epsilon_c^{\min}$ is an ultimate (at the moment of fracture) value of the applied shear strain for the sample with $A'_{fluid} = A'_{crit}$

An important characteristic of the curve shown in Fig. 5, a is its nonmonotonicity. Nonmonotonicity of the dependence $\tau_c(A'_{fluid})$ can be explained using analysis of change dynamics of pore pressure distribution along the width of the samples (in vertical section shown on Fig. 3, a).

At big values of the parameter A'_{fluid} at the beginning of the stage of interface inelastic deformation, followed by its

dilatancy, fluid pore pressure in the interface drops to zero. Due to this, the value of effective mean stress σ_{mean}^{eff} in the interface zone increases (in modulus) to the maximum value $\sigma_{mean}^{eff} = \sigma_{mean}$, where the value σ_{mean} is determined by compressional force of elastic blocks. The compressional force of elastic blocks directly depends on the amount of liquid in the blocks, which causes blocks to burst. That's why the maximum values σ_{mean} in the interface (and in the volume of blocks) are reached under conditions where filtration of fluid from blocks to the interface can be considered ignorable.

As an example, Fig. 5, *b* shows pore pressure distribution in the sample with almost impermeable blocks ($A'_{fluid} = 2 \cdot 10^5$ MPa) at different values of the applied shear strain ε_{xy} during inelastic deformation. One can see that the value of pore pressure in blocks increases during deformation. It is a result of interface dilatancy, which causes an increase of blocks compression by a growing interface area, and of negligibly small intensity of fluid outflow from the volume of blocks in the interface. Accordingly, the value σ_{mean} in the interface zone (and in the volume of blocks) during inelastic deformation increases in modulus and reaches the maximum limit by the time of fracture formation, which determines the high values of shear strength at big values of A'_{fluid} . The maximum shear strength of the interface is reached at $A'_{fluid} \rightarrow \infty$.

The decrease of the parameter A'_{fluid} , for example, due to increase of permeability of the medium or decrease of strain rate causes the fluid flow going into the dilating interface zone to increase. Meanwhile, pore pressure in the interface drops to zero when sufficiently large values of the applied shear strain ε_{xy} are reached and the growth of pore pressure in blocks becomes slower during shear deformation.

Moreover, at sufficiently small values of A'_{fluid} the growth of pore pressure in blocks is replaced by its decrease despite the interface dilatancy (curves for $A'_{fluid} = 20$ MPa shown in Fig. 5, *b*). As a result, at the same value of applied shear deformation the compression intensity of the interface zone and blocks (i. e. the values σ_{mean}) in more permeable systems is less than in less permeable ones. This effect causes decrease of the shear strength of the interface τ_c as the value of the system parameter A'_{fluid} decreases (area I in Fig. 5, *a*).

The shear strength of the interface τ_c reaches the minimum value (boundary of areas I and II in Fig. 5, *a*) at the specific "threshold" combination of filtration and deformation parameters $A'_{fluid} = A'_{crit}$. In the area $A'_{fluid} < A'_{crit}$ the ratio of fluid filtration and deformation rates becomes sufficient to maintain a non-zero fluid

pressure in the interface up to the fracture moment (curves for $A'_{fluid} = 2$ MPa shown in Fig. 5, *b*).

The shear strength of the interface τ_c reaches the minimum value (boundary of areas I and II in Fig. 5, *a*) at the specific "threshold" combination of filtration and deformation parameters $A'_{fluid} = A'_{crit}$ ($A'_{crit} \approx 20$ MPa in this case).

In the area $A'_{fluid} < A'_{crit}$ (area II in Fig. 5, *a*) the value of shear strength starts increasing as A'_{fluid} decreases. Note, that this area corresponds to the range of fluid filtration and deformation rates such that non-zero liquid pressure in the interface is maintained up to the fracture moment (curves for $A'_{fluid} = 2$ MPa shown in Fig. 5, *b*).

The reason for the increase in strength in the area II as the value A'_{fluid} decreases is a change of distribution behavior of the mean stress σ_{mean} in the cross-section of the interface zone. Fig. 5, *b* (curves for $A'_{fluid} = 2$ MPa) shows that final permeability of blocks causes occurrence of significant pore pressure gradients in the cross-section of the sample, including in the interface zone. The minimum values of P_{pore} are reached in the center of the interface, which is why this area is less subjected to inelastic deformation (and dilatancy) than peripheral areas of the interface. Consequently, distribution of mean stresses σ_{mean} on the periphery of the interface area is higher (in modulus) than that in the center. As an example, Figure 6 shows typical distributions σ_{mean} in the cross-section of the interface zone at the same value of the applied shear strain. One can see that mean stresses in the interface zone of the samples with almost impermeable blocks ($A'_{fluid} = 2 \cdot 10^5$ MPa) are maximum (in modulus) and almost uniformly distributed. As permeability of the blocks grows, the distribution σ_{mean} becomes significantly non-uniform and is characterized by two maxima (in modulus) in peripheral areas and a minimum in the center of the interface zone ($A'_{fluid} = 20$ MPa in Fig. 6). This central layer of the interface zone which is characterized by the lowest (in modulus) value of the effective mean stress is the place of future fracture. The nonuniformity of the distribution of mean stresses increases with the decrease of A'_{fluid} in the area I (see Fig. 5, *a*) and reaches the maximum level at the point A'_{crit} . In the area II (see Fig. 5, *a*), as A'_{fluid} decreases, pore pressure distribution in the cross-section of the interface zone becomes more uniform due to sufficient filtration capacity of the system. It ensures a more uniform distribution of σ_{mean} in the interface zone (the curve at $A'_{fluid} = 2$ MPa shown in Fig. 6) and, consequently, some increase of the shear strength of the sample.

At quite small A'_{fluid} (high permeability of blocks and/or low rate of applied shear strain), distribution of mean

stresses in the interface becomes almost uniform, and pore pressure in the volume of blocks almost drops to zero at the moment of fracture. This determines the end of rising trend of the dependence $\tau_c(A'_{fluid})$ and its attainment of saturation (in the area III in Fig. 5, *a*).

Fig. 6. Distribution of mean strain σ_{mean} in the cross-section of interface zone at $\varepsilon_{xy} = 0.96 \varepsilon_c^{min}$ in samples which are characterized with different values of parameter A'_{fluid} : $2 \cdot 10^5$ MPa (1); 20 MPa (2); 2 MPa (3)

Note that the described patterns of change of the system shear strength are valid for mechanically constrained localized shear bands (in this problem, the width of the sample L does not change during shear deformation) which include both localized shear bands in the thickness of bulk samples and areas of fault zones at sufficiently large depths.

4.2. General Form of the Ratio for Shear Strength of Fluid-Saturated Band of Localized Shear

Our assumptions about determining influence of the processes of dilatancy and liquid mass-transfer together with the results of numerical experiments allowed us to suggest the following form of dependence, that includes the obtained data on dependence of the shear strength of localized inelastic shear bands on permeability of the medium, fluid viscosity, characteristic band width and rate of shear strain:

$$\tau_c \approx \tau_0 + \frac{\tau_1}{1 + (c_1 A'_{fluid})^{-p}} + \tau_2 e^{-c_2 A'_{fluid}}, \quad (15)$$

where $(\tau_0 + \tau_1)$ determines shear strength of an unwatered sample; $(\tau_0 + \tau_2)$ is the shear strength of an impermeable watered sample. Parameters c_1 and c_2 characterize change rate of sigmoidal and exponential curves of dependence (15).

Note that the sigmoidal member in the equation (15) describes influence of fluid filtration on the intensity of compression of the interface zone by elastic blocks at zero pore fluid pressure. The exponential member describes

influence of filtration on the increase of pore pressure in the interface zone and, consequently, on dilatancy rate which determines the increase of mean stresses in the interface.

The values τ_0 , τ_1 and τ_2 depend on the width of the elastic-plastic interface, physical and mechanical properties of materials of blocks and interface, and on characteristics of the boundary conditions. As an example, Fig. 7 shows dependencies $\tau_c(A'_{fluid})$ for samples characterized by different intensities of initial compression and relative width of the interface zone. You can see that in the area of high values of $A'_{fluid} \sim 10^5$ MPa, which means a negligibly small influence of filtration on the change of pore pressure (in comparison with the influence of dilatancy), the specified value of the interface strength does not depend on normal load or relative width of the interface zone. At the same time, as the value A'_{fluid} decreases, which means increase of influence of filtration processes, curves that correspond to different values of σ_N and L_0/L start going apart. For instance, Fig. 7 shows that with increase of σ_N amplitude of changes of the specified value τ_c decreases throughout the entire range of values A'_{fluid} . This is associated with the fact that the relative influence of fluid pore pressure of effective stresses decreases with increase of the module of characteristic mean stresses in the system. Fig. 7, *b* shows that noticeable differences in shear strength of samples with interface zones that have different relative widths occur in the area of small values of A'_{fluid} that correspond to relatively high filtration rates (with regard to dilatancy rate). These differences are caused by the influence of "fluid capacity" of the interface zone. The amount of fluid filtered through the volume of blocks to the interface increases with increase of the interface width. At the same time, pore pressure in blocks and compressional force of the interface decrease and, consequently, the module of effective mean stresses in the interface and its shear strength decrease as well. Preliminary calculations have shown that $(\tau_0 + \tau_1) \sim (L_0/L)^{0.55}$ and $(\tau_0 + \tau_2) \sim (L_0/L)^2$. The subject of further research is determination of dependence type of parameters of equation (15) on combination of system properties.

The results of numerical studies apply for "waterproof" systems. In order to check similarities of the found patterns we performed special studies under conditions that simulate free fluid mass-transfer with the external environment. During these studies, fluid pore pressure at the upper and lower boundaries of the system (see Fig. 4, *a*) was maintained constant and equal to the value at the beginning of shear deformation. These conditions simulate fluid redistribution in an infinite permeable fluid-saturated medium. The modeling results have shown that the type of dependence of strength on the ratio of filtration and deformation rates (15) obtained for "waterproof" samples also applies to the samples with permeable boundaries

(there are only changes of numerical values of the parameters c_1 , c_2 and p).

Fig. 7. Example of dependencies of interface shear strength on the parameter value A'_{fluid} at different values of shear strain $\dot{\epsilon}_{xy}$:

- (a) is at different values of normal loading ($L_0/L = 0.052$);
- (b) is at different widths of interface zone ($\sigma_N = 41.7$ MPa)

Thus, nonlinearity and nonmonotonicity of dependence of the interface shear strength of blocks in brittle permeable mediums on the ratio of filtration and deformation rates is determined by using three processes together: 1) dilatancy of elastic-plastic interface under conditions of reaching the yield limit and corresponding increase (in modulus) of mean stresses in this interface; 2) transfer of liquid from filtration volume of elastic blocks to filtration volume of the interface zone and 3) redistribution of liquid pore pressure followed by this transfer.

6. Conclusion

The presented modeling results show that influence of the fluid in fracture pore space of permeable brittle materials on its strength is determined by competition of processes of the solid-phase skeleton deformation and fluid filtration initiated by a non-uniform distribution of volumetric deformations in the skeleton. In this connection, the type of dependence of the material strength on the rate ratio of these processes can qualitatively change with

increase of the absolute value of volume stresses in the skeleton.

At low compressive mean stresses which are usually lower than the material strength under pure shear conditions, brittle materials show an elastic response up to fracturing. Under such conditions, influence of pore-fluid filtration on the stress condition and strength of permeable brittle materials becomes significant under loading, which provides a continuous change of the pore space volume. For instance, in non-isolated systems under load that can exchange fluid with the external environment, competition between processes of pore pressure growth due to pore volume compression and outflow of excessive fluid from the system leads to the logistic dependence of the sample strength on the ratio of constants that determine rates of these processes. At the same time, the strength value reaches the lower limit under conditions close to the loading of waterproof samples and tends to the maximum limit as loading conditions become similar to free fluid mass-transfer with the external environment. It is significant that transition from the minimum strength values to the maximum ones is achieved in a quite narrow range of the rate ratio of competing processes which is one order of magnitude, and the absolute strength value can vary several-fold.

In the area of high values of compressive stresses that provide macroscopically inelastic behavior of brittle materials, the key factor that determines the type of influence of competition of deformation and filtration processes is localization of inelastic deformation in the form of localized shear bands. Inelastic shear in these bands is characterized by inelastic increase of the volume of fracture pore space (dilatancy). Therefore, in comparison with the elastic-brittle behavior, in this case, even under conditions of macroscopic compression or constrained shear, areas (bands) are formed in which fluid pore pressure drastically drops. The strength of samples is determined by the strength of localization bands which depends on the fluid inflow rate (not outflow rate). Consequently, logistic dependence of the sample strength under high external pressures has the opposite form with respect to the elastic-brittle pressure area: in the area of system properties that provide high fluid filtration rates, the strength of samples is significantly lower than that without or with insignificant influence of filtration. It is important to emphasize that under conditions of integral system compression competition between multidirectional processes of elastic compression of the pore space and its irreversible increase (dilatancy) causes an additional (in addition to logistic one) influence on dependence of the strength on the rate ratio of skeleton deformation and fluid filtration processes.

Similar conclusions were drawn earlier by different authors that had used qualitative analysis of experimental data and analytical estimates [23, 24, 26, 31, 39]. This is the first work that shows generalized analytical expressions describing dependence of the strength of permeable brittle samples on the ratio of parameters that determine filtration and deformation rates. These expressions show that the

strength of fluid-saturated materials depends not only on physical and mechanical properties of fluid and skeleton, but also on deformation rate, even in the area of small values of this parameter, where the strength of non-watered samples can be considered constant.

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