Microscopic mechanical model of the main structural element of Bazhenov Suite reservoir rocks

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Abstract. We propose a microscale model of the main structural element (“bearing” layers) of kerogen-clay-carbonate-siliceous rocks of the Bazhenov formation. The model treats the rock as a composite material with inorganic clay matrix and different content of organic inclusions (up to 25%) and micropores filled with low-viscous fluid (light hydrocarbon fractions). A computer simulation of the mechanical behavior of representative samples of structural elements of the studied rock under triaxial compression was carried out using the hybrid cellular automaton method and a coupled mechanical model that takes into account the mutual influence of porous rock deformation and filtration of a pore fluid. It is shown that the mechanical behavior of the “bearing” layer of rock at side pressures that meet the characteristic conditions of occurrence is satisfactorily described by rock plasticity models with two-parameter flow functions.

1. Introduction
The Bazhenov formation of the West Siberian oil and gas basin is recognized as one of the most promising targets for oil production. The oil collector in the Bazhenov Suite is fundamentally different from the previously developed fields [1-3]. This significantly complicates the development of this field. The influence of the well design and the opening method on the oil inflow was noted already at the early stages of studying the Bazhenov formation [4]. The processes of damage accumulation in the reservoir when it is opened for repressurization and a significant amount of drilling mud is introduced into the rock and clogs the bottomhole zone, have a decisive influence on the productivity of wells in fluid-saturated elastic-plastic fractured-porous reservoir in high-carbon kerogen-clayey-siliceous rocks. Previously, these processes were practically not studied due to the lack of verified adequate mathematical mechanical models of anisotropic elastic-plastic rocks of the Bazhenov formation. This model should be multiscale and based on microscale models of the structural elements of the reservoir. The aim of the present work is to develop a model of the mechanical behavior of fluid-saturated high-carbon kerogen-clay-carbonate-siliceous rocks that form the oil reservoirs in the Bazhenov Suite.

The numerical study of deformation of rocks is traditionally carried out using continuum mechanics based numerical methods (finite element and finite difference methods). Despite the well-known advantages of the continuum mechanics approach, these numerical methods have limited capabilities to directly study deformation processes in fluid-saturated materials and media accompanied by multiple fracture of the solid skeleton (including collapse of pores) and the contact interaction of fracture surfaces. These limitations are not inherent in numerical methods related to the...
particle-based concept of representing the heterogeneous solids. One of numerical methods of this group is the movable cellular automaton (MCA) method [5, 6]. Its formalism combines the advantages of a well-known discrete element method in the modeling of multiple fracture, and also makes possible implementation of various models and criteria of elasticity, viscoelasticity, plasticity and strength. Recently, the MCA method was modified to model interrelated processes of deformation of porous fluid-saturated materials and fluid filtration in their pore space (the hybrid cellular automaton method [7]). In the present work, this method was used to study the patterns of mechanical behavior of main structural element of the Bazhenov formation reservoir rock (the “bearing” layers separated by asphalten interlayers).

2. Model description

We proposed a microscale model of kerogen-clay-carbonate-siliceous rocks of the Bazhenov formation. The model describes the structure of the “bearing” layer as a composite material with an inorganic clay matrix and different (from <5% up to 20-25%) content of organic “inclusions” [4] and micropores filled with light petroleum fractions. The developed model was implemented in the framework of the hybrid cellular automaton method. The sample, which models a microscopic region of the “carrier” layer, is represented as an ensemble of discrete elements (movable cellular automata). Each element simulates a part of porous solid phase (solid skeleton). Pores smaller than a discrete element are taken into account implicitly through the effective mechanical properties of discrete elements (elements are treated as porous and permeable). The mechanical influence of interstitial fluid on the stress-strain state of discrete element is described with the Biot model of poroelasticity and the model of poroplasticity of rocks using Terzaghi’s effective stresses. Fluid flow in the pore space of the skeleton is modeled using the equation of fluid density transfer. A detailed description is given in [7]. Figure 1 shows a typical 2D model of the microscopic region of the main structural element of the Bazhenov formation reservoir rock.

![Figure 1. The structure of the sample modeling the representative “microscale” volume of the bearing element of the rock.](image1)

Microscale model of the “bearing” layer takes into account layered inclusions of organic substances enclosed in a clay matrix. Available information on the mechanical characteristics of such inclusions is extremely limited. Therefore, we modeled organic substances as a highly ductile material. The elastic moduli and parameters of the plasticity model were assumed to be close to the corresponding characteristics of xylite (“unprocessed” wood component of young brown coal lignite). The clay matrix of the sample was modeled as an elastoplastic material with mechanical characteristics close to kaolin clay. Hooke’s law for locally isotropic materials was used to describe the elastic mechanical response of the matrix and organic inclusions. The inelastic behavior of the components was described using the non-associated Nikolaevsky's plasticity model [5, 7].

![Figure 2. Scheme of the sample loading.](image2)
The fluid component of the “bearing” layer was taken into account in two ways. Pores smaller than a discrete element were taken into account implicitly through the parameters of the Biot poroelasticity and poroplasticity models [7]. These pores are filled with mobile fluid (light fractions of hydrocarbons). Larger pores (the size of which exceeds the diameter of the discrete element) were taken into account explicitly. It was assumed that the fractional composition of hydrocarbons in these pores is heterogeneous and contains heavy viscous fractions in addition to light fractions. Heavy fractions form a kind of soft “skeleton” with mobile light-low-viscous fractions inside. Such a “complex” fluid in large pores was simulated by an ensemble of highly porous automata (porosity $\gamma \sim 30$–50%). The properties of these discrete elements were determined in such a way that in case of filling the pore space of the heavy fraction “skeleton” (HFS) with light fractions (taken into account implicitly by the Biot poroelasticity model) the bulk modulus of such an element is equal to the bulk modulus of the simulated mobile pore fluid. The fluid mechanical properties in large pores are close to the properties of the light fractions of petroleum or gasoline.

The main mechanical characteristics of the components of the model materials are listed in Table 1.

|                     | Clay matrix | Organic matter | HFS     |
|---------------------|-------------|----------------|---------|
| Density, kg/m$^3$   | 2250        | 1500           | 1000    |
| Poisson ratio       | 0.1         | 0.15           | 0.46    |
| Young’s Modulus, GPa| 15          | 2              | 0.1     |
| Yield stress, MPa   | 50          | 2              | -       |
| Internal friction coefficient | 0.12 | 0               | -       |
| Dilatancy coefficient| 0           | 0              | -       |
| Compressive strength, MPa | 100  | -              | -       |
| Tensile strength, MPa | 25           | -              | 0.01    |

A 2D simulation was carried out assuming the plane stress state. We applied the generalized formulation of this approximation with constant but non-zero stress $\sigma_z$ in the normal axis to the considered plane $\sigma$. The triaxial compression tests of microscale fluid-saturated samples were simulated (Figure 2). The elements of the upper and lower surfaces of the sample are affected by a constant velocity $V$ along the Y axis. A constant compressive force $F$ along the X axis was applied to the automata of the side surfaces. The compressive stress $\sigma_z$ was specified equal to the specific value of the side force $F$. It is known that the modeled reservoir rocks are located at depths from 1 to 3 km [4], and the value of the horizontal pressure depends on the depth. Therefore, three values of horizontal pressure corresponding to different depths of the rock (1 km ~ 10 MPa, 2 km ~ 20 MPa, 3 km ~ 30 MPa) were considered.

3. Results
At the first stage of the study we analyzed the behavior of the model without mobile pore fluid (clay matrix and organic inclusions are “dry” and large pores contain only heavy fraction skeleton). We simulated the triaxial compression tests of microscale samples located at depths of 1 km, 2 km and 3 km. Figure 3 shows compression diagrams of sample at three horizontal/side pressures corresponding to the mentioned depths. Each curve can be divided into two main parts: the stage of elastic deformation and the stage of a pronounced inelastic behavior accompanied by low-amplitude sharp fluctuations (drops) of the stress. Drop in the axial stress is associated with the formation of damage in the sample, as well as with their integration into the internal cracks. Due to the peculiarities of the stress state (triaxial compression) the separation of the sample into parts does not occur and the sample continues to resist the applied loading and accumulate the damages and cracks.
Figure 3. Sample loading diagrams at different side pressures corresponding to different depths.

An important factor affecting the behavior of the sample is the magnitude of the horizontal (side) pressure. The change in the value of the side pressure has a significant effect on the quantitative characteristics of the sample mechanical behavior. In particular, the value of the axial stress at which the transition from the elastic stage to the plastic stage takes place changes significantly with a change in the value of the side pressure (or, equivalently, the depth) by 1.5-2 times (Figure 3).

Traditionally, materials that are characterized by the dependence of mechanical properties on the hydrostatic pressure are described by models with two-parameter plastic flow criteria. Such criteria often include the first invariant of the stress tensor, which allows taking into account the effect of mean stress on the mechanical characteristics of the material.

The simulation results described above can be presented in an invariant form (using invariants of stress and strain tensors). Analysis of the results showed that the use of a linear combination of the first and second invariant, which the basis of the plasticity criteria of Coulomb-Mohr, Drucker-Prager, Nikolaevsky and others, allows us to describe the behavior of the sample at different depths using a single mathematical formalism. Figure 4 shows the loading diagrams expressed in invariant values in the form of Mises-Schleicher (linear combination of the first and second invariants of the stress tensor or strain tensor, respectively [5]). To calculate the invariant values $\sigma_{ms}$ and $\varepsilon_{ms}$, we used the integral values of axial stresses and strains that were taken from the surfaces of the sample, or averaged over the sample volume (in the case of $\varepsilon_{zz}$). In this case, the value of the coefficient at the first invariant of the stress tensor (internal friction coefficient $\alpha$) is assumed to be constant and chosen so that the transitions of the curves from the elastic to the plastic stage coincide with each other. The fitted value is $\alpha = 0.02$.

Figure 4. The invariant form of sample loading diagrams shown in Figure 3 (triaxial compression).
Some differences between the three loading diagrams in Figure 4 appear only at the plasticity stage due to the different damage accumulation rates. The rate of damage accumulation depends on the magnitude of the side pressure. The analysis of the curves showed that the difference in the dynamics of damage accumulation is not fundamental. Therefore the behavior of the sample at different depths can be approximated with good accuracy by a single plasticity function \( \sigma_{ms} = A_1 + B_1(C_1 + \epsilon_{ms})^{0.6} \).

Bearing layers have clear microscopically inhomogeneous structure, which causes anisotropy of the integral properties. To study this factor we also simulated triaxial compression tests of the model samples with applied constant loading velocity along the X-axis and constant compressive force along the Y-axis. We applied the same values of compressive forces, which correspond to the above mentioned values of the side pressure. As in above simulations, compressive stress \( \sigma_c \) equal to the side pressure was also applied along the Z-axis.

The simulation results confirm the significant anisotropy of the mechanical properties of the sample (Figure 5). Shown loading diagrams differ significantly from similar diagrams obtained by compressing the sample along the Y-axis. However, this difference is quantitative, but not qualitative. The X-axis compression diagrams has the same features as for the loading diagrams along the Y-axis, and their (plastic stage) can be approximated with a certain accuracy by some power function. It should be noted that the index of power function approximating these curves differs from the index in the case of loading along the Y-axis \( (\sigma_{ms} = A_2 + B_2(C_2 + \epsilon_{ms})^{0.45}) \). Also, the fitted values of internal friction coefficient differ by an order of magnitude \( (\alpha = 0.12 \text{ for the case of loading along the X-axis versus } \alpha = 0.02 \text{ for the case of loading along the Y-axis}) \).

![Figure 5](image_url)

**Figure 5.** Invariant form of triaxial compression diagrams for the sample with “ductile” clay matrix: (1) compression along the Y-axis; (2) compression along the X-axis.

Experimental studies of the Bazhenov formation indicate at least two lithotypes of sediments. The first type includes plastic, the most high-carbon thin-layered silicates enriched in clay material. The second type includes brittle radiolarites and carbonates with low organic matter content (less than 5%), extremely low clay content and high mineralogical density [4]. The Bazhenov formation consists of alternating interlayers of the first and second types. Therefore we simulated compression tests of microscale samples with mechanical properties close to deposits of the second type. The structure of the sample of “brittle” sediments (Figure 6) is generally similar to the structure of the “ductile” sample discussed above (Figure 1). At the same time, the volume fraction of organic substances in the sample is reduced to 5%, and the matrix is modeled as elastic-brittle (the elastic and strength characteristics of the material of the matrix are equal to the “ductile” matrix, but there is no inelastic stage).
The triaxial compression tests of brittle samples were modeled at the same values of side pressure. The scheme of numerical experiment is the same as described above. The loading diagrams expressed in an invariant form are shown in Figure 7. The internal friction coefficient used to build common plasticity function ($\alpha = 0.3$) differs significantly from the internal friction coefficient for the samples with “ductile” matrix. This difference is due to the fact that the transition to the inelastic stage for a sample with an elastic-brittle matrix is determined by the applied fracture criterion. In the study we used the Drucker-Prager fracture criterion that is formally similar to the Mises-Schleicher plasticity criterion. Note that the value of coefficient at the first invariant in the fracture criteria, as a rule, significantly exceeds the value of internal friction coefficient in the criterion of plasticity.

At the first stage of the study we analyzed the behavior of the model with mobile pore fluid (clay matrix, organic inclusions and large pores contain mobile fluid modeling light fractions of hydrocarbons). Filtration of mobile fluid in the pore space of the sample was taken into account. We considered the samples of the first type (“ductile” matrix). It was assumed that the value of open porosity of the matrix and organic inclusions is 5%. The characteristic size of pores controlling fluid filtration in the matrix and the organic inclusions was assumed to be about 0.5 μm. The bulk modulus of the material of skeleton walls of porous matrix was specified 2 times higher than the modulus of the skeleton itself. The value of initial fluid concentration in the pore space of the sample (before the compressive load was applied) was assigned so that the fluid completely filled the pore volume (initial pore pressure is equal to atmospheric pressure). The input data used in the Biot poroelasticity and poroplasticity models [7] is shown in Table 2.

| Table 2. Biot model parameters for sample components. |
|------------------------------------------------------|
| Clay matrix | Organic matter | HFS |
| Open porosity, % | 5 | 5 | 30 |
| Permeability, $m^2$ | $1.25\times10^{-14}$ | $1.25\times10^{-14}$ | $7.5\times10^{-12}$ |
| Bulk modulus of skeleton walls, GPa | 37.5 | 5.7 | 6.6 |
| Coefficient of influence of pore pressure on yield stress and strength | 1 | 0.1 | - |

The simulation results showed that the mechanical behavior of Bazhenov formation rock samples changes significantly due to the taking into account the influence of fluid pressure on stress-strain state of the sample. Figure 8 shows the invariant forms of loading diagrams of the “fluid-saturated” samples at the different values of horizontal pressure imitating different depths. It can be seen that the strain hardening (slope of the curve at the plastic stage) depends on the value of the applied pressure.
Figure 8. Loading diagrams for triaxial compression of fluid-saturated sample with “ductile” clay matrix. Fluid filtration in the pore volume is taken into account.

In the first approximation we can assume that the dependence of the strain hardening modulus on the value of applied side pressure is linear. Therefore, the description of fluid-saturated rocks of the Bazhenov formation at the higher (mesoscopic) structural scale can be carried out on the basis of the two-parameter modified Mises-Schleicher plasticity criterion using the effective values of the stress tensor components as defined by Terzaghi.

4. Conclusion
We showed that the pronounced anisotropy of inelastic mechanical properties is characteristic for the Bazhenov formation rocks at the microscopic scale. At the same time, the anisotropy of the properties is expressed only in quantitative characteristics (parameters of the yield function), while the features of inelastic behavior are common for different directions of deformation. The mechanical behavior of the reservoir samples is satisfactorily described based on the use of mechanical models of rocks with two-parameter plasticity functions. The plasticity function in the form of Mises-Schleicher which takes into account the contributions of the local pressure and stress intensity in the linear approximation is proposed to describe the Bazhenov formation rocks at the mesoscale. Note that the estimated values of the internal friction coefficient of this function for mutually orthogonal directions of loading differ by almost an order of magnitude. This indicates the determining contribution of the microscopic organic component to the rheological characteristics of the kerogen-clay-carbonate-siliceous rocks.

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