MODELING OF METHANE RELEASE FROM INTACT COAL

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Development of percolating clusters when loading samples of a geomaterial that is hierarchically and stochastically heterogeneous is modeled. The conditions are analyzed for propagation of crack under pressure of methane in the transition phase from a bound state into a free one on the faces of the growing crack in coal.

Coal, hierarchical structure, methane, transportation channel, fractal crack

Intact natural coal is a heterogeneous geomaterial with complex structure of pores and high methane content. There is only a small portion of free methane (5–10%) in meso- and macropores. The methane molecules in the bound (absorbed or dissolved) state are mainly in micropores of nanometer dimension and inside hard coal substance [1]. Up to now it is unknown how the bound methane can release from initially almost impermeable coal under sudden coal and gas outbursts and during methane production from coal seams.

The studies of disintegration of the coal substance — methane system are based on different physical approaches [2–7]. Along with the development of new physical and physicochemical models, it is reasonable to modify mechanical models of methane-saturated coal failure as they can be used in geomechanical researches on coal mining. In the models considered below, the effect of heterogeneities in forming induced channels for the methane molecule migration and developing the methane-filled cracks is discussed.

MODELING OF HIERARCHICAL-HETEROGENEOUS GEOMATERIAL FAILURE

A rock and a natural coal have hierarchically heterogeneous structure traced within a scale range from a mine-field to a molecule. In any structural elements of these geomaterials, there are petrophysical and mechanical heterogeneities (inclusions, blocks, fissures) of less size [8–11]. According to the contemporary concepts, self-organization takes place in any open complex system in the course of its evolution and results in the formation of hierarchical structure [8].

Different approaches, including the scale invariance (self-similarity) and fractal [12–17] are employed to study the features of geomaterials with the hierarchical structure. In the present paper, the self-similarity conception is used for modeling distribution of permeable elements in a material with hierarchical heterogeneity with respect to Young’s moduli and strengths. The similar problems were discussed in [15, 18].

In modeling, a cubic sample made of an initially impermeable material was loaded from above and from the bottom by a vertical force \( Q \). The structure of the material hierarchy corresponds to the structure of “embedded blocks” [9–11, 16]; that is, each element (block) of a hierarchical level can be divided into a definite number of elements (blocks) of the following, lower hierarchical level.

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At first, consider a model material where elements have unequal Young’s moduli $E$. An element of the $i$th hierarchical level is assumed to be a cubic domain of a geomaterial with an edge length $s_0 / K^i$, where $s_0$ is the length of the sample edge, $K$ is the scale factor ($i = 0, 1, 2, 3, \ldots$). As follows from [9], let $K = 3$ so that each element of the $i$th level consists of 27 elements of the level $i + 1$. These elements are united into three horizontal layers by nine elements in each.

In each layer the values of Young’s modulus for the elements are distributed in a random way. The distribution of relative deviations $\Delta E / E_i$ for Young’s modulus of the elements from an average value in a layer is determined by a row: $-2\delta, -\delta, 0, \delta, 2\delta$ at probability $1/9, 2/9, 3/9, 2/9, 1/9$, respectively (an analogue of Simpson’s distribution), $\delta$ is the heterogeneity parameter.

For the given value of the force $Q$, find the vertical stresses in the elements of lower hierarchical levels in series, on the basis of the model of statically undetermined rod system. Assume that the following self-similarity conditions exist: a) in each element of the $i$th level the distribution of Young’s moduli for the elements of the $(i + 1)$th level is the same; b) in each element of the $i$th level the vertical strains in the elements of the $(i + 1)$th level are the same.

By calculations we obtain the distribution of stresses in the elements of the heterogeneous model material. If the lower hierarchical levels are taken into account, the heterogeneity in the stress distribution increases. Dividing the force value by an area of cross-section of the corresponding elements gives the values of the vertical stresses $\sigma$ in the elements.

For the last of the considered hierarchical levels, the vertical stresses are compared to the uniaxial compression strength $\sigma_0$, which has the same value for all elements.

If $\sigma > \sigma_0$, the element, where this condition exists, is considered as failed. Here, we interpret failure as a partial rupture of structural bonds, which leads to discontinuity, and the initially impermeable element acquires the property of permeability.

The typical situations in the stochastic distribution of permeable elements in a material are revealed by statistical testing. The results of a test are shown in Fig.1a–c, where a cubic sample is divided into layers. The permeable elements of the second hierarchical level were marked in black. The drawings are very informative thus the similar drawings of the permeable elements of the third and the next levels are not presented.

Figure 1a–c demonstrates the case when $\delta = 0.15$, and a ratio $\sigma = Q / s_0^2$ of the averaged load and strength $\sigma_0$ is equal to 0.67, 0.87, and 1.0, respectively. In Fig. 1a the local permeability subdomains form a chain passing through the whole sample, that is a percolating cluster [19]. It is assumed that there is a permeable contact between the black cubes if they have at least one common corner. The cumulative volume of such permeability zone amounts to about 6% of the total volume $W$ of the sample.

If the permeable contact between the black cubes is possible only when their facetsways touch each, the percolating cluster forms at $\sigma = 0.87 \sigma_0$ (Fig. 1b). In this case, the cumulative volume of the permeability zone is $0.35W$.

In Fig. 1c the permeability zone is shown when the load on the sample is such that $\sigma = \sigma_0$. Here, the volume of the permeability zone becomes $0.54W$. The failed elements, when connect, form areas that can be considered as macrocracks since they separate the sample into portions. So, modeling reveals the phenomenon of macrofailure of sample under ultimate load.