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From Digital Core Samples to Thermodynamically Compatible Model of Porous Media

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SUMMARY

We present a digital rock physics workflow to construct the thermodynamically compatible model governing seismic wave propagation in fluid filled porous media. Starting with the X-ray microtomograms the workflow includes:

- image processing techniques to construct digital model of the rock sample;
- hydrodinamical modelling to estimate filtration characteristics;
- static mechanical loading to reconstruct the mechanical properties of the dry rock sample;
- computation of the thermodynamically compatible model coefficients.

Presented approach allows to proceed from the microscale (pores, grains) to mesoscale (fractures, thin layers) model accounting for the mechanical and the filtration characteristics of the rock.

Introduction

Modern full waveform inversion and true amplitude imaging (Protasov and Tcheverda, 2011) procedures allow using valuable information about dynamics of wave propagation, thus frequency dependent features of wavefield, typically connected with fluid-saturation and local fluid flows in the rocks, such as attenuation seismic energy, dispersion of wave-package etc. can be used to reconstruct the permeability of reservoirs. However, there is a lack of phenomenological models governing seismic wave propagation in saturated rocks, taking into account the energy exchange between fluid and solid phases. The most well-known approach is the Biot model (Biot, 1956), however it has two principal drawbacks. First, it is not strictly hyperbolic that makes it difficult it implement this model for numerical simulations. Second, there is no clear connection between the coefficients of the Biot model and the microstructure of the rock. To overcome these difficulties the thermodynamically compatible model (TCM) of porous media was suggested in (Romenskiy et al. 2014), which was derived based on the conservation laws for two phase media. As the result the model is represented in divergence-free form, thus easy to use for numerical simulation, and all the coefficients are represented via rock microscale structure explicitly.

To construct the TCM for the particular rock sample with further analysis of stable manifestation of the microstructural features of the rock (fluid content; permeability; tortuosity, fractal dimension, topology of the porous space and solid phase) in this paper we suggest a digital rock physics workflow. Starting with the X-ray microscans the digital model of the core sample is computed based on the 3D image processing procedures. After that hydrodynamical and static elastic simulations are applied to reconstruct hydrodynamic permeability of the sample and elastic moduli of the dry rock sample. On the base of this information the TCM can be uniquely determined and used for simulation of seismic wave propagation in fluid-filled porous media.

Thermodynamically compatible model of porous media

To account for the fluid saturation of porous media when simulating seismic wave propagation we suggest using the thermodynamically compatible model (TCM), based on conservation laws (Romenskiy et al. 2014), written as velocity-stress formulation:

$$\rho\frac{\partial u^1}{\partial t}-\left(\frac{\rho}{\rho_1}-\alpha_1\right)\nabla p-\alpha_1 div\sigma=-c_2\chi\left(u^1-u^2\right)$$

$$\rho\frac{\partial u^2}{\partial t}+\left(\frac{\rho}{\rho_2}-\alpha_1\right)\nabla p-\alpha_1 div\sigma=-c_1\chi\left(u^2-u^1\right)$$

$$\frac{\partial p}{\partial t}+\alpha_1\widetilde{K}divu^1+\alpha_2\widetilde{K}divu^2=0$$

$$S\frac{\partial \sigma^1}{\partial t}=\frac{1}{2}c_1\left(\nabla u^1+\left(\nabla u^1\right)^T\right)+\frac{1}{2}c_2\left(\nabla u^2+\left(\nabla u^2\right)^T\right)$$

$$\chi=\frac{\eta}{\gamma\kappa},\qquad \frac{1}{\widetilde{K}}=\frac{\alpha_1}{K_1}+\frac{\alpha_2}{K_2},\qquad \rho=\alpha_1\rho_1+\alpha_2\rho_2$$

where ρ – mass density of composition, ρ_i – mass density of elastic and fluid phase, p – pressure, σ – stress tensor, α_1 – volume concentration of elastic medium (α_2 – of fluid) (α_2 = 1 - α_1, α_2 – porosity), c_1 – mass concentration of elastic medium (c_2 - of fluid) (c_2 = 1 - c_1), u_i – velocity of composition, u_i^1, u_i^2 – velocity of an elastic and liquid phases, χ – interface friction, η – dynamic viscosity of the fluid, γ – dimensionless coefficient, κ – permeability,

One of the main advantages of this model is the fully determined relations between microstructural properties of the rock and the coefficients of the TCP. In particular, the mass forces are defined by the densities of the solid and fluid phases; averaged bulk modulus is the harmonic average of those for fluid and solid phases, the effective compliance tensor is that of the dry rock. The dissipation of the seismic energy is governed by the interphase exchange, depending on the fluid viscosity, rock permeability, and tortuosity. Thus, construction of the TCM requires the detailed knowledge about the microscopic structure and properties of the rock, which can be obtained from the X-ray microscans.

From X-ray scans to a digital model

X-ray computed tomography (CT) provides excellent means for high-resolution 3-D imaging of such features. Fig.1 shows the workflow of building the digital model from CT-images. First, the non-local means filter (Buades et al. 2005) is applied to images for deleting the high-frequency noise. Later, the segmentation step divides all pixels into two groups – grains and pores. The Otsu (1979) method is used for the segmentation.

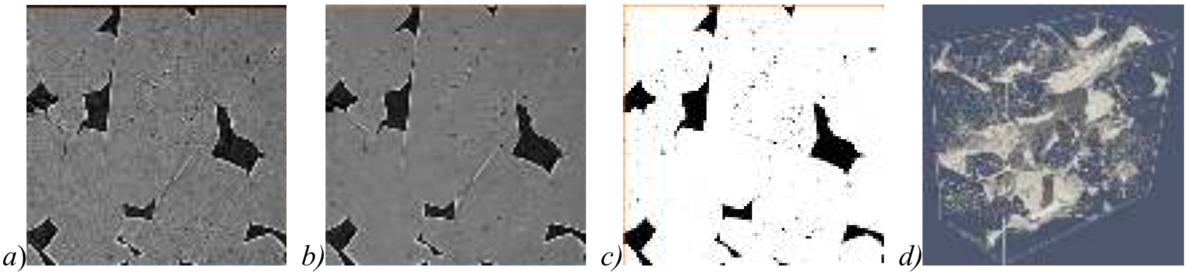


Figure 1 *Illustration of workflow for building the digital model of Dry Fontainebleau sandstone. a) initial image, b) non-local means filter result, c) Otsu method of segmentation result, d) digital model of sample – this is the pore space.*

The next step is the grids generation for numerical simulations. Fig. 2 shows the workflow of tetrahedral grids building. First, a surface mesh is created on the basis of an isosurface. Then tetrahedral grids are constructed by TetraGrid routine. Grids for solid and liquid phases are used for geomechanical and hydrodynamical simulations, respectively.

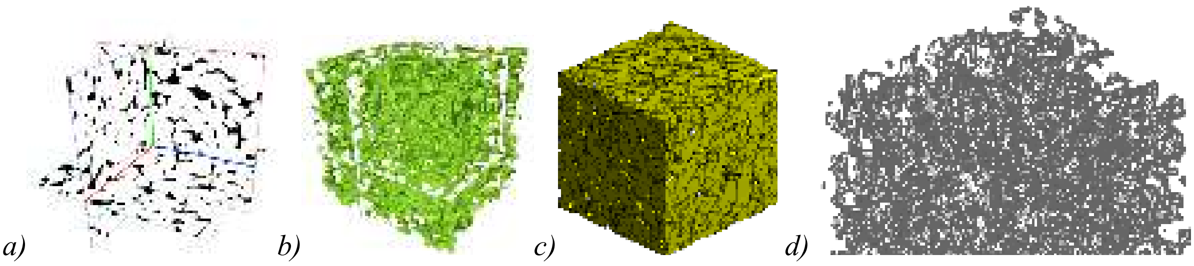


Figure 2 *Stages of building of tetrahedral grids. a) digital model of sample, b) generated surface, c) grid for solid phase, d) fragment of grid for liquid phase.*

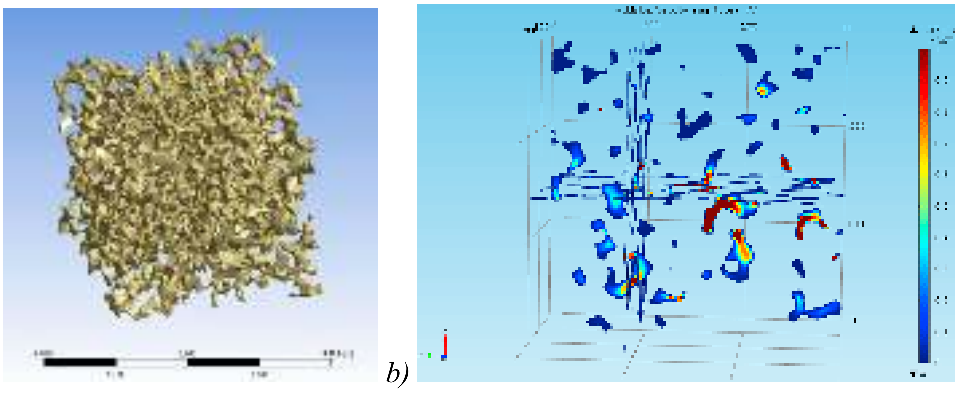
Hydrodynamical simulation

The hydrodynamical simulation of fluid flow in porous space is based on the solution of the Stocks equation. Specifying pressure drop the distribution of fluid velocities can be computed in each point in porous space. Fig. 3 shows the results of simulation in form of 3D slices. The total flow rate and permeability are calculated according to the equations:

$$Q = \int_S \vec{u} * \vec{n} * dS, \quad K = \frac{Q * \mu * l}{\Delta p * S},$$

where Q – total flow rate, u – velocity vector, S – cross-sectional area, K – permeability, μ – dynamic viscosity, p – pressure, l – length of sample in flow direction.

The porosity is directly derived from a digital model as the ratio of porous space volume to total volume of sample. The distribution of fluid velocities is used for calculation of the effective porosity. Only porous volume with non-zero velocities is taken into account.



a) b)

Figure 3 *The result of hydrodynamical simulation of the fluid flow in porous phase. a) porous space, b) calculated field of velocities in form of 3D slices.*

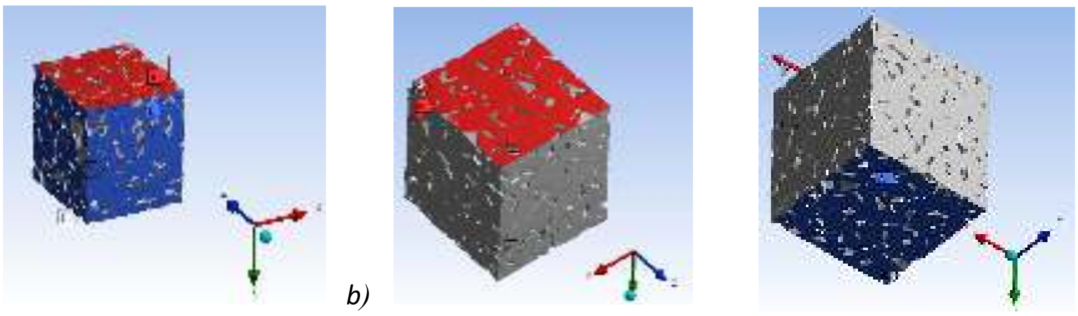
Assuming the fluid velocities distribution, it is also possible to count the tortuosity. Tortuosity is a parameter describing an average elongation of fluid streamlines in a porous medium as compared to free flow. The method for tortuosity calculation was proposed by Duda (2011) according to equation:

$$T = \frac{\int_V u(\bar{x})dV}{\int_V u_1(\bar{x})dV},$$

where T – tortuosity, u – velocity, u_l – velocity component, which is parallel to flow direction.

Reconstruction of elastic moduli

The calculation of the elastic parameters of porous medium is based on the numerical simulation of the static stress test of rock sample (Shulakova et al. 2013). It is possible to find the solution of linear elasticity theory in a static setting as the tensor of stiffness.



a) b)

Figure 4 *Numerical geomechanical simulation. a) unilateral compression, b) shear deformation.*

Conclusions

In this paper we presented a detailed description of the workflow to determine the parameters of the macroscopic thermodynamically compatible model governing seismic wave propagation in fluid-saturated porous media. The model is described by the system of hyperbolic equations which makes it easy to implement numerical methods such as finite differences or discontinuous Galerkin for simulation wave propagation taking into account the effects of fluid saturation and mobility. Reconstruction of the model coefficients is based on digital rock physics methods. The initial data are the microtomographic scans of the rock samples and knowledge of the mineral compound. Using image processing techniques the digital model of the core sample is reconstructed. After that the hydrodinamical and static elastic simulations applied to digital model are implemented to reconstruct the macroscopic model parameters.

Acknowledgements

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