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Digital-rock simulation of stress-dependent porosity and permeability for carbonate rocks

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During fluid production or injection, the reservoir rock undergoes deformation due to the temporal variations of the effective stress field, which can alter the rock porosity and permeability, and further affect the reservoir performance. Previous digital rock models primarily emphasized the quantification of rock properties of the original core, meanwhile often neglecting the alterations of rock properties under dynamic stress. For example, the stress-dependent porosity and permeability are often ignored, leading to disparities between the actual rock measurement and the values calculated by the digital rock models. Carbonate reservoirs exhibit significant heterogeneity in pore distribution, hence it becomes imperative to conduct post-compaction simulation of the stress-dependent properties for carbonate rocks.

Based on the digital rock methodology, our study constructed digital rock models using the real data from carbonate rock CT scan. The median filtering method was employed for noise reduction. Subsequently, simulation of uniaxial compression was conducted. Firstly, the solid mechanics simulation was performed to simulate the deformation of the rock matrix within the core after compression under various stress conditions (e.g., changing the confining stress under the constant axial stress). The digital rock models after compaction were then constructed. Secondly, the separation of the rock skeleton and pores was executed for the compressed rock as shown in Fig. 1. Then, the pore mesh model was reconstructed and gridded to generate a digital model exclusively containing the pores as shown in Fig. 2. Following this, the fluid dynamics simulation was carried out to obtain the porosity and permeability data of the rock after stress-induced deformation and finally, the evolution law of rock porosity and permeability to the effective stress.

The rock strain analysis reveals that the stress-induced deformation primarily occurs within the fractures of the fractured rocks. The rock skeleton undergoes minimal changes, and the fixed constraint surface (bottom surface) remains stationary, with displacement intensifying closer to the axial compression loading surface (the top surface in Fig. 3), as the external load increases, the changes of the rock become more obvious. The stress concentration phenomenon occurs at the interface between the skeleton and pores. The closer to the pores, the more pronounced this stress concentration becomes. Specifically, at the same height, the displacement of the pores after compression is consistently the largest, and the overall deformation of the rock is more significant in the middle and smaller on both sides. In places with a high degree of tortuosity, the flow velocity is relatively small as shown in Fig. 4. Our calculation shows as the external loads increase, the porosity and permeability would decrease, showing a nearly linear decreasing trend.

In this study, we established an improved digital rock model considering the stress-dependency effect and calculated the porosity and permeability under varying stresses through the coupled simulation of fluid dynamics and solid mechanics. This provides the theoretical foundation for a more accurate description of the formation properties after fracturing. Simultaneously, it offers insights that can guide the computation of properties for other porous rocks, such as tight sandstone and shale.

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Primary authors: Mr PU, Ziyi (Southwest Petroleum University); Dr TIAN, Ye (Southwest Petroleum University); Mr LEI, Yangyang (SINOPEC Zhongyuan Oilfield Company); Mr YANG, Yi (Southwest Petroleum University); Ms LI, Ying (Southwest Petroleum University); Dr ZHAO, Yulong (Southwest Petroleum University)

Presenter: Dr TIAN, Ye (Southwest Petroleum University)

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