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Unsupervised resolution boosting of µCT scans integrated into a supervised convolutional network to predict 3D rock properties

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The anticipation of fluid transport behavior within porous media holds significant importance in a diverse array of applications, encompassing subsurface hydrology (Hu and Pfingsten 2023); petroleum industry (Moslemipour and Sadeghnejad 2021), geothermal energy utilization (Meller et al. 2017), and secure subsurface storage of hydrogen or CO2 (Esfandi et al. 2023, Kanaani et al. 2023). Pore-scale properties can be obtained by building a reliable digital twin of porous media through the digital rock physics (DRP) workflow (Sadeghnejad et al. 2022).

Various imaging techniques, such as X-ray computed tomography (XCT), scanning electron microscopy (SEM), and focused ion beam-SEM, have been incorporated into the DRP workflow for capturing rock properties (Sadeghnejad et al. 2021). However, they all are plagued by a well-known battle between scanning resolution and field of view (FoV). When increasing the FoV, scan resolution diminishes, making it unfeasible to obtain high-resolution scans over a large FoV (e.g., laboratory-scale), which could encompass all small-scale heterogeneities. Moreover, direct numerical simulation (DNS) approaches cannot simulate digital twins at the Darcy scale because of their demanding computational power. Consequently, alternative approaches, like integrating deep learning with DRP, offer a more efficient means of estimating rock properties.

In this study, we integrate an unsupervised resolution-boosting algorithm with a supervised convolutional network to predict rock properties from 3D low-resolution micro-CT scans. The semi-supervised approach involves two networks: an auto encoder and a convolutional neural network (CNN). The auto encoder network is trained on unlabelled low- and high-resolution 3D image pairs to enhance the resolution of low-quality images. The dataset comprises 35,680 3D scans of five distinct rock types (i.e., Berea sandstone, Edward Brown Carbonate, Fontainebleau sandstone, and Rotliegend sandstone) captured at two different resolutions. The scans are segmented with a Random Forest classifier algorithm integrated in ilastik, version 1.3.3, (Berg et al. 2019). Subsequently, the latent information from the AE network is combined with a conventional CNN to directly predict the pore-scale properties (i.e., porosity, permeability, tortuosity, and specific surface area) form the low-resolution images. To assess the prediction performance of this coupled network, we compare the predictions with the DNS approach computed by GeoDict 2023 (Math2Market GmbH, Germany) via the R-Squared evaluation metric.

This approach enables us to leverage a small amount of labelled data for the direct prediction of pore-scale properties from cost-effective, low-resolution images. When applied to the validation dataset, the AE-CNN network achieved an R-Squared value higher than that for the CNN not integrated with AE. To assess the model's generalization capability, a new scan from a distinct Berea sandstone sample, which was neither part of the training nor the validation data, was utilized as a test dataset. A noteworthy mean R-Squared increase was observed on the test dataset, when the AE-CNN network was implemented. This outcome underscores the substantial enhancement in prediction performance achieved through the integration of the semi-supervised network when working with low-resolution images of porous media.

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