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Direct scale comparison of numerical linear elastic moduli with acoustic experiments for carbonate rock X-ray CT scanned at multi-resolutions

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ABSTRACT

Giant carbonate reservoirs hold almost 50–60% of the world's conventional hydrocarbons and are thus of major economic significance. The recently emerging Digital Rock Physics (DRP) based mechanical property predictions have been successful for sandstones when validated against laboratory results. For carbonates however the success has been limited due to their complex nature and heterogeneity. Typically experiments are conducted with core sample diameters in the order of several cm. Due to computational limitations numerical models are often of several orders of magnitude smaller than laboratory samples. In this study we used a standard carbonate rock called Silurian Dolomite to perform sonic wave experiments on two sample sizes: 1.5 in. and 0.5 in. diameter cylindrical cores. The latter unique size allowed us to compare our DRP based finite element method (FEM) simulations at a more compatible scale and higher image resolution. Through a multi-scale X-ray Micro-CT imaging of the same sample we studied the effect of resolution on elastic moduli simulation. We demonstrated the importance of determining Representative Volume Element (RVE) at each imaging resolution. Through determination of RVE as well as sampling of 40–55% volume fraction using non-overlapping cubes, we showed how our protocol leads to very satisfactory same scale validation of numerical linear elastic moduli predictions.

1. Introduction

Carbonate sediments have major economic importance as about 50–60% of the estimated world's conventional petroleum is stored in carbonate reservoirs with many giant reservoirs expected to have production lifetime exceeding 50 years (Burchette, 2012). Formation and diagenesis processes in carbonates are responsible for modifications in pore network and mineralogy resulting in complex heterogeneity and have significant influence on the elastic properties (Fournier and Borgomano, 2009; Lima Neto et al., 2015). Predicting accurate mechanical properties of rocks in relation to their pore structure is crucial for improved understanding of geophysical measurements used in reservoir exploration and production. Many previous works have recognized and verified that pore features like size, shape, aspect ratio and pore type strongly affect the elastic (and seismic) behavior of rocks e.g. (Anselmetti et al., 1998; Anselmetti and Eberli, 1993; Eberli et al., 2003; Kumar and Han, 2005; Wu, 1966). Detailed tomographic characterization of the granular and porous rock microstructure is therefore desirable and important for reservoir engineering.

With the advent of high resolution 3D imaging capability (X-ray Micro-CT (Cnudde and Boone, 2013; Wildenschild and Sheppard, 2013)) and ongoing advances in computational methods it is now possible to characterize actual rock microstucture in 3D at the micron scale. This approach of simulating elastic properties using 3D computer tomography images is known as Digital Rock Physics (DRP) and has received much attention in the last decade e.g. (Andrä et al., 2013a, 2013b; Arns et al., 2005, 2002; Garboczi and Kushch, 2015; Jouini and Vega, 2011; Knackstedt et al., 2009; Madonna et al., 2012; Saenger et al., 2011; Saxena and Mavko, 2016). Indeed the basic DRP workflow consists of three steps (Andrä et al., 2013b; Dvorkin et al., 2011): 1) Imaging of the rock samples (using high resolution 3D scanning techniques like X-ray Micro-CT, FIB/SEM) 2) Processing the images (e.g. segmenting the pore phase from the solid matrix mineral phases) and 3) Simulating the elastic mechanical behavior of the rock samples.

Despite the advancement in imaging resolution yielding fairly detailed microgeometry and progress in various numerical algorithms, accurate predictions for elastic moduli are rarely and only seen in studies working with very homogeneous sandstones (Arns et al., 2002; Han et al., 2014; Jouini et al., 2015; Saenger, 2008; Shulakova et al.,

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2013). Elastic property prediction studies such as (Jouini and Vega, 2011; Knackstedt et al., 2009; Madadi et al., 2009; Saenger, 2011) noticed significant disagreement with lab measurements for carbonates when processing microtomographs without considering the unresolved phase i.e. the region containing pore size below the scanning resolution. Assigning effective elastic moduli to the microporous phase based on self-consistent theory led Knackstedt et al. (Knackstedt et al., 2009) to improved sonic velocity predictions.

Indeed the complex pore structures in carbonates exist at multiple length scales from tens of nanometers to several centimeters (Sok et al., 2010). Thus numerical results can only be compared with experimental results after ensuring representativeness of the numerical model with respect to the bigger sample. Arns et al. and Saenger (Arns et al., 2002; Saenger, 2008) have highlighted the importance of RVE size effects in their studies.

Very few studies have compared numerical simulations with laboratory data for the same plug material at comparable size or established RVE size. Andrä et al. (Andrä et al., 2013b) found very good rock-physics trends through DRP that agreed with large scale laboratory observations. However they emphasized on the lack of direct comparison with laboratory data due to scale differences (e.g. mm size numerical models compared to experimental core of several cm diameter). Also Andrä et al. (Andrä et al., 2013b) and Saxena and Mavko (Saxena and Mavko, 2016) compared their carbonate elastic numerical simulations with laboratory data derived from ultrasonic measurements by Vanorio and Mavko (Vanorio and Mavko, 2008). They noted that the carbonate samples they compared came from two different formations but had similar microstructural characteristics. Shulakova et al.'s (Shulakova et al., 2013) detailed elastic simulation study on sandstones using Abaqus/Avizo combination also compared maximum 400^3 voxel cube at 2 µm resolution (i.e. 0.8^3 mm cube length) with acoustic experimental data for core of 1.5 in. diameter and 3 in. length. Their numerically up-scaled moduli only corresponded to the experiments at a certain effective stress level indicating that the numerical model worked as if all the microcracks were closed. Jouini et al., 2015 used multi-scale approach on carbonates by extrapolating simulation result at fine scale (0.3 µm resolution) into full core plug scale simulations of 1000^3 voxels. Details of the lab measurements are rarely highlighted in these studies and it is unclear whether the same/sister rocks at same scales have been used for these comparisons and how much effect that has on the comparison/validation of the numerical results.

In this work we used the acoustic velocity measurement equipment at Masdar Institute to obtain experimental results for the same carbonate rock type at two core sizes: 1.5 in. (38.15 mm) diameter and 0.5 in. (12.7 mm) diameter. Two cores were imaged (by Ingrain Abu Dhabi) at two resolutions of 39.93 µm and 13.24 µm respectively. The respective resolutions were the highest attainable imaging resolutions for each case. Resulting digital voxelized images were of 1000^3 voxel size or higher making numerical simulation load extremely heavy even with parallel computations using High Performance Clusters (HPC). We therefore stressed on the importance of identifying representative volume element (RVE) analysis for each property of interest and at each scanning resolution. To have better sense of reliability when moving to complicated and heterogeneous reservoir carbonates, we focused first on developing the experimental and numerical protocol using a standard commercially available carbonate. By using the 0.5 in. carbonate sister cores for acoustic experiments and elastic simulations, we reduced the uncertainty due to comparisons between different scales and different carbonate rock formations.

For numerical simulations we used an implementation of isotropic, linear elastic finite element method (FEM) solver developed originally by Garboczi and Day (Garboczi and Day, 1995). The algorithm is well-established and has been tested against other solvers (Andrä et al., 2013b). For laboratory validation however, mostly high resolution but very small sub-volumes or low resolution big sub-volumes have been tested. Specifically for carbonates this has shown a general over-prediction of numerical values (Jouini et al., 2015). In our work we further demonstrated the accuracy of the algorithm through a same scale validation.

2. Experimental work

2.1. Equipment

The Masdar Institute Geomechanics Lab is equipped with Autolab1000 (manufactured by New England Research, Vermont, USA) which is a servo-hydraulic operated system that can be used for hydrostatic acoustic experiments as well as permeability and electrical resistivity tests. The Autolab1000 set up is capable of generating confining pressures up to 103 MPa. Acoustic velocity measurements of compressional (P) and shear (S) waves can be performed for 1.5 in. diameter and 0.5 in. diameter cylindrical core samples using transducer core holders operating at frequency ranges of 500 KHz to 1 MHz.

2.2. Material

We used a commercially available carbonate rock called "Silurian Dolomite" (Fig. 1) which was a relatively homogeneous rock in terms of morphology and mineralogy. It consisted of 99.9% dolomite. Two different core plug sizes of diameter, D and length, L: 1) $D_{1.5''}$=1.5 in.=38.1 mm and $L_{1.5''}$=3 in.=76.2 mm and 2) $D_{0.5''}$=0.5 in.=12.7 mm and $L_{0.5''}$=1 in.=25.4 mm were used. Total six cores, three $D_{1.5''}$ cores and three $D_{0.5''}$ cores, were tested for acoustic velocity using Autolab1000. The rocks were room temperature dried. This presented us with the opportunity to obtain experimental elastic moduli results for the same rock type at two different sizes and check the representativeness of the smaller core compared to the bigger one. While diameters of 1.5, 2 and 4 in. cores are standard size in core analysis experiments e.g. (Mur et al., 2011; Shulakova et al., 2013), $D_{0.5''}$ core is not a commonly used size for acoustic experiments. We opted for this size as it is the smallest size at which reliable acoustic testing can be done in Autolab1000.

2.3. Test set-up

For acoustic measurements, sample end flatness is extremely important for good contact with coreholders and hence good signals. The core plugs were prepared by enclosing them in rubber jackets. The jacket internal diameter snugly fit the sample diameter and the jacket length extended over coreholders where the connections were sealed with steel wires. The seal prevented the confining pressure oil from getting into the sample. The coreholder transducers were aligned for

Fig. 1. Silurian dolomite samples of 1.5 in. diameter and 3 in. length.