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Elastic Properties of Lochaline Sandstone - Numerical Experiment vs. Measurements

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SUMMARY

P- and S- velocities of clean quartz Lochaline sandstone are numerically simulated using microtomographic images with resolution of 2 micron and compared with the velocities measured at ultrasonic frequencies. The numerically simulated velocities are in a good agreement with velocities measured at confining pressure of about 30-40 MPa which is high enough to close soft pores but do not cause noticeable deformation of equant pores yet. The obtained results shows that while effects of soft porosity on elastic properties of sandstones cannot be directly simulated from microtomograms, such simulation give reliable results when soft pores are closed.

Introduction

Modelling elastic properties from rock microstructure is a promising method in seismic rock physics. However there is often significant discrepancy between simulated and measured elastic properties. The reason lies in the fact that resolution of most commercial micro-CT scanners is insufficient to resolve tiny inter- and intra-granular cracks and characterize their surface areas, roughnesses and orientations. These contact areas control elastic properties of rock and govern velocity-porosity dependencies (e.g., Quintal et al., 2011, Shulakova et al., 2011a, Shulakova et al., 2011b, Pervukhina et al., 2010, Arns et al., 2007). Recently, attempts have been made to assign specific properties to these contacts (Arns et al., 2007; Qintal et al., 2011). Unfortunately, this approach is not predictive and requires calibration using experimental measurements.

If indeed the discrepancy between simulated and measured elastic properties is caused by compliant pores, then there should be a better agreement at higher pressures, where these compliant pores are closed. Indeed, Shulakova et al. (2011a, b) showed that the effective moduli of the Donnybrook sandstone simulated from microtomographic images are in a good accordance to the ones measured at confining stress of about 40-50 MPa. However Donnybrook sandstone is a multi-mineral rock and thus there was some uncertainty about its effective mineral modulus. It is thus important to test a similar approach on a monomineral rock. To this end, we compare elastic properties simulated from a microtomogram with experimental measurements obtained for clean quartz Lochaline sandstone. We also present a newly developed workflow that allows predicting elastic properties at different confining stresses without any adjustable parameters.

Lochaline sandstone: petrophysical, experimental and micro-CT data

For this study we use Cretaceous sandstone from Lochaline White Sandstone Formation, which is located around the west coast of the Scottish Highlands. This sandstone is a well sorted quartz arenite with average porosity of ~4% consisting of subangular to subrounded quartz grains with an average size of about 200 μm (Figure 1a). These detrital quartz grains are coated quartz overgrowth and cemented with the partially dissolved quartz cement.

(a) (b)

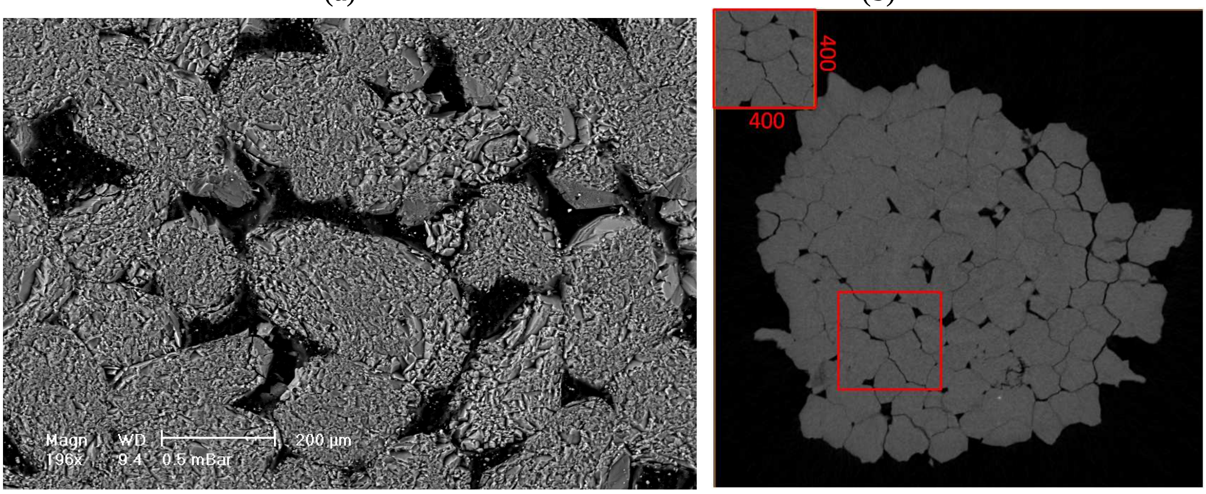

***Figure 1** Lochaline sandstone: (a) SEM, (b) a slice of microtomogram.*

P- and S-wave ultrasonic velocities are measured using time of flight method with central frequency of 0.5 MHz as functions of confining pressure ranged from 4 MPa to 50 MPa with a step of 4 MPa. The velocities are first measured on the dry sample, and then on the sample saturated with distilled water with pore pressure fixed at 5 MPa and variable confining pressure. Experimental error is estimated as 2% for both P- and S-wave velocities.

The micro-CT images are obtained with the resolution of 2 μm on an X-ray phase-contrast microscope which has an advantage of imaging weakly absorbing or non-absorbing samples as well as high spatial frequency features in these samples (Mayo et al., 2003). A cube of 400x400x400 voxels is cropped from the centre of the microtomogram and used for further analysis.

Simulation of elastic properties of Lochaline sandstone

For simulation of elastic properties of the Lochaline sandstone specimen we used the same workflow as described in detail by Shulakova et al. (2011a, b). First, using AVIZO (Visualization Sciences Group) software, we segment the cropped cube of 400^3 voxels into solid phase and pore space and produce volumetric mesh of both phases welded together at the interfacial surface (Figure 2a). Then we transfer this mesh to ABAQUS FEA (SIMULIA) and apply normal and tangential strain to the surfaces of the cube as shown in Figure 2(b, c). For the simulations the Young's modulus and Poisson's ratios are assumed to be equal to 94.5 GPa and 0.08 for the solid phase (quartz, Mavko et al., 2003) and 1e-5 Pa and 0.5 for pores, respectively. The P-wave (M) and shear (μ) moduli are then calculated as follows:

$$M = \frac{\langle \sigma_{xx} \rangle}{\langle \varepsilon_{xx} \rangle} \text{ and } \mu = \frac{\langle \sigma_{xy} \rangle}{2\langle \varepsilon_{xy} \rangle},$$

where $\langle \sigma \rangle$ and $\langle \varepsilon \rangle$ are stress and strain averaged over all the elements of the cube, respectively.

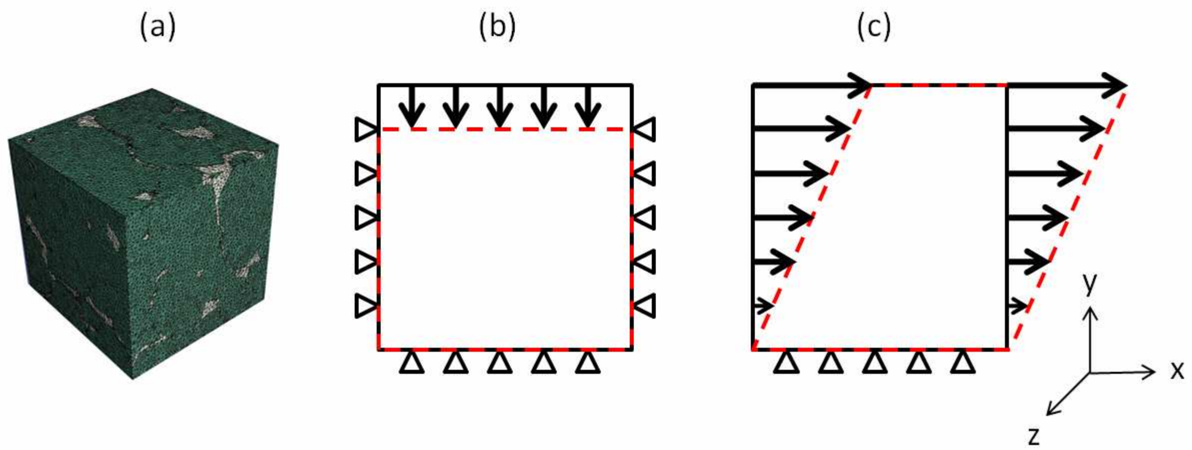

Figure 2 *Segmented and meshed cube of 400^3 voxels (a) and schematic displacements applied to its faces to calculate (b) P-wave modulus and (c) shear modulus.*

To simulate elastic properties of Lochaline sandstone at non-zero stresses the following workflow is developed. At the first step, a volumetric mesh is produced only for the solid phase of the same segmented cube. Then the mesh is transferred to ABAQUS where a confining stress is applied to all exterior faces of the cube. Generation of the volumetric mesh of the stand-alone solid phase allows large deformations of pore space or even complete closure of soft pores, which would not be possible if the pore space is also attached to the solid phase mesh. At the second step, we transfer modified solid skeleton back to AVIZO to mesh the deformed pore space and to weld two meshes along the interfacial surface. Finally, the same procedure that was developed in Shulakova et al. (2011a, b) is applied to calculate elastic moduli of the specimen at a particular confining stress.

Results and discussion

Figure 3a shows numerically simulated *Vp* and *Vs* in comparison with experimentally measured velocities. The experimentally measured *Vp* and *Vs* are shown by blue and red solid dots, respectively. The numerically simulated values are shown by open circles at zero confining stress and solid lines.

We simulated *Vp* in three perpendicular directions and the results are shown by open blue circles and an average value is shown by blue line. As the differences between the simulated velocities are below 2%, i.e., below the experimental errors, hereafter, the sample is assumed to be isotropic.

The reason why in this study Lochaline sandstone is chosen as a specimen for numerical simulations of elastic properties is two-folded. Firstly, the grain contacts are clearly observable and segmentation of the images into solid phase and pores can be easily done robustly using standard watershed algorithms in AVIZO software package. Secondly, the Lochaline sandstone is clean sandstone with quartz grains cemented with quartz cement and thus the mineral elastic moduli should are known. By segmenting images with clearly visible grain contacts, we can make a definitive comparison between simulations and experiment without adjustable parameters.

(a) (b)

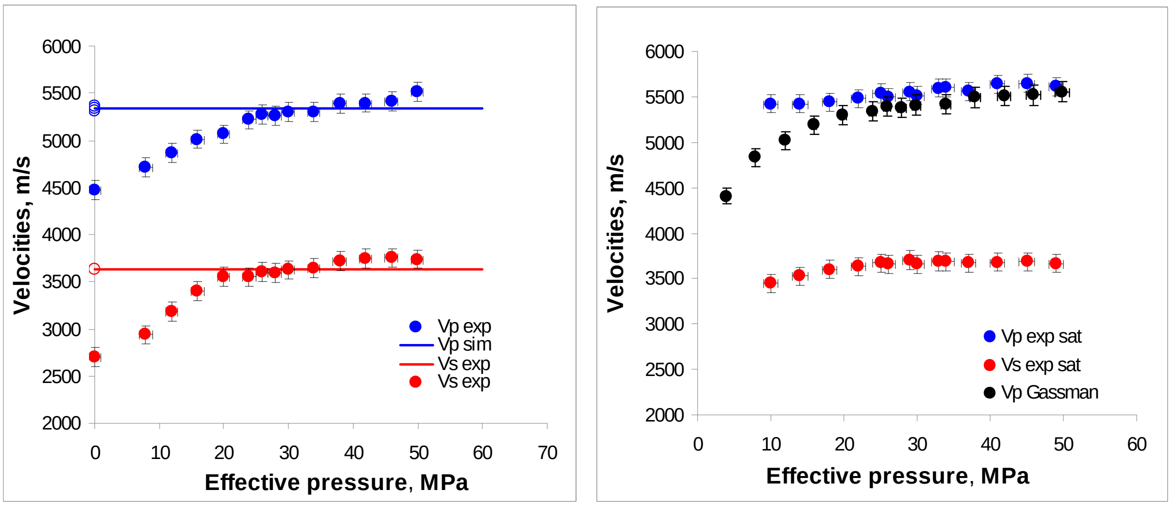

Figure 3 *Comparison of numerically simulated elastic moduli with experimentally measured ones: (a) on the dry sample, (b) on the saturated sample. Simulated data are shown with open circles and solid lines and experimental data are shown with solid dots with error bars.*

In practice, simulated velocities are in a good agreement with velocities measured at 30-40 MPa. This suggests that at this confining pressure, soft pores, pores with low stiffnesses, are closed. This fact can be confirmed by analysis of ultrasonic velocities measured on the same sample at fully saturated state. In Figure 3b saturated compressional (blue) and shear (red) velocities are shown in comparison with *Vp* calculated by Gassmann substitution (black circles). Gassmann predictions strongly underestimate measured velocities at low effective stresses and are in a good agreement with the measurements at effective stresses above 30 MPa. Gassmann's relation does not work when pore pressure induced by passing elastic wave has no time to equilibrate. In the case of laboratory experiments at ultrasonic frequencies, pore pressure may not have time to equilibrate in ultrathin cracks (Mavko and Jizba, 1991). Gassmann predictions apply for the case when pore pressure has time to equilibrate or in the case of ultrasonic experiments at high confining stress when these pores ultrathin inter- and intra-grain cracks are closed (Shapiro, 2003, Angus et al., 2009, Pervukhina et al., 2010, Gurevich et al., 2010).

Similar results were obtained by Shulakova et al. (2011a, b) for Donnybrook sandstone for which numerically simulated results are in a good agreement with experimentally measured at confining pressure of 40-50 MPa. Consequently for both sandstones, velocities simulated using microtomograms equal to velocities measured at confining stresses, at which soft pores are closed.

Simulated velocities underestimate the measurements at confining stresses of 50-55 MPa. This fact can be explained with deformation of equant porosity at such stresses. We are planning to use the developed workflow to simulate stress dependency of elastic properties of sandstones at high confining stresses. At the same time, some pore opening image processing techniques might be employed to simulate velocities at lower confining stresses.

Conclusions

P- and S- velocities of clean quartz Lochaline sandstone are numerically simulated using microtomographic images with resolution of 2 µm and compared with the velocities measured at ultrasonic frequencies. The numerically simulated velocities are in a good agreement with velocities measured at confining pressure of about 30-40 MPa which is high enough to close soft pores but do not cause noticeable deformation of equant pores yet. The obtained results shows that while effects of soft porosity on elastic properties of sandstones cannot be directly simulated from microtomograms, such simulation give reliable results when soft pores are closed.

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References

Angus, D. A., Verdon, J. P., Fisher, Q. J. and Kendall, J. M. [2009] Exploring trends in microcrack properties of sedimentary rocks: An audit of dry-core velocity-stress measurements. *Geophysics* **74**(5), E193-E203.

Arns, C. H., Madadi, M., Sheppard, A. P. and Knackstedt, M. A. [2007] Linear elastic properties of granular rocks derived from X-ray-CT images. *77th Annual International Meeting, SEG,* Expanded Abstracts, 1711–1715.

Gurevich, B., Makarynska, D., De Paula, O. B. and Pervukhina, M. [2010] A simple model for squirt-flow dispersion and attenuation in fluid-saturated granular rocks. *Geophysics* ***75****, N109-N120*.

Mavko, G. and Jizba, D. [1991] Estimating Grain-Scale Fluid Effects on Velocity Dispersion in Rocks. *Geophysics* **56**(12), 1940-1949.

Mavko, G., Mukerji, T., and Dvorkin, J. (Eds.) [2003] *The rock physics handbook*. Cambridge University Press.

Mayo, S. C., Davis, T. J., Gureyev, T. E., Miller, P. R., Paganin, D., Pogany, A., Stevenson, A. W. and Wilkins, S. W. [2003] X-ray phase-contrast microscopy and microtomography. *Opt Express* **11**(19), 2289-2302.

Pervukhina, M., Gurevich, B., Dewhurst, D. N. and Siggins, A. F. [2010] Experimental verification of the physical nature of velocity-stress relationship for isotropic porous rocks. *Geophysical Journal International* **181**, 1473–1479.

Quintal, B., Frehner, M., Madonna, C., Tisato, N., Kuteynikova, M. and Saenger, E. H. [2011] Integrated numerical and laboratory rock physics applied to seismic characterization of reservoir rocks. *The Leading Edge* **30**(12), 1360-1367.

Shapiro, S. A. [2003] Elastic piezosensitivity of porous and fractured rocks. *Geophysics* **68**(2), 482-486.

Shulakova, V., Pervukhina, M., Lebedev, M., Mueller, T., Mayo, S., Schmid, S., Clennell, B. and Gurevich, B. [2011 a] Computation of elastic properties based on microtomogram images. *73th EAGE Conference & Exebition*, Extended Abstracts.

Shulakova, V., Pervukhina, M., Müller, T. M., Lebedev, M., Mayo, S., Schmid, S., Golodoniuc, P., De Paula, O. B., Clennell, B. M. and Gurevich, B. [2011 b] Computational elastic up-scaling of sandstones on the basis of X-ray micro-tomographic images. *Geophysical Prospecting, [submited]*.