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Towards a Representative Rock Model from a Micro-CT Image

E.H. Saenger* (ETH Zurich), C. Madonna (ETH Zurich), N. Tisato (ETH Zurich) & B. Quintal (University of Lausanne)

SUMMARY

Digital rock physics combines modern imaging with advanced numerical simulations to analyze the physical properties of rocks. However, it remains difficult to resolve microstructures on submicrometer scale and image a representative volume at the same time, which is essential to understand the elastic properties of rocks. This leads to a mismatch between laboratory measurements and digital rock physics estimates. In this paper we suggest the usage of digital rock physics templates as recipe to obtain accurate numerical predictions. In those templates optimized pressure-dependent elastic properties are given for each phase of a rock identified on a micro-CT image. For one Berea sandstone sample we describe such a template by using a laboratory-based calibration technique.

Introduction

Three-dimensional (3D) information on rock microstructures is important for better understanding physical phenomena and for rock characterization at the micro-scale (Madonna et al., 2012). Various methods for obtaining a 3D image of the rock microstructure exist (Madonna et al., 2013, and references therein). They can be separated into two major groups: destructive and non-destructive methods. The most common non-destructive 3D imaging method for earth sciences is X-ray computed tomography (CT). A common problem, however, is a clear trade-off between sample size and resolution. For each material sample, it has to be clarified if the chosen sample size is representative for the physical property to be computed. In the last decade, the X-ray micro-computed tomography (micro-CT) method became widely available and many modern studies have made use of it to obtain 3D rock images. The resolution of micro-CT is high enough to image the spatial distribution of grains, pores, and pore fluids.

3D CT rock images (e.g. Figure 1) can be used for predicting properties such as porosity, permeability, pore size distribution, effective elastic moduli, or electrical conductivity. For example, permeability can be successfully predicted by numerically simulating fluid flow through 3D rock models, with the numerical results being in reasonable agreement with laboratory measurements. In this case, the resolution of the micro-CT technique is sufficient because fluid pathways predominantly follow larger pores. However, if the porosity is much smaller than 1µm (e.g., shale) the agreement might be less satisfactory due to resolution limitations. On the other hand, mechanical properties, such as the effective elastic moduli, strongly depend on the microstructural details of the rock, which stay unresolved by the micro-CT technique. The inability to fully characterize the microstructural details of a rock sample can lead to disagreements between numerical estimates of mechanical properties based on micro-CT images and laboratory data.

An example of such a disagreement between laboratory and digital rock physics (DRP) estimates is described in Andrä et al. (2013). In this benchmark paper a comparison between different numerical methods is presented. Among others, a sample of Berea sandstone is considered (see Figure 1, left hand side). All DRP estimates of the effective elastic bulk modulus (Figure 1, right hand side) use the same segmented dataset. Regardless of the approach all numerical predictions overestimate the bulk modulus measured in the laboratory. Therefore we conclude here that the digital rock image itself have to be improved to be representative for a real rock.

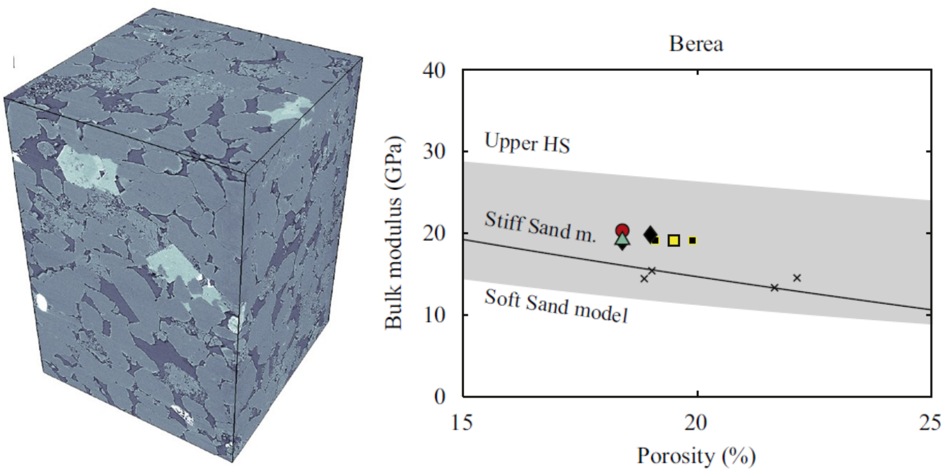

Figure 1 *The CT scan of a Berea sandstone sample used in the benchmark paper of Andrä et al. (2012) is displayed on the left hand side. The numerical estimates of the bulk modulus computed using different numerical approaches (polygons in the graph) are compared with laboratory results (crosses in the graph) on the right hand side.*

Strategies to derive a representative digital rock image

Several methods can be used to overcome the resolution issues of CT images. Ringstad et al. (2013) suggest a multiscale method to generate representative digital rock models. They construct synthetic 3D models of small-scale features (nm-scale) by analysing 2D backscattered scanning electron microscope (BSEM) images. The effective elastic properties of those nm-structures are assigned to the 3D CT images on the µm-scale.

Mahabadi et al. (2012) derive the elastic properties of the different phases of the CT images by micro-indentation testing. The accuracy and the possible limitations of this technique are elaborated in their study as well. They determine the mean Young's modulus of the quartz-phase as E ≈ 80 GPa. This is 15 GPa less than what is used in the benchmark study of Andrä et al. (2013). This is for us a confirmation that reduced values for mineral moduli should be assigned to the phases segmented out of micro-CT images.

In this paper we suggest an alternative strategy to derive a representative rock model from a 3D micro-CT rock image. As an input we use the results and findings of Madonna et al. (2012). They use a DRP method to predict pressure-dependent ultrasonic velocities. The basic idea is to segment out three different phases for a rock: A stiff phase for the minerals, another phase for the pores, and a third phase, composed of grain contacts and micro-cracks, which will change its elastic moduli under confining pressure. Madonna et al. (2012) identify the grain contacts as the pressure-dependent phase of Berea sandstone. They assign to the mineral phase the known elastic properties of quartz (as in Andrä et al. 2013); for the grain contacts they vary the elastic moduli linearly from the value of quartz moduli to 0. Interestingly, the elastic response by this variation is similar to the pressure-dependent behaviour of rocks. However, the numerical results overestimate the observed velocities using this technique as well. Therefore a specific calibration using laboratory data is applied so that a good match between numerical and laboratory results is obtained (see Figure 2).

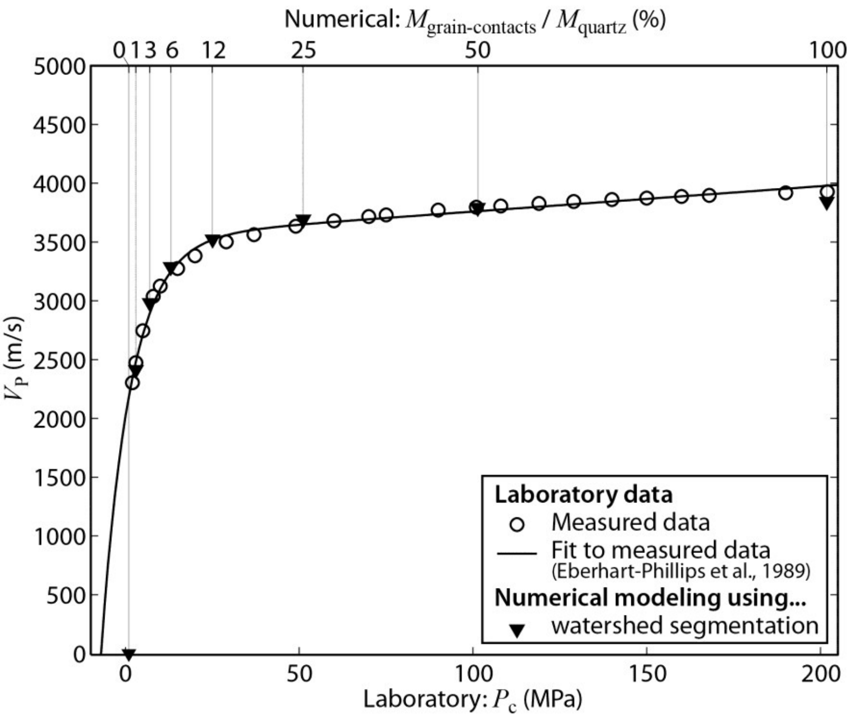

Figure 2 *Laboratory and numerical results for the P-wave velocity at 3 MHz as a function of confining pressure, P_c, in a Berea sandstone sample (modified figure from Quintal et al. 2011). The P-wave velocity is obtained by numerically modeling wave-propagation through a digital rock model generated by a watershed grain reconstruction segmentation technique.*

The digital rock physics template

The next step is to translate the calibration technique performed by Madonna et al. (2012) into a template (we name it digital rock physics template) which can be used by others to use DRP as a predictive tool for rock characterization. Such a template is shown for our Berea sandstone case in Figure 3. Basically, we apply the reduction of the overall rock sample velocity determined by Madonna et al. (2012) directly to the stiff and compliant phase of the mineral phase. In this way we are able to determine an optimal P-wave modulus which should be assigned to the stiff phase of the segmented rock sample. We checked this inversion step with several test simulations. This optimized modulus can be directly used as input for similar segmented CT scans and is reduced more significantly as suggested by micro-indentation testing as described above. The optimization is of course only valid for this specific rock type, for this specific resolution of the CT image and for this specific segmentation technique. However, we think such templates should be derived and compared for different scan or segmentation setups and rock types. This will allow the determination of effective elastic properties to become more accurate in the future.

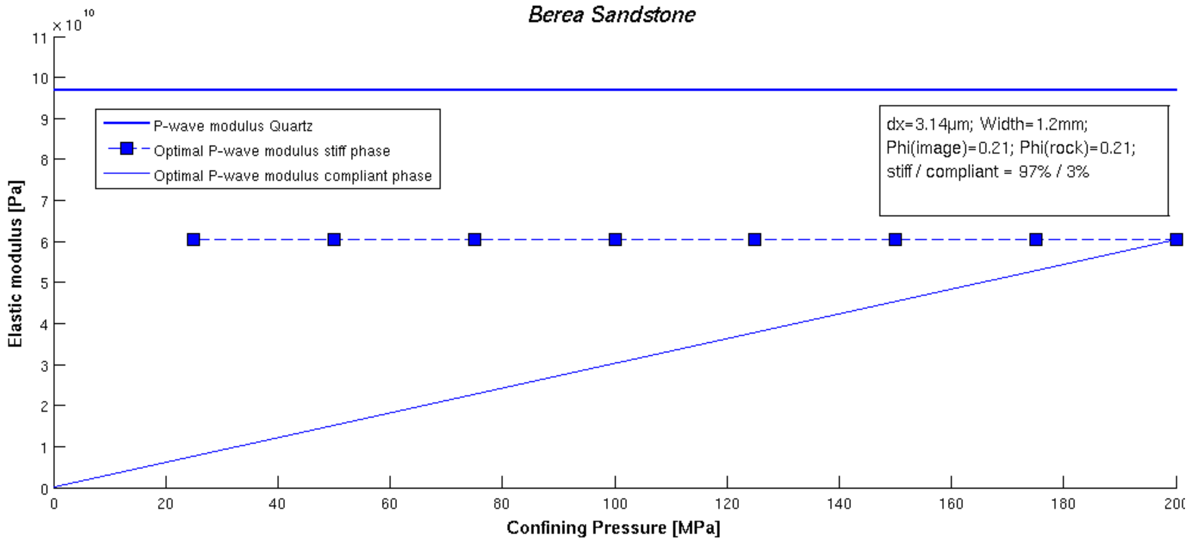

Figure 3 *Digital rock physics template: Calibrated P-wave moduli of the stiff (grains) and the pressure-dependent (grain contacts) phase of a segmented micro-CT image of Berea sandstone. By using these moduli values the excellent match between numerical and laboratory results as shown in Figure 2 can be obtained. Note that this DRP template is derived for a specific rock type, a specific resolution of the CT scanner and a specific segmentation technique.*

Discussion

In case DRP templates as described above are provided for a reasonable large number of different rocks and micro-CT resolutions, the application of DRP can be used as a predictive tool for estimating pressure-dependent effective elastic properties. With the development of this work, we will learn which effective elastic properties for each rock type we have to assign on the micro-CT resolution scale to estimate properties on a larger scale. The goal is that the micro-CT image can yield a representative numerical model for the real rock. However, there are a few limitations and important assumptions:

(1) The finite digital rock sample should be representative for the rock formation under consideration (this criterion applies to laboratory considerations).

(2) Most of the rock samples are scanned so far under ambient room conditions, neglecting therefore the effect of confining pressure on the rock skeleton itself. Only the effect on unresolved micro-cracks is approximated.

(3) The accuracy of the DRP calibration is limited by the accuracy of the underlying laboratory measurements.

(4) A comparison between laboratory experiments on one scale and DRP predictions on another scale should be handled carefully. We suggest using an appropriate up-scaling or down-scaling technique.

(5) For Berea sandstone we have identified the grain contacts as the most significant pressure-dependent phase. This may change for other rock types.

Conclusions

With modern imaging techniques, it remains difficult to resolve microstructures (on submicrometer scale) and image a representative volume at the same time, which is essential to understand the elastic properties of rocks. To overcome this problem, we suggest a careful calibration of DRP estimates with laboratory data as described in Madonna et al. (2012). This is necessary to avoid an overestimation of seismic velocities and to reproduce their pressure dependence. Those calibrated results should be summarized in DRP templates as described in this paper. This will allow establishing rules for an optimal representative rock model derived from a micro-CT image for different rock types.

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