Seismic velocity estimation using a digital rock without segmentation - tips for accurate calibration and estimation

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ABSTRACT: Estimating physical properties of rocks from X-ray CT images is useful when preparation of rock core specimens for lab measurement is difficult. In this study, we examined and extended the recently-proposed segmentation-less method to construct digital rock model for seismic velocity estimation. We first examined the effectiveness of the method to two sets of CT images of Berea sandstone with voxel resolutions of 7 and 11 μm, respectively. We further applied the method to Kumamoto andesite to examine its effectiveness to a volcanic rock. Our results showed that the method successfully estimated P-wave velocity of these cases. The setting of the parameters to link CT values to mineral phase was important, and the parameter setting was linked with the internal structure of the volcanic rock. A proper knowledge of pore and mineral properties of the rock of interest is useful for accurate seismic velocity estimation by the segmentation-less method.

Keywords: Digital rock, Seismic velocity, X-ray CT, Sandstone, Andesite.

1 INTRODUCTION

Digital rock physics has been an active research field estimating physical properties of rocks from X-ray CT images. A three-dimensional digital model of rock is constructed from CT values, which reflects the X-ray attenuation at the locations, and numerical simulation allows to compute physical properties of rocks. X-ray CT imaging is useful because it is nondestructive and can be used to measure rock properties without preparing rock core specimens for experiments. The approach also has the potential advantage to continuously acquire physical properties for long cores. Seismic velocity is one of the fundamental physical properties of rock for understanding mechanical properties of rocks and interpreting seismic data. Therefore, the methodology to estimate accurate seismic velocity using a digital rock physics has been an important research topic.

One of the well-known approaches to construct a digital model of rock is to segment X-ray CT images into mineral and pore phases (Andrä et al. 2013). The segmentation requires the thresholding of CT values to assign a voxel to either mineral or pore domain, and elastic modulus of each domains are set at each voxel. However, the result of the segmentation depends on the thresholding method used, and previous studies has shown that the estimated seismic velocity tend to be overestimated

(Madonna et al. 2012). Recently, the segmentation-less method has been proposed to construct the digital rock model for seismic velocity calculation (Ikeda et al. 2020; Goldfarb et al. 2022). The segmentation-less method assumes that most of voxels contain the mixture of mineral and pore phases, and the ratio of the mixture is estimated from the CT value of each voxel for determining density, porosity and elastic modulus. The segmentation-less method is divided into two categories: one assigns the properties to each voxel based on observed knowledge of the relationship between the target density and CT values (the segmentation-less method with target) (Goldfarb et al. 2022) and another estimates the relationship between densities and CT values solely from CT images, which named as the segmentation-less method without target (Ikeda et al. 2020).

The segmentation-less method without target has been shown its effectiveness through the applications to Berea sandstone (Ikeda et al. 2020), carbonate (Ikeda et al. 2021) and Shirahama sandstone (Ishitsuka et al. 2022). In this study, we examined the effectiveness of the segmentation-less method by applying it to the CT image of Berea sandstone with two different voxel resolutions. Further, although the method has been applied to sandstones and carbonates, we applied the method to Kumamoto andesite, and examined the effectiveness of the method to the volcanic rock.

2 METHODOLOGY

The processing flow of the segmentation-less method without target is divided into four steps. The detailed description can be found in Ikeda et al. (2020), Ikeda et al. (2021) and Ishitsuka et al. (2022).

1) The first step is to search CT values corresponding to major minerals and pore. Considering that the CT values at most of voxels reflect the mixture of minerals and pores, the CT value with a voxel with either mineral or pore would exhibit maximum or minimum CT value compared with those at the surrounding voxels. Thus, to identify CT values with mineral or pore, we made a histogram of CT values showing locally extrema (maximum or minimum) values. More specifically, we set a cubic window, and extract the CT value for the histogram when the center of the local cubic window is the extrema value compared with those at other voxels within the cubic window. The local cubic window moves sequentially until all area of interest is searched. The CT values of minerals and pore are determined as the peak of the histogram. We used this standard processing for Berea sandstone. For Kumamoto andesite, instead of extracting local maximum CT value of a single voxel, we took the averaging of the CT values at neighboring pixels within a cubic window, and extract the averaged CT value when the value is locally maximum. This modification could consider the phenocryst and groundmass phase of Kumamoto andesite.
2) An empirical relationship of CT values and density is constructed based on the CT values of minerals and pores. The empirical relationship is used to map density and porosity of each voxel. The previous studies derived the porosity of a voxel from density based on monomineralic assumption (Ikeda et al. 2020; Ishitsuka et al. 2022), and we used the assumption when the CT image of Berea sandstone was analyzed. For Kumamoto andesite, we considered the weighted average of mineral components of the rock based on quartz index obtained from X-ray diffraction analysis of Kumamoto andesite.
3) The estimated porosity of the digital rock is compared with the measured value of rock. If the estimated porosity agrees with the measure quantity, we proceed to the next step. Otherwise, we modify the cubic window size in step 1, and conduct the step1 and step 2 again.
4) The elastic modulus of each voxel is assigned from the estimated porosity and a mixing relation. For the bulk and shear modulus of minerals, we referred the values in Schön (2015). For the mixing model, we used the average of the upper and lower bound of the modified Hashin-Strikman-Wapole equations in this study. The choice of the mixing relation was discussed in Goldfarb et al. (2017) and Ishitsuka et al. (2022).

We simulated wave propagation in the constructed digital rock model using the staggered-grid finite-difference technique. Equations of momentum conservation and stress-strain relations were used. To conduct finite-difference simulation, we used the fourth-order central difference approximation in the spatial domain and second-order central difference approximation in time domain.

3 ROCK SAMPLES AND X-RAY CT IMAGES

We used Berea sandstone (Mississippian, Ohio, USA) and Kumamoto andesite (Kumamoto, Japan) in this study. For Berea sandstone and Kumamoto andesite, we used the cylindrical samples with the diameter/height of 30 mm/60 mm and the diameter/height of 60 mm/60 mm, respectively. The qualitative composition of minerals of the rocks were obtained by X-ray diffraction analysis. The quartz index was then obtained from the intensity of the X-ray diffraction pattern. Berea sandstone is composed mainly of silica and tiny amount of potassium feldspar, illite, chlorite, smectite, calcite, plagioclase and ankerite. Kumamoto andesite is composed primarily of plagioclase and partly of magnetite and clinopyroxene. Porosity of the specimens were measured using the buoyancy method. The P-wave velocities (Vp) of the rocks were measured by the pulse transmission method. A rectangular wave with a frequency of 100 kHz was used. For Berea sandstone, we used the X-ray CT images with two different spatial resolutions. One has a spatial resolution of approximately 11 μm and another has approximately 7 μm. For Kumamoto andesite, we used the X-ray CT image with spatial resolution of approximately 22 μm. These X-ray CT images were taken using an inspeXio SMX-225XT FPD HR microfocus X-ray CT system. The length of the CT arrays of Berea sandstone and Kumamoto andesite to simulate seismic wave propagation were 300 voxels and 387 voxels, respectively.

4 RESULTS AND DISCUSSION

The 3D array of density, bulk and shear modulus of the constructed digital rock model of Berea sandstone with 7 μm voxel resolution are shown in Figure 1a. The estimated average porosity and density of the digital rock model are consistent with measurements. The measured porosity and density of the Berea sandstone used were 18% and 2.12 g/cm^3, respectively, and those of the digital rock models with spatial resolutions of 7 μm and 11 μm were 19% and 2.15 g/cm^3. The optimal cubic window sizes of the first step described in section 2 were 13 and 9 voxels in the CT images with 7 μm and 11 μm resolution, respectively. Although the results came from only two different CT resolutions, our results showed that optimal cubic side becomes larger as the spatial resolution is finer. This pattern agrees with the discussion by Ikeda et al. (2020). The optimal cubic size is linked to the size of grains and pores, and larger grain and pore sizes require larger cubic window sizes. Thus, when CT images with a fine spatial resolution is used, we recommend to use a large cubic size in the first step.

The measured Vp by the pulse transmission method was 2.73 km/s, and the estimated Vp of Berea sandstone were 2.76 and 2.93 km/s, respectively, when the CT images with 7 μm and 11 μm resolution were used. Thus, the percentage errors were 1.1% and 7.3% in 7 μm and 11 μm resolution cases, respectively. As the estimation error of Vp in Ikeda et al. (2020) was 1.6% and 3.1% when CT voxel size of 40 μm was used, the estimated Vp by 7 μm resolution case was exhibited higher accuracy compared with the 11 μm resolution case in this study.

With the same processing strategy with Berea sandstone, the porosity and density of the digital rock model of Kumamoto andesite were 19% and 2.14 g/cm^3, respectively. As the measured porosity and density were 9% and 2.51 g/cm^3, the digital rock model overestimated these quantities. Thus, to improve the digital rock model, we applied the modified processing as described in section 2. The porosity and density of the modified digital rock model were 7% and 2.49 g/cm^3, respectively, which were consistent with the measured values. The array of density, bulk and shear modulus of the modified digital rock model of Kumamoto andesite are shown in Figure 1b.

To estimate Vp from the digital rock model of the Kumamoto andesite, we first applied the monomineralic assumption that the mineral phase is composed only of feldspar. This assumption yielded that the estimated Vp was 3.00 km/s, while the measured Vp by the pulse transmission method was 3.64 km/s. On the other hand, when we considered the mineral phase composed of the composite of feldspar, magnetite and pyroxene-augite, the estimated Vp was 3.82 km/s. The percentage error between the estimated and measure Vp was 5.0%. Considering the percentage error of the digital rock model of Berea sandstone, the estimated Vp of Kumamoto andesite was enough accurate.

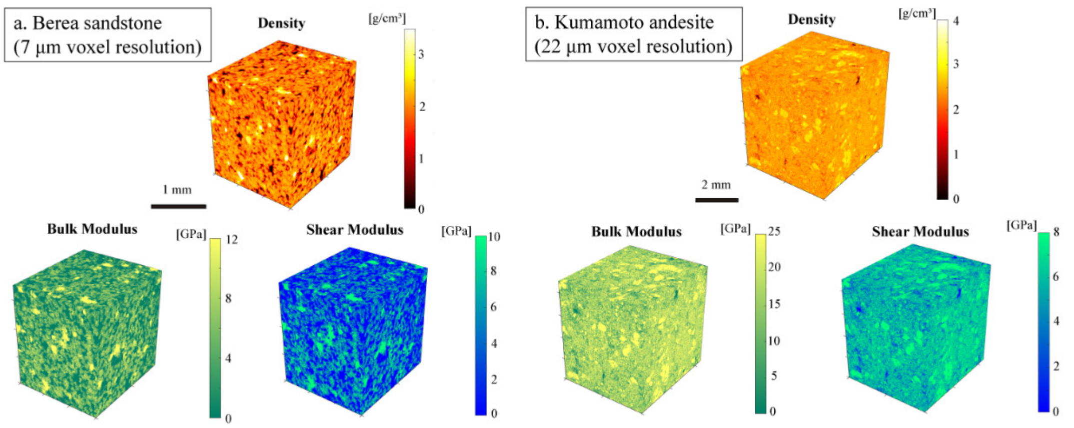

Figure 1. The 3D array of density, bulk modulus and shear modulus of (a) Berea sandstone (voxel resolution of 7 μm) and (b) Kumamoto andesite (voxel resolution of 22 μm).

5 CONCLUSIONS

In this study, we examined the segmentation-less method to construct digital rock model for P-wave velocity estimation. Our results showed that the digital rock models of the Berea sandstone constructed from CT images with voxel resolutions of 7 μm and 11 μm, respectively showed porosities and densities consistent with measurements. Our results demonstrated that the setting of cubic window size accounting for the voxel resolutions of the CT images was a key for the accurate estimation. We further applied the segmentation-less method to Kumamoto andesite. With the modified processing considering rock structure and multi-mineral compositions, our results suggest that the method is also effective for the volcanic rock.

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