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A method of rough pore surface model and application in elastic wave propagation

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ABSTRACT

Surface roughness is known to have significant influence on acoustic waves. However, the studies of the pores in rocks are mainly on porosity, pore shape and tortuosity, the effect of rough pore surfaces is still unknown. In this paper, we quantitatively analyze the micro-computed tomography (micro-CT) scan images, and define a new parameter, pore roughness index (PRI), to characterize the surface roughness and randomly generate pores with rough surfaces. We propose an algorithm for generating large numbers of randomly distributed and mutually isolated pores with different surface roughness. A 2D pore-scale modeling of rough pore surfaces and the corresponding models of smooth pore surfaces are established based on the parameters extracted from micro-CT images of seven carbonate cores. Elastic wave propagation using finite element analysis is simulated to validate the proposed model. Compared with the raw micro-CT images, the rough surface model can greatly reduce the amount of meshes and computation cost. The deviations of wave velocities between raw images and our models are less than 5% in the carbonate cores. To analyze the influence of rough pore surfaces on P- and S-wave velocities, a variety of models with varying PRI (from 0 to 4) at porosity of 5%–30% are tested. The results indicate that the velocity difference between smooth surface model and rough surface model increases as the roughness of pore surfaces increases. The largest velocity variations caused by rough pore surfaces can be more than 8% for V_P and 12% for V_S at 30% porosity. A positive linear relationship of the velocity difference and total pore perimeters is developed. The effect of rough pore surfaces is stronger in models with air saturation than water saturation for P-wave, while has rarely effects on S-wave. Our method can improve the simulation accuracy while minimizing computational cost. This is of critical importance for modeling elastic wave propagation in complex porous media. The result is appropriate to ultrasonic laboratory conditions and can be extended to acoustic logging interpretation.

1. Introduction

Elastic wave propagation is strongly affected by the presence of pores, especially in carbonate rocks. Wyllie et al. [1] notice that velocities in vuggy carbonates are higher than predicted by the porosity using time average equation. In the decades following Wyllie's study, many researches indicate that complex pore structure causes wide scattering in the velocity-porosity cross-plots of carbonate rocks [2–4], which results in large uncertainty in predicting the properties (porosity, permeability and saturation) of carbonate reservoirs. The studies of elastic wave characteristics in carbonate rocks are of critical importance for reservoir fluid prediction, fracture identification, pore structure prediction and seismic inversion [5–7]. In addition to the factors of rock type, fluid-saturation, porosity, pore size and shape [8], pore surface characteristics (such as the roughness of surfaces) also have significant influence on wave velocity [9] and scattering attenuation [10,11].

No actual surface is perfectly smooth. The surfaces of natural rock pores developed during secular geological diagenesis are far from smooth, and are in fact very rough. Propagation over completely rough and porous surfaces is of interest. Brown [12] establish a simple mathematical model of a single rough fracture and describe it with three parameters: fractal dimension, rms roughness and a length scale. Kahraman [13] build experimental models to investigate a polynomial relationship between fracture roughness coefficient and wave velocity. Leucci and Giorgi [14] select four parameters (the discontinuity index, fracture density, linear fracture and the rock quality designation) to describe the rock

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mass property and investigate the effects of fracture geometry on compressional (P) and shear (S) wave propagation. Lai et al. [15] examine three different measures of roughness using an image of a large rock surface based on a geometric property. There are some theoretical and experimental investigations of the effect of the surface roughness on the scattering and attenuation of the surface acoustic waves [16–18]. However, these studies are limited to a single interface in a large scale, without considering the real situation of surfaces in pore-scale.

Four parameters, AR (ratio of the major axis to the minor axis), PoA (ratio of pore perimeter over area), gamma (ratio of pore perimeter to the perimeter of equivalent circle) and DomSize (the dominant pore size), based on digital image analysis (DIA) can effectively describe the pore shape and pore size with respect to velocity deviation [19]. Verwer et al. [20] also regard PoA as a 2D parameter that is equivalent to a specific surface defined as the ratio between pore surface and pore volume. Generally, the smaller the PoA, the simpler the geometry and the lower the acoustic velocity at a given porosity. To date, there are also some researchers [21–23] who use equivalent medium theory (EMT) models to analyze the pore structure effects on wave propagation, such as KT model [24], the differential effective medium model [25], the self-consistent scheme [26] and KT-DEM model [27]. These theoretical or laboratory models simplify different pore shapes by regular elliptical pores where the actual pore surface is ignored, and assume the pore AR of inclusions in carbonate rocks [28,29]. However, these models are always over-simplified, with regard to the geometry they represent and, at times, with the physical property. Further efforts and improvements are still required to approach the actually irregular pore surfaces. Studying the relationship between rock properties and its micro-structure in porous media by rock physical experiments is the most direct way, but quantitative analysis of the pore surfaces in the actual core is relatively expensive and complicated. As an alternative approach, numerical simulation has become an effective complementary method for elastic wave characterization in complex pore structure medium. This method has the advantages of 1) conveniently achieving single-factor control, and 2) minimizing uncertainties caused by human errors. Thus, a large amount of researches has been carried out for numerical simulating the elastic heterogeneity scattering of velocity and attenuation in the pore-scale model [30]. With the developing of high-resolution 3D modern micro-computed tomography (micro-CT) scanners in industry and academia, digital rock physics (DRP) has rapidly emerged as a potential source of valuable rock property relations, such as permeability, elastic moduli, and formation factor [31–33]. However, computational challenges primarily stem from the enormous data size of microtomography [34], which result in the application of DRP on a really small numerical model (on the order of mm^3). Consequently, we need to establish an integrated approach to both the complex of pore surface and computation cost.

In this paper, we report a method to simulate the pore-scale carbonate rocks by defining a new parameter to characterize the surface roughness. The parameters of pore structure are determined by micro-CT scan images of carbonate cores. The drastically lower triangle elements of our 2D rough surface model (10^5–10^6) than the raw micro-CT image (10^7–10^8) greatly reduce the computation time (about one-tenth time of raw image) for elastic wave propagation through porous rocks using finite element method (FEM). Then we build two sets of pore-scale modeling with rough pore surfaces and the corresponding smooth pore surfaces to analyze the effect of surface roughness on the elastic wave velocities, which provides an effective way to reveal the internal mechanism of pore surface effect. This work gives us new ideas and methods for establishing the larger scale DRP models.

2. Model generation

2.1. Description of surface roughness

Since properties of the actual pore largely depend on surface roughness, it leads to a discrepancy to simply model it by a regular ellipse with smooth surfaces. The surface roughness is quantified by the deviations in the direction from the nominal surface in geometry. There are many different roughness parameters in use, but common methods of evaluating the roughness include the parameters of height, width and shape characteristic [35]. In this paper, we keep the roughness height and shape characteristic the same, which means that using the same number of lines to depict 2D elliptical pore surfaces. By setting the maximum height deviation of the surface contour (the distance between the peak line and the bottom line), a parameter of pore roughness index (PRI) is defined to quantitatively express the degree of surface roughness. Let us consider a semi-infinite substrate bounded by a rough surface (see Fig. 1). The rough surface is determined by a random perturbation relative to the mean height.

2.2. Generation step of rough surface model

Segmentation of CT scan images has been relatively mature [31,36]. Various methods and softwarehave been developed, such as 3DMA-rock, Image-pro, function of regionprops, Avizo1 and more. The pore-scale structure representing the porous media are extracted from the micro-CT images of carbonate cores (see Fig. 2), after noise reduction, binary conversion and simplification. The black region represents the solid matrix, while the white region represents pores. The pore-scale microstructure is complex, especially the rough surface, which makes it hard to simulate porosity, percolation and anisotropy directly. Wang et al. [37] have developed a pore-scale modeling method to describe the actual pore shape as randomly distributed ellipses, which may cause a discrepancy with actual rocks. Therefore, we need to find a simple method to describe the rough surface from micro-CT images. In this paper, based on the segmentation and quantitative analysis of each pore in micro-CT images, we assume that the rough surface is generated by adding the random height to the initial elliptical pores. Pores are isolated with respect to flow at high frequency because pore fluids do not have enough time to reach pressure equilibrium. Moreover, isolating pores can avoid the singular points in the process of calculation and low-quality mesh. Therefore, in our geometric model judging rules of intersect and including estimation between two pores should be improved to ensure the pores do not intersect. A simplified model consisting of large numbers of randomly distributed and mutually isolated pores with rough surfaces can be drawn based on MATLAB and AutoCAD software. The main steps in the geometric model are:

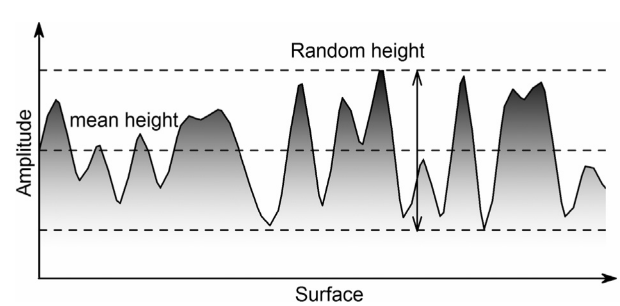

Fig. 1. Schematic view of a rough surface. The X-axis represents the direction of the surface and the Y-axis represents the direction of height. The double-headed arrow is the maximum fluctuation range of the random height.