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FROM PERCOLATION OF FRACTURED MEDIA TO SEISMIC ATTENUATION: A NUMERICAL STUDY

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ABSTRACT

Absorption of seismic energy in fractured porous fluid-saturated media is of great interest in modern geophysics. One of mechanisms causing attenuation is the wave-induced flow (WIFF), which appears between fracture-filling material and between connected fractures. Thus, seismic attenuation estimations may serve to detect fractured fluid-filled highly permeable reservoirs. Previous study of this mechanism mostly involve quasi-static tests, or numerical wave propagation modeling with relatively simple fracture models, so further analysis of seismic attenuation on more complex systems of connected fractures is needed.

Keywords: wave-induced fluid flow, poroelasticity, Biot model, seismic attenuation, wave propagation, discrete fracture network.

INTRODUCTION

One of the most rapidly developed direction of modern digital rock physics is wave-induced fluid flow in fractured porous fluid-saturated rocks. Resent study of this attenuation mechanism involves theoretical investigations (Guo, 2017) as well as several numerical techniques, including numerical analysis based on quasi-static oscillatory tests (Rubino, 2014) and full waveform simulation (Novikov, 2017). One of the principal interests of wave-induced flow study is estimation of correlation between fractures connectivity and frequency-dependent anisotropy at the wavelength scale in seismic and acoustic frequency band. However, most studies apply quite simple models of fractured media, for example, ones with two sets of aligned, and each fracture of one set have at least one intersection with fracture from other set. Unfortunately, inter-fracture connectivity in such medium is local, and there is no mesoscale percolating systems formed. The only known attempt to use a more complex models was reported in (Nunziker, 2018), where authors considered uniform distribution of the fracture orientation and studied dependence of the attenuation on the fractures length and number of intersections.

In our paper, we first generate fractured media models with simulated annealing technique, where we include percolation in functional under maximization. We consider starting model with two sets of microscale fractures orthogonal to each other and distributed uniformly in domain. Then we apply simulating annealing to form mesoscale fractures clusters with prescribed percolation length. Next, we use models obtained on different percolation stages for statistical analysis of their mesoscale geometrical properties. Finally, we perform wave propagation through fluid-filled porous fractured domain and use resulting wavefields to estimate seismic attenuation caused by wave-induced fluid flow. Results show that mesoscale structure of fractured media plays key role in seismic attenuation, when original microscale fractures mostly affect scattering.

FRACTURE NETWORK GENERATION

In our study, we consider fractured models containing two sets of aligned fractures, oriented parallel and perpendicular to the wave propagation direction, i.e. at 0 and 90 degrees to horizontal axis. Fractures are presented by rectangles with the length of 30 mm and width of 4 mm. Starting model is uniformly distributed fractures. Then we use simulated annealing to generate models with increasing the probability of percolation within arbitrary 250x250 mm window in all fractured domain (also called connectivity index) (Xu, 2006). Figure 1 demonstrates several fractured models with different values of this probability ("stages"), increasing linearly with equal step. In total, we generated 10 realizations consisting of 6 different stages.

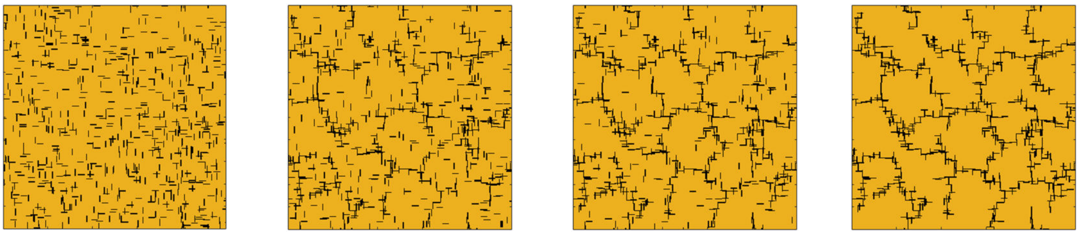

Fig. 1 - Fragments of fractured domain models. Percolation increases from left to right.

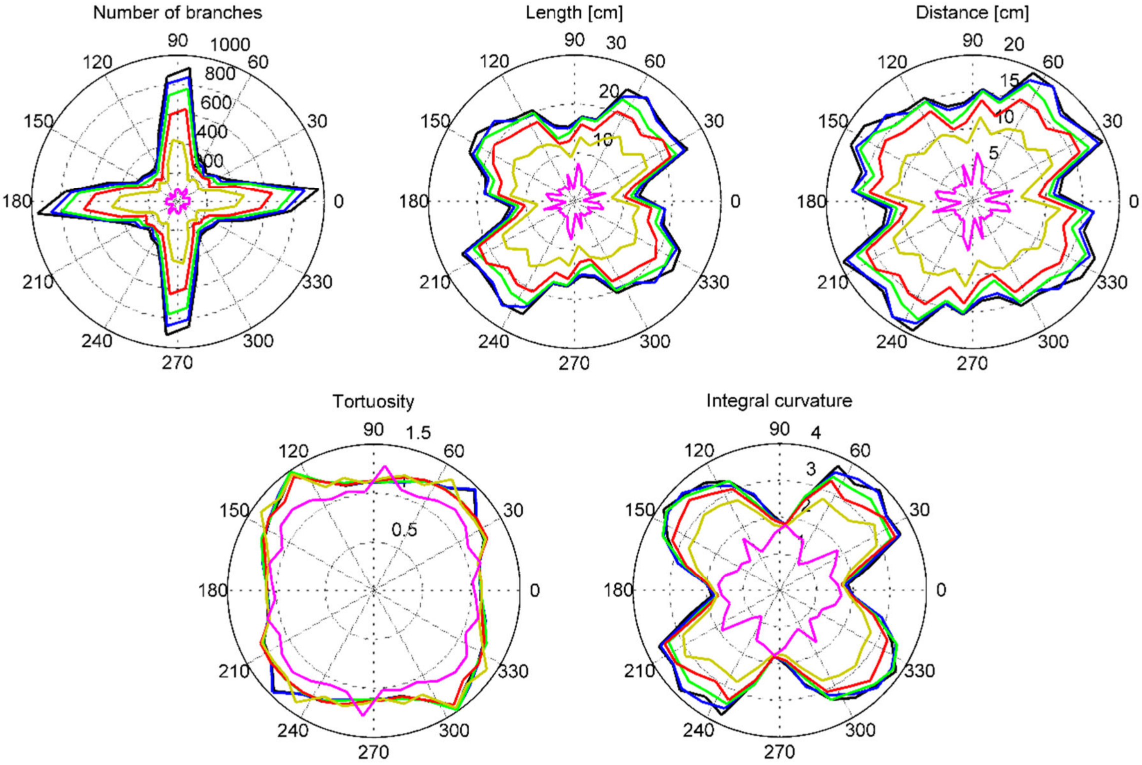

Fig. 2 - Statistical parameters of the meso-scale structures in following order: number of branches oriented at particular direction, mean length of the branches in cm, mean distance between the branch endpoints in cm, mean tortuosity, mean integral curvature with respect to branch orientation. Colors correspond to different percolation stages in the descending order: black, blue, green, red, yellow, pink.

Next, we perform geometrical and topological analysis to investigate models structure. In particular, we construct medial axis for fractures set, represented as graph, and divide it into a set of branches connecting its nodes. This technique was implemented on all generated models to estimate distribution of average number of branches, length, tortuosity and curvature in dependence of branch orientation. Results are presented in Figure 2.

One can see that most branches are oriented along axis directions in correspondence with orientation of original small-scale fractures. However, statistical analysis for branches lengths and distances between branches endpoints show that the biggest branches are aligned at the angle of +/- 45 degrees to axis. Thus, we can conclude that this is the main directions, in which percolation is delivered. Also note, that quantitatively geometrical parameters are sufficiently different at the low-percolation stages, whereas geometrical structure are weakly varies where percolation is quite high.

WAVE PROPAGATION MODELLING

To investigate fracture systems connectivity effect on attenuation of propagating seismic wave, we numerically solve dynamic Biot equations (Biot, 1956a; Biot, 1956b) using explicit staggered grid second-order finite-difference scheme (Masson, 2006; Masson, 2007; Masson, 2010; Carcione, 2010). To account for the model inhomogeneity we use the modification of the f-d scheme coefficients, based on the balance technique (Moczo, 2002; Lisitsa, 2002; Vishnevsky, 2014). We admit that the full-scale seismic modelling and more complex fracture systems would require the use of the advanced numerical approaches such as discontinuous Galerkin method (Lisitsa, 2016) or local time-space mesh refinement (Kostin, 2015; Lisitsa, 2012) or their combination. However, in this paper we study wave propagation at sonic scale, i.e. with the wavelength comparable with the fracture size, thus standard finite difference scheme. We use generated fractured models and consider background and fracture-filled materials to be fluid-filled porous media. Background have permeability 10-13 m^2 while for fracture-filling material it is 10-9 m^2 . The other parameters are provided in table 1, and they coincide with those used in (Novikov, 2017).

We considered the computational domain as a rectangle with fractured section, schematically demonstrated in Figure 3. We establish periodic boundary conditions at the top and bottom of the domain, while at right and left sides we construct perfectly matched layers to get rid of reflections from these boundaries. Propagating wave is plane and presented by Ricker wavelet. Wave propagates from the source line and we record signals at the two receiver lines in front of and behind fractured section. Simulations were performed for 10 central frequencies from 1 to 10 kHz for all 10 realizations with 6 stages each.

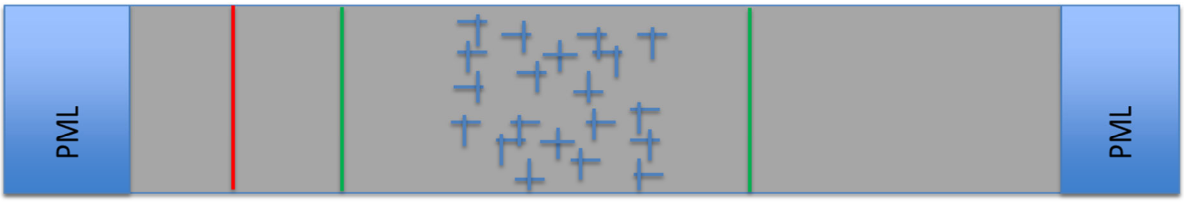

Fig. 3 - Schematic illustration of the computational domain. Red line corresponds to the source positions, green lines represent the receiver positions.

Table 1 - Material properties

	Bulk modulus [GPa]	Shear modulus [GPa]	Density [kg/m^3]	Porosity
Mineral phase	37	44	2650	
Dry properties of the fracture model				
Fracture	0.02	0.01		0.5
Background	26	31		0.1
	Bulk modulus [GPa]	Viscosity [Pa s]	Density [kg/m^3]	
Fluid properties	2.25	1090	0.001	

RESULTS

Figure 4 shows resulting fluid pressure fields for different percolation stages with central frequency of input signal equal to 3 kHz. In all cases permeability contrast causes fluid flow between background and fracture-filling material, but its intensity clearly depends on fracture connectivity. We can see that attenuation of seismic energy grows with connectivity increase. Moreover, increase of connectivity causes higher pressure gradients between fractures and background, which result in stronger fracture-to-background fluid flow, thus, more intense attenuation of propagating seismic waves. Also note, that in domains with highly connected fractures pressure is high in fracture material, where fluid mobility due to material permeability is enough for pressure to distribute freely, causing fracture-to-fracture flows within mesoscale fracture clusters.

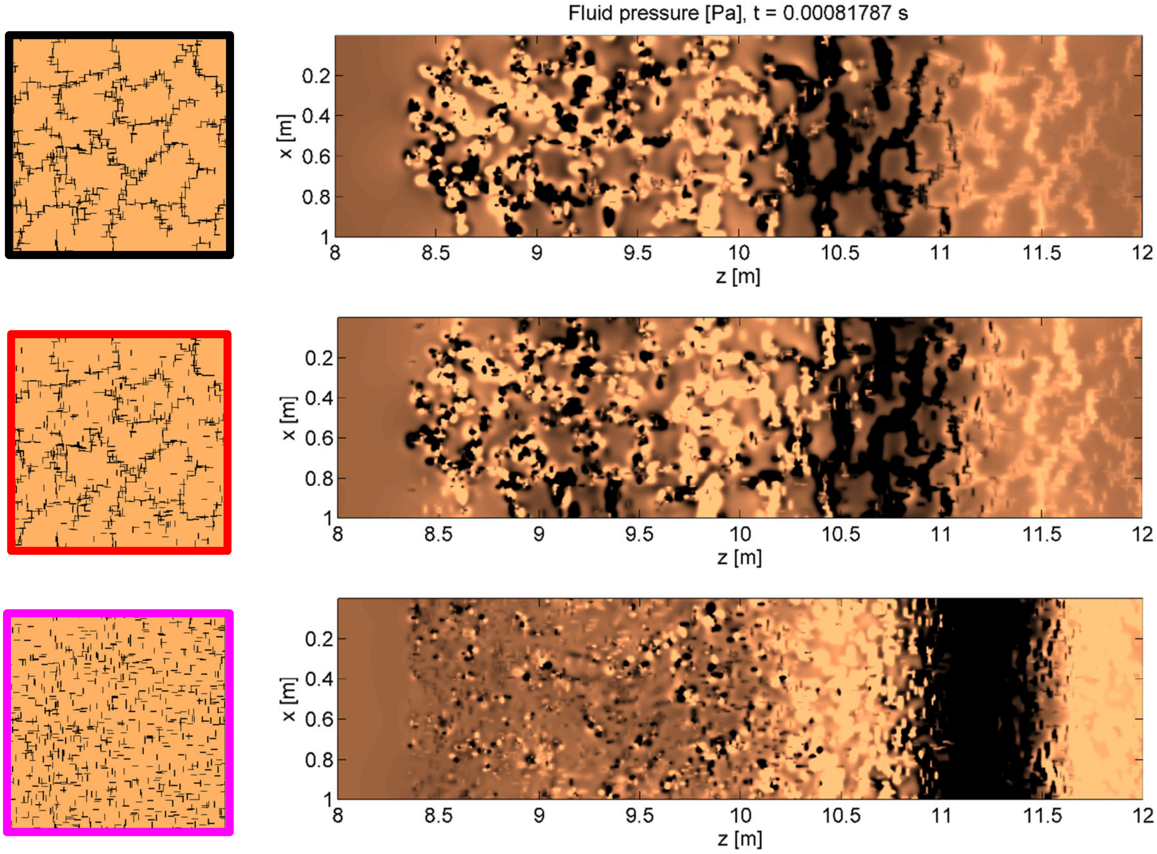

Fig. 4 - Fragments of the models for different percolation stages (left) and corresponding snapshots illustrating fluid pressure for different stages of fracture connectivity

Each realization and averaged signals recorded at receiver lines for different connectivity stages are presented in Figure 5 to demonstrate the effect of dispersion and attenuation increase for highly connected structures. Note, that realizations are close enough to each other, so our domain sizes for numerical experiments are quite representative. It is again clearly seen, that higher connectivity leads to much stronger attenuation, especially in compare with almost nonintersecting fractures set.

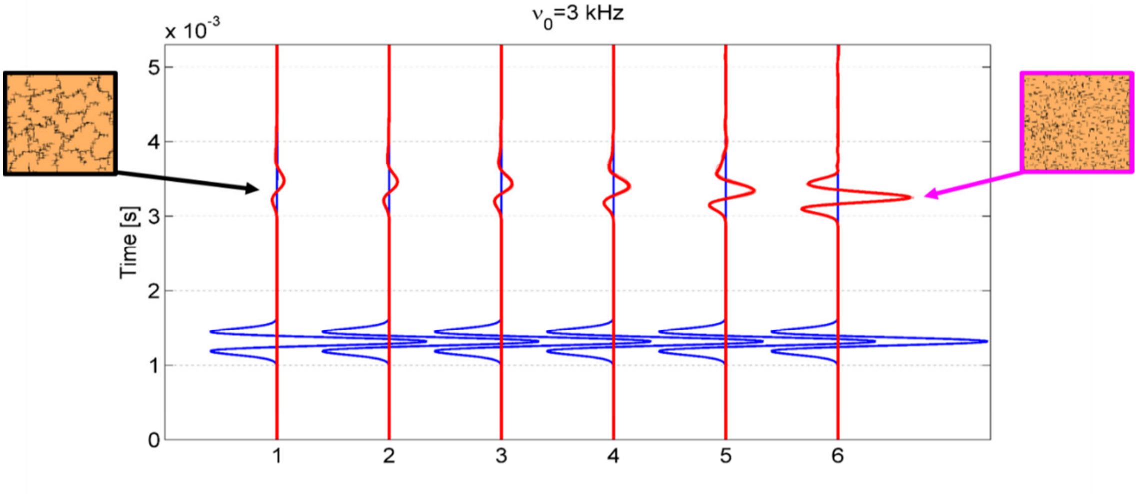

Fig. 5 - Signals recorded at two receiver arrays blue lines represent signal before interaction with fractures, red lines correspond to the signal after interaction with fractures. Connectivity of the structures decreases from the left to the right.

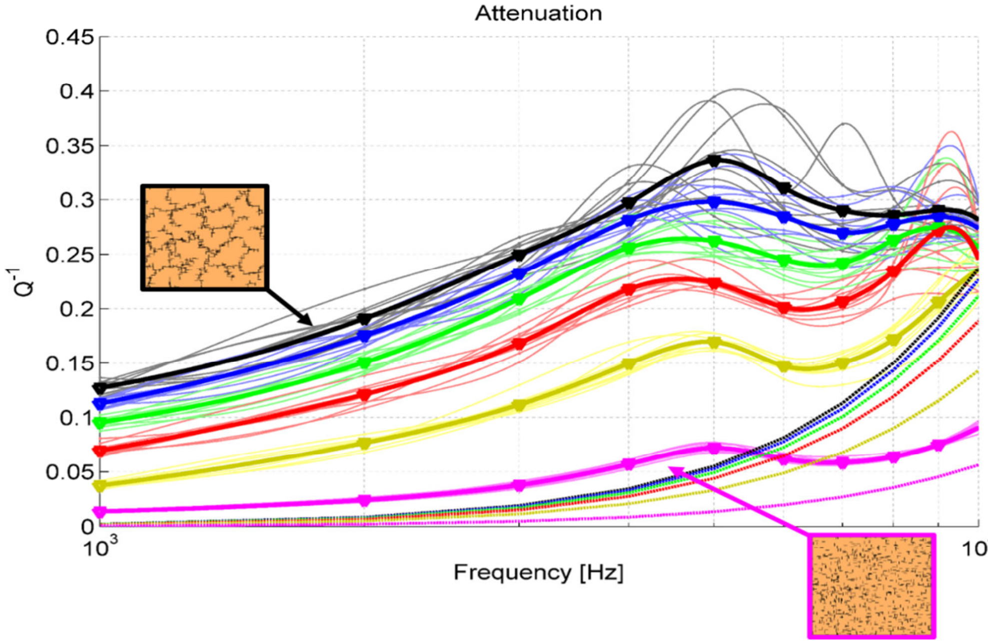

Fig. 6 - Inverse quality factor with respect to frequency. Different colors correspond to different connectivity stages of the models. Connectivity decreases from black to pink. Thick lines correspond to average over realizations, thin lines represent estimation for single realization. Dashed lines represent theoretical estimates of the attenuation due to the scattering.

We use obtained signals to estimate frequency-dependent attenuation by applying the spectral ratio technique. With this technique, we can estimate attenuation and velocity within the range of frequencies of about $[0.5\nu_0, 2\nu_0]$, where ν_0 is a central frequency of the wavelet, which lets us cover frequency band from 1 to 10 kHz. Resulting set of frequency-dependent inversed quality factor values for different realizations in considered frequency range is showed in Figure 6. One can see, that increase in connectivity, thus in average length of structures, leads to higher attenuation. However, more sufficient changes in the attenuation occur, when connectivity is relatively small. For the highly percolated models difference in attenuation is lower. Thus relative changes of average structure influence are more intensive when original structures are small.

Besides, we obtained theoretical estimations for attenuation due to scattering using technique presented in (Rytov, 1988). Results are also shown in Figure 6. These estimations have a good correlation with results of numerical experiments and demonstrate that at high frequency range scattering is dominant.

CONCLUSION

In our paper, we described the approach to generate complex fractured models containing mesoscopic structures with prescribed percolation. Simulated annealing technique was used to establish percolation level in the model. Six sets of models with different connectivity index were generated. We applied numerical geometry techniques to construct medial axis of fractures set and estimated distribution of its average geometrical properties. Results showed that, although most branches oriented in directions of small-scale structures, branches defining percolation length are oriented along +/-45 degrees. One important note is that at high connectivity length of branches almost not changes compared to one at relatively low fracture connectivity.

Several wave propagation numerical experiments were performed to estimate the attenuation of seismic wave in fractured porous fluid-filled media and influence of fracture connectivity on attenuation and dispersion. Numerical simulation results and theoretical predictions both illustrate that the main parameter causing attenuation due to wave-induced fluid flow as well as due to scattering is mesoscale structure size. Compared with statistical analysis, results showed great correlation between branches length and attenuation of seismic wave. Presented snapshots showed, that growth of structure length causes increasing of pressure gradients between background and fracture material, thus the attenuation due to fracture-to-background fluid flow, and illustrated presence of fluid flow between connected fractures. Further investigations of relations between geometrical structure of fracture system and percolation are needed to be done to make considered seismic attenuation approaches applicable to the transport properties analysis for fractured reservoirs.

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