Comment on "Sensitivity of the active fracture model parameter to fracture network orientation and injection scenarios" by Basağaoğlu et al. (2009)

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Basağaoğlu et al. (2009) present a study on detailed unsaturated flow behavior in two-dimensional fracture networks using numerical experiments (simulations) based on the lattice-Boltzmann method. Their results are valuable for improving our understanding of unsaturated flow processes and evaluating the active fracture model (AFM) that was developed for capturing large-scale preferential flow in fractured rocks (Liu et al., 1998; 2003).

As indicated in Basağaoğlu et al. (2009), a previous study was conducted to evaluate the AFM with numerical experiments (Seol et al., 2003). However, the methodology used in that study and the corresponding conclusions are highly questioned for the following two reasons. First, the evaluation relies on a condition that simulated water flow processes in a fracture network are adequately represented with a continuum approach, because they draw their conclusions by comparing simulation results with those obtained from a dual-continuum model based on the AFM. No effort was made by Seol et al. (2003) to justify the validity of the continuum approach for their specific fracture network that includes a small number of fractures only. (The analyses of Basağaoğlu et al. (2009) do not need the similar condition.) Second, Seol et al. (2003) use numerical dispersion to represent the matrix diffusion process. This treatment is not valid simply because numerical dispersion results from numerical errors and is not a physical process.

The AFM divides fractures into two parts, active and inactive. Flow occurs only in the active part (Liu et al., 1998). The portion of the active part (f_a) is given by

$$f_a = S_e^{\gamma} \qquad (1)$$

where S_e is the effective saturation in fractures and γ is the so-called AFM parameter that is considered to be a constant for a given fracture network. Equation 1 was originally

proposed as an empirical relationship (Liu et al., 1998) and later shown to be a result of a fractal flow pattern commonly observed in unsaturated and multiphase flow systems (Liu et al., 2003; 2005). The AFM parameter γ is found to be a function of fractal dimension of the corresponding flow pattern (Liu et al., 2003). The interface area between fractures conducting water and rock matrix (A_{fm}') is given by (Liu et al., 1998; Basağaoğlu et al., 2009):

$$\frac{A_{fm}'}{A_{fm}} = S_e \qquad (2)$$

where A_{fm} is the total interface area between fractures and the rock matrix. Equations 1 and 2 are the key AFM relationships.

Basağaoğlu et al. (2009) use lattice-Boltzmann simulation results to determine how the AFM parameter values are related to fracture network orientations and injection rates. The unique aspect of their study is that values for S_e and f_a are directly available from simulation results. Basağaoğlu et al. (2009) report that γ value depends on fracture network orientation. It is somehow expected because parameter γ is considered a constant for a given fracture network. Fracture networks with the same geometry and different orientations should be considered different fracture networks.

The major purpose of this comment is to extend the analyses of Basağaoğlu et al. (2009) for evaluating the AFM. For a given fracture network (with the same orientation), Basağaoğlu et al. (2009) performed numerical experiments for different injection rates (or different S_e values). The generated data set [Figure 9 of Basağaoğlu et al. (2009)] provides an interesting opportunity to directly evaluate key AFM relationships (Equations 1 and 2). Figure 1 shows a comparison between Equation 2 and the simulation results [Figure 9(a) and 9(b) of Basağaoğlu et al. (2009)] and an excellent agreement is obtained. The saturation and area ratio (A_{fm}'/A_{fm}) values for a data point in Figure 1 are obtained from Figure 9(a) and 9(b) of Basağaoğlu et al. (2009), respectively, for a given tilt angle. Several representative tilt angles (5, 15, 25 and 35 degrees) are employed for data points in Figure 1.

Shown in Figure 2 are comparisons between results calculated from Equation 2 and those determined from Figure 9 for a number of tilt angles. Figure 9(d) of Basağaoğlu et al. (2009) shows that γ value varies for each tilt angle, but the variation is considerably smaller than that among different tilt angles. In Figure 2, a constant γ value is used for each tilt angle to be consistent with the AFM assumption that γ is an intrinsic property of a fracture network. For a given tilt angle, the corresponding saturation and f_a values are obtained from Figure 9(a) and 9(c) in Basağaoğlu et al. (2009), respectively. The γ value for a given tilt angle (Figure 2) is obtained by averaging γ values in Figure 9(d) of Basağaoğlu et al. (2009). No curve-fitting exercise is conducted in Figure 2. Given the simplicity of the AFM and the complexity of the unsaturated flow processes in a fracture network, the AFM relationship reasonably matches the simulation results of Basağaoğlu et al. (2009).

In summary, comparison results from Figures 1 and 2 suggest that the AFM has done a reasonable job in characterizing key water-flow features simulated by Basağaoğlu et al. (2009). It may also be of interest to note that the AFM concept has been extended to describing preferential flow processes in unsaturated soils (Liu et al., 2005). The corresponding model is called the active region model (ARM). A recent evaluation of the ARM was performed with well-documented field infiltration and tracer tests in natural soils (Shen et al., 2009). The evaluation results support the validity of the ARM.

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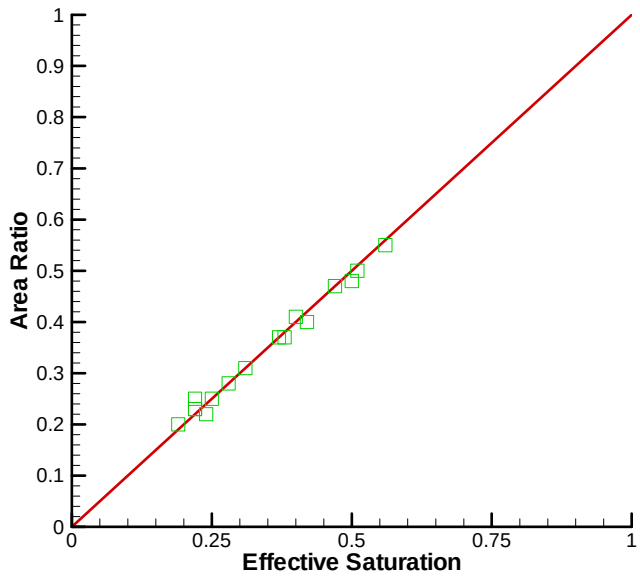
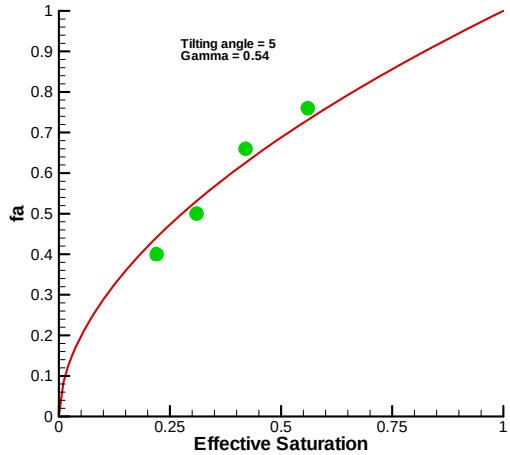


Figure 1. A comparison between area ratios (A_{fm}'/A_{fm}) calculated with Equation 2 and simulation results (data points) from Basağaoğlu et al. (2009) for tilt angles of 5, 15, 25 and 35 degrees. The solid line is 1:1 line.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Gamma = 0.54
fa
Effective Saturation
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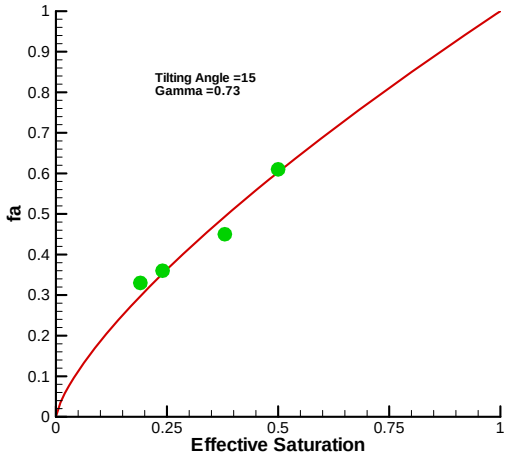
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.25
0.5
0.75

(a)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Gamma =0.73
fa
Effective Saturation
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0.1
0.2
0.3
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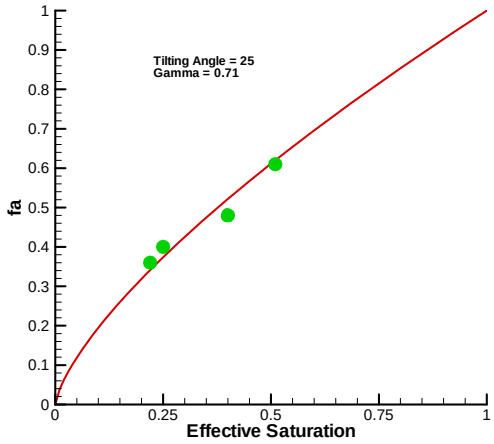
0.6
0.7
0.8
0.9
1
0.25
0.5
0.75

(b)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Gamma = 0.71
fa
Effective Saturation
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0.2
0.3
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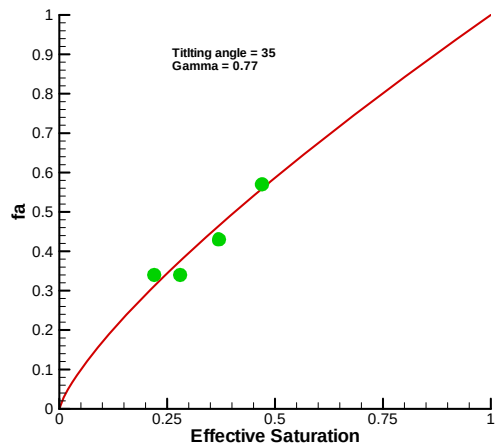
0.5
0.6
0.7
0.8
0.9
1
0.25
0.5
0.75

(c)



(d)

Figure 2. A comparison between theoretical relationships (Equation 1) and simulation results (data points) from Basağaoğlu et al. (2009) for tilt angles of 5, 15, 25 and 35 degrees.

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