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What does a tensiometer measure in fractured rock?

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Abstract. Tensiometers are routinely used in both the laboratory and the field for measuring the capillary pressure in unsaturated porous media. We conducted a laboratory experiment on a fractured basalt core. We also examined the performance of a tensiometer in fractured-porous media by means of numerical simulation, in which the tensiometer itself and its interaction with the formation were explicitly modeled. We conclude that the gauge pressure is primarily affected by the fracture rock component—fracture or matrix—that conducts water into or out of the ceramic cup of the tensiometer. Fracture flow is accurately monitored during imbibition events, whereas during drainage, the matrix capillary pressure is registered, leading to a strong hysteretic behavior in the pressure measurements.

INTRODUCTION

Observations of a physical system are influenced by the method and devices used to determine the quantity of interest. For example, the temperature of a small volume of liquid may be changed by the temperature of the immersed thermometer. In hydrogeology, drilling an observation well may alter the hydraulic properties of the aquifer, and skin and wellbore storage effects must be taken into account when analyzing well test data. Measurements of contaminant concentrations are affected in many ways by the sampling method, e.g., because pressure and flow conditions in the vicinity of the observation point are changed during the extraction of the soil water and gas samples. Apart from direct physical impact of the measuring device on the system there is also the question of how to interpret the observed value, i.e., whether the measurements refer to a microscopic or macroscopic quantity, what sampling volume they cover, and what kind of average they represent. These issues have been discussed for a variety of methods used for determining the state or the hydraulic properties of the subsurface. These examples show that a thorough interpretation of observed data has to consider not only the system of interest, but also the measuring device and methods used to obtain the data. In general, measured data represent the combined system "measuring device plus object to be studied," and deconvolution of the data is required to obtain information about the object of interest.

The capillary pressure is one of the main driving forces governing flow and transport in partially saturated soils and rocks. Knowledge of the relationship between capillary pressure and saturation is required for predicting multiphase fluid flow in the subsurface. There is an increasing need for monitoring water flow in unsaturated fractured rocks where the fractures are potential fast flow pathways for contaminants. Tensiometers, which are routinely used to measure the capillary pressure in soils, are potentially useful for directly observing the transient response of a partially saturated fracture-matrix system to imbibition and drainage events. Tensiometer readings may provide insight into the velocity with which water pulses propagate through a fracture network and how the redistribution of water is affected by matrix imbibition.

A number of questions arise when using tensiometers in fractured rocks. They are mainly related to the design of the tensiometer and its interaction with the formation. For example, it is impossible to install a tensiometer such that it measures only the pressure in the fracture. The ceramic tip of a tensiometer intersects the fracture but also contacts the matrix. Since fracture and matrix are not in equilibrium during transient flow events, it is important to determine whether the tensiometer gauge water pressure reflects the fracture or the matrix component or how the two are combined. Moreover, the tensiometer itself may lead to local redistribution of water between the fracture and the matrix, affecting the system to be studied. Additional issues one might consider include temperature effects, gas diffusion through the porous cup, capillary barrier effects, and the impact of the tensiometer installation on the local flow field.

The importance of capillary pressure measurements in fractured rocks has been emphasized by *Evans and Nicholson* [1987] and *Pruess and Wang* [1987]. The performance of tensiometers and water sampler in soils has been studied by a number of authors (see for example *Klute and Gardner* [1962], *Towner* [1980], *Narasimhan and Dreiss* [1986], *Morrison and Szecsody* [1987], *Thomas and Phillips* [1991], *Stannard* [1992], *Tokunaga* [1992]). The purpose of this work is to better understand the functioning of a tensiometer installed in fractured rock under wetting and draining conditions using experimental data and numerical modeling. The analysis is based on numerical modeling, in which the tensiometer itself and its interaction with the formation is simulated. We analyze how the pressure measured by the tensiometer is related to the capillary pressure in the fractured formation at some short distance from the porous cup. The modeling results are compared with tensiometer data from field and laboratory experiments, which are described in the following section.

FIELD AND LABORATORY OBSERVATIONS

Field Data

We first present data sets from field and laboratory experiments to illustrate the tensiometer responses obtained in fractured systems. Figure 1 shows tensiometer measurements at three different depths before, during, and after ponded infiltration into fractured basalt at the Box Canyon site, Idaho [*Faybishenko et al.*, 1998]. The sharp increase in pressure immediately after the beginning of flooding the surface of the infiltration pond (7 by 8 m) suggests that fracture flow is relatively fast and that the front of the water pulse is registered with a short response time of the tensiometer. The drainage phase, however, is considerably slower. This may be due to an actually slower change in saturation during drainage as a result of hysteresis. This phenomenon is investigated in our laboratory and modeling experiments as discussed below.

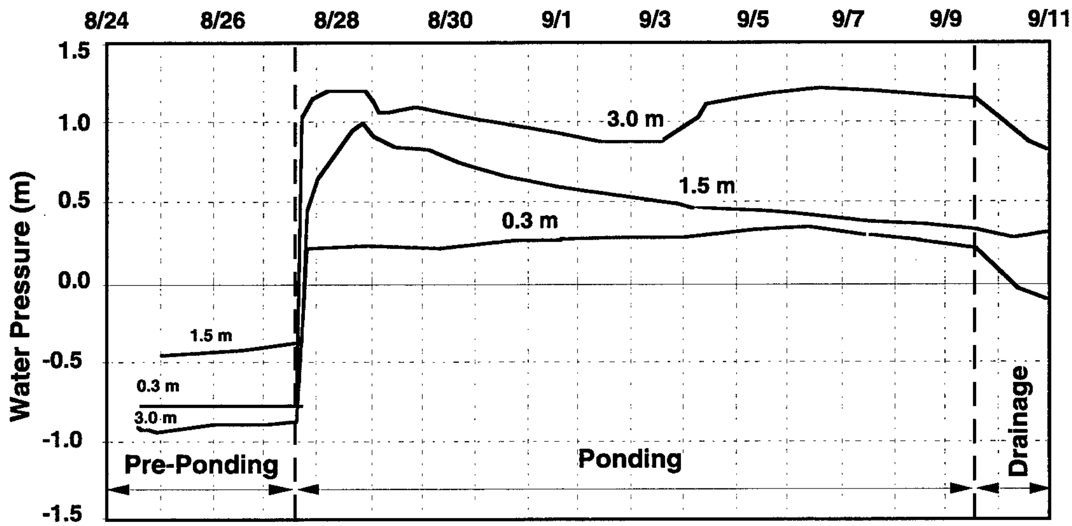

Figure 1. Pressure data measured by tensiometers at three depths (1, 5, and 10 ft), installed in fractured basalt before, during, and after the ponded infiltration test conducted at the Box Canyon site in Idaho in 1996 [*Faybishenko et al.*, 1998]. Shown are records of averaged daily pressures (except at the beginning of flooding and drainage). The pulse of liquid flowing through the fractures after the beginning of ponding is immediately registered by the tensiometers. The pressure change during drainage is considerably slower.

Laboratory Data

The second example consists of a laboratory experiment performed on a basalt core with a single vertical fracture. The cylindrical core 10 cm high and 5 cm in diameter was equipped with porous ceramic plates at the top and bottom edges. Four horizontal tensiometers were installed at two levels: two tensiometers in the matrix and the other two intersecting the fracture. A schematic of the experimental apparatus is shown in Figure 2. Water is injected from the bottom into the initially air dry core for two hours with a pressure head equivalent to the height of the core. Subsequently, a suction of -9 m is applied, draining the system. Figure 3 shows tensiometer pressures measured during (a) imbibition, and (b) drainage. During imbibition (Figure 3a) from the bottom, the tensiometers intersecting the fracture show a faster response than the matrix tensiometers. The fast response of the fracture tensiometer is due to fracture flow and is followed by slower, transient effects, which are explained as the result of water imbibition into the matrix. During drainage (Figure 3b), the responses of the fracture and matrix tensiometers are identical and slower compared with the response during imbibition.

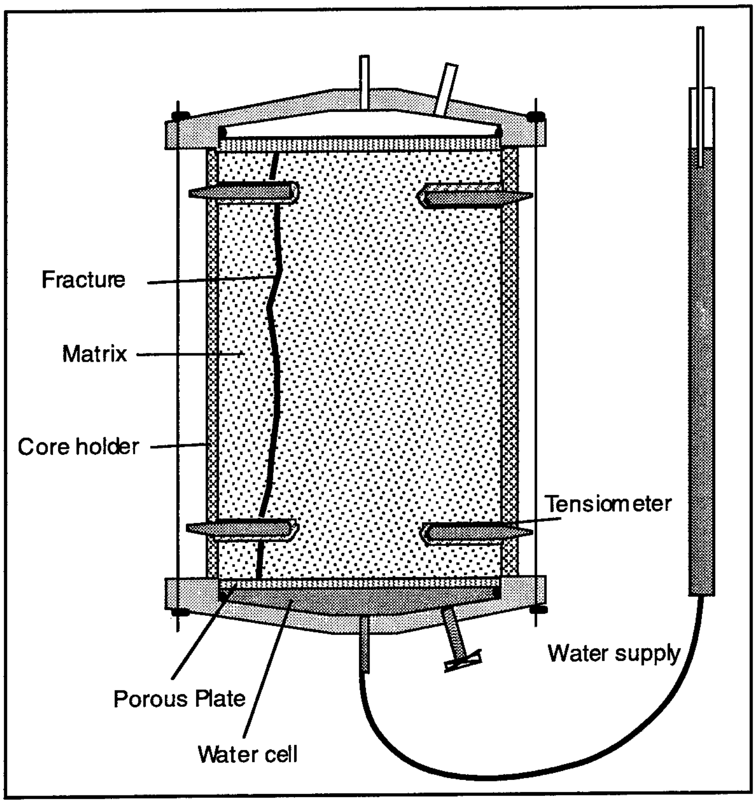

Figure 2. Schematic of apparatus for measuring pressures in fractured core during drying and wetting.

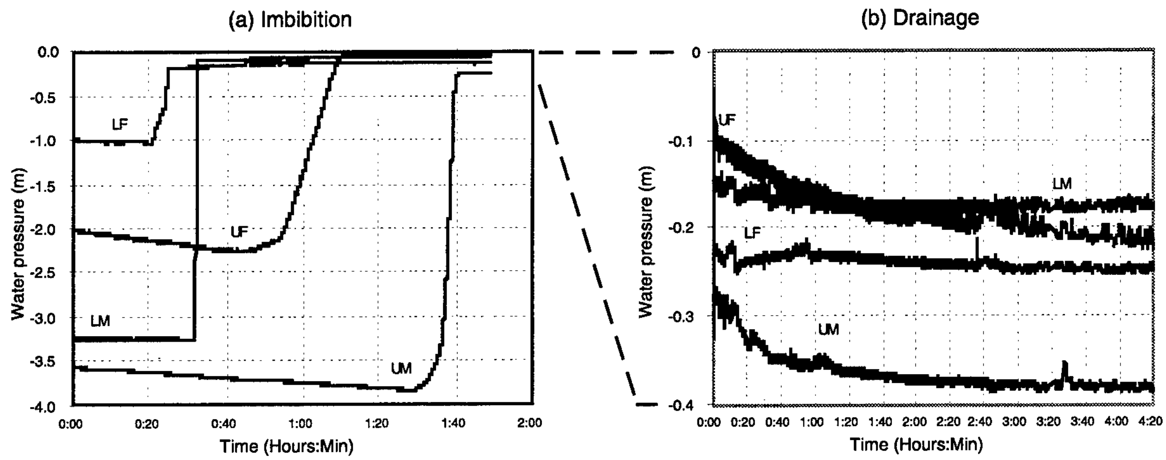

Figure 3. Results of laboratory experiment on fractured basalt core showing (a) the fast response during imbibition, and (b) the slower drainage process. Note the different vertical scale of Figures (a) and (b).

SIMULATIONS

Model Assumptions

The performance of a tensiometer in a fractured system is studied here by means of numerical simulations. We used the TOUGH2 code [*Pruess*, 1991] for simulating two-phase flow of air and water in the fractured rock and the tensiometer. As pointed out above, the interaction between the formation and the tensiometer intersecting the fracture may be crucial in that it affects the local distribution of liquid and the gauge pressure reading. This requires that the tensiometer itself must be modeled, taking into account the flow of water from the fracture and the matrix through the ceramic cup and the tubing. Furthermore, the sensitivity of the tensiometer determines the amount of water exchanged between the tensiometer and the formation.

The tensiometer is discretized as shown in Figure 4, where the ceramic cup is modeled as a porous medium with an air entry pressure of 1 bar. The chamber in the tensiometer tip and the tubing consist of a highly-conductive, water-filled series of elements, and the pressure transducer is represented by a small gas bubble. Two columns of elements delineate the fracture. Flow in the core is considered two-dimensional with locally three-dimensional flow around the tensiometer tips to simulate more precisely the interaction of the tensiometer with the fracture and the matrix. Richards' equation with van Genuchten's water retention and unsaturated hydraulic conductivity model are solved using integral finite differences. The key parameters used in the simulation of the laboratory experiment are summarized in Table 1.

Pressure changes in the formation result in a slight compression or expansion of the gas bubble due to water in- and outflow through the ceramic cup. The pressure in the gas bubble is considered to be the tensiometer gauge pressure, and is compared with the actual capillary pressure in the fracture and the matrix. Note that the capillary pressure in the formation is defined as the difference between the pressure in the liquid and gas phase, whereas the pressure in the tensiometer gas bubble is an absolute pressure. Subtracting the atmospheric pressure from the gauge pressure yields a negative pressure comparable with the formation capillary pressure. However, changes in the air pressure potential also affect the tensiometer gauge pressure, as will be discussed below.

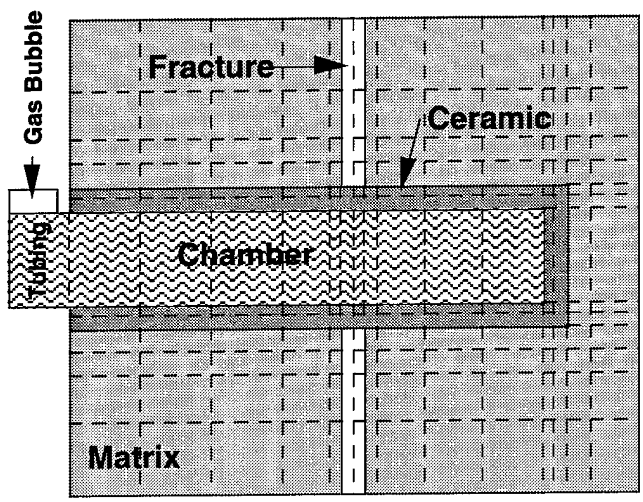

Figure 4. Schematic of tensiometer discretization (not to scale). The ceramic cup, the tensiometer chamber, the tubing, and the compressibility of the pressure transducer are explicitly modeled, enabling water exchange between the tensiometer and the fracture-matrix system. The model is locally three-dimensional to allow water flow around the tensiometer tip.

Table 1. Parameter Set Used in Fractured Core Simulation

	Core		Tensiometer	
Parameter	Matrix	Fracture	Ceramic Cup	Chamber
permeability [m^2]	1.0E-14	1.0E-10	1.0E-16	1.0E-9
porosity	0.23	-	0.30	1.00
aperture [mm]	-	0.10	-	-
air entry pressure [Pa]	2.0E3	2.0E1	1.0E5	0.0
van Genuchten n	1.47	1.47	-	-
initial saturation	0.39	0.03	1.00	1.00

Simulation Results

Saturation distributions and liquid flow directions 15 minutes and 2 hours after changing the boundary conditions are shown for the imbibition and drainage events in Figures 5 and 6, respectively. Figure 5 shows that during injection, water quickly flows through the highly permeable fracture, from where it imbibes horizontally into the matrix. Imbibition also occurs also axially from the bottom boundary, efficiently saturating almost the entire core within two hours. Figure 6 shows that the reverse process, i.e., drainage to the bottom boundary, is much less efficient because the fracture is emptied almost immediately, turning it into a capillary barrier. Drainage has to occur through the matrix alone, requiring a longer time period for desaturation despite the much stronger pressure gradient. Note on Figures 5 and 6 that the flow field in the core is slightly affected by the presence of the tensiometers, which in turn affects the measured pressure.

Figure 7 shows the time trend of the relative gauge pressure in the two lower tensiometers, and comparison is made with the capillary pressure in the fracture and matrix at the same level. Immediately after starting imbibition, the capillary pressure in the fracture jumps to zero. Therefore, the tensiometer intersecting the fracture responds almost instantaneously. In other words, a tensiometer is capable of accurately depicting the arrival of water in a fracture. However, water flow from the fracture to the tensiometer and back into the matrix as well as the compressibility of the pressure transducer lead to a slower increase in the pressure compared with that in the fracture. Even if the tensiometer sensitivity were increased by reducing system compliance and flow resistance through the ceramic cup, the transient capillary pressure observed by a tensiometer may, nevertheless, differ from the fracture capillary pressure due to its contact to the matrix. This matrix component becomes larger with increasing matrix permeability and decreasing fracture permeability. The difference between the matrix tensiometer reading and the actual capillary pressure in the matrix can be attributed to suboptimal tensiometer sensitivity. Notice that the tensiometers show slight positive gauge pressures, reflecting the positive water potential encountered at the lower tensiometers as a result of the imposed boundary potential. The simulations also indicate that the two-dimensionality of the flow field, the asymmetry of the fracture plane with respect to the core axis, and the geometrical boundaries lead to a highly non-uniform saturation distribution, rendering the use of analytical solutions impractical even for this simple, axial flow experiment. During drainage, the tensiometers register the matrix capillary pressure because practically no water is flowing through the fracture.

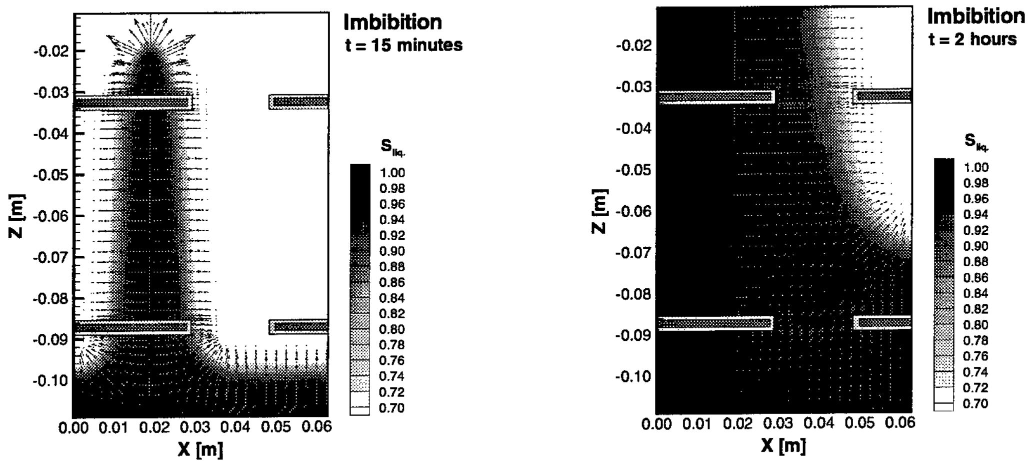

Figure 5. Saturation distribution and liquid flow direction 15 minutes and 2 hours after start of imbibition from the bottom.

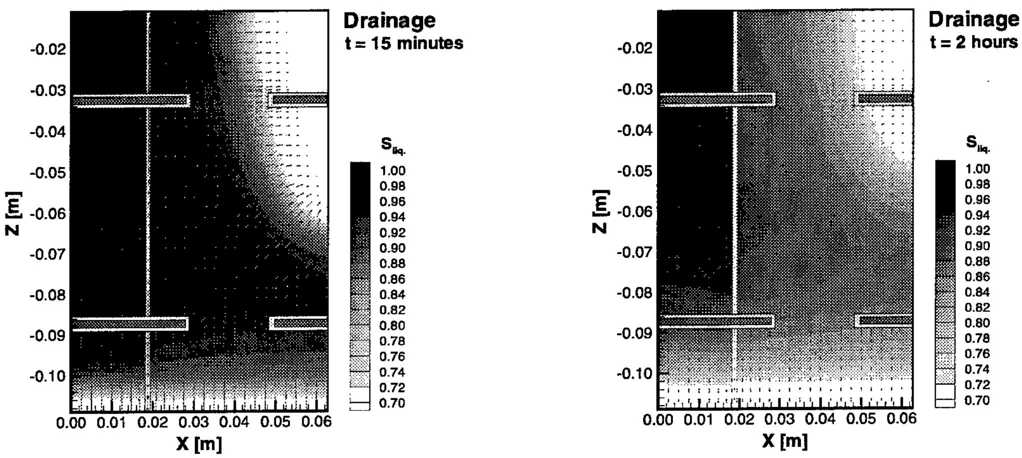

Figure 6. Saturation distribution and liquid flow direction 15 minutes and 2 hours after start of drainage from the bottom.

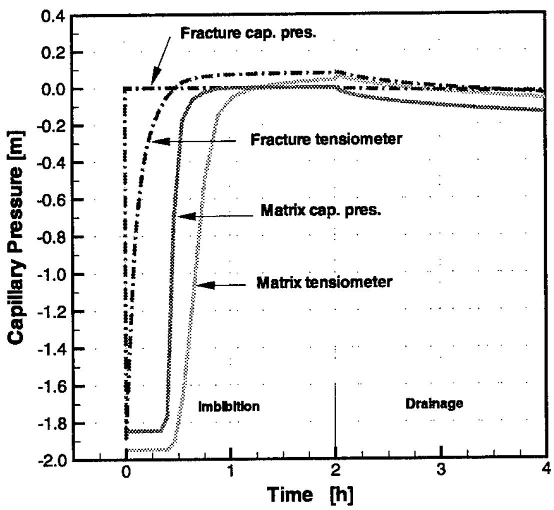

Figure 7. Actual capillary pressure and relative pressure in tensiometer gas bubble at level of lower tensiometers as a function of time.

CONCLUSIONS

We have investigated the performance of a tensiometer in a fractured-porous medium by conducting laboratory experiments on a fractured basalt core. Furthermore, we have performed numerical simulations, in which the interaction between the tensiometer and the fractured formation is explicitly modeled.

The time-trend of the tensiometer gauge pressure obtained in fractured rock under field conditions (Figure 1), in the laboratory (Figure 2), and using numerical simulations (Figure 7) consistently showed that the gauge pressure is primarily affected by the fractured rock component that conducts water into or out of the ceramic cup of the tensiometer. During wetting, the tensiometer gauge pressure reflects the capillary pressure in the fracture. During drainage, the gauge pressure is dominated by the matrix pressure. The interaction between the fracture, the matrix, and the tensiometer leads to hysteretic behavior in the observed water pressure, even though the matrix and fracture themselves do not necessarily have to exhibit hysteretic effects in their hydraulic properties. Future work will have to demonstrate how effective hysteretic parameters can be incorporated into a numerical model for the simulation of unsaturated flow in fractured-porous media.

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