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Improved Tension Infiltrometer for Measuring Low Fluid Flow Rates in Unsaturated Fractured Rock

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ABSTRACT

The search for a permanent storage facility for the geological disposal of high-level nuclear waste has motivated extensive research during the past several decades to characterize and predict fluid flow into and through unsaturated fractured rock. Tension infiltrometer experiments are extremely useful to investigate infiltration into fracture networks, but are difficult to perform using commercially available equipment developed mostly for soils. Our objective was to develop a tension infiltrometer suited for accurate measurements of infiltration into fractured rock at very low flow rates and for long equilibration times. We constructed several prototype instruments from porous stainless-steel membrane, stainless-steel casing, acrylic tubing, several temperature-compensated pressure transducers, solenoid valves, and a data logger for automated control and data acquisition. An automated refill system was also developed to facilitate long unattended equilibration periods typical in infiltration experiments on unsaturated fractured rock. Results show that the improved design reduces temperature effects on the infiltration rate, allows for much longer periods of unattended operation (auto-refill), and reduces evaporation from the infiltrometer. The estimated upper flow-rate limit of our new infiltrometer is about 1 mm d^{-1}, based on the conductance of the porous steel membrane (11 mm d^{-1}). We were able to make measurements of the fluid flux as low as 10 mm yr^{-1} at a pressure head of about −110 cm.

Plans to use the unsaturated zone of Yucca Mountain, Nevada as a permanent storage facility for the geological disposal of high-level nuclear waste has motivated extensive research aimed at understanding fluid flow processes into and through unsaturated fractured rock formations (e.g., NRC, 2001; Bodvarsson et al., 2003; Wu et al., 2004). Yucca Mountain, located in a semiarid region of southern Nevada, is characterized by alternating welded and nonwelded volcanic tuff layers. Generally, nonwelded units have relatively high matrix porosities and permeabilities and lower fracture densities, whereas the welded layers, such as those that may host the envisioned repository, have lower porosities and higher fracture densities. One major challenge is to estimate the unsaturated hydraulic properties of the major hydrologic units of Yucca Mountain (e.g., Flint et al., 2001) or similar fractured rock formations elsewhere. One possible means for obtaining such estimates is the use of tension infiltrometers.

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Tension infiltrometers have long been used in soil hydrology to measure field soil infiltration rates and/or to estimate various infiltration parameters such as the sorptivity and the saturated hydraulic conductivity (Perroux and White, 1988). Others have used tension infiltrometers to characterize flow through soil macropores at or near saturation (e.g., Wilson and Luxmoore, 1988; Lin and McInnes, 1995; Jarvis and Messing, 1995; Mohanty et al., 1996). Unfortunately, tension infiltration experiments are much more problematic to conduct in fractured rock than in most soils. Extremely low infiltration rates are expected in fractured rocks, particularly at high tensions, thus making accurate measurements difficult. Because of low rock permeabilities and long equilibration times, various environmental factors normally neglected during tests with soils may not be negligible for rock formations.

Recent attempts to use tension infiltrometers to measure water flow properties of welded tuff layers exposed along the Exploratory Study Facility (ESF) at Yucca Mountain (a tunnel constructed to provide access along the eastern edge of the potential repository area) showed that traditional soil infiltrometer designs are inadequate to accurately describe flow in fractured rock media (Hudson et al., 2000, unpublished data). Many fractures, measured in micrometers, are still fully functional at infiltrometer supply tensions above 100 cm of water. These fractures are most likely responsible for the recharge rates of 5 to 10 mm yr^{-1} (1.6×10^{-10} to 3.2×10^{-10} m s^{-1}) estimated to occur at Yucca Mountain (e.g., Flint et al., 2002). Tensions needed to fully characterize the flow regime of these fractures are unattainable using current soil infiltrometer technology. Furthermore, because of extremely low infiltration rates and long equilibration times at especially higher tensions, evaporative fluxes that inevitably occur between the disk and the ring (normally neglected during tests in soils) may become important error sources when measurements are made on fractured rock. As well, temperature fluctuations causing pressure variations at the rock surface may reduce the accuracy of the measurements. Finally, the need to periodically refill the reservoir tower, which requires an operator and induces severe disturbances to the infiltration process, can become an important practical problem. Hence, the primary objective of this study was to develop a tension infiltrometer that overcomes some of these limitations and can be used to measure infiltration rates at levels thought to occur at the Yucca Mountain site.

Abbreviations: ESF, Exploratory Study Facility.

OPTIMAL DESIGN CRITERIA FOR ROCK TENSION INFILTROMETER

The design specifications for a rock tension infiltrometer are somewhat different from those for a soil tension infiltrometer. The infiltration process in fractured rock is expected to proceed much slower than that in most soils, especially at tensions of about 20 cm or higher. In our own studies (e.g., Wang et al., 1998; Simunek et al., 1998) we have measured equilibrium infiltration rates of about 10^{-8} m s^{-1} (≈1 mm d^{-1}) for clay soils to about 10^{-4} m s^{-1} (10 m d^{-1}) for sandy soils, which required equilibration times from several minutes to several days depending on soil type and the applied tension. By comparison, infiltration rates for rocks may be as low as 10^{-10} m s^{-1} (≈3 mm yr^{-1}) or less, with required equilibration times of 1 to 2 mo. Also, tension infiltrometer experiments on fractured rock will be most useful if they can be performed at relatively high tensions (e.g., tensions of 100 cm or more to characterize flow in fractures that are only a few micrometers wide).

An infiltrometer for characterizing water flow in fractured rock formations needs to be made from robust materials to allow operation of the infiltrometer under relatively unusual environmental conditions (Kilbury et al., 1986; Kilbury, 1984; ASTM, 2002). For example, exposed rock surfaces are often jagged, with relatively sharp edges that may easily damage the porous nylon membrane materials frequently used in commercially available infiltrometers. The membrane itself may also limit the effective tension applied to the rock surface. While the nylon material on the disk may have a relatively low bubbling (air-entry) pressure, stretching and clamping material to the plastic base may cause distortions in the pore size and reduce the contact angles, thus significantly increasing the bubbling pressure of the instrument.

Kilbury et al. (1986) gave specifications for a robust double ring infiltrometer for measuring saturated water flow in fractured rock. Several of their design concepts have been adapted to our tension infiltrometer. One of these addresses evaporation from the infiltrometer. Rock tension infiltrometers must be vapor tight to limit or eliminate evaporation from the device during very long equilibration times. Evaporation, if present, would be measured as an equivalent infiltration flux and hence would compromise the accuracy of the infiltration data. The second adaptation addresses the usually uneven rock surfaces which require a cap material that makes good contact between the rock and the infiltrometer membrane. Also, the cap itself must facilitate a relatively high flux rate, or at least a rate that equals or exceeds that of the rock. The anticipated long equilibration times coupled with limited access to the test site, warrant an instrument that is capable of refilling itself. The device must also have data acquisition and control systems so it can take readings over time and initiate refilling. The need for high-accuracy measurements requires that the reservoir tube diameter must be made as small as possible to maximize the ratio of the disk to the reservoir diameter, thus enabling accurate readings. Accuracy further requires that the disk be as large as possible so a reasonable number of fractures at the surface is included in the infiltration measurements at a given pressure head. The integration of fractures and matrix pores of differing size should lead to more representative infiltration data.

MATERIALS AND METHODS

Tension infiltration experiments were performed in the laboratory on a large sample of volcanic tuff (Fig. 1) extracted from the Yucca Mountain ESF site. The lithologic characteristics of the block, in particular the matrix porosity and the typology of fractures, were very similar to those observed in situ near Alcove 8 (e.g., Wang and Bodvarsson, 2003). The final design of the tension infiltrometer was tested on the large rock sample (Fig. 1), as well as on smaller blocks in a controlled temperature room.

Infiltrometer Disk

The infiltrometer disk was designed to transmit water to the rock surface at high tensions, to prevent evaporation during infiltration experiments, and to be made from robust materials. A schematic of our final design is shown in Fig. 2. The disk was made of a thick stainless-steel lamina at the top (30-cm diam.), a metal ring (4 cm high, 27.5-cm diam.), and a 0.32-cm-thick (1/8 in) stainless-steel porous membrane (Mott Corporation, Farmington, CT) at the bottom (Kilbury et al., 1986; Kilbury, 1984; ASTM, 2002). The parts were welded together to form a chamber. The porous membrane is characterized by a relatively narrow pore size distribution, having a mean pore size of 0.2 μm, and a relatively high porosity of about 80%. We measured a bubbling pressure of −60 cm. The saturated conductivity of the membrane was measured to be 1.3 10^{-7} m s^{-1} (11 mm d^{-1}). Previous infiltration studies (Hudson, 2000, unpublished data) indicated the membrane conductivity is approximately three orders of magnitude higher than the expected tension infiltration rate at a pressure head of −50 cm. However, the membrane conductivity was comparable to infiltration rates observed in saturated conditions (Hudson, 2000, unpublished data), which suggests that the disk may not be suitable for measurements at or near saturation (Perroux and White, 1988). The top lamina contained two ports. One port was connected to the reservoir tower and the other to a fully temperature-compensated Setra 230 pressure transducer (Setra Systems, Inc., Boxborough, MA) mounted on top of the disk to monitor the pressure head during infiltration. The second port also facilitated the removal of air from the disk.

A stainless-steel ring (4 cm high, 27.5-cm diam.) hosting the contact material was placed over the rock surface. Having a proper seal between the metal ring and the rock is critical to prevent evaporation. For our laboratory experiments we cut a circular groove into the rock with a diamond bit, and placed the ring in the groove as shown in Fig. 2, but in the field the ring simply rested on the bedrock. The field experiment required several applications of silicone to properly seal the ring to the rock.

Because of the particular shape of the disk, the thick top lamina on top of the metal ring forms a closed chamber that prevents evaporative flux from the contact material. Sealing was assured by using a soft rubber gasket glued beneath the lamina (Fig. 2) and by taking advantage of the weight of the disk (≈14 kg). We note also that the contact material needs to be slightly deformable to achieve a good seal at the disk–ring interface, while at the same time ensuring good contact with the rock surface. We found that diatomaceous earth material with a saturated conductivity of 4×10^{-5} m s^{-1} (≈3.5 m d^{-1}) was suitable contact material. The pressure head of the contact material was measured using a temperature-compensated pressure transducer tensiometer inserted through the ring. The tensiometer permitted monitoring of the advancing wetting front within the contact material, thus providing possible additional information for optimal analysis of the tension infiltrometer data using inverse procedures (e.g., Simunek et al., 1998).

The effectiveness of the design in limiting or eliminating evaporative losses was tested by gluing the contact material host ring to an impermeable surface (acrylic sheet), then adding the contact material, the disk, and the Mariotte and reservoir towers, and subsequently adding water as in an ordinary

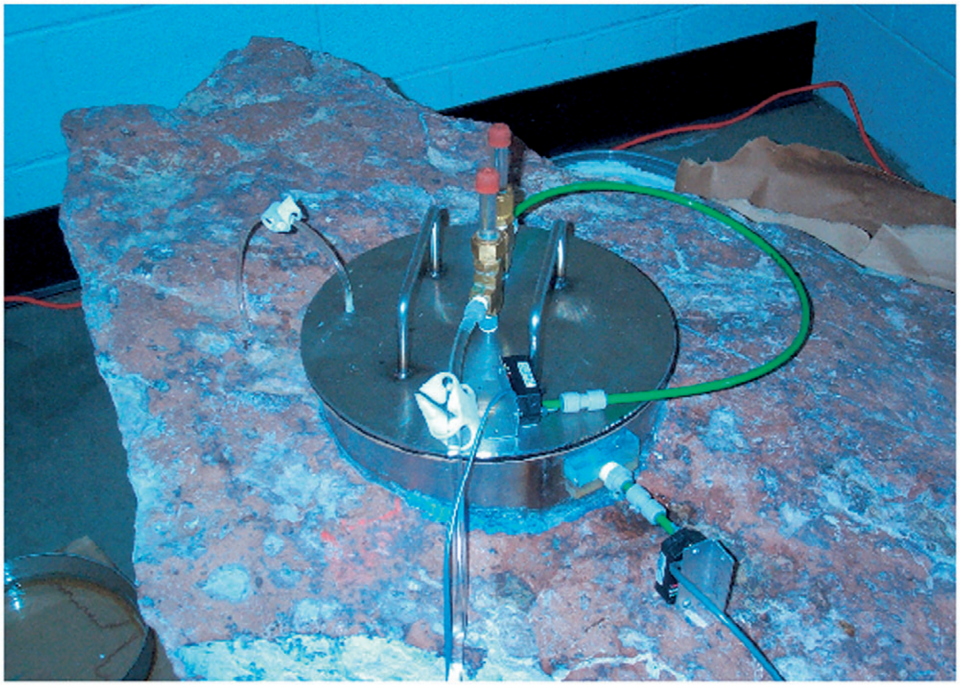

Fig. 1. View of improved tension infiltrometer disk setup on large fractured rock sample used in this study.

infiltration experiment. Once the diatomaceous earth was wet and the infiltration process terminated, the entire assembly was weighed and placed in an environmental chamber for one-week periods at 15 to 20% relative humidity, with the temperature set at 20, 30, or 40°C. These conditions permitted estimates of the evaporation rate from the weight loss measurements. We observed an evaporation of 1.2 g of water after 1 wk at 40°C, while no evaporation could be measured at 20 and 30°C. Performance of the disk hence seemed to be more than satisfactory, considering the ambient temperature (≈22°C) and relatively high relatively air humidity (≈80%) conditions in the ESF tunnel at Yucca Mountain.

Tension Infiltrometer

Our design of the Mariotte and reservoir towers (Fig. 3) was based in part on an analysis of the effects of temperature on infiltrometer performance (Castiglione et al., 2005) and temperature-induced water flow dynamics within air pocket tensiometers (Warrick et al., 1998; Butters and Cardon, 1998).

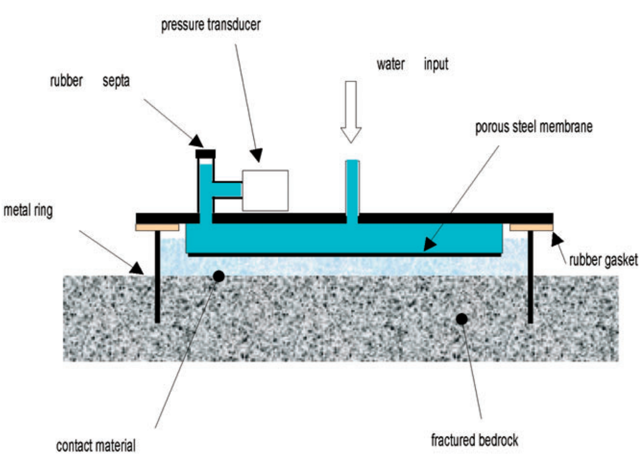

Fig. 2. Schematic of improved infiltrometer disk showing major components.

We refer to Castiglione et al. (2005) for a detailed analysis of these effects. The infiltrometer consisted of a single Mariotte tower (150 cm tall) and a reservoir tower (180 cm tall), both made of small-diameter acrylic tubes. The diameter of the tubes was selected to be as small as possible (0.953-cm i.d., 3/8 in), while still allowing free movement of air bubbles (Perroux and White, 1988). This was done to achieve maximum accuracy in the measurements of the infiltration rate and to minimize the initial volume of the air pockets.

As shown by Castiglione et al. (2005), it is important to keep the height of the air pocket in the Mariotte tower as small as possible (≈1 cm) to limit temperature effects. Tube C (Fig. 3), connecting the reservoir and Mariotte towers, consisted of two segments separated by a normally open solenoid Valve S3 (the function of this valve is explained below). The horizontal segment of Tube C consisted of a 10-cm-long, 0.635-cm i.d. (1/4 in) tygon tube, while the vertical segment was made of 0.318-cm i.d. (1/8 in) nylon tubing. As discussed in more detail by Castiglione et al. (2005), an advantage of the above design is that it dampens pressure changes caused by temperature fluctuations in the reservoir tower air space.

The vertical air tube in the Mariotte tower was replaced by 12 external horizontal segments of tygon tubes (0.635-cm i.d., 1/4 in), placed 10 cm apart at different depths, each having a ball valve (Fig. 3). The tension applied to the rock surface was regulated by choosing the proper segment for air entry, and by keeping the remaining valves closed. This design modification further reduces pressure variations associated with temperature fluctuations in the Mariotte tower air space (Castiglione et al., 2005).

Automated Refilling System

Before describing the automated refilling system, we first briefly discuss disturbances induced by normal refilling of an infiltrometer. The reservoir tower of soil tension infiltrometers is usually refilled manually by removing a stopper or similar device at the top and then filling the reservoir tower with water. To preserve the tension applied at the soil or rock sur-

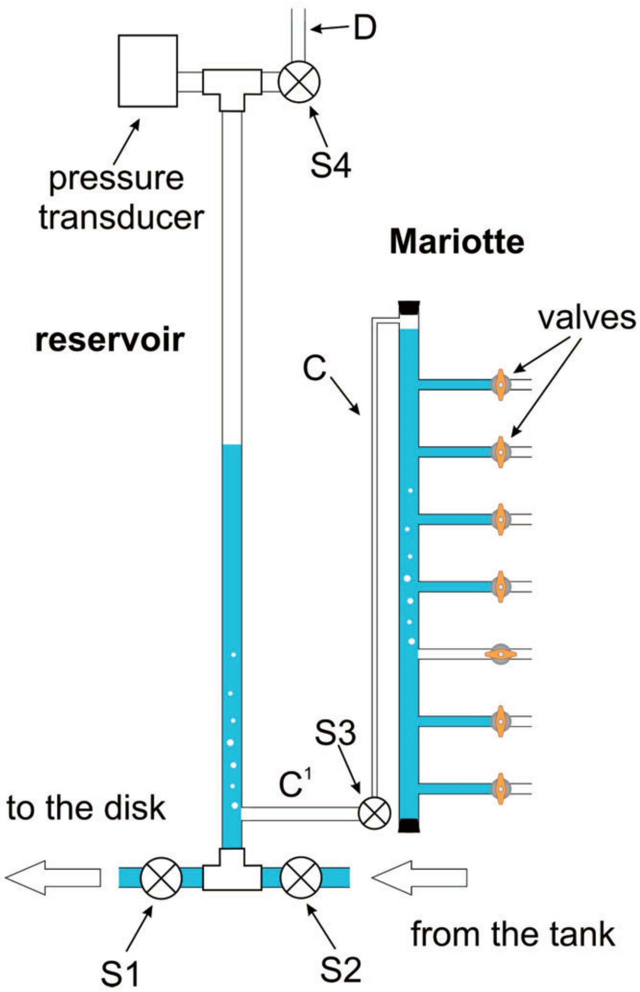

Fig. 3. Schematic of Mariotte and reservoir towers used for the improved low-flux, high-tension infiltrometer.

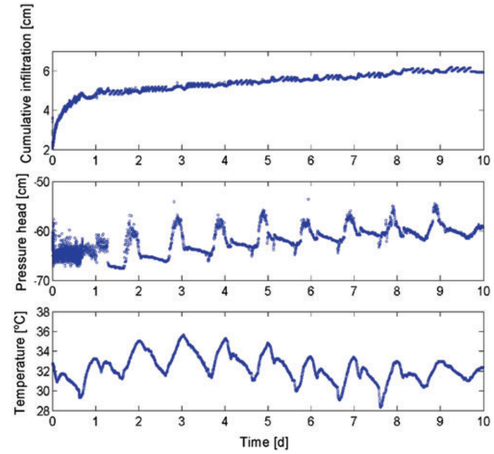

Fig. 4. Plots vs. time of (a) observed cumulative infiltration, (b) the applied pressure head at the rock surface, and (c) ambient temperature using an early high-tension infiltrometer prototype. Notice how the observed surface pressure heads are affected by the ambient temperature fluctuations.

face, the disk is usually disconnected from the tower (e.g., using a valve or clamp) before removing the stopper. This procedure establishes a positive pressure at the bottom of the reservoir. When infiltration restarts, this positive pressure is inevitably transmitted to the soil surface and hence will affect the infiltration rate. The pressure head within the infiltrometer disk is further affected by the thermodynamic status of the small volume of air inevitably left at the top of the reservoir (when using rubber stoppers). The pressure, in fact, drops upon the expansion of this volume of air as the water level in the reservoir descends. As infiltration proceeds, the pressure eventually returns to the value before refilling. Only at this time does bubbling start again in the reservoir tower, with the desired tension at the soil surface finally being reestablished. The time needed to restore the original tension thus depends on the height of the air pocket left upon refilling and on the rate of expansion of the pocket (i.e., on the infiltration rate). While this does not usually represent a problem for tension infiltrometer experiments on soils, the disturbances induced during the refill maneuver may last from many hours to several days with high-tension infiltration rates involving fractured rock.

To eliminate any disturbance, we designed the tension infiltrometer in such a way that no volume of air is left when the reservoir is filled. In this way the negative pressure at the surface is instantaneously reestablished as the infiltration is restarted. This is accomplished by connecting the reservoir tower to a large tank (Fig. 3) and using the tank to refill the tower from the bottom. The tank itself is placed at a sufficient height above the rock or soil surface to completely fill the tower by gravity. A system of four solenoid valves (S1 through S4 in Fig. 3) controlled by a data logger via a relay driver permits the automatic refill. Valves S1 and S3 are normally open, while the other two are normally closed (i.e., they are powered only when the reservoir is being filled). When the water level in the reservoir (monitored by the pressure transducer mounted on top) is sufficiently low, the data logger controls the valves in the following sequence. Valve S1 is closed (the system is disconnected from the disk), Valve S3 is closed (reservoir and Mariotte towers disconnected), and Valves S4 and S2 are open (water can freely flow from the tank into the reservoir tower). This process allows the water to rise rapidly in the tower until it reaches the small Tube D (Fig. 3). The top of the reservoir was designed in such a way that this refilling displaces all air in the reservoir tower. Completion of the filling process is indicated by a positive head recorded by the pressure transducer as water reaches Tube D. To terminate refilling and reestablish the infiltration process, the valves are operated in the following reverse sequence: S2 closes, S4 closes, S1 opens, and S3 opens. The entire refilling process using the above design was found to require $<$10 s.

APPLICATION TO FRACTURED ROCK SAMPLE

Figure 4 shows results of an infiltration experiment performed with an early prototype of the rock tension infiltrometer. Plotted are cumulative infiltration, the pressure head applied at the rock surface, and the temperature data, all as a function of time. The cumulative infiltration curve (Fig. 4a) shows a pronounced initial sorption phase characterized by high infiltration rates, followed by an approximately constant infiltration rate starting at about 1 d. As indicated by the tensiometric data recorded within the contact material, the wetting front at this time reached the bedrock. Although a steady-state infiltration process seemingly had developed after 1 d, thus allowing approximate estimates of the infiltration rate, the data were subject to persistent noise that clearly correlated to the daily temperature fluctuations (Fig. 4c). The temperature effects were most evident from the measured surface pressure heads (Fig. 4b), which followed a quasiperiodic pattern. Notice that temperature variations of about 4°C

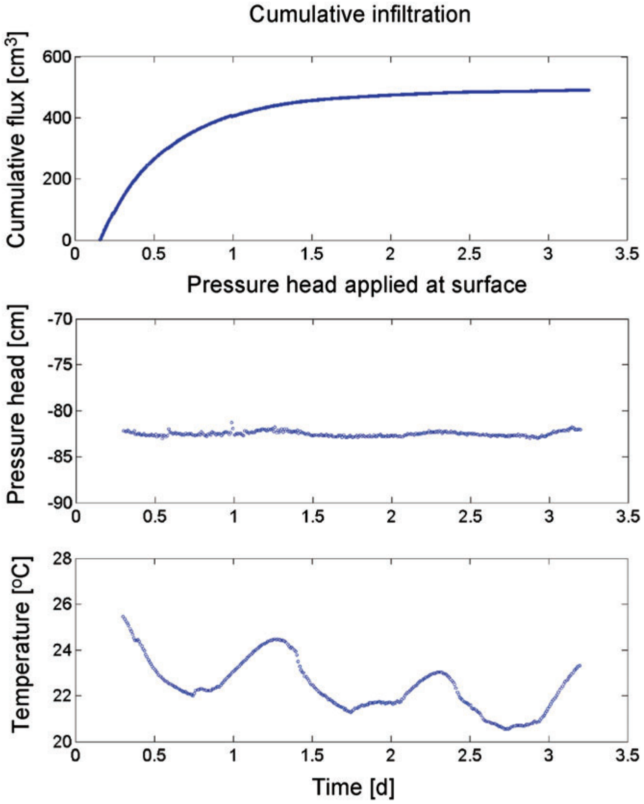

Fig. 5. Plots vs. time of (a) observed cumulative infiltration, (b) applied pressure head at rock surface, and (c) ambient temperature of the improved high-tension infiltrometer prototype. Notice that temperature effects on the pressure head at the rock surface are now minimized relative to the results in Fig. 4.

caused overpressures of more than 10 cm, which made the early prototype unacceptable for long-term infiltration experiments on unsaturated fractured rock.

Upon drying the rock, a new series of experiments were performed with the final prototype tension infiltrometer. Figure 5 shows in more detail data for infiltration with an applied pressure head at the rock surface of about −82 cm. Although the temperature fluctuations during this experiment were somewhat less severe as compared with the data in Fig. 4, system response was now much better. Surface pressure head variations were now <1 cm, and without any noise in the cumulative infiltration data (Fig. 5a).

The steady-state infiltration rates recorded for three surface pressure heads (triangles) are plotted in Fig. 6. The figure also includes data obtained for the same rock sample using a traditional tension infiltrometer setup (Soil Measurement Systems, Tucson, AZ) at higher pressure heads (circles). The traditional setup was found to produce inaccurate results for pressure heads below about −25 to −30 cm and to fail completely below −40 cm. We note that the two sets of data in Fig. 6 should be comparable since disks with the same diameter were used for the two sets of measurements.

The objective of this study was to develop a reliable technique to measure extremely small fluxes at relatively high tensions at the fractured rock surface. Although the analysis and interpretation of the data in Fig. 6 are beyond the scope of this paper, it is interesting to note the vastly different infiltration rates observed for the imposed range of tensions. There is little doubt that the rock matrix remained saturated throughout this range of tensions. Hence, differences in Fig. 6 must be ascribed to different classes of fractures being involved

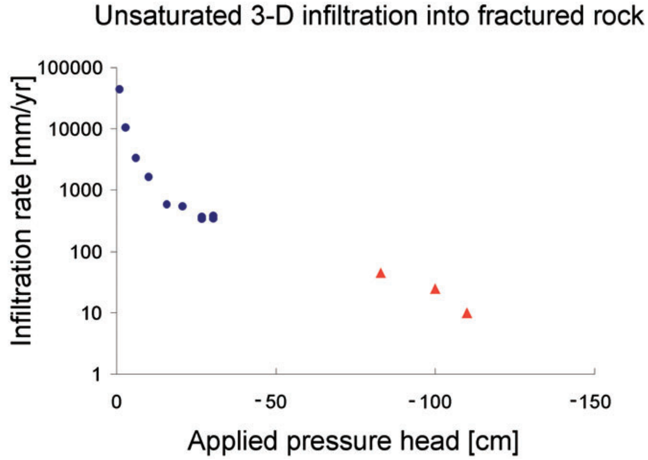

Fig. 6. Steady-state infiltration rates measured with a traditional soil tension infiltrometer (solid circles) and the improved low-flux, high-tension infiltrometer (solid triangles).

in the infiltration process. With the appropriate adaptations described here, the tension infiltration technique therefore represents a very useful tool for investigating flow in fractured media. It also interesting to note that the lowest flux we measured with the improved tension infiltrometer was about 10 mm yr^{-1}, corresponding to a pressure head of about −110 cm (Fig. 6). This flux is approximately equal to the average percolation rate estimated for Yucca Mountain (Flint et al., 2001, 2002). Our experience with the newly designed rock tension infiltrometer suggests that the applied pressure head can be easily extended to about −150 or −160 cm, thus potentially providing additional data about the infiltration process at rates far less than 10 mm yr^{-1}. Such experiments, also if performed in situ (e.g., in the ESF tunnel), are best implemented using relatively large porous stainless-steel membrane disks (e.g., 50-cm diam.).

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