Analysis of Uncertainty for 2-D Fracture Flow and Seepage Into an Excavated Drift

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Introduction

In this study we perform simulations of fracture flow by releasing a finite water pulse above an excavated niche in a 2-D vertical cross section. The amount of water that infiltrates the niche is observed through time and we analyze its sensitivity with respect to permeability, k and van Genuchten's fitting parameter analogous to the inverse of air entry pressure, $1/\alpha$. Evaluation of uncertainty in the total percent infiltrate as a result of parameter uncertainty is performed using linear First-Order-Second-Moment and Monte Carlo methods. In addition, the effects of heterogeneity within the fracture continuum on flow and infiltration are observed by replacing the homogeneous fracture continuum with two randomly generated permeability and air entry pressure heterogeneous continua.

Conceptual Model

Fluid flow through a 2-D vertical cross section fracture continuum is simulated using TOUGH2, an integral finite difference simulator developed at LBNL (Pruess, 1991). In this study TOUGH2 is used to calculate an isothermal, 2-D solution to Richards Equation for unsaturated flow above and around a short excavated drift, or niche.

Simulations of fluid flow presented here are loosely based on field experiments currently being performed at Yucca Mountain, Nevada, in which a water pulse of a known volume is released above an excavated niche. In the field, movement of the water pulse is observed by collecting infiltrate through the niche ceiling. Similarly, in this numerical study, we quantify the amount of water infiltrating the niche by means of the percent infiltrate, defined as the percentage of the total liquid release volume that enters the niche. In the simulations, a water pulse of 1.4 l is released instantaneously at time zero, roughly 1 m above the niche ceiling. Within the niche, a boundary condition of 100% relative humidity is assumed such that the excavated niche acts as a capillary barrier. Table 1 describes the homogeneous fracture continuum parameter distributions for the two uncertain parameters. Mean values of permeability and air entry pressure are based on a 30 μm fracture aperture and cubic law. Figure 1 illustrates saturation contours within the 2-D fracture continuum surrounding the excavated niche 12 hrs after the water pulse release.

Sensitivity Analysis

Figures 2 and 3 illustrate the sensitivity of total percent infiltrate to permeability and air entry pressure. For the simulation conditions of water ponded in the release wellbore, permeability (Figure 2) affects the time frame over which infiltration occurs, but not the amount of infiltration entering the niche. Figure 3 shows percent infiltrate sensitivity to air entry pressure; as air entry pressure increases, percent infiltrate drops and as $1/\alpha$ decreases, more water infiltrates the niche. Air entry pressure significantly affects the percent infiltrate but only mildly alters the time frame over which infiltration occurs.

Uncertainty Analysis

Uncertainty analysis is performed using ITOUGH2 (Finsterle, 1997), an inverse modeling code written to interface with the TOUGH2 family of codes. In this study, ITOUGH2 provides estimates of uncertainty in the amount of water that enters the niche as a result of parameter uncertainty by linear First-Order-Second-Moment (FOSM) and Monte Carlo methods. Linear FOSM analysis assumes that uncertainty in any observable system response (e.g. percent infiltrate) can be approximated as a linear function of all uncertain system parameters (e.g. k and $1/\alpha$). Generally, this method will not provide acceptable estimates of uncertainty for non-linear system behavior. A Monte Carlo analysis of uncertainty in the total percent infiltrate is performed for comparison purposes and is regarded as a more accurate but computationally costly estimation method. One hundred Monte Carlo simulations are executed, drawing randomly generated values of permeability and air entry pressure from lognormal distributions described in Table 1.

Figure 4 illustrates the results of both FOSM and Monte Carlo uncertainty analyses for parameter set 1. Horizontal lines bound the area that describes physically plausible values of percent infiltrate, from 0% to 100%. The 100 Monte Carlo simulations are presented as dashed lines. Results of the FOSM analysis are indicated on either side of the mean total infiltrate of 78%. Monte Carlo results produce percent infiltrate values ranging over 38%. The FOSM analysis fails to estimate transient uncertainties, often exceeding the boundaries of what is physically plausible. Figure 5 shows the analysis repeated for a domain of higher permeability and lower capillarity described in Table 2. This system allows a greater mean percent infiltrate (88%) while reducing uncertainty to 24%. The reduction of uncertainty in the percent infiltrate with a higher mean percent infiltrate shows the sensitivity of the uncertainty analysis to the mean.

We repeated the uncertainty analysis, this time introducing two randomly generated permeability fields. Each field was created with a vertically dominant structure (vertical correlation length of 3.0 m; horizontal correlation length of 0.2 m). Correspondingly heterogeneous air entry pressure fields were created using the J-Leverett function (Bear, 1972) to relate k and $1/\alpha$. Uncertainty analyses resulted in mean percent infiltrates (and Monte Carlo ranges) of 88% (23%) and 92% (14%) for the two fields, respectively. Due to the sensitivity of the uncertainty in percent infiltrate to the mean, it is difficult to separate the effects of heterogeneity on uncertainty.

Conclusions

The amount of water to infiltrate the niche is very sensitive to van Genuchten's air entry pressure. Under these simulated conditions, (i.e., ponding conditions in the borehole) permeability affects only the time frame over which infiltration occurs and does not affect the total percent infiltrate. Linear FOSM analysis does not produce an acceptable estimate of the uncertainty in the amount of water to infiltrate the niche. The effect of heterogeneity on the uncertainty in percent infiltrate is not resolved due to the sensitivity of uncertainty to the mean percent infiltrate.

Acknowledgments

This work was supported by the Director, Office of Civilian Radioactive Waste Management, through a Memorandum Phase Order EA9013MC5X between TRW Environmental Safety Systems, Inc. and E.O. Lawrence Berkeley National Laboratory through U.S. Department of Energy Contract No. DE-AC03-76SF00098.

References

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Table 1. Parameter Set 1 (Based on a 30 μm fracture aperture and cubic law).

Parameter	mean μ	standard deviation σ
log k (m^2)	-14.58 (2.6 millidarcies)	0.5
log $1/\alpha$ (Pa)	3.66 (4550 Pa)	0.166

Table 2. Parameter Set 2 (Higher permeability, lower capillarity).

Parameter	mean μ	standard deviation σ
log k (m^2)	-13.96 (11 millidarcies)	0.5
log $1/\alpha$ (Pa)	3.45 (2818 Pa)	0.166

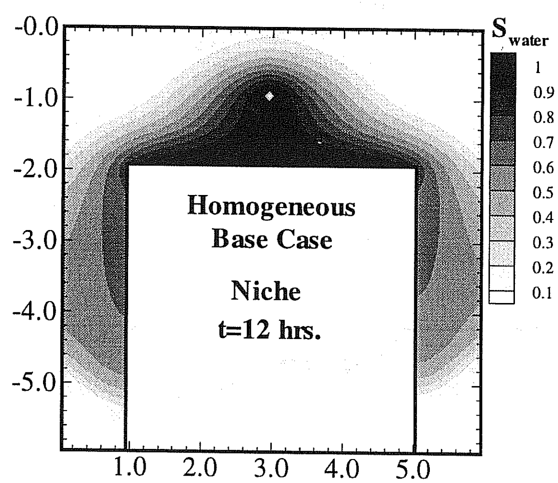

Figure 1. Contours of liquid saturation within the 2-D fracture continuum surrounding the excavated niche 12 hrs after the water pulse release.

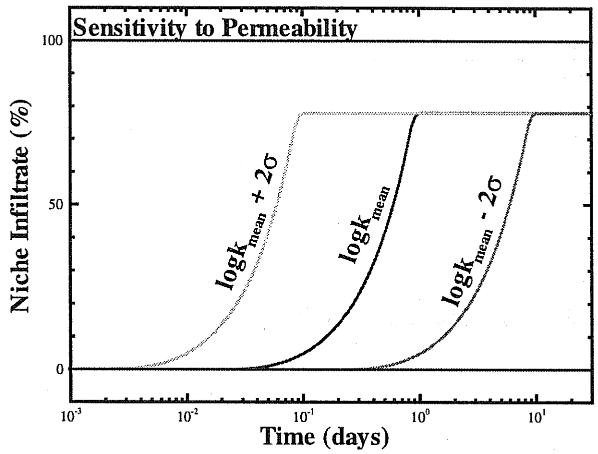

Figure 2. Sensitivity of total percent infiltrate to permeability.

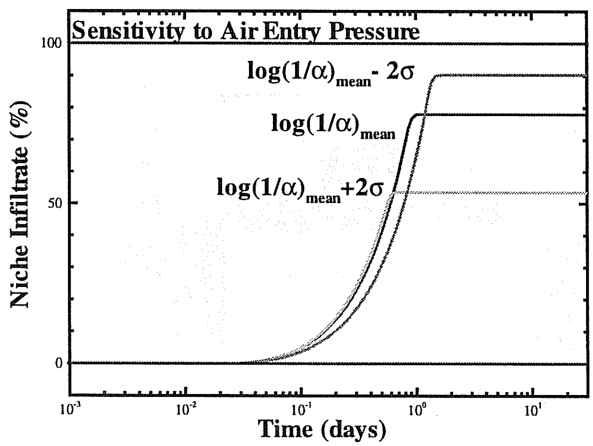

Figure 3. Sensitivity of total percent infiltrate to air entry pressure.

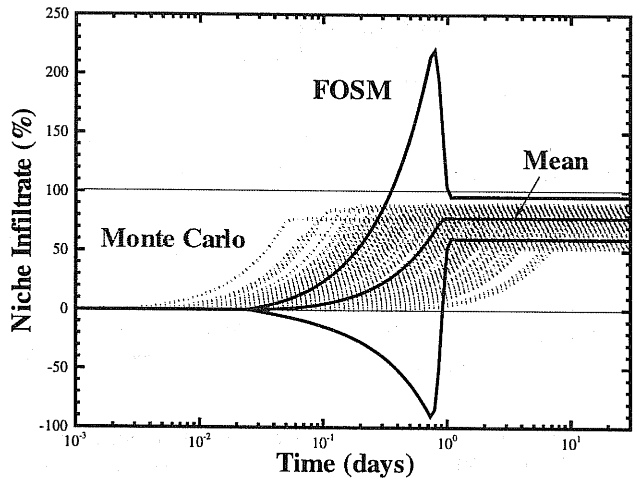

Figure 4. FOSM and Monte Carlo uncertainty analyses for Parameter Set 1. The mean percent infiltrate is 78%. Uncertainty in steady-state percent infiltrate is 38%.

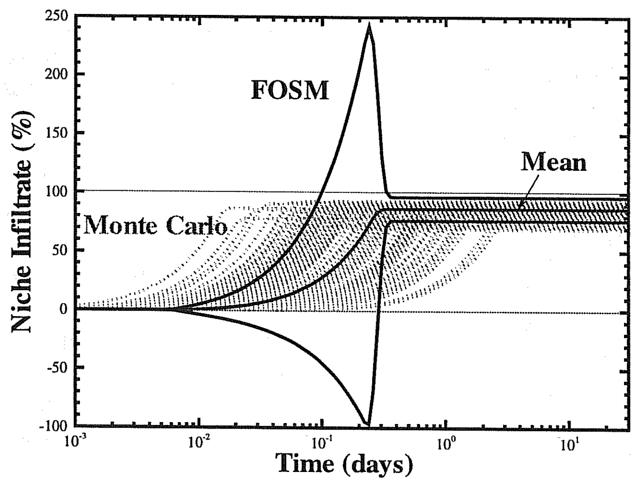

Figure 5. FOSM and Monte Carlo uncertainty analyses for Parameter Set 2 (higher permeability, lower capillarity). The mean percent infiltrate is 88%. Uncertainty in steady-state percent infiltrate is reduced and ranges over 24%.