LATERAL DIVERSION IN THE PTn UNIT: CAPILLARY-BARRIER ANALYSIS

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INTRODUCTION

It has been conventional wisdom for some time in the Yucca Mountain Project that the Paintbrush nonwelded hydrogeologic unit (PTn) above the potential repository location should act as an effective capillary barrier and divert much infiltrating water laterally away from the potential repository.^{1,2}

Much of the early flow modeling used the hydrologic properties (saturation and hydraulic-conductivity characteristic curves) developed by Klavetter and Peters,³ in which the air-entry pressure and saturated hydraulic conductivity for the PTn matrix were very high, leading to a large capillary suction in that unit in water-flow simulations. However, more recent estimates of the air-entry pressure have not been as high—e.g., values used for the three-dimensional site-scale model being developed by Lawrence Berkeley Laboratory and the United States Geological Survey⁴ and mean values of the probability distributions developed for Total-System Performance Assessment (TSPA) 1993.⁵ With the lower values of the air-entry pressure, there is still a capillary-barrier effect at the interface between PTn and the Topopah Spring welded hydrogeologic unit (TSw), but an analysis using the method of Ben Ross⁶ shows that the capillary barrier is not as effective as the earlier analyses indicated.

DIVERSION CAPACITY

Ross⁶ developed an expression for the diversion capacity of a capillary barrier by looking at an idealized two-dimensional problem and then reducing its asymptotic behavior to a one-dimensional problem that could be solved easily. The idealized problem has two homogeneous, isotropic hydrogeologic units separated by a dipping interface, with uniform infiltration coming from a distant top boundary, and a distant water-table boundary below.

The asymptotic behavior, which is expected to describe the flow far enough down-dip, has unit-gradient flow (constant ψ , $K(\psi) = q$, where ψ is pressure head, K is hydraulic conductivity, and q is the water flux or Darcy velocity) below the interface, unit-gradient flow asymptotically far enough above the interface, and a transition region just above the interface. It is this transition region that is of interest, and where the lateral diversion takes place.

Ross used quasilinear hydraulic-conductivity curves ($K \sim e^{\alpha\psi}$, where α is a constant, not to be confused with the van Genuchten or Brooks-Corey α parameter) in his discussion because in that case the asymptotic solution could be found analytically; with other characteristic curves the solution can be found semi-analytically with a numerical integration. Ross defined a quantity that he called the diversion capacity of the capillary barrier as follows:

$$Q = \tan \theta \int_{\psi_u}^{\psi_t} K_u(\psi) d\psi. \quad (1)$$

(See Equation 13 of reference 6.) In this equation, θ is the dip of the interface, ψ_t is the pressure head for the unit-gradient solution below the interface, ψ_u is the pressure head for the asymptotic unit-gradient solution above the interface, and $K_u(\psi)$ is the hydraulic-conductivity function for the upper layer (note that ψ is negative for unsaturated flow). Ross then estimated the effective horizontal width of the capillary barrier (the width of the region that could stay dry, with water being diverted laterally above it) as

$$L \sim Q/q_i, \quad (2)$$

where q_i is the infiltration. The effectiveness of a capillary barrier is nicely parameterized by the width L , and L can be calculated by a simple numerical integral over the conductivity function $K_u(\psi)$. The width thus calculated is only an approximation of the results of a real calculation,

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Figure 1. Hydraulic-conductivity curves for PTn from four sources.

---of course. It could be an overestimate or an underestimate depending on details of how a more complicated problem differs from the idealized one.

Taking an infiltration of 4 mm/yr as an example, if the hydrologic properties used by Prindle and Hopkins¹ are put into the above formulas, a diversion length L of 17,000 m is calculated. Thus, with their parameter values the PTn/TSw interface is an extremely effective capillary barrier and most flow is diverted laterally. On the other hand, using the average hydrologic properties from the Groundwater Travel Time (GWTT) 1994 simulations,⁷ a diversion length of only 110 m is calculated. The GWTT-1994 simulations are much more complicated than the idealized problem discussed above, with irregular unit interfaces and highly heterogeneous hydrologic properties, but this simple calculation of the diversion length suggests that one would not expect a great deal of lateral diversion in the PTn in the GWTT-1994 simulations. And, indeed, those simulations do not show much lateral diversion—most water enters the simulation domain on the western slope of the mountain, where PTn is at the surface,⁸ and flows primarily vertically downward. Similar behavior has been shown in other recent flow simulations as well.⁹ Note that the effective width of the capillary barrier is less for higher infiltrations ($L \sim Q/q_i$), so a high infiltration into the PTn

outcrop should be diverted even less than illustrated for 4 mm/yr.

CONCLUSIONS

Repository performance is very sensitive to the amount of water percolating through the repository,⁵ so the diversion or lack of diversion in the PTn unit is important to performance assessment. One obvious conclusion is that the characterization of the saturation/desaturation behavior of the PTn unit is important. Hydraulic-conductivity curves used in several different studies are shown in Figure 1, and it can be seen that there are large differences, leading to large differences in the capacity for lateral diversion. Most of the difference between the Prindle and Hopkins¹ simulations and more recent simulations results from a large difference in the matrix van Genuchten α parameter for PTn, with differences in the matrix van Genuchten β (or n) and the matrix saturated conductivity K_s also contributing, but to a lesser extent.

The asymptotic solution of Ross⁶ can also be used to illustrate a warning to numerical modelers. The one-dimensional, asymptotic solutions for two cases are shown in Figure 2. It can be seen that, for the hydrologic parameters used in earlier work,^{1,3} the pressure head varies linearly through the PTn unit, so it is easy to resolve with a numerical mesh. However, for the more recently obtained PTn

Figure 2. Asymptotic pressure-head profiles for two sets of characteristic curves (4-mm/yr infiltration).

hydrologic properties,^{5,10} the lateral diversion takes place within a narrow band above the PTn/TSw interface. If the numerical mesh does not resolve that band, the amount of lateral diversion will be calculated incorrectly. The width of the band is given roughly (within a factor of a few) by α^{-1} , where α is the van Genuchten air-entry parameter.

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