Journal of Hydrology (2006) **327**, 235–248

available at www.sciencedirect.com

journal homepage: www.elsevier.com/locate/jhydrol

Temporal damping effect of the Yucca Mountain fractured unsaturated rock on transient infiltration pulses

Keni Zhang *, Yu-Shu Wu, Lehua Pan

Earth Sciences Division, Lawrence Berkeley National Laboratory, MS 90-1116, 1 Cyclotron Road, Berkeley, CA 94720, United States

Received 3 May 2005; received in revised form 31 October 2005; accepted 3 November 2005

KEYWORDS
Unsaturated zone;
Damping effect;
Yucca Mountain;
Episodic infiltration;
Model

Summary Performance assessment of the Yucca Mountain unsaturated zone (UZ) as the site for an underground repository of high-level radioactive waste relies on the crucial assumption that water percolation processes in the unsaturated zone can be approximated as a steady-state condition. Justification of such an assumption is based on temporal damping effects of several geological units within the unsaturated tuff formation. In particular, the nonwelded tuff of the Painbrush Group (PTn unit) at Yucca Mountain, because of its highly porous physical properties, has been conceptualized to have a significant capacity for temporally damping transient percolation fluxes. The objective of this study is to investigate these damping effects, using a three-dimensional (3-D) mountain-scale model as well as several one-dimensional (1-D) models. The 3-D model incorporates a wide variety of the updated field data for the highly heterogeneous unsaturated formation at Yucca Mountain. The model is first run to steady state and calibrated using field-measured data and then transient pulse infiltrations are applied to the model top boundary. Subsequent changes in percolation fluxes at the bottom of and within the PTn unit are examined under episodic infiltration boundary conditions. The 1-D model is used to examine the long-term response of the flow system to higher infiltration pulses, while the damping effect is also investigated through modeling tracer transport in the UZ under episodic infiltration condition. Simulation results show the existence of damping effects within the PTn unit and also indicate that the assumption of steady-state flow conditions below the PTn unit is reasonable. However, the study also finds that some fast flow paths along faults exist, causing vertical-flux quick responses at the PTn bottom to the episodic infiltration at the top boundary.

* Corresponding author. Tel.: +1 510 4867393.
E-mail address: Kzhang@lbl.gov (K. Zhang).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2005.11.023

Introduction

Technical considerations for selection of the Yucca Mountain site as the US national waste disposal site include arid climate, thick unsaturated zone, and remote location. In addition, the strategy of building the permanent subsurface repository is based on the capability of the thick UZ as a natural barrier, slowing rapid water percolation, limiting the availability of water for contacting waste and transporting radionuclides from the unsaturated zone to the saturated zone. This natural barrier idea is also supported by the presence at Yucca Mountain of several geological layers with large pore spaces, strong capillary barriers and damping effects. One of these geological layers identified during site characterization is the layered, nonwelded PTn unit tuffs that exist between the ground surface and the repository horizon. Infiltrating water descending from the land surface may be effectively damped spatially and temporally by these layers, and thus percolation could be approximated as a steady-state condition once passing them (Montazer and Wilson, 1984; Wu et al., 2000, 2002a,b).

The performance of the proposed repository for long-term storage of high-level radioactive wastes is critically dependent on the rate of UZ percolation. This is because percolation flux through the UZ is one of the most important factors in underground repository performance. The quantity as well as spatial and temporal variations in percolation flux directly affect: (a) the amount of water flowing into waste emplacement drifts; (b) moisture conditions and the corrosion environment of canisters within the drifts; (c) waste mobilization from the potential repository; (d) thermo-hydrologic behavior of the potential repository; and (e) radionuclide migration from the UZ to the saturated zone. Net infiltration consists of only a small fraction of the total precipitation at the ground surface, representing the amount of water which penetrates the ground surface to a depth where liquid water can no longer be removed (for example, by evapotranspiration). Net infiltration is spatially varying, and its values range from several millimeters to several hundred millimeters per year, as estimated by an infiltration model using precipitation and other field data for present and future climates (Flint et al., 1996; BSC, 2004b). The infiltration data from BSC (2004b) are used for convenience only. Different infiltration distribution does not impact the results of this study.

The land-surface boundary employed by UZ models and modeling studies for the Yucca Mountain site has been traditionally described with water recharge, using estimated steady-state infiltration maps (e.g., Wu et al., 2004) i.e., temporal average infiltration rates for different time periods. However, the net infiltration is in fact episodic over seasons and years, with significant pulses probably occurring once every few years (BSC, 2004b). Spatially and temporally variable infiltration pulses may percolate rapidly through the highly fractured tuffs of the Tiva Canyon Welded (TCw) unit, the top of the UZ layers, as indicated by the numerous bomp-pulse chlorine-36 signatures measured within the TCw (Fabryka-Martin, 2000), and recent see page in the south tunel. A review of the study for fast pathways at the site has been provided by Flint et al. (2001). Down below, the character of the rock formation changes from welded tuffs to non-welded tuffs at the TCw—PTn interface, and flow behavior changes from fracture-dominated to matrix-dominated flow (Wu et al., 2002a). Wang and Narasimhan (1985, 1993) suggested that effects of infiltration pulses at the surface are damped by the underlying tuff units, especially the PTn. The highly porous and less fractured PTn unit may attenuate the episodic infiltration liquid flux significantly, such that the net episodic infiltration, once crossing the PTn, may be treated as steady state flow. It is believed that damping effects might be caused by lateral diversion and/or capillary barriers (Ross, 1990; Oldenburg and Pruess, 1993; Ho and Webb, 1998). The lateral diversion might reduce the volume of water that would penetrate the TSw. Flow diversion of the PTn has been confirmed by a number of modeling exercises (Ho, 1995; Wilson, 1996; Wu et al., 2002b; Pan et al., 2004).

In the past two decades, many site-specific studies have been carried out, with significant progress made in characterizing flow and transport processes at the Yucca Mountain site (e.g., Wu et al., 1999; BSC, 2004b). Most of these studies, however, have been focused on analyzing the spatial variability of UZ flow and percolation patterns (for example, steady-state lateral flow resulting from capillary barriers or perched water). Very few investigations have been attempted for transient flow behavior, such as temporal damping effects (Wu et al., 2000). In the past several years, however, a limited number of modeling efforts have investigated the temporal damping effect of the PTn unit. Those efforts primarily used one-dimensional (1-D) or two-dimensional (2-D) flow or transport models to examine the responses of vertical flux to the pulse-infiltration boundary conditions at the land surface. Wu et al. (2000) investigated how surface transient infiltration affected capillary barriers and percolation, using both one-dimensional and two-dimensional models. Their models clearly indicate the importance of PTn-unit damping effects. The model results show that the surface transient infiltration pulse can be significantly smoothened, temporally, after the early transient period of several hundreds of years. Guerin (2001) developed 1-D models to examine the flow and transport behavior in 1-D columns. These 1-D models correspond to several boreholes at the Yucca Mountain site. Guerin's models were run using different infiltration scenarios. From model calculations, she concluded that the PTn unit damped infiltration pulses no matter what infiltration scenarios were applied. Calibration results indicated that for most parameter changes, no notable movement of contaminant occurred below the PTn. Differences in contaminant transport behavior for the various simulations were only noted above the bottom of PTn unit. Other modeling studies indicate that the damping effect may be caused by lateral flow within the PTn unit (Wu et al., 2002b; Liu et al., 2003b). However, 1-D and 2-D models generally have difficulty describing the 3-D unsaturated flow system-for example, the lateral flow paths and flow focusing phenomena through heterogeneous 3-D layers of the Yucca Mountain UZ. In addition, those previous studies have not provided in-depth discussions or insights into the mechanisms of PTn damping effects.

In addition to modeling investigations, Salve et al. (2003) carried out a series of field tests for understanding flow patterns within the PTn. They examined whether the non-welded tuffs of the PTn effectively damp pulses of infiltration, or whether preferential flow paths forming within the PTn serve to promote flow focusing. Their test results suggested that the PTn matrix has few discrete flow