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Unsaturated Zone Flow Modeling for GWTT-95

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I. Introduction

In accordance with the Nuclear Regulatory Commission[1] regulation regarding groundwater travel times at geologic repositories, various models of unsaturated flow in fractured tuff have been developed and implemented to assess groundwater travel times at the potential repository at Yucca Mountain, Nevada. Kaplan[2] used one-dimensional models to describe the uncertainty and sensitivity of travel times to various processes at Yucca Mountain. Robey[3] and Arnold et al.[4] used a two-dimensional equivalent continuum model (ECM) with inter- and intra-unit heterogeneity in an attempt to assess fast-flow paths through the unsaturated, fractured tuff at Yucca Mountain (GWTT-94). However, significant flow through the fractures in previous models was not simulated due to the characteristics of the ECM, which requires the matrix to be nearly saturated before flow through the fractures is initiated. In the current study (GWTT-95), four two-dimensional cross-sections at Yucca Mountain (Figure 1) are simulated using both the ECM and dual-permeability[5] (DK) models. The properties of both the fracture and matrix domains are geostatistically simulated, yielding completely heterogeneous continua[6]. Then, simulations of flow through the four cross-sections are performed using spatially non-uniform infiltration boundary conditions. Steady-state groundwater travel times from the potential repository to the water table are calculated.

II. Description of Work

The unsaturated flow simulations are performed with a version of the numerical code TOUGH2[7] (SNL Software Configuration Management v. 3.1) that performs single-phase (EOS9), isothermal calculations

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(i.e. solves Richards' equation). Comparisons of single-phase and multi-phase simulations of infiltration through the unsaturated zone at Yucca Mountain showed that single-phase simulations are justified[5]. The grid for each cross-section is created by a pre-processor and contains refinement in areas of faults and important geohydrologic features, such as the PTn and vitrophyres. The hydrologic properties of each element are then determined geostatistically[6]. The bottom boundary of each grid is specified as the water table, and the lateral boundaries are specified with no-flow conditions. Along the top row of elements, infiltration rates are specified, based on the spatial distribution estimated by the US Geological Survey. The rates are spatially non-uniform, with higher infiltration occurring at regions with high precipitation and thin soils (Figure 2a).

Both the ECM and DK models use van Genuchten parameters to describe the unsaturated characteristic curves for the fracture and matrix domains. These parameters are correlated, along with other hydrologic properties, to properties that are geostatistically simulated, which include matrix porosity, matrix saturated conductivity, and fracture frequency[6]. The DK model requires additional information regarding the conductance between the fracture and matrix elements. The fracture-matrix (f-m) connection area has been shown to significantly affect the propagation of flow through fractures in the DK model[5]. The f-m connection area has been reduced by two orders of magnitude from geometrically based values to account for small scale processes such as fingering and channeling. This reduction can be conceptualized by assuming that only one of every ten fractures contains liquid flow and that only one tenth of the surface of these fractures has water flowing on it. The resulting DK model has twice as many elements as the ECM due to the explicitly modeled fracture and matrix domains. Thus, each grid in the ECM and DK models is comprised of up to several thousand elements, each element with its own unique set of hydrologic properties and characteristic curves. Ten realizations are simulated for each of the four cross-sections[†].

Travel times are calculated using a particle tracking method[8] developed for TOUGH2. Particles are released along the potential repository horizon and tracked until they reach the water table at the bottom of the model domain. The pore velocities in both the fracture and matrix elements are calculated at each

† Only ten realizations were simulated for each cross-section as a result of time and budget constraints. More emphasis was placed on performing sensitivity analyses to determine important hydrologic processes and parameters.

particle location along the particle's path. The particle is then advected at the faster of the two velocities. Random dispersion can also be added during the transport of the particle at each time step.

III. Results

The simulations are run until the outflow through the water table equals the specified total infiltration along the top boundary, indicating steady-state flow conditions. Steady-state saturations and velocity distributions can then be plotted for each realization. Figure 2 shows an example of matrix saturations and particle travel times for one realization of section A-A. Higher fluxes and faster travel times are observed in regions of higher infiltration. The results of all the realizations from each cross-section showed similar trends, with the DK travel times being considerably faster than the ECM travel times as a result of increased flow through the fractures in the DK model. In addition, travel times in all the realizations ranged from hundreds to hundreds of thousands of years depending on the flow path taken by each particle. An important influence on the travel times was found to be the relative proportions of matrix and fracture flow along the flow paths. The PTn played an important role in this aspect by acting as a barrier to fracture flow above the potential repository, imbibing much of the water from the fractures into the matrix in that unit. Additional analyses have also revealed the sensitivity of travel times to other parameters such as infiltration rate, residual fracture saturation, fracture-matrix conductance, and PTn parameters[9].

Figure 3 shows a comparison between predicted and measured matrix saturations in the vicinity of drillhole SD-9 for ten realizations of section A-A. The simulated saturations are generally consistent with the measured saturations, although the DK model shows lower matrix saturations near the upper units as a result of significant flow through the fractures.

IV. Conclusions

A dual-permeability TOUGH2 model with heterogeneous elements in both the fracture and matrix domains has been successfully used to model unsaturated flow at four cross-sections of Yucca Mountain. The groundwater travel times are considerably faster in the DK model than the corresponding ECM model as a result of greater flow through the fractures. The travel times range from hundreds to hundreds of thousands of years, depending on the location of the flow path. The travel times and fluxes through the unsaturated zone have also been found to be sensitive to infiltration rates, residual fracture saturations, fracture-matrix conductances, and PTn parameters.

Acknowledgments

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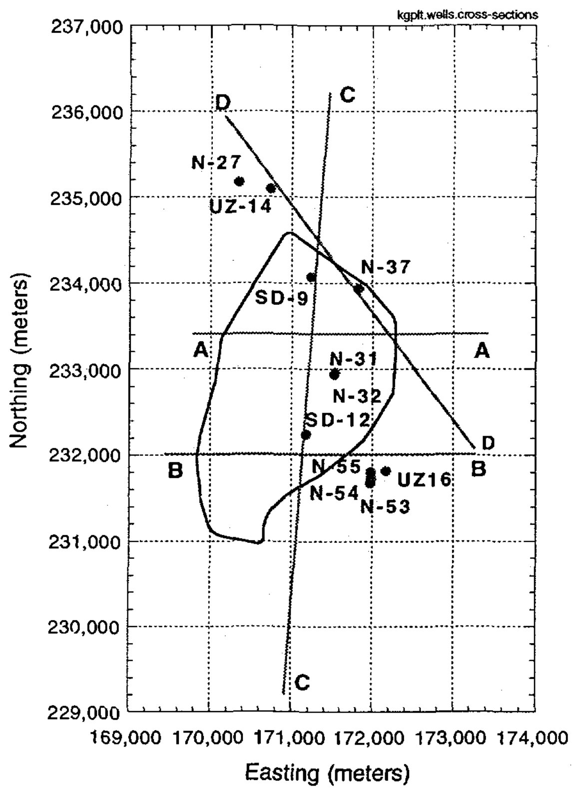

Figure 1. Outline of potential repository at Yucca Mountain, Nevada, and nearby drillholes.

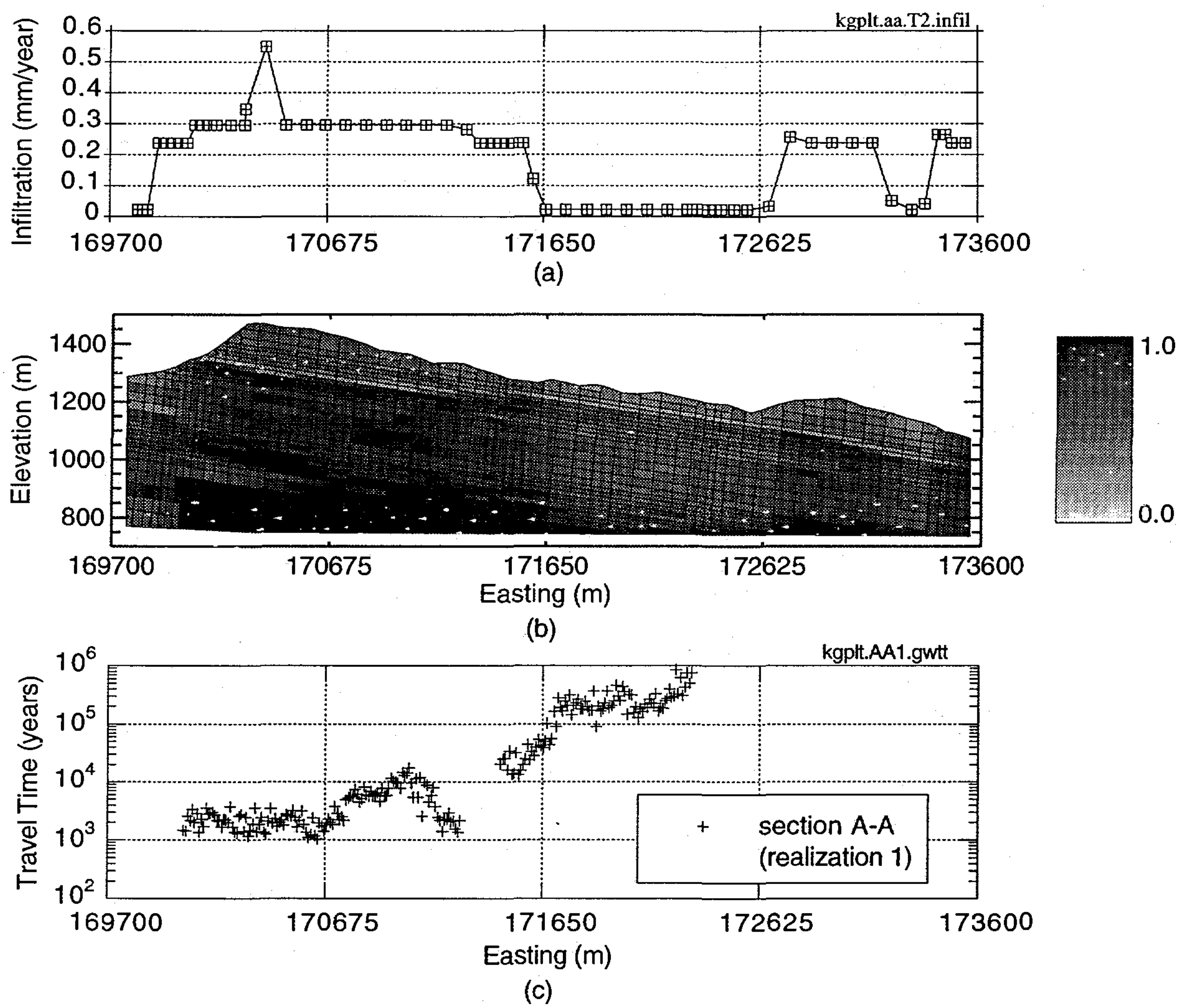

Figure 2. a) Infiltration for cross-section A-A. b) Matrix saturations for one realization of cross-section A-A using the dual-permeability model. c) Corresponding travel times along the same cross-section.

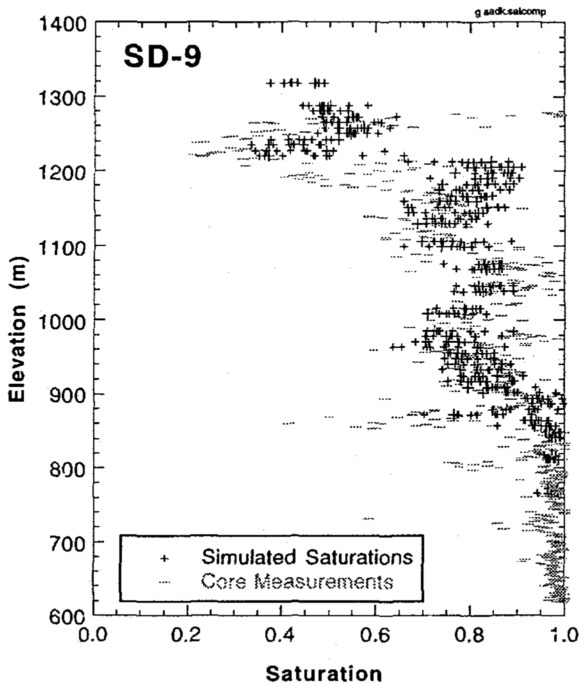

Figure 3. Comparison of predicted and measured matrix saturations in the vicinity of drillhole SD-9 for ten realizations of cross-section A-A (DTN: GS950308312231.004. Note: the SD-9 data were unqualified at the time of writing).