Development and Calibration of Dual-Permeability Models in Complex Hydrogeologic Settings: An Example from the T-Tunnel Complex, Rainier Mesa, Nevada National Security Site

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ABSTRACT

A dual-permeability flow model of the T-tunnel nuclear testing complex and surrounding area was developed to facilitate predictions of radionuclide migration from the tunnel tests through a thick sequence of variably-saturated, faulted, low-permeability volcanic tuff units to an underlying regional flow system. The hydrogeologic complexity necessitated a multi-stage calibration effort to capture the dominant flow characteristics including: laterally and vertically extensive saturation of an upper perched interval with simulated pressure heads supporting water level measurements, a thin unsaturated zone situated between two saturated zones, and fracture saturations congruent with field observations that range from fully saturated to dry. Moreover, the tunnel complex served as a drain to the perched flow system during operation with a total estimated water volume of $1.36 \times 10^6$ m$^3$ exiting the portal over a 24 year period, and a quasi steady-state portal discharge rate of $1.01 \times 10^{-3}$ m$^3$/s prior to portal sealing. A dual-permeability model with discontinuous fracture networks reconstructed from site-specific data was able to reproduce the salient hydrologic features identified above, including only a 15% discrepancy between simulated and estimated total portal discharge volume and a near exact match to the quasi steady-state portal discharge rate. This excellent reproduction of field observations builds confidence that the numerical model captures the relevant flow characteristics of the site.

INTRODUCTION

Dual-permeability flow models are typically developed to simulate variably-saturated fluid flow in hydrogeologic systems consisting of fractured, porous rock. Different flow and moisture retention characteristics between the porous rock and fractures cause a pressure disequilibrium necessitating the numerical treatment of fractures and porous matrix blocks as separate, interacting continua. These two continua are parameterized according to permeability, porosity, unsaturated hydraulic parameters, and parameters describing the interfacial area and volume of the two continua (e.g., Pruess et al., 1999; Nitao, 2004). This allows for the solution of pressure at two nodes within the same grid block, with fluid flow occurring in the model between fracture nodes, matrix nodes and fracture-matrix nodes.

Applications of dual-permeability models to specific field sites typically assert that fracture density is sufficiently high relative to the scale of the grid block such that representative elementary volume (REV) assumptions are valid; and hence, constant hydraulic fracture properties are assigned to entire geologic units (Wu et al., 1999; Robinson et al., 2003). This approach, however, can be problematic in that: (1) REV assumptions are frequently not satisfied in natural rock fracture networks (Neuman, 2005); (2) equivalent fracture parameters in the model are derived from inverse modeling that may not correlate to physical fracture characteristics (e.g., Wu et al., 1999); and (3) over-homogenization through the use of constant fracture properties neglects important geometrical characteristics of fracture networks, such as complex patterns of connectivity (Liu et al., 1998).

In this paper, we develop a dual-permeability model that incorporates spatially discontinuous fault networks for the T-tunnel complex, Rainier Mesa, Nevada National Security Site. The approach allows for direct parameterization of the fracture continua based on fault networks generated from site-specific data. The model is able to reproduce both measured and observed flow characteristics for a complex hydrogeologic setting through a simple calibration process involving the adjustment of only two parameters. This reflects the advantages of incorporating discontinuous networks over equivalent fracture continuum properties in dual-permeability models.
CONCEPTUAL MODEL OF FLOW

The T-tunnel complex, located in Area 12 of the Nevada National Security Site, is the site of six underground nuclear tests conducted between 1968 and 1988. The tunnel complex has north-south and east-west dimensions of 0.8 and 1.6 km, respectively, and consists of more than 10.6 km of tunnels with a total estimate volume of 231,500 m³ (Figure 1). The T-tunnel complex is mined in predominately Tertiary-age zeolitic ash-fall tuffs, and is located approximately 100 m below a laterally and vertically extensive zone of perched saturation and approximately 400 m above a regional ground water flow system. Inflow into the tunnel complex from the perched zone of saturation occurs along large faults and smaller background fractures, and the tunnel complex is angled slightly toward the portal to facilitate water drainage. The portal was sealed in 1992 and the tunnel complex became completely inundated as early as 2000.

Recharge to the perched water system above the tunnel complex is derived from natural precipitation, with the most reliable modern recharge estimates ranging between 11.5 to 15.2 mm/yr. Hydraulic testing of core samples from the volcanic tuff units show that some stratigraphic units at the T-tunnel level and below have lower matrix permeability values than the estimated recharge rates. A weathered zone at the Tertiary volcanic/Paleozoic carbonate interface consisting of clay and calcite-filled fractures is thought to further promote the perching of water in the Tertiary volcanics and cause a second unsaturated zone extending from the top of this contact downward to 200 meters in the underlying regional carbonate flow system. There are no observations of springs at the site and downward vertical flow through the porous matrix blocks and fractures of the Tertiary volcanics to the underlying Paleozoic carbonates is the most likely flow conceptualization. Fault and fracture frequencies are low in the Tertiary volcanics and mining activities in the tunnel complex show poor connectivity between different fault/fracture clusters. Fracture saturations in the tunnel range from fully saturated to dry.

MODEL FORMULATION

A numerical model was developed for the T-tunnel complex using the dual-permeability option of the NUFT US1P module to simulate variably-saturated flow (Nitao, 2004). The north, south, and west model boundaries were selected to be 100 m from the nearest nuclear test, and the east model boundary occurs at the main drift where the tunnel complex is sealed. The upper boundary of the model corresponds to the top of the perched zone of saturation at 1815 m amsl, and extends to the water table in the underlying Paleozoic at 1315 m amsl. A spatially-varying recharge flux condition based on simulated net infiltration is applied to the top model boundary, and a water table condition is assigned to the lower model boundary. No flow boundaries are assigned to the sides of the model. Cell discretization in the model was influenced by the properties of the fault networks, in particular fault density. A grid block size of 20m on a side was found to provide sufficient resolution of the mapped fault networks on the continuum grid. Details on the fault characterization will follow shortly.

Figure 1. T-tunnel complex along with deterministic faults (numbered). The box denotes the domain of the T-tunnel complex dual-permeability model. Selection of domain was based on distance from nuclear tests located at the end of the tunnel drifts.
Hydraulic properties, including permeability, porosity, and unsaturated van Genuchten parameters (Van Genuchten, 1980), were obtained from rock cores from the Tertiary volcanics and Paleozoic carbonates. These values are applied to the matrix continuum. A fracture continuum method, originally proposed by Reeves et al. (2008) and further refined by Parashar and Reeves (2011), is used to map fault networks generated according to site-specific fracture attributes onto a continuum grid. The fracture continuum approach preserves heterogeneity and flow anisotropy of fault networks through a series of fracture mapping rules as presented in Parashar and Reeves (2011).

Characterization of the fault data collected along the tunnel drifts is consistent with the methods found in Reeves et al. (2012) where probabilistic distributions are used to describe fault orientation, spacing, and length. The fracture analysis yielded one approximately north-south fault set with considerable scatter about the mean orientation. High degrees of spatial clustering were observed with an average spacing of approximately 12 m. The spatial clustering necessitated the development of a multiplicative cascade process conditioned on the largest faults mapped in Figure 1. Discrete fracture network analyses determined that fracture clustering is essential in forming poorly connected fault networks consistent with observations of flow and drainage from the tunnel complex (Figure 2).

Fault dimensions are unknown at the site and the fault displacement-length (d-L) relationship proposed by Schultz et al. (2008) was used to estimate length from fault displacement. A perfect correlation between faults with known surface traces and faults predicted to have surface traces by the d-L scaling relationship provided additional confidence on the utility of the estimated fault dimensions. The largest faults (Figure 1) are mapped as deterministic features in the model and background faults are added stochastically to the networks using a lognormal distribution of fault displacement converted to fault length. Van Genuchten unsaturated parameters were assigned to the faults based on aperture using the method of Kwicklis et al. (1988). The tunnel complex, including partial barriers constructed in some drifts, and damage zones and chimneys caused by the nuclear tests are included in the model grid (Figure 3). Damage zone dimensions are predicated on the announced yields of each test (Stoller-Navarro, 2008).

Figure 2. Site representative discrete fracture network (left) along with isolation of hydraulic backbone (right) showing tree shaped, poorly-connected fault networks. Distances are in meters.

Figure 3. T-tunnel complex, nested-mesh transient calibration model showing tunnel complex and damage zones. The dark blue (at the bottom) denotes the Paleozoic carbonates and the Tertiary volcanics range from medium blue to yellow. Note that the Tertiary volcanics are located within a synclinal structure.
VARIABLY-SATURATED FLOW CALIBRATION

The hydrogeologic complexity of the T-tunnel complex necessitated a multi-stage calibration effort to capture dominant flow characteristics of the site. The model was first calibrated in steady-state to match the observed laterally and vertically perched water levels in the Tertiary volcanics with an upper elevation of approximately 1815 m, fracture saturations ranging from fully saturated to dry, and maintaining unsaturated conditions in the Paleozoic carbonates above the regional water table at 1315 m. This was accomplished by changing the aperture value assigned to all fractures. Sensitivity analyses indicated that the aperture value assigned to the major deterministic faults exert the most influence on saturation and head levels, while apertures of the stochastic faults only exert a minimal influence. A cubic law aperture value of 30 microns was found to best reproduce the aforementioned dominant hydrogeologic characteristics at the site (Figure 4). Saturation and head values were found to be highly sensitive to fault aperture, and thus, this parameter is highly unique in the model.

A nested mesh was then incorporated into the steady-state model to more accurately capture the tunnel interfacial area and volume (Figure 3). This model was run to steady-state followed by a 24.1 year transient period to simulate the drainage of water from the tunnel complex through the portal. This outflow was simulated by assigning an atmospheric boundary condition to the tunnel cell located on the east boundary of the model. With a slight adjustment to the permeability assigned to the tunnel complex itself (the void area), the model simulated within 15% of the estimated cumulative water discharge of $1.36 \times 10^6$ m$^3$ exiting the portal and the quasi steady-state discharge rate of $1.01 \times 10^{-3}$ m$^3$/s (16 gpm) measured prior to portal sealing (Figure 5). The fracture aperture value computed during the first calibration stage remained unchanged in the transient calibration.

Figure 4. Plots of matrix and fracture saturation and pressure head (m) in the rock matrix. Note the simultaneous saturation in the Tertiary volcanics and unsaturation in the adjacent carbonates. Also, note the variable saturation of the faults in the fracture saturation plot.

Figure 5. Simulated portal discharge for the 24.1 year transient period of the calibrated, nested-mesh T-tunnel model reproduces the $1.01 \times 10^{-3}$ m$^3$/s flow rate observed prior to tunnel closure in 1992, and is within 15% of the cumulative estimated tunnel discharge.
CONCLUSIONS

Accurate incorporation of discontinuous fault networks in the dual-permeability formulation led to a model that reproduces all major hydrogeologic observations – both steady-state and transient – while allowing for a robust calibration achieved through the adjustment of only two parameters. The transient simulation of portal discharge greatly increases model confidence that the discontinuous fault networks provide the correct permeability and connectivity structure to the tunnel complex and underlying tuff units. These positive results clearly demonstrate the advantage of incorporating discrete fault networks over equivalent fracture properties and builds confidence that the numerical model captures the relevant flow characteristics of the site. Flow fields from the above model are used in conjunction with a fully Lagrangian particle transport code to investigate the propensity for radionuclides to reach the regional water table over a 1,000 year compliance period.

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REFERENCES