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<https://escholarship.org/uc/item/0x98t15v>

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### Publication Date

2001-11-14

## **Understanding Isothermal and Nonisothermal Flow in Partially Saturated Fractured Porous Media through Field Tests and Modeling**

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Field tests and model analyses are complementary approaches to improve our knowledge of site characteristics and our understanding of governing processes. The understanding of field measurements and observations can be enriched through formulation of proper models. Models can either be simple, for deriving hydrological parameter distributions, or detailed and numerical, for evaluating complex coupled processes. Lessons learned from studies in underground drifts in partially saturated fractured porous media are presented in this paper.

Different approaches to field testing can be adopted, depending on how much is known about a particular site and what the specific objectives of the field investigation are. When great uncertainty exists pertaining to the hydrological attributes of a site, and when spatial heterogeneity dictates that the hydrological characteristics at one location are not representative of the entire site, then running “identical” and relatively simple tests at numerous locations may be required. This method of repetitive testing in multiple locations is described as a “systematic” approach to testing; it complements the more commonly practiced “feature-based” testing in which a test location is selected because of the special geological and hydrological features it exhibits. Such features may not be pervasive over the region of interest.

The approaches for analyzing and interpreting field data would also differ based on the types of data collected. When great uncertainty about processes exists, sophisticated numerical modeling of a site is not only inappropriate, it can even be misleading, because a “good” match between modeled and measured results may be obtained with an incorrect conceptual or structural model. On the other hand, when there is greater confidence in the hydrological attributes of a site, then detailed numerical modeling can be extremely valuable in giving a more in-depth understanding of the site’s *in situ* processes.

In this paper, two field examples in partially saturated fractured porous volcanic tuff at Yucca Mountain, Nevada, the potential site for an underground high-level radioactive waste repository, are used to illustrate different approaches for bridging the gap between field testing and modeling.

The approach taken in the first example is to rely predominantly on systematic, multiple-location field data collection for developing knowledge of the hydrological attributes and parameter distributions governing isothermal flow. Modeling efforts in this example involve simple “order-of-magnitude” estimates. Comparison of these “model predictions” to a large volume of multiple-location data can provide an understanding of the hydrological attributes of a geological medium. The hydrological characterization of the

lower lithophysal unit of the Topopah Spring welded tuff was carried out in an underground facility along a 5 m diameter drift at Yucca Mountain. The welded tuff in the lower lithophysal unit is intersected by many small fractures (less than 1 m long) and interspersed with lithophysal cavities ranging in size from 15 to 100 cm. The size and spacing of both the fractures and lithophysal cavities vary appreciably along the drift walls over an 800 m stretch. Because of spatial heterogeneity, we are adopting a systematic approach—testing in boreholes drilled at regular intervals along the drift, regardless of specific features *in situ*—to acquire knowledge of the hydrological characteristics of this unit. Field measurements in borehole sections isolated by inflatable packers include: (1) air-injection tests that measure fracture permeability, (2) liquid-release tests that determine flow characteristics and the ability of the open drift to act as a capillary barrier to divert water around itself, and (3) crosshole gas-tracer tests to measure the effective porosity of the rock mass. Testing is designed to have the borehole sections large enough (i.e., 2 m in section length) so that effects arising from small-scale heterogeneity from cavity size and fracture length are averaged out

Comparison of collected data to simple, order-of-magnitude estimations is instrumental in leading to (1) insights into how flow is partitioned among fractures, matrix, and lithophysal cavities in the unsaturated rock; and (2) an understanding of how the flow channeling arising from spatial heterogeneity, together with the open drift acting as a capillary barrier, prevent water from entering the drift. The approach of simple order-of-magnitude estimates for model prediction is easily utilized for hydrological characterization, using data collected at regularly spaced intervals along the drift. The systematic approach here complements the “feature-based” approach of other hydrological testing (in the same underground facility), in which the test locations are selected either by avoiding or focusing on specific features (such as large fractures or extra abundance of fractures or cavities).

Another approach was taken in the second example. In this instance, investigators used very detailed numerical modeling to predict the test outcome prior to commencement of field measurements. The experiment in question is a large-scale (a 60 m × 50 m × 50 m, test block, instrumented with thousands of sensors) and long-duration (eight years) thermal test in the middle nonlithophysal unit of the Topopah Spring welded tuff. In this unit, both short fractures (less than a meter in length) and long fractures (a few meters in length) are common, but lithophysal cavities are scarce. The site is well characterized by nearby smaller-scale tests and by densely spaced instrumentation within the test block. Introduction of heat into the rock mass sets in motion coupled thermal-hydrological processes such as heat transport by conduction and convection, phase transitions between liquid and vapor, and the movement of gaseous and liquid phases under pressure, viscous, and gravitational forces according to Darcy’s law. The numerical model constructed for this experiment accounts for all the above thermal-hydrological processes, incorporates a complex, realistic test geometry in three dimensions, and utilizes site-specific characterization data as input parameters to the model.

Sophisticated numerical modeling is utilized to predict (in detail) the thermal-test outcome. Two categories of measurements are used to compare with model predictions:

(1) temperature at close to 2,000 spatial locations, and (2) time evolution of moisture redistribution in the rock matrix and fractures, based on geophysical methods (electric resistance tomography, ground penetrating radar cross-hole tomography, and neutron logging) and air-injection tests. For the first category of data, temperature, statistics such as mean error and root mean error at different times are obtained to demonstrate the goodness of fit between model predictions and data. For the second category of data, simulated time evolution of drying and wetting (in the vaporization and condensation zones, respectively, of the rock matrix and fractures) is qualitatively compared to the trends of drying and wetting deduced from the geophysical and hydrological tomograms. The detailed numerical modeling approach works in a number of ways for the thermal test. It is appropriate because for thermally driven processes, the impact of fracture heterogeneity in the nonlithophysal unit is minimal for vapor transport. And though heterogeneity does impact gravity drainage of condensed water, the geophysical and air injection measurements used for comparison with modeled predictions are shown to be insensitive to these transient flow processes of liquid drainage in the fractures. It is also necessary for our numerical model to incorporate realistic three-dimensional test geometry such as drifts (that act as open boundaries) at a slight decline as well as the locations of temperature sensors. This is because most of the temperature rise in the test block is caused by heat conduction, hence in order to meaningfully evaluate thermal hydrological processes by comparing predicted and measured temperature we need to eliminate discrepancies arising from incorrect test geometry.

The two different modeling approaches illustrated in this paper each work for their particular situation. A simple order-of magnitude modeling approach is appropriate for the first example because large uncertainty for hydrological characteristics exists prior to collection of data. Thus, a large volume of collected data is utilized for determining the hydrological attributes of this lithophysal geological unit. The data from regularly spaced locations are also instrumental in allowing investigators to discriminate between phenomena resulting from fundamental flow processes and that from site-specific heterogeneity. In the second example, the dominant heat transfer processes serve to minimize the complexity of heterogeneity-induced flow effects. With sufficient sampling points for field measurements, it is appropriate to construct a numerical model that realistically represents the complex test geometry and boundary conditions to interpret the test data. Overall, the presence of thermally driven physical processes (such as heat conduction, heat convection, vaporization, and condensation) are confirmed by the modeled results.

Clearly, the choice of approach to be used in bridging the gap between measurements and modeling is guided by the state of knowledge about the site and the objective of the testing effort. These factors help in deciding the required amount and sufficient accuracy of measured data, as well as the degree of model sophistication that should be applied. Systematic characterization of hydrological parameter distribution does not necessarily require complex models. Rather, we advocate keeping the model simple and the interpretation straightforward to gain an overall understanding of the basic attributes of the geological medium under investigation. On the other hand, for a well-characterized site where we have confidence that both the governing processes and the effects

associated with site features can be represented well, numerical modeling is a powerful approach. The model calibration and confirmation steps associated with complex numerical models greatly enhance the credibility of our modeling capability. They lend confidence that we can use models to predict the system behavior, even for a larger spatial scale and longer time duration than that of the field measurements.