Title
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Authors
Ahlers, C.F.
Trautz, R.C.
Cook, P.J.
et al.

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Testing and Modeling of Seepage into Underground Openings in a Heterogeneous Fracture System at Yucca Mountain, Nevada

C. F. Ahlers, R. C. Trautz, P. J. Cook, and S. Finsterle
Lawrence Berkeley National Laboratory
M/S 90-1116, 1 Cyclotron Rd., Berkeley, California 94720
Rick_Ahlers@lbl.gov

We discuss field activities designed to characterize seepage into an underground opening at the potential site for geologic storage of high-level radioactive waste (HLRW) at Yucca Mountain, Nevada, and the use of these data for development and calibration of a model for predicting seepage into planned HLRW emplacement drifts. Air-injection tests were conducted to characterize the permeability of the fractured rock, and liquid-release tests (LRTs) were conducted and seepage monitored to characterize the seepage-relevant properties of the fractured rock. Both air-injection and liquid-release tests were performed in the same borehole intervals, located above the underground openings. For modeling, three-dimensional, heterogeneous permeability fields were generated, conditioned on the air-permeability data. The initial seepage data collected were used to calibrate the model and test the appropriateness of the modeling approach. A capillary-strength parameter and porosity were the model parameters selected for estimation by data inversion. However, due to the short-term nature of the initial data, the inversion process was unable to independently determine the capillary strength and porosity of the fractured rock. Subsequent seepage data collection focused on longer-term tests, a representative selection of which was used for data inversion. Field observations also played a key role by identifying factors such as evaporation and ceiling geometry that can enhance or reduce seepage. These observations help guide future test and model development by ensuring that relevant processes that influence seepage are identified, characterized, and incorporated into the model, thus increasing confidence in the parameter estimates. It is this iterative and collaborative approach to field testing and modeling, and the feedback mechanisms of field-test-methodology and model review and revision, that has been employed to continuously improve the scientific quality of the study. Initiation of modeling as soon as the first liquid-release data were available, review of the models with the field-testing team, and feedback of model results to the field-testing team proved to be important for optimizing both data collection and model development, resulting in increased confidence in the predictive models.

Introduction

Seepage is an issue of some importance when mining tunnels for many different purposes, from mineral extraction to nuclear waste storage. When a tunnel is in the unsaturated zone, it forms a capillary barrier that may exclude some or all of the percolating water from entering the tunnel. Philip et al. (1989) showed that for an idealized circular opening in a homogeneous isotropic porous medium, and for uniformly-distributed steady percolation, the seepage threshold, i.e., the percolation rate at which seepage into the opening will be initiated, is dependent on the capillarity and permeability of the porous medium and the size of the opening (the radius at the crown of the opening).

One particular problem, for which seepage is a key issue, is the proposed long-term geologic disposal of HLRW at Yucca Mountain. Seepage into the tunnels in which the waste will be emplaced can impact the integrity of the storage system in several ways. Water and its mineral content will corrode the waste canisters, potentially breaching all the containment layers. Water can then dissolve and mobilize the waste allowing it to escape the storage canisters. Water contaminated with HLRW can then enter the natural flow system and eventually reach the accessible environment through natural springs or man-made wells in neighboring valleys down gradient.

A testing program was initiated to characterize the process of seepage into tunnels in Yucca Mountain in the same stratigraphic unit as the proposed waste emplacement tunnels. The seepage characterization data are then used to create predictive models to assess the risk and magnitude of seepage under future conditions.

Background

Yucca Mountain, located about 145 km northwest of Las Vegas, Nevada, is composed of Tertiary volcanic rocks. Variably welded tuffs make up the majority of the unsaturated zone where the HLRW is proposed to be emplaced. The stratigraphic unit of interest for this study is the middle nonlithophysal unit of the Topopah Spring tuff (Tptpmn). This is a densely welded tuff with low matrix porosity and permeability (11% and ~10^{-18} m^2, respectively) and high fracture density and permeability (4.3 fractures per meter — the frequency for fractures longer than about half of a meter — and ~10^{-13} m^2, respectively). Because of the large contrast in permeability between the matrix and fractures in this unit, water and gas flow are thought to occur mainly in the fracture system.

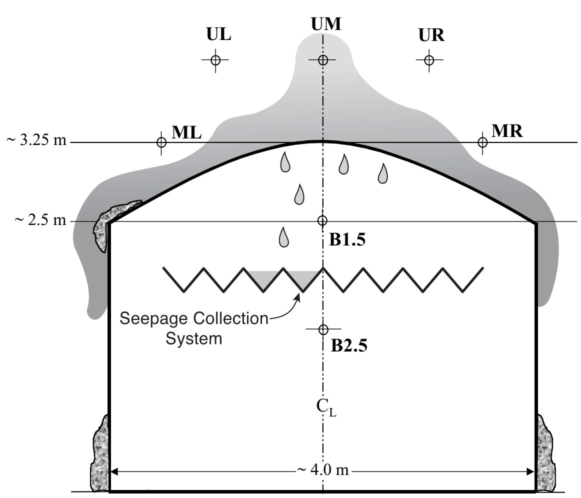

Figure 1. Schematic cross section showing the generalized layout of a niche, boreholes for testing, and seepage collection system. Cross section is perpendicular to the axes of the niche and boreholes. Note: upper boreholes are approximately 0.6 m above the crown of the Niche.

Off the main underground tunnel at Yucca Mountain, called the Exploratory Studies Facility (ESF), several niches, or short tunnels about 10 m long, were excavated to be used for seepage characterization. The niches, from which data were collected for the analysis discussed here, are all in the Tptpmn. Three boreholes were drilled (prior to mining the niche) about 0.6 m above the crown of the niche. These are used for air-injection and liquid-release testing and are labeled UL (upper left), UM (upper middle), and UR (upper right) in Figure 1.

The first niche to be tested was Niche 3650. Air-injection testing was carried out in the boreholes above the niches. Intervals were isolated every 0.3 m along the boreholes by means of an inflatable packer system. Each interval was tested twice to find the interval pressure needed to maintain a chosen steady gas-flow rate. If leakage past a packer is detected in the adjacent guard zones, the target pressure is automatically reduced and the test repeated. Repeatability of the tests in each interval was good, giving an indication that the tests are representative of the characteristics of the rock. The tests were analyzed using a solution for steady gas flow from a finite-length line source (LeCain, 1995) to determine the fracture system permeability of the rock.

After the air-injection tests were completed, liquid-release tests were initiated. The 0.3 m intervals that were used for the LRTs were the same as were used for the air-injection tests. In this way, intervals with very low permeability could be identified and LRTs in these intervals initiated at lower rates. LRTs of short duration were performed at Niche 3650. A capture system was set up beneath the drift ceiling, as shown in Figure 1, so that potential seepage could be weighed and compared to the mass of water injected into the rock during that test. The seepage data for these tests included only the time of seepage initiation and the total mass of water that seeped. The LRTs were conducted under gravity drainage conditions by not allowing the injection intervals to completely fill with water. Multiple injection rates were tested in many of the intervals in order to capture the rate of injection below which no seepage occurs.

Geostatistical analysis of the permeabilities inferred from the air-injection tests is used to characterize the heterogeneity of the fracture system. The cumulative distribution function of air permeability shows an approximate lognormal behavior, while a spherical semivariogram, fitted to the data, shows little spatial correlation, even between adjacent measurements (0.3 m apart). Sequential indicator simulation (Deutsch and Journel, 1992) is used to create a three-dimensional heterogeneous-permeability field, shown in Figure 2, that is conditioned on the air permeabilities.

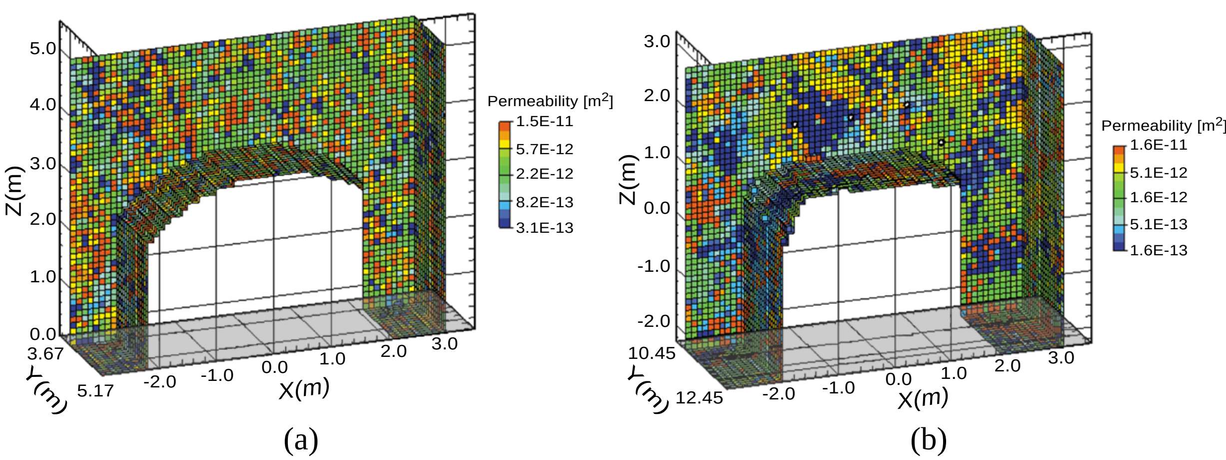

Figure 2. Computational meshes and realizations of heterogeneous permeability fields for Niches (a) 3650 and (b) 4788.

A three-dimensional, single-continuum model (predominantly representing the fractures) is used for simulation of the LRTs and any potential seepage. The effect of the relatively impermeable matrix, while not explicitly included in the model, is captured by estimating model-specific, effective parameters. Model boundary conditions are 1) a small but constant background percolation rate distributed over the upper boundary, 2) no-flow lateral boundaries, 3) a gravity-drainage condition at the lower boundary, 4) a zero capillary pressure condition at the niche boundary (this corresponds to 100% relative humidity in the niche and, thus, no loss of the seeping water to evaporation), and 5) injection rates and times at injection intervals in the model that duplicate the LRTs. The niche shape used, as shown in Figure 2(a), was based on the construction plans; however, the actual shape of the niche deviated slightly from this.

The seepage data are inverted using the automated data inversion software iTOUGH2 (Finsterle, 1999) to produce model-specific, seepage-relevant effective parameters. The seepage predicted by the model is mainly sensitive to variations of three model parameters, namely permeability (k), capillarity ($1/\alpha$) (a parameter in the model proposed by van Genuchten (1980) for relating capillary pressure to saturation), and porosity (ϕ). When seepage is first initiated and the seepage rate is not approximately steady, as is the case for the Niche 3650 seepage data, all three of these parameters are strongly correlated, i.e., a change in any of the three parameters will change the timing of seepage initiation and the shape of the seepage transient. Thus, these parameters cannot be determined independently by inversion of the seepage data alone. However, permeability may be fixed, and eliminated from the parameters to be calibrated, because it has been determined independently by the air-injection testing. This leaves $1/\alpha$ and ϕ as the parameters to be calibrated. For the Niche 3650 model, $1/\alpha$ is heterogeneous and correlated to k in each grid block using Leverett's scaling rule (Leverett, 1941); The calibrated parameter is the average $1/\alpha$. Porosity is assumed homogeneous.

Five LRTs from one interval in borehole UM were selected for joint data inversion. These data were selected because they included seepage results for a range of injection rates. The resulting calibrated parameters are $\log_{10}(1/\alpha\ [\text{Pa}]) = 1.82$ and $\log_{10}(\phi) = -2.89$, which give a very good match between the simulated and measured seepage, as shown in Figure 3. Note, however, that because of the correlation between the calibrated parameters, as discussed above, they are not independent, and there are likely to be other parameter combinations that are equally valid for reproduction of the data. In order to build confidence in the calibrated parameters, seepage resulting from four LRTs from another interval in borehole UM was simulated. For three of the four tests, the simulation matches the seepage data with acceptable accuracy. Finsterle and Trautz (1999) discuss the confidence-building exercise as well as other aspects of testing and data analysis for Niche 3650 in more detail.

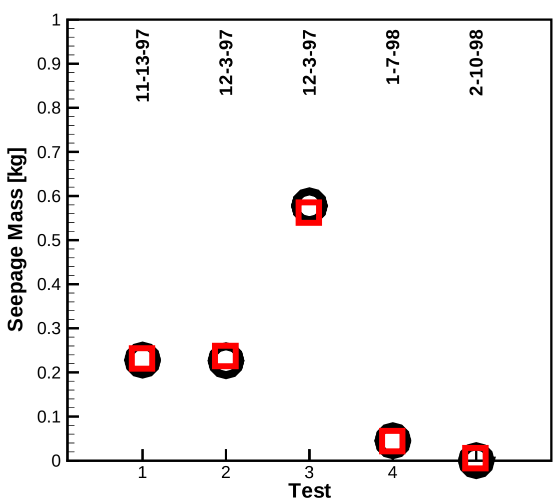

Figure 3. Comparison of the results of the calibrated simulation (squares) to the cumulative seepage mass data (circles) for Niche 3650.

Discussion of Initial Data Collection and Analysis

Review of the Niche 3650 data collection and analysis through regular discussions between the field-testing and modeling personnel resulted in several recommendations for improvements to testing and analysis for the purpose of producing model predictions of seepage due to long-term steady percolation:

1) The calibrated $1/\alpha$ and ϕ were found to be highly correlated, i.e., changes in either parameter similarly affect the calculated time of seepage initiation and cumulative seepage mass for each of the simulated Niche 3650 LRTs. Furthermore, the short-term LRTs only test a small portion of the fracture system that is responsible for the first arrival of water at the niche wall. These fractures may not be representative of the larger-scale fracture network that would be responsible for diverting water around the niche, which is the process of interest. Also note that porosity is not needed for predictions of seepage in response to long-term, steady percolation. Under these conditions, seepage depends on $1/\alpha$ (and k) only.

   The following changes to data collection and analysis were proposed to reduce the parameter correlation and increase confidence that the estimated parameters are appropriate for their intended purpose. First, longer-term LRTs that result in near-steady seepage should be performed. Second, seepage data should be collected throughout the test, rather than just the cumulative-seepage mass at the end of each LRT, so that the near-steady seepage rate into the niche can be identified. Third, seepage-rate data should be inverted so that early-time mismatches between simulation and data do not affect the late-time match between simulation and data. Note that a mismatch in the early-time behavior is considered acceptable as we are interested in the average behavior of the network on the drift scale rather than the first arrival. In fact, forcing a match of the first arrival may induce an unwanted bias in the estimated parameters if the fracture connecting the injection interval with the niche ceiling is not representative of the average network behavior.
2) Because the shape of the niche ceiling strongly affects the diversion potential of the capillary barrier, it may be important to accurately reproduce the shape of the mined niche, especially if the niche ceiling has an extended flat area directly under the injection interval(s).
3) Evaporation of water as it enters the niche or in the collection system is a possible source of error for the analysis. The data inversion, as performed above, relies on the assumption that all the water is accounted for, i.e., that the mass of water injected is balanced by the mass of water remaining in the rock above (and around) the niche and the mass of water that seeps into the opening and is captured. If a significant portion of the water evaporated either before it dripped from the ceiling or while in the capture system, then this assumption is violated. There are several ways in which potential evaporation may be controlled or accounted for. The niche can be sealed and/or actively humidified during the testing in order to minimize the potential for evaporation. The capture system can be continuously drained into a sealed container to minimize the potential for evaporation of the collected water. Finally, a non-isothermal model with an active gas/vapor phase can be used for data inversion in order to capture potential evaporation effects.
4) Detection of water flowing in the rock at or near the spring line (or the highest point where the niche wall is still vertical) during LRTs would confirm that the injected water is being diverted around the niche and that the LRTs are, in fact, testing the diversion capacity of the capillary barrier formed by the niche.

Modified Data Collection and Analysis

During and after analysis of the Niche 3650 data, testing in two more niches (3107 and 4788) was performed. Air-injection testing was carried out in the same manner as in Niche 3650. The LRT protocol was modified to address some of the issues raised above. Longer-term tests were run in order to allow a near-steady seepage rate to develop. The niches were closed and/or humidified in order to minimize the potential for evaporation both from the seepage face (i.e., the niche ceiling) and from the collection system. Finally, continuous drainage of the collection system and measurement of the seepage mass allowed the seepage rate to be calculated and a near-steady seepage rate to be identified for those tests where seepage occurred. Continuous drainage also minimized the opportunity for evaporation from the collection system itself.

Air-permeability data analysis and generation of one realization of a heterogeneous permeability field for each niche, conditioned on the air-permeability data of the niches, are carried out in the same manner as before. The numerical meshes are constructed to reproduce the roughness of the niche ceiling, at the scale of the mesh discretization (10 cm), as shown in Figure 2(b).

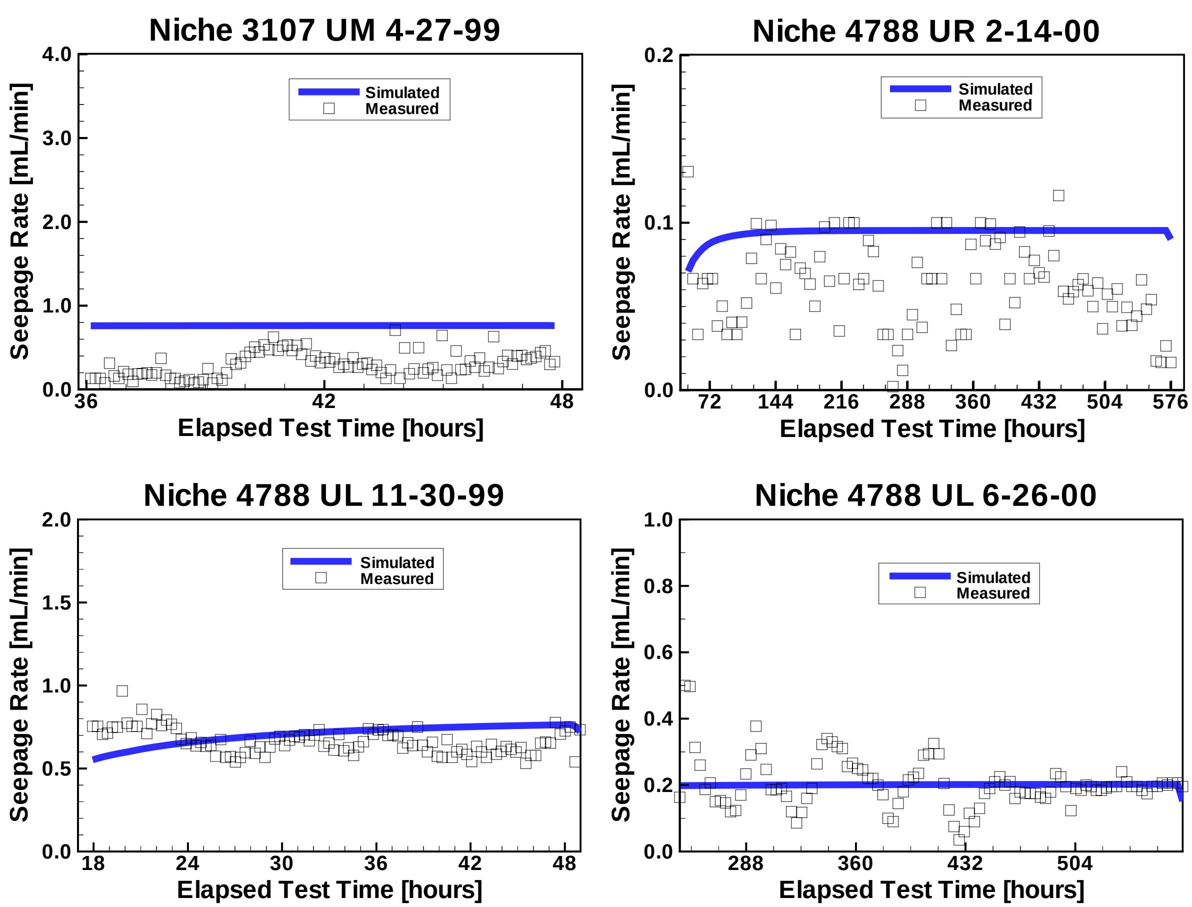

Figure 4. Comparison of a selection of the results of the calibrated simulation to the seepage rate data for Niches 3107 and 4788.

Data from three LRTs at three different injection rates in one borehole in Niche 3107 and from two LRTs at different rates in each of the three boreholes in Niche 4788 are selected for inversion. Only data from the near-steady seepage portion of the data are selected for inversion. This portion of the data better characterizes flow through the relevant portion of the fracture system (i.e., data related to early-time seepage, which would characterize only a small number of fractures involved in the first arrival of water at the drift ceiling, are eliminated from the inversion). Using only this portion of the data should also reduce the correlation between $1/\alpha$ and ϕ. Instead of inverting cumulative-seepage-mass data as was done previously, the inversion is performed on the seepage-rate data. This also helps reduce the correlation between $1/\alpha$ and ϕ and a potential bias in their estimates because errors in the simulated first arrival time due to ϕ are not propagated through the simulated seepage rate. Note, it is necessary to continue to include ϕ as one of the calibrated parameters so that the simulated seepage is initiated and approaches near-steady conditions prior to the period over which the simulation is compared to the data.

Figure 4 shows a representative selection of the matches between the results of the calibrated simulations and the seepage-rate data, and Table 1 shows the calibrated parameters determined for each of the four data sets inverted. Again, to build confidence in the calibrated parameters, additional LRTs and the resulting seepage data not used for inversion are simulated using the averages of the calibrated parameters (from inversion of data from Niches 3107 and 4788). The simulations match the data with acceptable accuracy as shown by Finsterle et al. (2000).

Conclusions

Data collection and analysis were conducted to characterize seepage into three niches at Yucca Mountain. Data analysis begun soon after testing at Niche 3650 was initiated and collective review of field observations, data collection, and data analysis by all personnel led to an improved testing and analysis regimen for the remaining two niches (Niches 3107 and 4788). Longer-term LRTs resulting in near-steady seepage-rate data and selection of near-steady seepage-rate data (rather than transient and/or cumulative seepage data) allowed model calibration with reduced correlation between the parameters. Minimization of evaporation potential in Niches 3107 and 4788 during the LRTs and using numerical models with a realistic ceiling geometry contributed to better model reproduction of the physical environment in the niches that ultimately provided better calibrated parameters for prediction of future seepage.

This example demonstrates the benefits of integrating data analysis and modeling into a field experiment as soon as practical after data acquisition begins. Data collectors must be aware of the ultimate use for the data, which in this case is to produce a calibrated model suitable for prediction of seepage into waste emplacement drifts at Yucca Mountain under steady percolation conditions. However, because data may be used for several purposes, tailoring experiments exactly to one particular use may not be feasible. In the same way, data analysts must account for as many aspects as possible of the

Inversion	$\log_{10}(1/\alpha\ [\mathrm{Pa}])$	$\log_{10}(\phi)$
Niche 3107	2.87	-3.00
Niche 4788 borehole UL	2.81	-1.75
Niche 4788 borehole UM	2.78	-1.78
Niche 4788 borehole UR	2.63	-2.15

Table 1. Calibrated parameters and correlation coefficients from inversion of seepage rate data from Niches 3107 and 4788.

physical environment in which the data were collected in order to produce the best possible analysis. Acknowledging the limitations of the data and the analysis is also important. In this data collection and analysis exercise, the close working relationship between the team members collecting the data and the team members using the data allowed us to address potential shortcomings in the data and analysis early on, so that the final product was of higher quality.

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