HIGH LEVEL RADIOACTIVE WASTE MANAGEMENT

Proceedings of the Fifth Annual International Conference
Las Vegas, Nevada, May 22-26, 1994

VOLUME 4
1994

Sponsored by the
American Society of Civil Engineers
American Nuclear Society

in cooperation with:

American Association of Engineering Societies
American Chemical Society
American Institute of Chemical Engineers
American Medical Association
American Society for Testing and Materials
American Society for Quality Control
American Society of Mechanical Engineers
Center for Nuclear Waste Regulatory Analysis
Edison Electric Institute
Geological Society of America
Health Physics Society
Institute of Nuclear Materials Management
National Conference of State Legislatures
Society of Mining Engineers
U.S. Department of Energy
U.S. Geological Survey
U.S. Nuclear Regulatory Commission
University of Nevada Medical School
American Institute of Mining, Metallurgical and Petroleum Engineers
American Underground-Space Association
Atomic Energy Council Radwaste Administration
Atomic Energy of Canada Ltd.
British Nuclear Fuels Ltd.
Chinese Institute of Civil and Hydraulic Engineering
Commission of the European Communities
Conseil National des Ingenieurs et des Scientifiques de France
Electric Power Research Institute
Her Majesty's Inspectorate of Pollution
Hungarian Nuclear Society
Institution of Civil Engineers
Institution of Engineers-Australia
Institution of Engineers of Ireland
Japan Society of Civil Engineers
Korea Advanced Energy Research Institute
Korean Society of Civil Engineers
Ministerio de Industria y Energia-Uruguay
National Association of Corrosion Engineers
National Association of Regulatory Utility Commissioners
Nationale Genossenschaft fur die Lagerung Radioaktiver Abfalle (NAGRA)
National Society of Professional Engineers
Organization for Economic Cooperation and Development (OECD)- Nuclear Energy Agency
Power Reactor and Nuclear Fuel Development Corp.
Romanian Nuclear Energy Association
Swedish Nuclear Fuel and Waste Management Company
Swedish Nuclear Power Inspectorate
Swiss Society of Engineers and Architects
U.S. Council for Energy Awareness
Verein Deutscher Ingenieure

Hosted by
University of Nevada, Las Vegas
Howard R. Hughes College of Engineering

Published by the

American Nuclear Society, Inc.
La Grange Park, Illinois 60525, USA

American Society of Civil Engineers
345 East 47th Street
New York, New York 10017-2398, USA

MODELING A PONDED INFILTRATION EXPERIMENT AT YUCCA MOUNTAIN, NV

David B. Hudson
Foothill Engineering, Inc.
Box 327, MS 721
Mercury, NV 89023
(702) 295-5970

Alan L. Flint
U.S. Geological Survey
Box 327, MS 721
Mercury, NV 89023
(702) 295-5970

William R. Guertal
Foothill Engineering, Inc.
Box 327, MS 712
Mercury, NV 89023
(702) 295-5970

ABSTRACT

One-dimensional and two-dimensional radial flow numerical models were used to evaluate the results for a 60.5 h ponded infiltration experiment done around a 24 m deep, 0.15 m diameter, cased borehole at Yucca Mountain, NV. Nine distinct morphological horizons in the soil profile had been identified; physical and hydraulic properties had been measured for each horizon; and a porosity profile at the borehole had been measured. During the infiltration experiment, 10 cm of water was ponded in a 3.5 m diameter infiltrometer around the borehole, the volume of water applied was measured, and water content profiles were measured with a neutron moisture meter. The infiltrometer applied 86.9 cm of water during the first 60.5 h of infiltration, but only 52.8 cm of additional water was measured in the borehole profiles. Assuming a linear relationship between cumulative infiltration (I) and the square root of time ($t^{0.5}$), an experimental sorptivity of 11.5 cm h^{-1} was estimated for the first 4.5 h of infiltration. An assumed washout zone around the borehole casing accounted for the discrepancy between the measured water content profiles and the applied water. A uniform property, 1-D model with an applied flux upper boundary described by the sorptivity confirmed the probable washout zone, and indicated that significant lateral flow into the dry soil around the infiltrometer could occur. A 2-D radial flow model with the same properties and upper boundary demonstrated that significant lateral flow occurred. The upper boundary in this model caused the upper portion of the profile to drain. This suggested using a saturated upper boundary to keep the upper portion of the profile saturated. When the saturated upper boundary was used, the permeability of the soil was decreased from the measured value of 3.28E-11 m^2 to 1.5E-12 m^2 so that the simulated wetting front was at a similar depth as the observed wetting front after 60.5 h. Even with this lower permeability, the saturated boundary caused 371.0 cm of infiltration during the first 60.5 h. Also, the simulated results remained saturated behind the wetting front, but the measured saturation profiles were not saturated below 1.2 m. A second layer below 1.2 m was introduced into the model and a lateral to vertical anisotropy ratio of 0.02 was assumed so that the simulated water content profiles were similar to the observed water content profiles and to have approximately the right simulated amount of infiltration. The vertical permeability of the top layer was 5.0E-13 m^2 and the vertical permeability of the second layer was 5.0E-11 m^2. Numerical modeling of the infiltration experiment showed: a possible washout zone around the borehole existed, significant lateral flow away from the borehole occurred, measured permeabilities were too large to simulate infiltration, layering in the profile affected infiltration, and permeabilities were anisotropic.

I. INTRODUCTION

Yucca Mountain, Nevada is being evaluated as a potential site for a geologic repository for high level radioactive waste[1]. As part of the site characterization activities at Yucca Mountain, a field-scale ponded infiltration experiment was done to help characterize the hydraulic and infiltration properties of a layered dessert alluvium deposit. Calcium carbonate accumulation and cementation, heterogeneous layered profiles, high evapotranspiration, low precipitation, and rocky soils make the surface difficult to characterize. The effects of the strong morphological horizonation on the infiltration processes, the suitability of measured hydraulic properties, and the usefulness of ponded infiltration experiments in site characterization work were of interest. One-dimensional and two-dimensional radial flow numerical models were used to help interpret the results of the ponding experiment.

The characteristics and rates of natural infiltration, exfiltration, percolation, and movement of water in the unsaturated surface at Yucca Mountain provide a description of the upper boundary condition for modeling water flow in the mountain. Hydraulic properties of the surficial materials are required to estimate and model this boundary. The essential hydraulic properties for describing unsaturated water flow are the water retention and the hydraulic conductivity relationships. While many techniques for determining the unsaturated hydraulic properties of the soils were developed for agriculture[2,3], there are few procedures specifically designed for the dry conditions common in arid environments such as Yucca Mountain. The suitability of the measured properties for the conditions found at Yucca Mountain were evaluated by applying them in a model and comparing simulated results with the observed results from a ponded infiltration experiment.

The objective of this study was to evaluate the results of a ponded infiltration experiment done around borehole UE25 UZN #85 (N85) at Yucca Mountain, NV. The effects of morphological horizons on the infiltration processes, lateral flow, and measured soil hydraulic properties were studied. The evaluation was done by numerically modeling the results of a field ponded infiltration experiment. A comparison between the experimental results and the modeled results was used to qualitatively indicate the degree to which infiltration processes and the hydraulic properties are understood. Results of the field characterization, soil characterization, borehole geophysics, and the ponding experiment are presented in a companion paper[4].

II. LOCATION AND SITE DESCRIPTION

Yucca Mountain is located 160 km northwest of Las Vegas in Southern Nevada. The mountain consists of nonwelded and welded tuffs with very large ranges in their physical and hydrologic characteristics. Unconsolidated alluvium underlies the washes that dissect Yucca Mountain and forms the surficial deposits on broad interridge areas and flats near Yucca Mountain. Alluvium thickness in the washes ranges from 0.3 m to > 20 m[5]. The climate is arid with an average annual precipitation estimated at 170 mm/yr[6] and potential evapotranspiration is estimated at approximately 5 to 6 times the annual rainfall[7].

The ponded infiltration experiment was done at neutron access borehole N85. This borehole is 24.7 m deep and 0.15 m diameter, with steel casing to the total depth of the hole. This hole was drilled approximately 3 m from the edge of an 18 m exposure along the edge of Forty Mile Wash. This exposed cliff permitted visual identification of the various morphological horizons and allowed samples to be taken from each horizon for characterization. The morphology of the N85 exposure and the soil characteristics are described by Guertal et al.[4] Nine major morphological horizons were identified in the 18 m profile. The base of each layer (depositional sequence) was defined by a boulder and/or petrocalcic horizon. The material above the bottom layer boundary is composed of sands and gravels that fine upward. The average porosity (ϕ) through the borehole profile is 0.32 with four distinct high porosity zones located from 3.5 to 3.9 m (ϕ=0.54), from 5.0 to 5.6 m (ϕ=0.45), from 7.3 to 7.7 m (ϕ=0.36), and from 14.9 to 15.2 m (ϕ=0.41). These zones were interpreted as possible washout zones near the borehole casing[4]. There also is a slight decrease in porosity with increasing depth. Particle size distribution data and water retention data for samples from each of the nine model layers were measured and saturated hydraulic conductivities (K_{sat}) for each layer were calculated using the particle size distribution data[4].

The water retention data were used to estimate the parameters in a modified van Genuchten water retention relationship[8]

$$S = (1+(\alpha|\psi|)^n)^{-(1-1/n)} \qquad (1)$$

where S is saturation ($\theta\ \phi^{-1}$), θ is volumetric water content ($m^3\ m^{-3}$), ψ is water potential (Pa), and α (Pa^{-1}) and n are fitting parameters. The closed-form hydraulic conductivity equation given by van Genuchten[8] was used to predict unsaturated hydraulic conductivities (K) from measured K_{sat} values and measured water retention relationships. This equation is

$$K(S) = K_{sat}\, S^{0.5}\, [1-(1-S^{1/m})^m]^2 \qquad (2)$$

III. PONDING EXPERIMENT

A 3.5 m diameter ponded infiltrometer was constructed with borehole N85 at its center[9]. During the first 60.5 h of the ponded infiltration experiment (3/9/93 to 3/11/93), 86.9 cm of water infiltrated. Ten cm of water were maintained on the soil surface inside the infiltrometer during the infiltration experiment. The water content profile at N85 was monitored with a neutron moisture meter at hourly intervals. The cumulative infiltration for the first 60.5 h calculated by the increase in measured water content profiles is 52.8 cm. The measured infiltration rate is compared to the calculated infiltration in Figure 1. More water was measured in the borehole during the first 16 hours of the infiltration experiment, but, after 16 hours, less water was measured in the borehole. Initially the cumulative infiltration (I) estimated from the water content profiles appears to be linearly related to $t^{0.5}$. A linear $I(t^{0.5})$ relationship was estimated using the first 4.5 h of calculated infiltration data. This relationship is

$$I = 11.5\,(t)^{0.5} \qquad (3)$$

and is given in Figure 1. The slope of this line is an estimate of the experimental sorptivity (S=11.5 cm h^{-1}). Extrapolation of equation 3 to 60.5 h predicts a cumulative infiltration of 89.4 cm. This is a reasonable approximation of the measured infiltration of 86.9 cm.

The observed neutron moisture meter cumulative infiltration data in Figure 1 shows a decrease in the infiltration rate between 5 h and 48 h and an anomalous increase in the infiltration rate between 48 h and 65 h. These slope changes without changes in the surface boundary and consequential changes in the water content profile are inconsistent with single valued $K(\theta)$

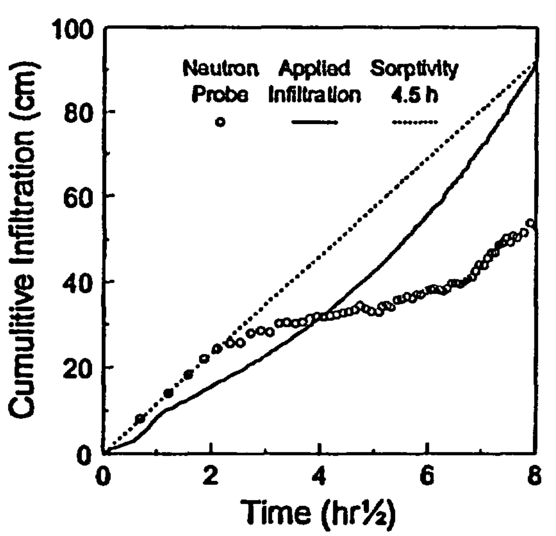

Figure 1. Cumulative infiltration applied, measured with a neutron moisture meter, and estimated from the 4.5 h sorptivity.

and $\theta(\psi)$ functions and a linear $I(t^{0.5})$ relationship. The cumulative infiltration calculated from the water content profiles is also less than the measured cumulative infiltration. These inconsistencies suggest problems with using a simple interpretation of the neutron moisture meter measurements. The similarity between the slope at $t<4.5$ h (S=11.5 cm $h^{-0.5}$) and the slope at 48 h$<t<$60.5 h (S=9.2 cm $h^{-0.5}$) indicates that the problems occurred between 4.5 h$<t<$48 h. For modeling purposes, this inconsistency needed to be reconciled. For this flux change to occur, the hydraulic conductivity of the profile behind the wetting front would have to increase without the water content increasing.

A washout zone (assumed as a relatively large void space behind the casing) would easily account for this inconsistency. Depending on the size of the washout, neutron moisture meter water content measurements might not increase even though the water content of the soil outside the washout zone was increasing. Because the infiltration rate was calculated from changes in the measured water content profile, the infiltration rate would decrease during the wetting of the soil around a washout zone. After the wetting front passed the washout zone, the neutron moisture meter would again measure the correct changes in water content and consequently the infiltration rate would increase. In addition, the similarity between the infiltration rates between $t<4.5$ h and 48 h$<t<$60.5 h and the unexplained increase in measured porosity to 0.54 between 3.5 and 3.9 m support this hypothesis. It is reasonable to assume that equation 3 describes the cumulative infiltration during the first 60.5 h. The disagreement between the measured cumulative infiltration and the infiltration predicted by equation 3 suggests possible spatial variability in the infiltration rate across the 9.6 m^2 area of the infiltrometer. It is possible that the neutron access hole is in a more permeable zone.

IV. MODEL DEVELOPMENT

Numerically models were used to simulate the infiltration experiment initially using the measured hydraulic properties[4]. TOUGH[10] was used to model the infiltration experiment as a 1-D and 2-D radial flow process. This FORTRAN program is a finite-difference approximation of water and gas flow through porous media which can use arbitrary boundary and initial conditions. Isothermal conditions were assumed. Initially, the hydraulic properties of Layer 2 given in Guertal et al.[4] were used for the entire profile. The Layer 2 properties were chosen because the K_{sat} for Layer 1 was much lower than the other K_{sat} values.

The hydraulic property parameters used in equations 1 and 2 were: α=5.18E-4 Pa^{-1}, n=1.29, m=0.2231, and K=3.28E-11 m^2. The initial conditions were set to the measured initial volumetric water contents, and the measured porosities at 10 cm increments were used. Infiltration was modeled as a semi-infinite column (i.e. the bottom boundary and the side boundary away from the infiltrometer did not influence the infiltration process). Initially, equation 3 was used to describe an applied flux upper boundary condition to assure that the proper amount of water was applied in the simulations. The flux boundary model is relatively insensitive to permeability provided, the permeability is higher than the applied flux. This model does provide a method for evaluating the retention properties and the uniform property model. After reasonable results were obtained using the applied flux upper boundary, a saturated upper boundary was used and the permeability was adjusted to provide the correct water input.

A 1-D model was used to simulate the first 60.5 h of the infiltration experiment. This model used a node spacing of 0.25 m for the top 0.25 m, node spacings of 0.1 m from 0.25 to 5.15 m, node spacings of 0.3 from 5.15 to 6.35 m, and a semi-infinite node spacing for the bottom node. The time steps were left adjustable to allow for convergence and were initially set t 60 s.

The 2-D radial flow models used the same depth increments, initial time step, and properties as the 1-D model and radial symmetry around the borehole was assumed. The profile under the infiltrometer was modeled as 1.5 m diameter inner cylinder with a 3.5 m diameter concentric ring surrounding the inner cylinder. The profile outside the infiltrometer was modeled as 6 additional concentric rings. The radius of each outside ring increased by 1 m to model 6 m from the outside of the infiltrometer. The total modeled flow domain had a diameter 15.5 m. The effects of the exposed cliff 3 m away from the borehole were ignored because water was not observed at the cliff face during the experiment. For the upper flux boundary condition, the flux from equation 3 was applied to the top two inner elements and a no-flux boundary was used for the remaining 6 top elements. For the saturated upper boundary, the top of the two inner elements was saturated and a no-flux boundary was used for the remaining 6 top elements.

V. RESULTS AND DISCUSSION

Four models were used to simulate the first 60.5 h of the infiltration experiment. Model descriptions are presented in Table 1. The same uniform retention properties were used in all models. Discussion of the model results follows.

Table 1. Model descriptions.

Figure	2	3	4	5
Model	1-D	2-D	2-D	2-D
Boundary	Flux	Flux	ψ	ψ
$K_1 x 10^{13}$ (m^2)	328	328	15	5*
$K_2 x 10^{13}$ (m^2)	328	328	15	500*

* Anisotropic.

A. 1-D Models

The uniform property 1-D model was used to model 60.5 h of infiltration with an applied flux upper boundary described by equation 3. A washout zone between 3.5 and 3.9 m was assumed. The porosity and properties of the washout zone were assigned the properties of the surrounding soil. The observed water content profiles and the modeled water content profiles are given in Figure 2. The lower observed water contents in the washout zone are expected because the increased water content in the soil around the washout zone would not be measured with a neutron moisture meter. The uniform water contents behind the wetting front and the fair agreement between the observed and simulated results indicate that the uniform property model is adequate for initially modeling the infiltration experiment. The variation in the modeled water contents behind the wetting front is entirely due to porosity changes. The simulated wetting fronts after 4.5 hours are deeper than the observed wetting fronts indicating that there is more water in the modeled profiles than in the observed profiles even if the washout zone is considered. This discrepancy could be due to an inaccurate description of the infiltration rate given by equation 3 or it could be due to water being removed from the observed profile by lateral flow.

B. 2-D Radial Flow Models

A 2-D radial flow model was used to model the first 60.5 h of infiltration. As in the 1-D model the upper applied flux boundary given by equation 3 was applied to the infiltrometer. The hydraulic properties were the same properties used in the 1-D model and the hydraulic conductivity was assumed to be isotropic. The observed water content profiles and the modeled water content profiles are given in Figure 3. In contrast to Figure 2, the simulated wetting front depths are all shallower than the observed wetting front depths. This is entirely due to water being removed from the borehole profile by lateral flow. The same infiltration depth was applied to both the 1-D and 2-D radial flow models. Lateral flow in the simulated profiles wet the soil to 3 m beyond the radius of the infiltrometer at 60.5 h. The simulated profiles were never saturated near the surface and the surface soil begins to drain as the applied flux decreased with time. This happened because the applied flux was less than the saturated conductivity.

To keep the surface of the simulated profiles saturated, the upper boundary of the 2-D radial flow model was changed from an applied flux boundary to a saturated boundary. The same uniform retention properties were used, but the permeability was reduced from 3.28E-11 m^2 to 1.5E-12 m^2 to obtain reasonable agreement between the observed wetting front depth and the simulated wetting front depths. The observed water content profiles and the modeled water content profiles are given in Figure 4. Even with the lower permeability, this model infiltrated 371.0 cm of water during 60.5 h of infiltration, while the measured infiltration was only 86.9 cm. The saturated upper boundary produced a simulated water content profile that was saturated behind the wetting front (i.e., the water content was equal to the porosity). The observed water content profile was saturated to 1.2 m but was unsaturated below 1.2 m. Lateral flow in the simulated profiles wet the soil to 2 m beyond the radius of the infiltrometer after 60.5 h.

The 2-D radial flow model with the saturated boundary was modified to decrease the cumulative infiltration and to allow the water content profile to be unsaturated below 1.2 m. The permeability of the top layer was reduced to reduce the infiltration rate and a second model layer was used below 1.2 m. The second layer was given a higher permeability than the first layer so that it would remain unsaturated. Also, the lateral permeability was made lower than the vertical permeability to allow the simulated wetting front to penetrate as deep as the observed wetting front for the measured infiltration. This is consistent with an assumed increase in density and decrease in permeability nearer to the cliff face. A qualitative, iterative, trial and error, inverse parameter estimation technique was used to estimate the permeabilities of the two model layers. The objective criteria were comparisons of the observed and simulated wetting front depths, the observed and simulated water content profiles, and the observed and simulated infiltration rates. The observed water content profiles and the final modeled water content profiles are given in Figure 5. The top layer permeability was set to 5E-13 m^2 and the second layer permeability was set to 5E-11 m^2. The lateral to vertical anisotropy ratio was set to 0.02. The simulated cumulative infiltration after 60.5 h was 120.3 cm. Although the simulated water content profiles are not as deep as the observed water content profiles at the beginning of the simulation, there is reasonable agreement between the observed and simulated profiles after 29.5 h. Lateral flow in the simulated profiles wet the soil to 1 m beyond the radius of the infiltrometer after 60.5 h. The higher permeability of the second layer caused it to be unsaturated even though a saturated upper boundary was used. Further modification of the permeability could be used to obtain better fits to the early infiltration but not enough data was available to support additional adjustments.

VI. CONCLUSIONS

Numerical modeling of a ponded infiltration experiment was used to evaluate the results of a ponded infiltration experiment done around borehole N85 at Yucca Mountain. The available information from the experiment consisted of the cumulative infiltration through the 3.5 m diameter infiltrometer, measured water content profiles from a cased borehole in the center of the infiltrometer, a porosity profile at the borehole, a morphological description of the layered soil profile from an exposed cliff 3 m from the borehole, and measured hydraulic properties form samples taken from the exposed cliff[4]. The first 60.5 h of the infiltration experiment was evaluated. The measured water content profiles and cumulative infiltration provided data for comparison of simulated results.

Measured hydraulic and physical properties alone could not accurately predict the observed infiltration. The modeling results, porosity profile, and the measured infiltration were used to identify a possible washout zone around the borehole casing. This zone affects the measured water content profiles and consequently the infiltration rate as measured by the water content changes in the measured profile. Rather than constructing a very complicated flow system, the hypothesized washout zone simply solved the problems and was consistent with the measured densities. However, the borehole casing made it impossible to verify the washout zone at this time.

Lateral flow away from the borehole had a significant effect on the measured water content profiles. A 1-D flow model with the measured infiltration applied as a flux upper boundary resulted in

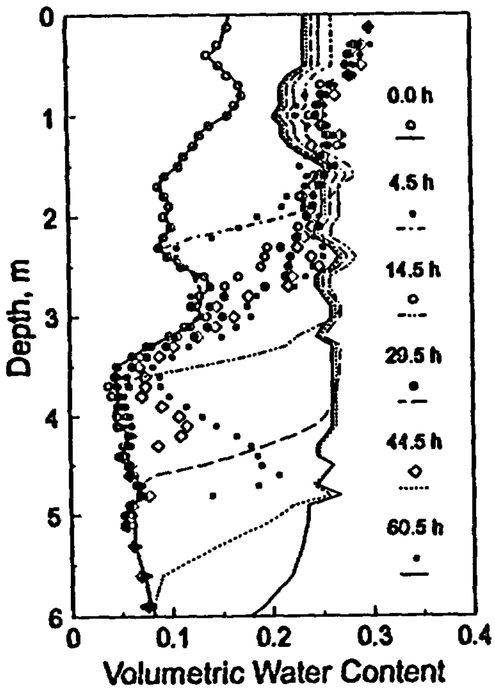

Figure 2. Observed and simulated results for the uniform property, 1-D model with an applied flux upper boundary.

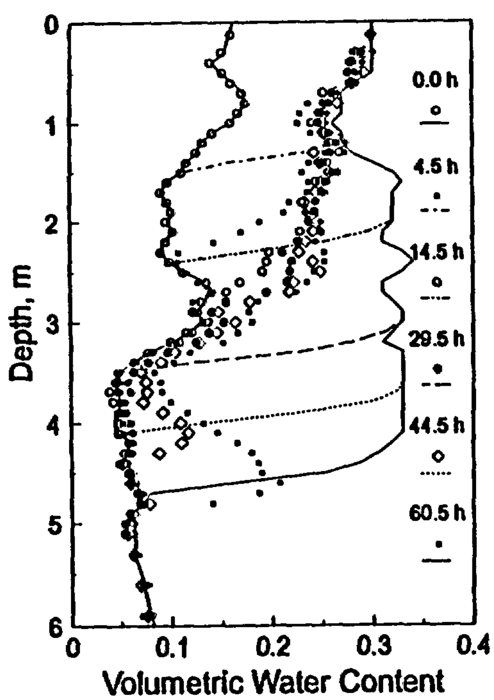

Figure 3. Observed and simulated results for the uniform property, 2-D radial flow model with an applied flux upper boundary.

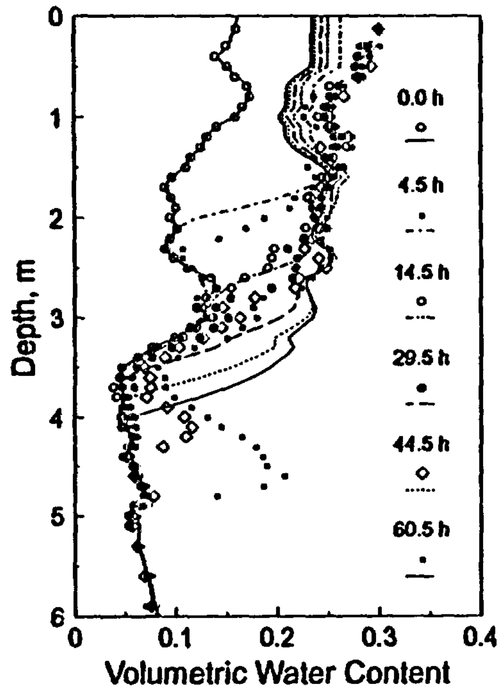

Figure 4. Observed and simulated results for the uniform property, 2-D radial flow model with a saturated upper boundary.

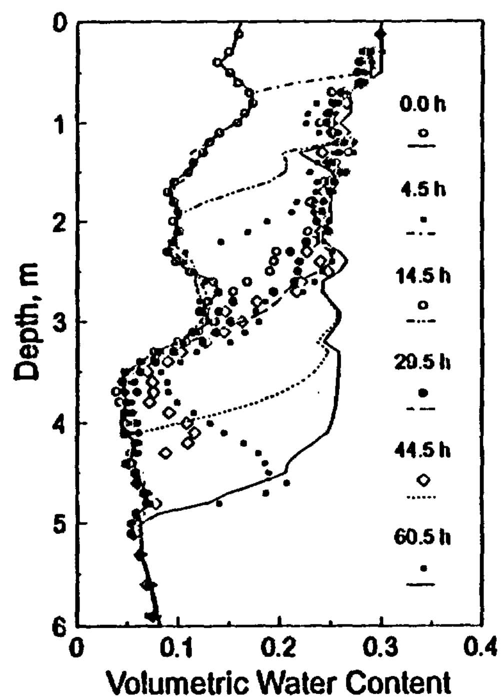

Figure 5. Observed and simulated results for the layered property, 2-D radial flow model with a saturated upper boundary and anisotropic permeabilities.

simulated wetting fronts that penetrated deeper than the observed wetting front. A 2-D radial flow model with the measured infiltration applied at the boundary resulted in simulated wetting fronts that were not as deep as the observed wetting fronts. Lateral flow had removed too much water from the simulated profile. The simulated profiles from the models that used the measured infiltration as a boundary were not saturated behind the wetting front because the infiltration was lower than the hydraulic conductivity.

A saturated upper boundary condition replaced the measured infiltration flux boundary in a 2-D radial flow model. This resulted in simulated water content profiles that were saturated behind the wetting front. The observed water content profiles were not saturated below 1.2 m. The permeability in this model was decreased from the measured value of 3.28E-11 m^2 to 1.5E-12 m^2 so that the simulated wetting front depths were similar to the observed depths. Even with this lower permeability the simulated infiltration was over four times larger than the observed infiltration at 60.5 h. A second model layer below 1.2 m with a higher permeability was used in the 2-D radial flow model to allow the lower portion of the water content profiles to be unsaturated. The permeability of the soil above 1.2 m was lowered to 5E-13 m^2 to give approximately the right simulated infiltration and the permeability of the second layer was set to 5E-11 m^2 to give the proper saturation below 1.2 m. To have simulated wetting front depths similar to the observed wetting front depths it was necessary to use a lateral to vertical anisotropy ratio of 0.02.

Numerical modeling of a ponded infiltration experiment was used to identify the factors affecting the infiltration processes. Infiltration into this layered desert alluvial sequence was influenced by a washout zone around the borehole casing, lateral flow into the dry soil around the borehole, permeabilities much lower than previously measured values, differences in the hydraulic properties between layers, and anisotropy of the permeability.

REFERENCES

1. U.S. Department of Energy, *Yucca Mountain Site Characterization Plan*, DOE/RW-0199, U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Washington, D.C. Section 8.3.1.2.2.1.2 (1988).

2. Klute, A., *Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. 2nd ed. Agronomy 9*, American Society of Agronomy, Madison, WI (1986).

3. Smith, K.A. and C.E. Mullins, *Soil Analysis: Physical Methods*, Marcel Dekker, Inc., New York, NY (1991).

4. Guertal, W.R., A.L. Flint, L.L. Hofmann, and D.B. Hudson, "Characterization of a desert soil sequence using field experiments and geophysical logging at Yucca Mountain, NV," *Proceedings, International High level Nuclear Waste Conference*, Las Vegas, NV, May 22-26, 1994, American Nuclear Society, La Grange Park, IL (1994).

5. Montazer, P. and W.E. Wilson, "Conceptual hydrologic model of flow in the unsaturated zone, Yucca Mountain, Nevada," *U.S. Geological Survey, Water Resources Investigations Report 84-4345*, Lakewood, CO (1984).

6. Hevesi, J.A., A.L. Flint, and J.D. Istok, "Precipitation estimation in mountainous terrain using multivariate geostatistics. Part II. isohyetal maps," *Journal of Applied Meteorology* 31:677-688 (1992).

7. Hevesi, J.A. and A.L. Flint, "The influence of seasonal climatic variability on shallow infiltration at Yucca Mountain," *Proceedings, International High Level Nuclear Waste Conference*, Las Vegas, NV, April 26-30, 1993, p.122-131, American Nuclear Society, La Grange Park, IL (1993).

8. van Genuchten, M.Th., "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils," *Soil Science Society of America Journal* 44:892-898 (1980).

9. Hofmann, L.L., A.L. Flint, and W.R. Guertal, "Field determination of hydrologic parameters of Yucca Mountain surficial materials," *Proceedings, International High level Nuclear Waste Conference*, Las Vegas, NV, May 22-26,1994, American Nuclear Society, La Grange Park, IL (1994).

10. Pruess, K., "*TOUGH User's Guide*", Lawrence Berkeley Laboratory, University of California, Berkeley, CA., NRC FIN No. A1158, U.S. Nuclear Regulatory Commission, Washington, DC (1987).