FINITE ELEMENT MODEL EVALUATION OF BARRIER CONFIGURATIONS TO REDUCE INFILTRATION INTO WASTE DISPOSAL STRUCTURES: PRELIMINARY RESULTS AND DESIGN CONSIDERATIONS

A. H. Lu
S. J. Phillips
M. R. Adams

Rockwell Hanford Operations
Richland, Washington 99352

ABSTRACT

Barriers to reduce infiltration into waste burial disposal structures (trenches, pits, etc.) may be required to adequately provide waste confinement. The preliminary engineering design of these barriers should consider interrelated barrier performance factors. This paper summarizes preliminary computer simulation activities conducted to further engineering barrier design efforts. Several barrier configurations were conceived and evaluated. Model simulations were conducted for each barrier configuration using a finite element computer code. Results of this preliminary evaluation indicate that barrier configurations, dependent on their morphology and materials, may significantly influence infiltration, flux, drainage, and storage of water through and within waste disposal structures.

INTRODUCTION

Waste materials generated by chemical, nuclear and other producers are typically disposed below the ground surface. Disposal structures may consist of tanks, trenches, pits, injection wells, etc. Geohydrologic transport of potentially hazardous constituents in unacceptable concentrations from these structures is of concern. Of particular concern is: (1) infiltration of meteoric water (rainfall, snowmelt and runoff) through overburden materials into structures and contact with the waste, (2) migration in the partially saturated and saturated geologic media, and (3) subsequent transport to the biosphere, either to the atmosphere through evaporative or transpirative processes or to the ground water by percolation. Several ground surface barriers designed to prevent or reduce infiltration into disposal structures have been constructed at Hanford, Oak Ridge and Savannah River Department of Energy sites. However, the complex mechanisms and processes which govern migration of water under partially saturated conditions have often not been adequately considered during design. Therefore, the barriers may act to not reduce, but rather to enhance contaminant transport. Hence, it is important to consider those factors and their interrelationships which control barrier performance during initial engineering barrier design studies.

This paper discusses initial efforts to use a partially saturated finite element model to evaluate ground surface infiltration barrier performance for preliminary engineering design purposes. A demonstration of a method to evaluate the effect of infiltration barrier configurations under specific initial boundary and environmental conditions will be made. Furthermore, the results will identify further efforts needed to evaluate barrier performance.

MATERIALS AND METHODS

Fine, medium and coarse soils (unconsolidated glaciofluvial sediments) within the textural range of materials typically surrounding waste disposal structures at the Hanford Site, Richland, Washington, were collected and analyzed. Soil moisture retention curves (Fig. 1) were obtained on several samples and values interpolated using computer cubic spline techniques. The saturated hydraulic conductivity of each soil was determined by laboratory analysis and partially saturated hydraulic conductivity values were estimated by the Millington-Quirk method(1) and the results plotted in Fig. 2.

Barrier Configurations

Barriers to reduce or preclude infiltration and water under partially saturated conditions into buried waste materials may prove to be effective in reducing radionuclide transport to the biosphere. Numerous barrier configurations, both surface and subsurface, can be envisioned. Several configurations, ranging from simple to relatively complex, were developed which were amenable to simple finite element grid superposition. The model cases evaluated include: (1) control, (2) impermeable off-flow, (3) impermeable no off-flow, and (4) multilayer. The description for each configuration is given below.

Control

A control barrier configuration was used to serve as a base line for comparison to other barrier configurations. The control configuration consists of 1.0 m of medium textured soil overlying a trench and surrounding undisturbed soil. The undisturbed soil extending laterally and vertically downward from the trench is fine textured. The material in the trench is equivalent in texture to the barrier. The control barrier is similar to the overburden placed over existing burial trenches at the Hanford Site.

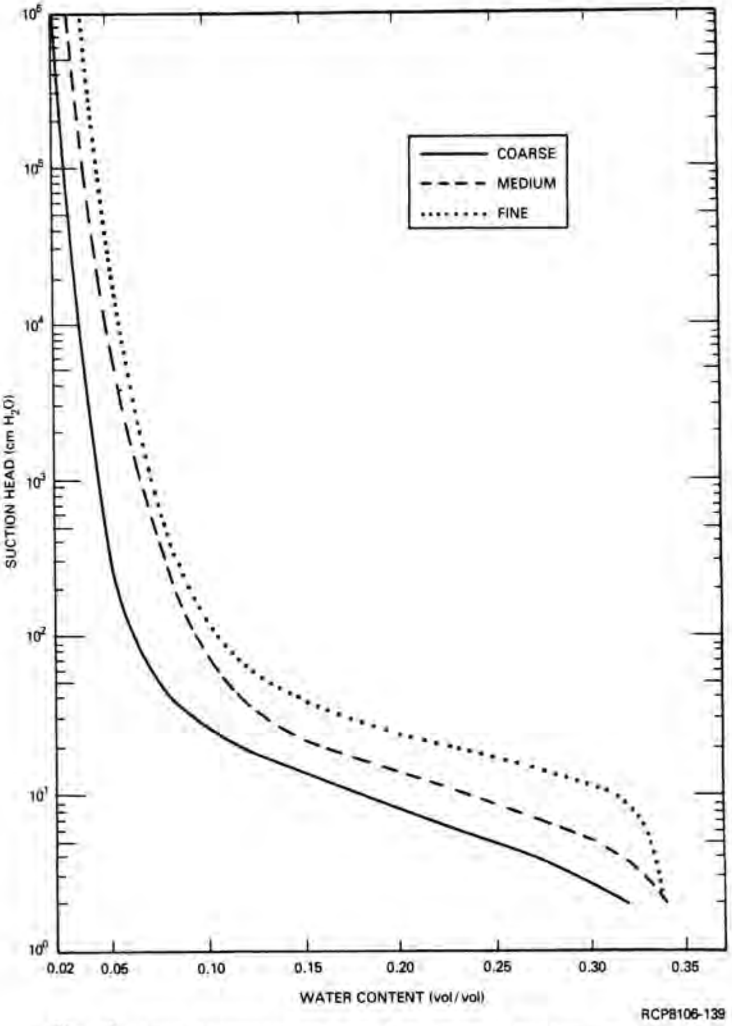


Fig. 1 Soil Retention Curves for Coarse, Medium, and Fine Textured Hypothetical Material Used to Simulate Natural Soil, Barrier Material and Waste/Waste-Matrix Material.

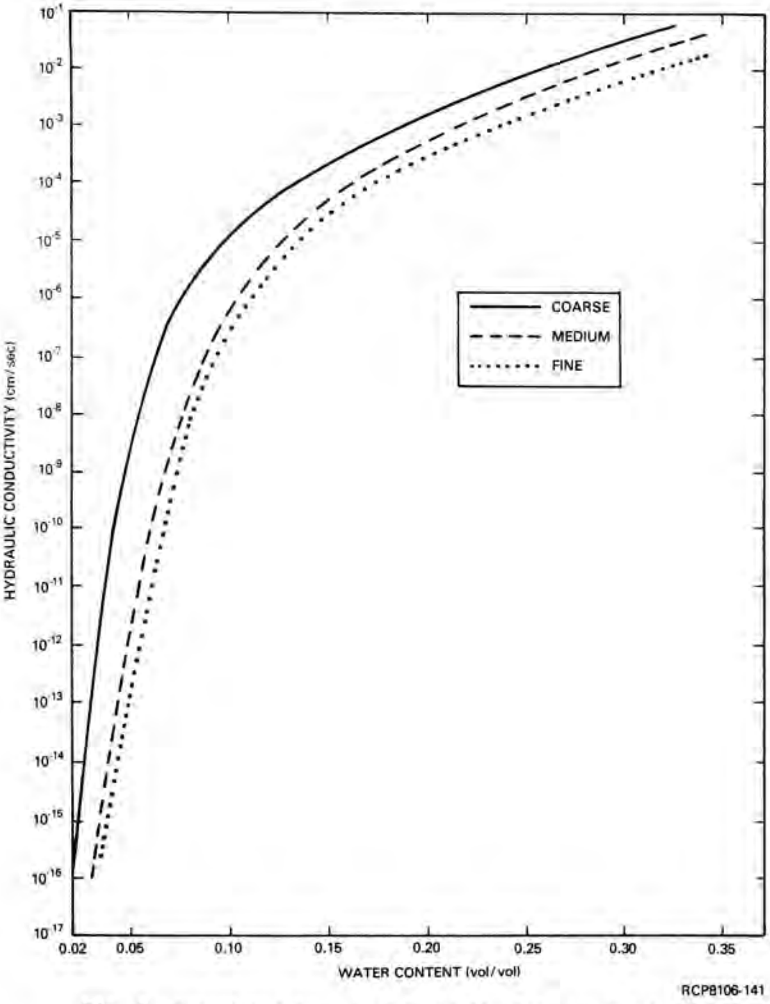


Fig. 2 Calculated Curves of Partially Saturated Hydraulic Conductivity vs. Volumetric Water Content For Coarse, Medium and Fine Soils.

Impermeable (Off-Flow)

The use of impermeable surface barriers to cover waste disposal structures has often been suggested as an effective way to preclude infiltration. Thus, a barrier configuration consisting of an impermeable media (no-flow boundary) above a trench was evaluated. The configuration is equivalent to superimposing a no-flow boundary that extends outward 8.0 m from the center line of the trench. The underlying configuration was the same as the control configuration. The volume of precipitation from the barrier during each rainfall event was summed and simultaneously accumulated as infiltration adjacent to the barrier.

Impermeable (No Off-Flow)

Emplacement of an impermeable surface barrier over a waste disposal structure that would preclude any infiltration either through or around the barrier could prove to be effective. An impermeable barrier with no off-flow into surrounding soil was evaluated. This configuration assumed total evaporation of precipitation from the barrier. The no off-flow impermeable barrier is equivalent to the off-flow barrier except that water incident on the barrier is not permitted to infiltrate beneath the barrier or flow into the surrounding soil.

Multilayer

A barrier consisting of alternating layers of different textured soil overlying a waste disposal trench was evaluated. This configuration utilizes the layering effect to reduce infiltration. This barrier consists of layers of coarse and medium textured soil. The coarse upper layer extends above the surface, whereas, the lower medium and coarse layers extend below the surface. The soil within and external to the trench consists of medium and fine soil, respectively.

Barrier Performance Modeling

The one-and two dimensional computer code was a modified version of a model described by Baca and King(2). The algorithms employ nonlinear Galerkin finite element numerical techniques. Model cases were run on a UNIVAC 1110 computer system.

The model simulations were conducted under simplified conditions using assumptions including: (1) Darcian flow, (2) liquid phase migration only, (3) isothermal conditions, (4) incompressible fluids, (5) partially saturated soil, and (6) cyclic dynamic equilibrium.

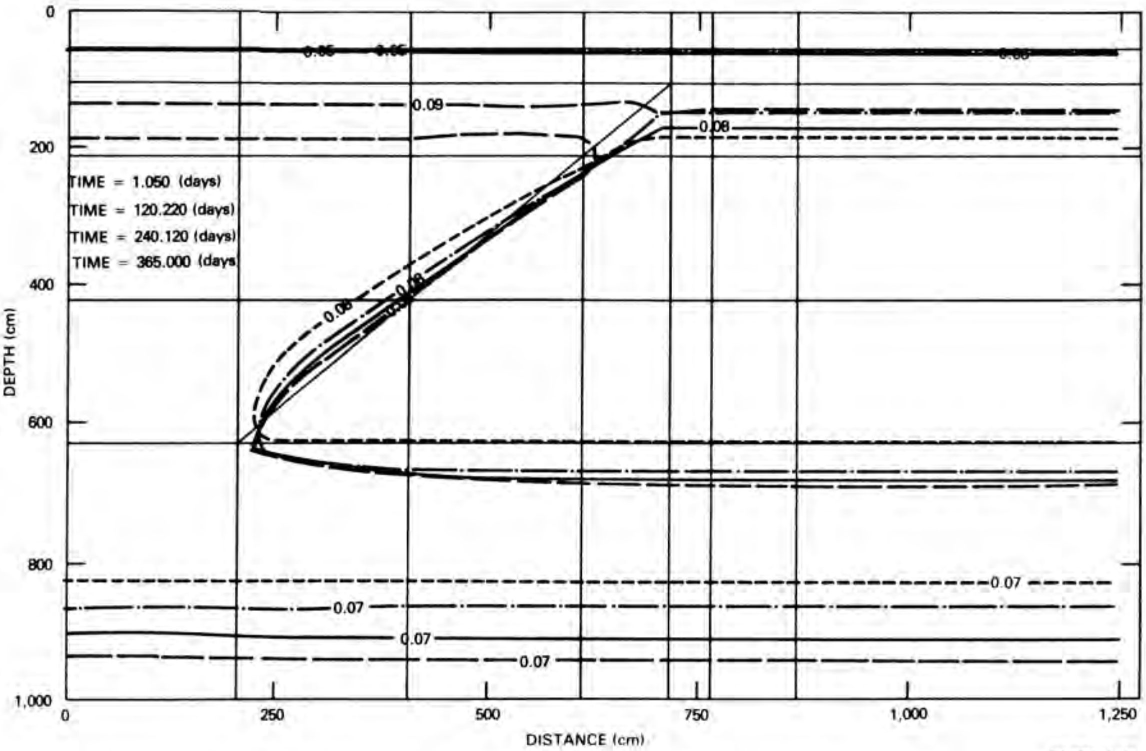
The concept of potential evaporation (PE) was employed and the calculation of PE was incorporated in the code as a negative surface flux. Several methodologies to calculate PE were reviewed(3,4). The Blaney-Criddle method was adopted due to its ease of use where climatic data are sparse.

Simulations were initiated by arbitrarily setting the control configuration volumetric moisture content constant at all depths in the medium textured soil within the trench. The moisture content in the fine textured soil surrounding the trench was set equivalent to typical conditions determined by existing field data. The model simulations were completed for a three-year period. After this three-year period (within which cyclic dynamic equilibrium is reached in near surface soils), the model case base line initial conditions were set (volumetric water vs. depth). Barriers were assumed to be emplaced at day zero of the fourth simulation year. Subsequently, during the fourth year of simulation, detailed results were output for each month. This information was then evaluated by visually comparing isoconcentration lines and moisture storage change vs. depth between each barrier configuration.

RESULTS AND DISCUSSION

Simulation results of several hydrogeologic barrier configurations were compared such that the design performance of each barrier could be systematically evaluated with respect to water infiltration into the trench. The comparisons were not made to determine absolute performance, rather, to determine relative generic performance. For example, if water continuously infiltrates under a barrier and into a trench for one year under cyclic dynamic equilibrium conditions, infiltration would be expected to continue ad infinitum. Hence, a performance trend is established. As a result, engineering design of barriers based on an analytical methodology can proceed. In addition, field experiments and barrier performance monitoring systems can be better designed. Controlled field testing of barriers is the second sequential step in the development and demonstration of proven and effective barriers for waste burial sites.

The performance of each barrier configuration was compared to the control condition (Figs. 3,4). The volumetric water content and change in water storage at any one or any number of points evaluated over several time intervals was used to determine performance. The results of barrier performance are evaluated and discussed herein.



RCP8111-34

Fig. 3 The Volumetric Moisture Content at Approximately 1 (----), 120 (·— ·—), 240 (——) and 365 (— —) Days of Fourth Year of Simulation. The Trench Configuration is for the Control Case.

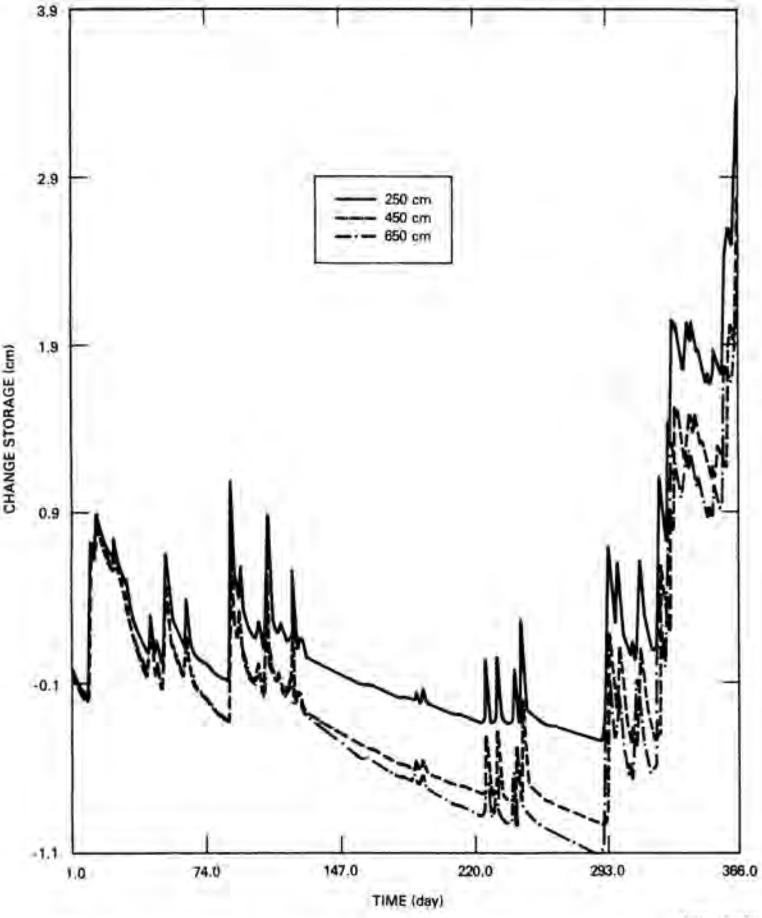


Fig. 4 Change of Storage vs. Time for One Simulation Year for the Control Configuration. Data Plotted for a Vertical Profile 7.0 m from the Center Line of a Trench. The Curves are Plotted at Depth of 2.5, 4.5, and 6.5 m from the Ground Surface.

Control

After a simulation time of three years wherein cyclic dynamic equilibrium was reached in the soil near the ground surface, two-dimensional computer plots of moisture concentration were produced. Plots were graphically drawn from the center line of the hypothetical trench to 12.5 m in the horizontal direction and 10.0 in the vertical. Moisture concentration at approximately 1, 120, 240 and 365 days of the fourth year of simulation, as shown in Fig. 3, overlie the trench configuration. Moisture concentration lines produced by computer plotting are approximate in that they are drawn by interpolation of spatially changing iterative data over a rather coarse finite element grid.

After approximately 120 days, no significant change in lateral or horizontal moisture content is found at a depth between 1.0 m and 9.0 m, albeit, a slight increase in moisture content with depth is shown by the concentration lines at about 6.0 m and 8.0 m. A general movement of moisture downward near the ground surface is shown. For example, the moisture concentration line of 8.0 vol% moves vertically downward about 0.25 m. At a depth below 1.0 m the influence of moisture infiltration through different textural materials (coarse, medium) is shown. Moisture tends to infiltrate or be retained in the fine textured soil exterior to the trench as opposed to that medium textured soil within the trench. As before, the moisture concentration at a depth tends to increase, i.e., at day one, the 0.7 isoconcentration line was at about 8.5 m, and after one-year, the same line was found at a depth of approximately 9.5 m. This supports the concept that moisture under uncontrolled conditions (no barrier) will migrate vertically downward throughout time under the simulated hydrogeologic and meteorological conditions. The moisture content between 2.0 m. and 7.5 m also tends to slightly decrease laterally from the trench to the outlying fine textured soil.

The change of quantity of moisture in the soil between the ground surface and a certain depth, over time, is also evaluated to understand the moisture flow both under control and barrier conditions. The change of moisture storage near the ground surface will be influenced by precipitation, evaporation, liquid saturation, and may be quite variable over one year. At greater depth, however, because storage is calculated from the ground surface vertically to a specific depth, the variation will be reduced. Positive storage change is in the increase of moisture, whereas, negative change of storage is a decrease. From a distance of 7.0 m from the center line of the trench and depths of 2.5, 4.5, and 6.5 m, accumulated moisture storage in the soil for model simulation over year four is shown in Fig. 4. Storage change appears generally negative through the first eight months of the simulation year then trends to positive storage through the remainder of the year. Annual storage change at all depths is of the order of 2.0 cm to 3.0 cm of water.

Impermeable Off-Flow

The impermeable barrier model case with runoff at the edge of the barrier is shown in Fig. 5 for simulation times of one and 365 days for the fourth year. The moisture content below the barrier edge is significantly higher than the surrounding soil. The lateral seepage under the barrier due to capillary force is apparent. The 8.0 vol% isoconcentration line extends inward from the lateral terminus of the barrier with slightly greater moisture concentration outward. The annual change of storage for the impermeable off-flow barrier configuration at 7.0 laterally away from the trench center line is shown in Fig. 6. An increase in storage over that of the control at the 4.5 m and 6.5 m depths is shown.

Impermeable No Off-Flow

An impermeable barrier with no precipitation off-flow shown in Fig. 7, assumes precipitation on the barrier is non-existent (zero flux upper boundary layer condition) or an equivalent mechanism whereby infiltration (ambient) will only enter the geologic media peripheral to the barrier. The plot is essentially the same outward and vertically downward from the barrier as shown in the control case. The annual change of storage at 7.0 m from the trench center line is shown in Fig. 8. At the depth of 2.5 m the change in storage remains normally constant through the simulation year. At lower depths storage change is negative and decreases through the year.

Multilayer

The lines exemplifing equivalent moisture concentration at depth for the multilayer barrier over one simulation year are shown in Fig. 9. Four months after the beginning of the fourth year of simulation a general downward vertical flux may be seen at a depth of about 1.5 m. The influence of the multilayer barrier at the intersection of the ground surface and at its below-surface extremity is also shown in this figure. Very near the ground, exterior to the barrier, the moisture content increases. At a simulation time of 240 days after the beginning of the fourth year, no significant overall change in lateral and vertical moisture concentration is delineated. Under the barrier to a lateral distance of approximately 4.5 m and depth of 2.0 m, the moisture content increases about 1.0 vol%.

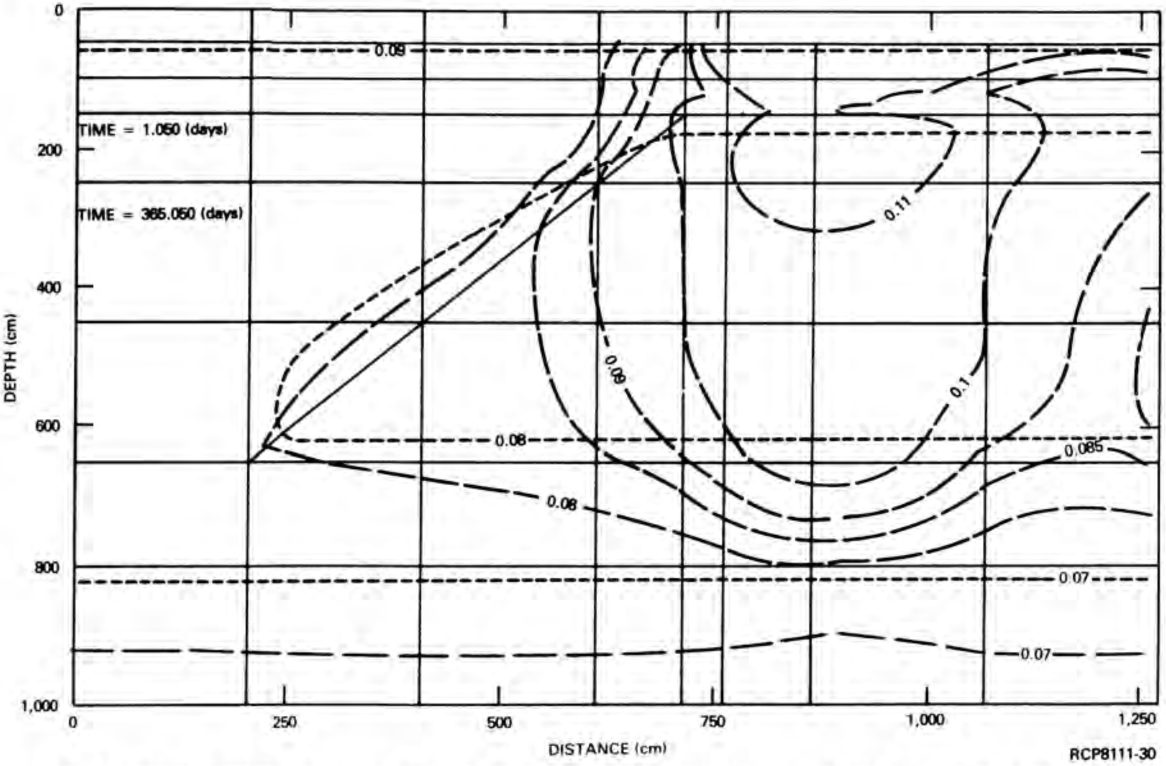


Fig. 5 The Volumetric Moisture Content at Approximately One (----) and 365 (— —) Days of Fourth Year of Simulation. The Trench Configuration is for the Impermeable Barrier Case With Precipitation Runoff at the Barrier Edge.

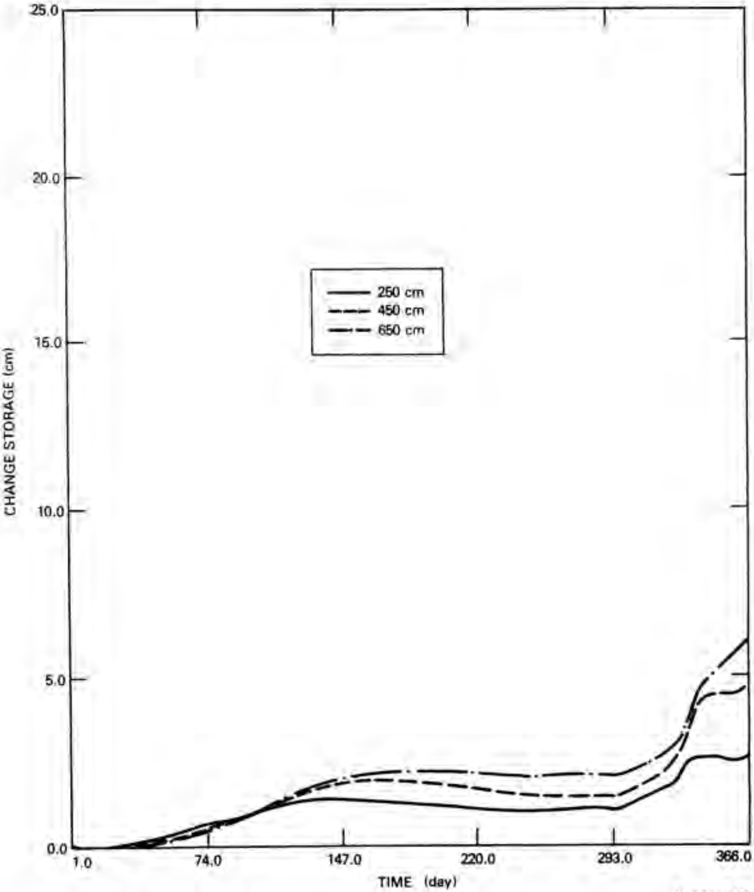


Fig. 6 Change of Storage vs. Time for One Simulation Year For the Impermeable Off-Flow Barrier Configuration. Data Plotted for a Vertical Profile 7.0 m From the Center Line of the Trench. Curves Plotted at Depth of 2.5, 4.5, and 6.5 Meters from the Ground Surface.

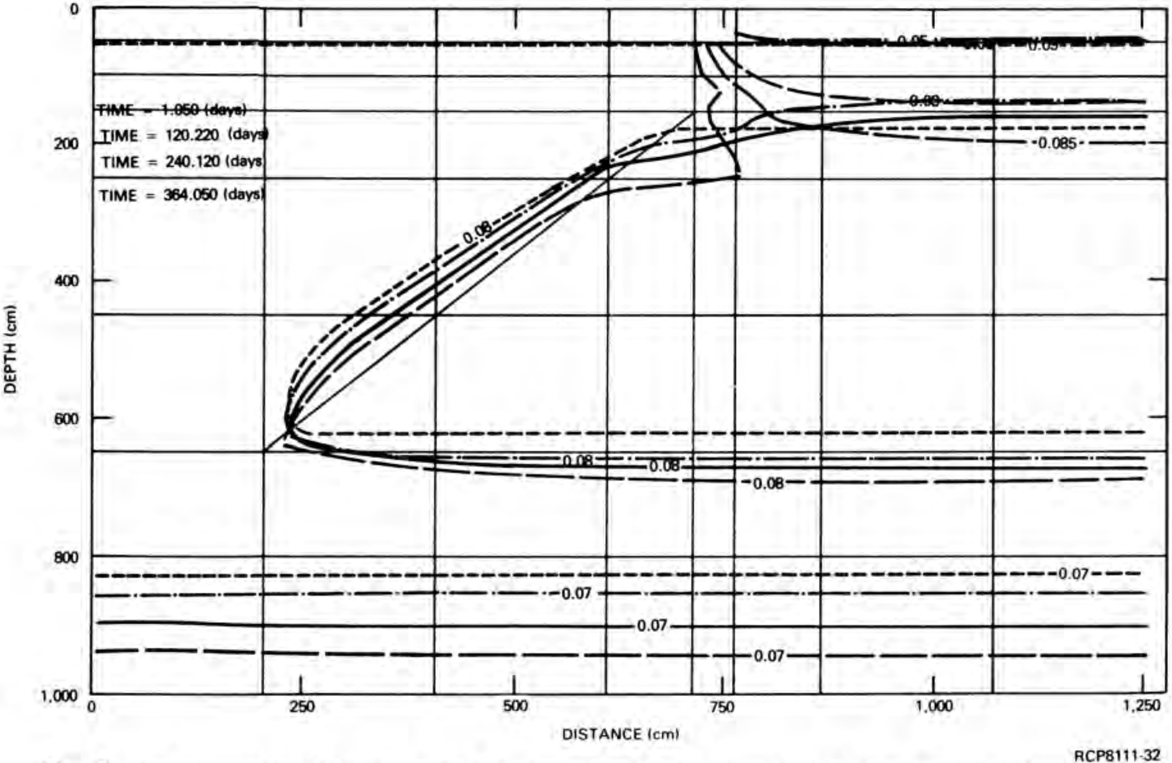


Fig. 7 The Volumetric Moisture Content at Approximately One (----), 120 (·— ·—), 240 (——), and 365 (— —) Days of Fourth Year of Simulation. The Trench Configuration is for the Impermeable Barrier Model Case With no Precipitation Off-Flow.

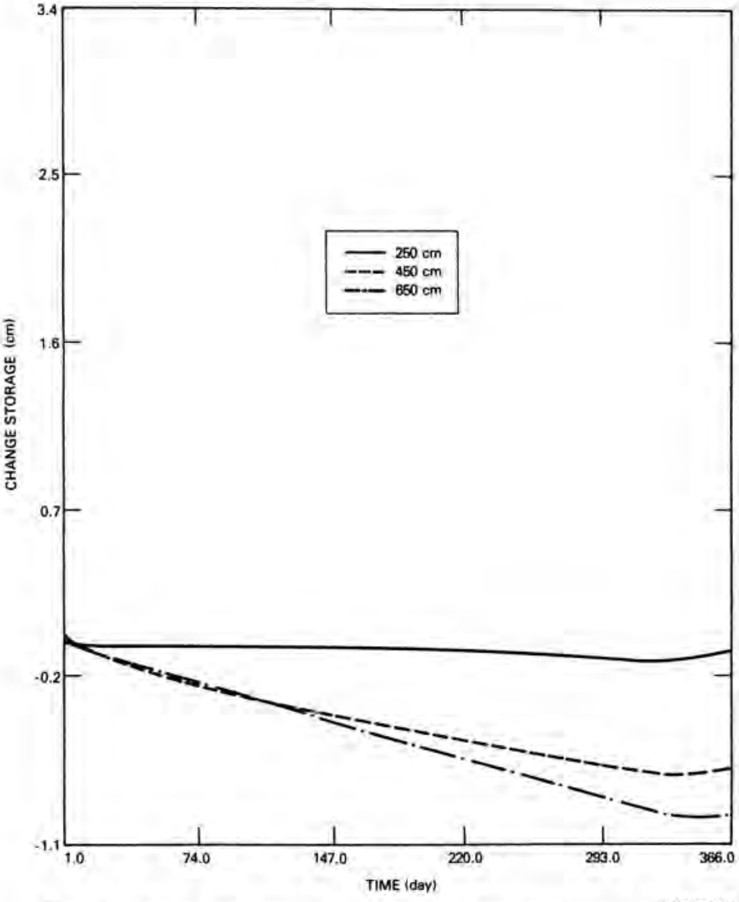
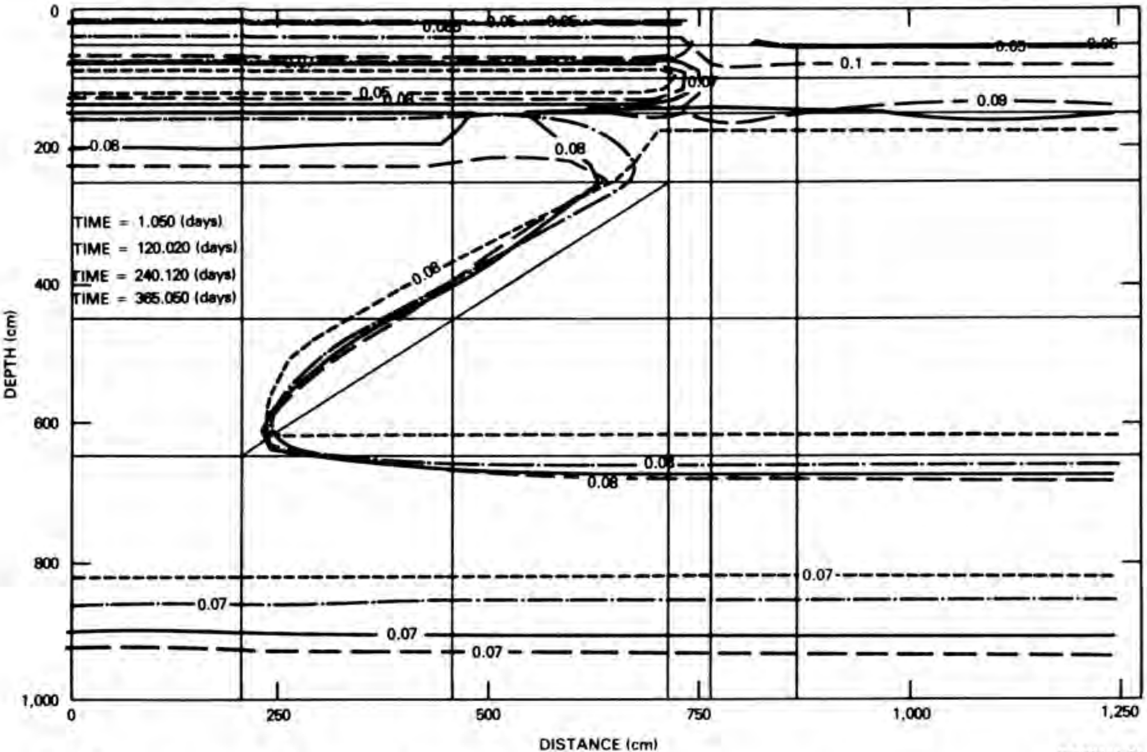


Fig. 8 Change of Storage vs. Time for One Simulation Year For the Impermeable No Off-Flow Barrier Configuration. Data Plotted for a Vertical Profile 7.0 m from the Center Line of the Trench. Curves Plotted at Depth of 2.5, 4.5, and 6.5 m from the Ground Surface.



RCP8111-31

Fig. 9 The Volumetric Moisture Content of Approximately One (----), 120 (·— ·—), 240 (——) and 365 (— —) Days of Fourth Year of Simulation. The Trench Configuration is for the Multilayer Barrier Case.

The change of storage of moisture with depth in the multilayer (not shown) and control configurations are essentially equivalent. No significant changes in moisture migration or storage through the simulation year are noted as compared to the control configuration data. However, significant moisture storage in the barrier layers is shown.

CONCLUSIONS

The design of barriers to mitigate moisture infiltration into waste material must account for complex interrelationships of partially saturated water flow and variable surface boundary layer conditions. Simulation of several barrier configurations has led to a better understanding of barrier performance and criteria for waste disposal sites. The effects of barriers on infiltration at depth vary from almost insignificant in the case of the impermeable barrier with no off-flow, to dramatic for the case of the off-flow impermeable barrier. Multilayer barrier affects infiltration to some degree, albeit, the influence is moderate. Horizontal migration under impermeable barriers with off-flow and increase of moisture storage is explicitly shown. Layering effects tend to mitigate the surface infiltration and influence the direction of subsurface moisture movement.

Of three cases evaluated, the impermeable barrier with off-flow is least desirable. This is due to the potential for moisture to infiltrate under the barrier and into the trench. Thus, barrier configurations causing surface runoff or partial surface runoff should be avoided.

Impermeable barriers with no off-flow were evaluated to compare barrier performance relative to the off-flow case. This type of barrier minimized infiltration and percolation. However, impermeable barriers are not capable of maintaining their integrity over long periods of time. If this type of barrier structurally failed, i.e., if fractures developed, increased infiltration into waste materials would result. The multilayer barrier appears to be desirable in that moisture is retained in the barrier above the waste where it is subject to evapotranspiration. However, simulation results show little reduction of moisture flow over one simulation year. Perhaps, greater simulation time (or substitution of a less permeable layer, such as silt and silty sand for medium sand in barrier layers) would show less percolation with this barrier configuration.

Further modeling and engineering designs will augment the development and demonstration of safe and cost effective waste confinement.

REFERENCES

1. Reisenauer, A. E., 1972, Calculations of Soil Hydraulic Conductivity from Soil-Water Retention Relationships, Pacific Northwest Laboratory, BNWL-1710, Richland, Washington.
2. Baca, R.G., and I. P. King, 1978, Finite Element Models for Simultaneous Heat and Moisture Transport in Unsaturated Soils, RHO-SA-31, Rockwell Hanford Operations, Richland, Washington.
3. Gee, G. W., and C. S. Simmons, 1979, Characterization of the Hanford 300 Burial Grounds, Task III - Fluid Transport and Modeling, PNL-2921, Pacific Northwest Laboratory, Richland, Washington.
4. Gupta, S. K., et al., 1978, "Field Simulation of Soil Water Movement with Crop Water Extraction," Water Science and Engineering Papers, No. 4013, University of California, Davis.