WASTE MIGRATION UNDER UNSATURATED FLOW CONDITIONS

G. G. Eichholz, F. N. de Sousa, J. Whang and D. Y Suh
Nuclear Engineering and Health Physics Program
Georgia Institute of Technology
Atlanta, Georgia 30332

ABSTRACT

Most shallow waste burial sites in the U.S. are located in areas of low or intermittent rainfall. However, most predictive models for shallow trench disposal sites are based on assumptions of saturated soil conditions. Tests have been performed, both in the laboratory and the field, to study water flow regime and moisture concentrations in the region surrounding any loosely distributed waste material, that occur under unsaturated conditions. A two-dimensional computer model has been developed to account for unsaturated flow through or around the waste material and for the consequent reduction in the leach source term.

INTRODUCTION

A great deal of effort is currently being devoted to the design of future low-level waste burial facilities. These designs are aimed to avoid the kind of problems that have arisen in older facilities, where often unconsolidated or liquid waste materials were buried and where the use of an impermeable base material led to trench flooding or overflow. In order to demonstrate phenomena, that may arise in a well-monitored site and to provide benchmark data for effluent models, special lysimeter tests have been conducted, at Hanford to simulate arid-zone conditions[1] and at Savannah River for humid conditions[2,3], respectively. At both locations the waste material will normally find itself in an unsaturated zone, a situation that has not been reflected in most calculational models that are used to predict environmental impact. The relevant federal regulations, 10CFR61, postulate waste placement well above the water table, but they do not clearly eliminate the possibility of flooding of the trench. To counteract this possibility, increasing emphasis has been placed on the design of a long-lasting impermeable trench cap[4,5].

In the mean time, it is important to develop realistic computer models, capable of handling unsaturated flow conditions and non-vertical flow, at depth, in the waste horizon, in contrast to the surface layer for which a number of models have been formulated[1,6,7]. To represent humid-site conditions, extensive studies have been conducted[8,9,10]. Reference 10, in particular, contains much of the relevant literature. The impact calculations in that Statement are more thoroughly developed for the airborne pathway than the liquid one, which is primarily based on the AQUAMAN code[11] and the ORNL methodology[12]. These models typically assume a uniform geological medium surrounding the waste, saturated flow conditions, and do not readily accommodate the special conditions associated with a back-filled near-surface trench in a humid climate. Beyond that, many of the problems associated with the incorporation of unsaturated flow conditions are generic in nature. Lysimeter tests[2,3] serve as thoroughly monitored benchmark test systems. The main thrust of this paper then is to review some experimental tests that have been done to explore unsaturated flow conditions and some model development on a two-dimensional model intended to simulate migration of waste material through unsaturated soil.

EXPERIMENTAL TESTS

Moisture Fluctuations in Subsurface Soil

Near the surface, flow conditions are largely determined by the balance of evaporation, evapotranspiration and gravitational effects, with only 15-28% of precipitation infiltrating into deeper layers. As a consequence, many models pay particular attention to the surface conditions[1,6]; in the Southeastern coastal plain, for instance, heavy showers may result in considerable surface run-off, but only low infiltration if the surface layer is already near saturation[13]. Below that layer, moisture concentrations are governed by gravitational forces downwards, counteracted by surface tension or capillarity effects. These depend on pore size, surface area, and surface properties (e.g., wettability) of exposed minerals and to a large extent can be described in terms of the hydraulic conductivity.

Drainage Tests

To evaluate the dynamic response of trench soil to periodic or uneven episodes of infiltration, several tests were run on soil columns and a large test bed to determine some relevant hydrological properties. The soils used consisted of two types of washed sand, two clayey soils, #1 and #2, and an intermediate soil mixture, "FP soil". The basic properties and composition of these materials are listed in Table I.

Moisture concentrations for each of these materials were measured by means of electric conductivity probes, whose construction and calibration have been described elsewhere[14]. One of the principal properties of interest is the residual water content, that is, the minimum moisture content to which an initially saturated soil will drain to. Since this level is controlled entirely by capillarity forces, it depends primarily on average pore size, as well as on surface properties. Table II shows the residual water content for screened fractions of consolidated sand. Table III compares the residual water content of the sands and the soils #1 and #2.

One of the consequences of the capillarity effect, also, is the retention of moisture due to surface tension at any major interface. This applies particularly, whenever a dense soil layer lies above a cavity, such as a waste volume or a gravel bed. If the interface is sloped, this effect can lead to substantial lateral water movement.

TABLE I

Soil Properties

Soil Type	Bulk Density (g/cm^3)	Porosity	Sand Fraction (%)	Silt Fraction (%)	Clay Fraction (%)	Saturated Hydraulic Conductivity (cm/day)
Rollo Sand	1.40	0.472	98.9	1.1	0.0	-
G. T. Sand	1.38	0.479	97.4	2.6	0.0	2000
Soil #1	1.24	0.32	62.0	9.0	29.0	30
Soil #2	1.20	0.547	56.0	4.0	40.0	60
FP Soil	1.42	0.466	73.4	15.5	11.4	49

TABLE II

Residual Water Content of Sand

Mesh Size	Residual Water Content (%)
14-16	0.50
16-20	0.16
25-30	0.18
30-55	0.25
40-50	0.33
50-60	0.61

TABLE III

Residual Water Content

Soil Type	Residual Water Content
Rollo Sand	0.89 %
G. T. Sand	1.59
Soil #1	10.51
Soil #2	17.37

Table IV records measurements of the wet layers at the open bottom ends of columns. For the soils this retained wet layer was substantial and even after 30 days there was some continued water loss.

TABLE IV

Residual Wet Layers at Open Ends
(30 Days)

Material	3 Cm Column	1.2 Cm Column
Rollo Sand	2 cm	2 cm
G. T. Sand	8	2
Soil #1	14	2
Soil #2	16	2

Similar observations have been carried out on the test bed for Rollo sand, G. T. sand and FP soil. The observed minimum wet base layers were found to be 15 cm high for the GT sand and 30 cm for the FP soil.

Drainage rates have been obtained in tests on laboratory columns and a larger, 1.2 m-high test bed. These tests are of value to establish moisture profiles around any waste-containing zone and to obtain rate constants for water flow and water recharge. Figure 1 illustrates one set of drainage curves for Rollo sand. For sands where initially drainage is fairly rapid, the gravitational component and the suction component give rise to readily resolved rate constants. For the soils, where water retention is higher, these two effects are less easily resolved and an average drainage coefficient must be determined. This determination is important to provide input into any calculational model that will describe transient phenomena in the trench soil.

Flow Diversion Tests

Since lysimeter experiments are a principal source of input data for any computer simulation, it is important for the computer model to be able to describe the lysimeter situation. The main difference between large trenches and the lysimeters lies in the disposition of the wastes. In the trenches, they can be assumed to form a uniform, if somewhat inhomogeneous layer, whereas in the lysimeters the waste lies in a lumped form in the center of a cylindrical system[15] well away from the walls. Despite, or because, of the irregular nature of the interface between the waste material and backfilled soil above it, in the trenches the overlying soil is likely to retain moisture that, under saturated conditions, will seep through the waste layer and may perch there if the underlying material is very poorly permeable.

In the lysimeters the situation is different. The waste forms a distinct, roughly cylindrical volume of undefined permeability and it is not intuitively obvious if infiltrated water will necessarily pass through the waste volume or around it nor, whether it would attract water from the surrounding soil that might follow a less resistive path. Compression tests have been conducted on assorted laboratory waste materials, similar to those loaded into lysimeters. In four separate tests, it was found that under pressures of over 13 lb/sq. in., well above the estimated soil load, the waste volume was compressed to one third of its initial height and its permeability to air flow was, roughly halved. This certainly would not constitute a significant barrier to throughflow.

Test on flow patterns through and around the compressed waste material have been performed in the configurations shown in Fig. 2 for sand and FP soil. Moisture values were monitored with electrical conductivity probes. The results showed that, for sand, no lateral movement into the waste volume occurred. The wick effect above the waste results in water collection above the waste until saturation is reached. At that point, water may flow into the waste and drain out very rapidly. If the interface between soil and waste is sloped, the water may be diverted through the wick layer around the waste. This effect becomes more pronounced for less permeable soil and is under study at present.

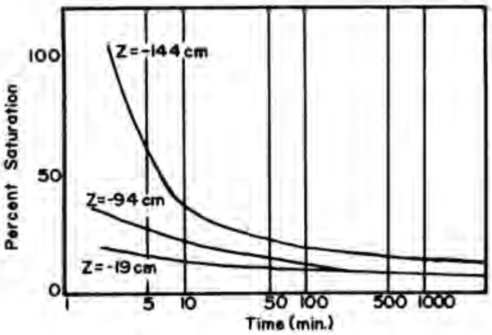

Fig. 1. Drainage Curves: Rollo Sand.

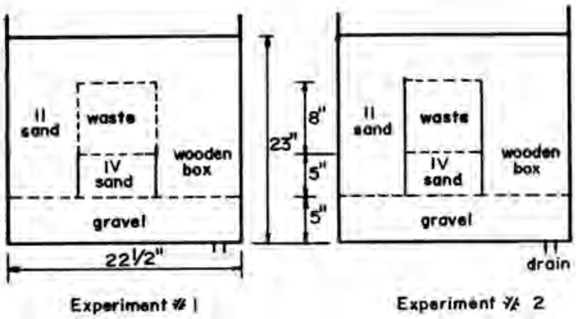

Fig. 2. Diagram of Flow Diversion Experiments.

MODEL DEVELOPMENT

To provide an adequate description of flow and leach conditions in a disposal trench under time-varying, unsaturated flow conditions, a model has been developed that attempts to incorporate the various rate-determining steps shown in Fig. 3. The model is a two-dimensional finite-element, one consisting of a combined system for the solution of the flow equations and transport equations. The general approach follows Van Genuchten[16]. Figure 4 presents a flow diagram for the model. Details on the model development have been presented by de Sousa[14].

For initial validation, the model has been used to reproduce the results of Van Genuchten's one-dimensional model. Good agreement was obtained in every case. As a next stage, water infiltration into the test bed was simulated. Figure 5 shows the movement of the water profile with time as measured and as calculated. It is evident that good agreement was obtained.

Separate tests are under way to measure the hysteresis between wetting and drying episodes and it is hoped that the model will prove capable of reproducing such conditions.

CONCLUSIONS

The accuracy of predictions for radiological impact of future low-level waste disposal sites depends to a large extent on the ability of the impact models to represent realistic flow scenarios. Both arid- and humid- zone disposal sites will undergo unsaturated flow conditions most of the time, if they are properly designed. For moderately permeable soils, this means that water concentrations surrounding the waste are lower than predicted in saturated-flow models and waste leaching conditions are different. Subsequent migration and soil retardation effects will also be reduced and the work described here has shown that flow condition may be more complex than in generally assumed.

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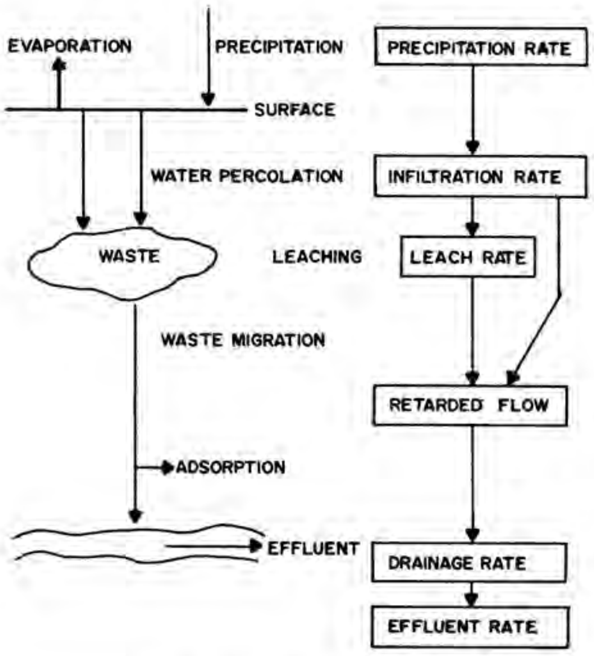

Fig. 3. Migration Model Diagram.

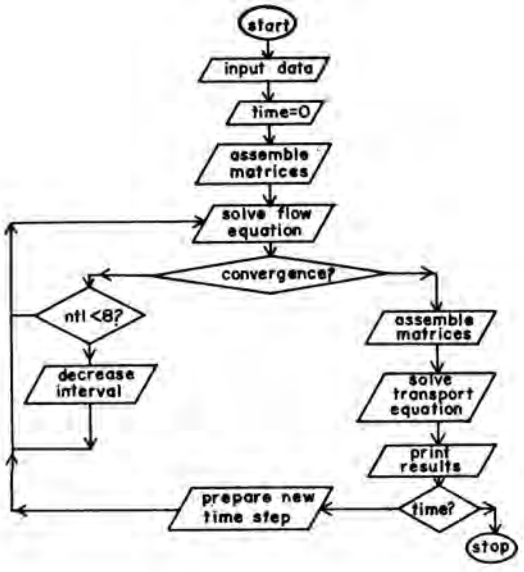

Fig. 4. Flow Diagram for the Calculational Model.

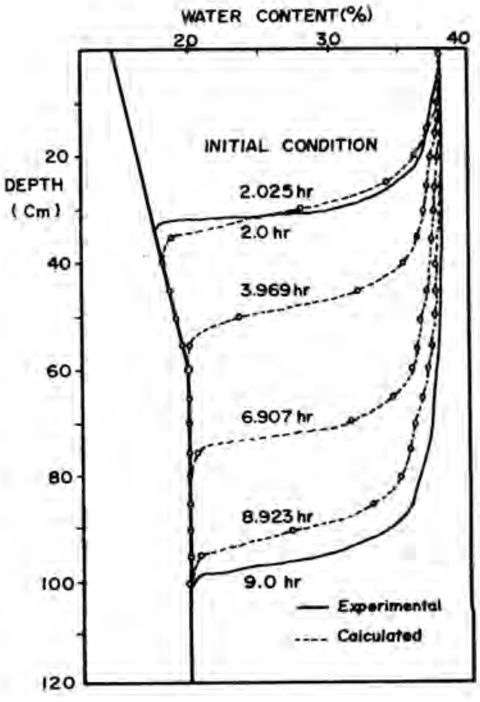

Fig. 5. Water Infiltration: Comparison of Experimental and Calculated Results.

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