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FINITE ELEMENT ANALYSIS OF UNSATURATED FLOW THROUGH SOLID WASTE MATERIALS

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ABSTRACT

The disposal of solid waste materials produced by coal-burning utilities requires a detailed environmental impact assessment. This paper illustrates how numerical analysis can be used as part of the overall design and licensing process to assess the impact on ground water of leachates emitted by a waste pile. The results pertain to the analysis of saturated-unsaturated flow through the solid waste and to a parametric study evaluating the sensitivity of the flow characteristics to various input parameters.

INTRODUCTION

The disposal of solid waste materials produced at electric generating stations in the United States requires a comprehensive program of data collection, testing, and analysis in order to comply with federal and state regulations. A typical 600 MW station burning bituminous coal generates approximately 500,000 tons of waste products per year which may have a considerable environmental impact if proper measures are not taken. One method of waste disposal consists of storing the waste above the ground at specially prepared sites. Such landfills are built in stages which are placed sequentially over the thirty-year life of a typical plant, covering nearly 700,000 m^2 (172 acres) with an average height of 12 m (40 ft). Site preparation consists of determining the ground-water levels, removing vegetation and trees from the disposal grounds, filling low-lying areas with soil, and constructing dikes and sediment ponds to control surface-water runoff. Site preparation may also include procedures to control standing water and insure that the solid waste is kept on dry ground. After the site preparation has been completed, the waste is spread, compacted by a bulldozer,

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and sloped to maintain a proper drainage. When the solid waste pile reaches the final grade, it is covered with an impermeable layer to prevent infiltration from precipitation. The site preparation and solid waste disposal procedures are summarized in Figure 1. A typical waste pile configuration is shown in Figure 2.

This paper illustrates how numerical analysis can be used as part of the overall design and licensing process to assess the impact on ground water of leachates emitted by a waste pile. The results pertain to the analysis of saturated-unsaturated flow through the solid waste and to a parametric study evaluating the sensitivity of the flow characteristics to various input parameters.

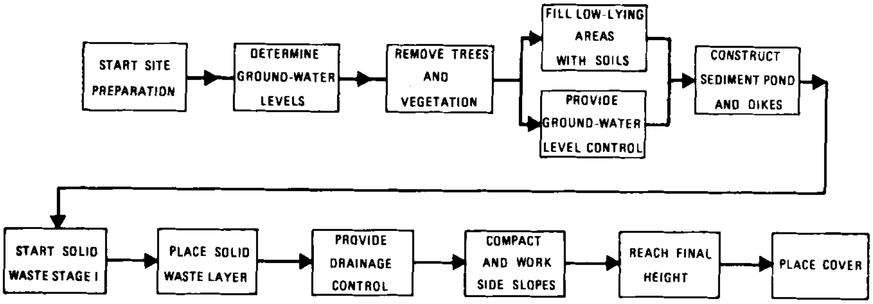
FINITE ELEMENT ANALYSIS

The disposal pile was idealized as a 13 meter-(44 foot-) high, two-dimensional column of unsaturated porous material, discretized into 150 quadrilateral elements with 302 nodes; the nodal spacings ranged between 2.5 cm and 15 cm. The following boundary conditions were assumed for this system: the top of the column was subjected to a specified flux, Q, the sides of the column were assumed to be no-flow boundaries, and the head was held constant at nodes along the base of the column. This constant-head boundary condition only approximates the field conditions. Since in actual practice the solid waste pile is erected above a layer of fill material which acts as a buffer zone between the solid waste and the ground-water table, the moisture content and pressure head at the base of the column are unknown and are time-dependent. However, because the degree of saturation of the fill material is approximately constant, and because experience has shown that changes in the column propagate at a slow rate, the pressure head at the base can be treated as a constant without introducing significant errors in the results. The influence of this boundary condition will be examined in the sensitivity analysis discussed below.

The initial conditions used in the simulations are shown in Figure 3. A discontinuous moisture distribution was chosen to approximate conditions resulting from the specific waste disposal methods used at the site. The influence of these initial conditions will also be examined below.

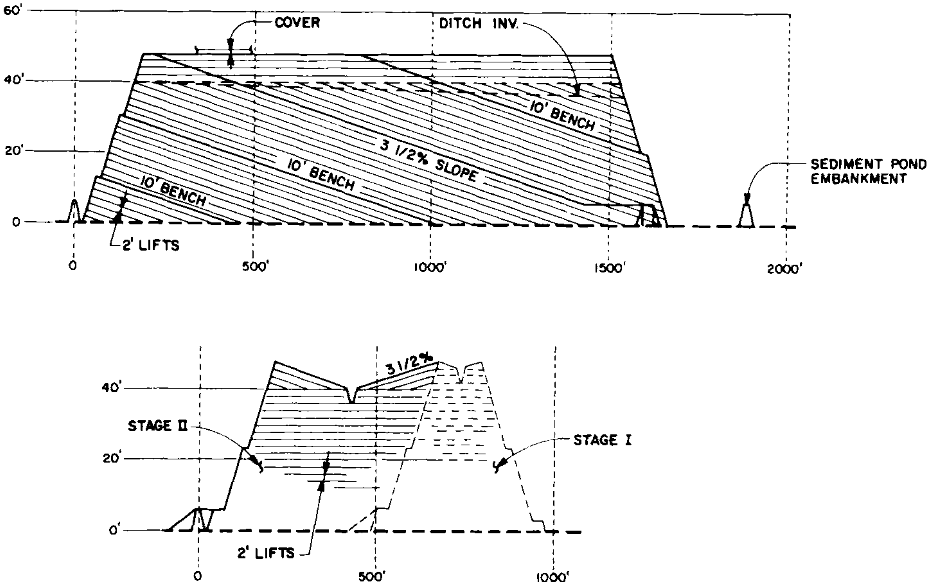
Variations of moisture content with pressure head were available from laboratory tests. Figure 4 shows the characteristic curves $\theta(\psi)$ obtained on different samples.

Variations of hydraulic conductivity with moisture content for typical waste materials were available, the values of saturated hydraulic conductivity



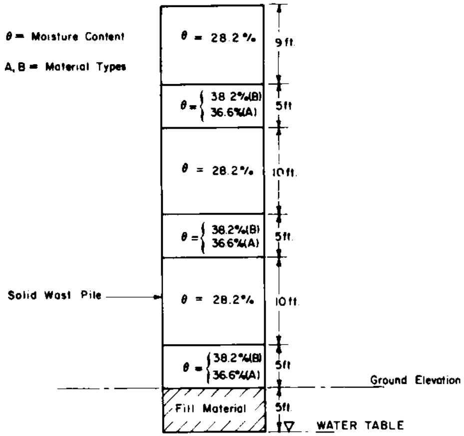
SIMPLIFIED FLOW DIAGRAM OF SOLID WASTE DISPOSAL PROCEDURES

FIGURE 1



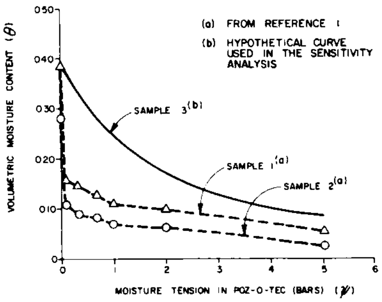
TYPICAL WASTE PILE ELEVATION

FIGURE 2



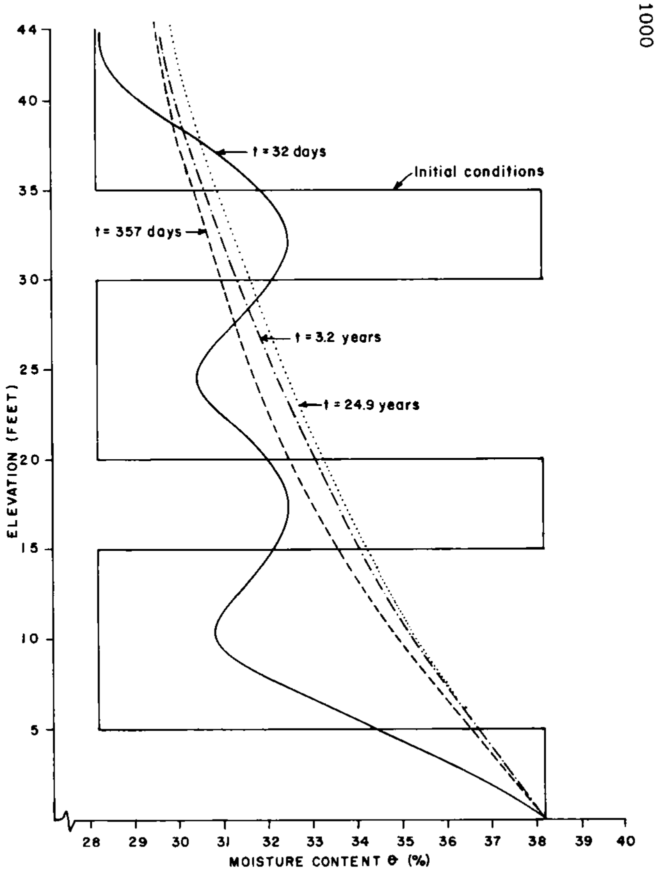
INITIAL CONDITIONS

FIGURE 3



MOISTURE CHARACTERISTIC CURVES

FIGURE 4



MOISTURE CONTENT DISTRIBUTION WITHOUT INFILTRATION

FIGURE 5

ranging from 10^{-4} cm/sec to 10^{-7} cm/sec, depending on the waste product and on the fixation process.

The leachate flow rate at the base of the solid waste pile was calculated using the two-dimensional Galerkin-finite element model developed by Reeves and Duguid (2) which was adapted to the UNIVAC 1110. A single precision version of this program was used since tests have indicated that there is no significant difference between the single- and double-precision results; the savings in core storage, however, are considerable.

RESULTS

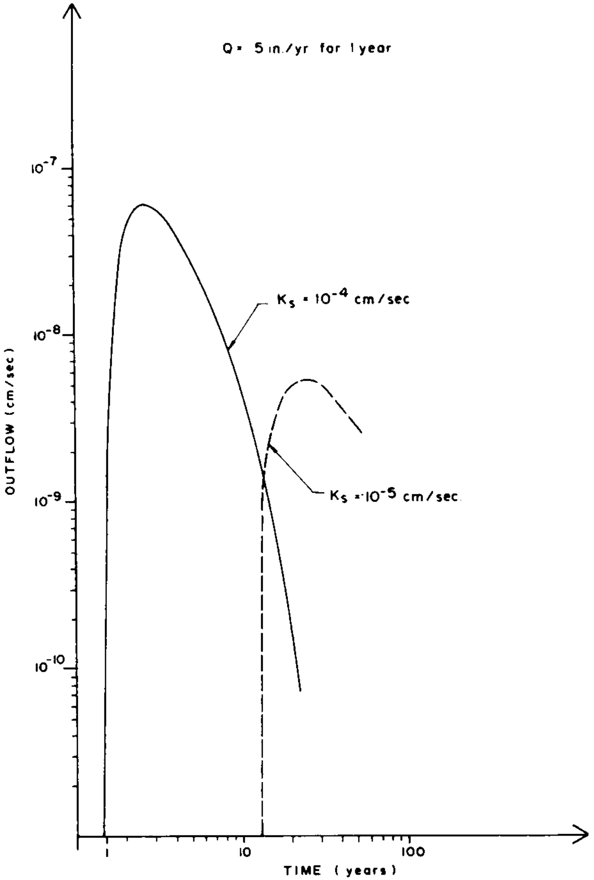
Simulations were performed for differing permeabilities, infiltration rates, initial conditions, and boundary conditions to obtain conservative estimates of the system's behavior. The most significant results are given below.

1. Influence of Infiltration rate. The results obtained for Mix B (K_s = 10^{-4} cm/sec), assuming that there would be no infiltration through the upper boundary of the solid waste pile (Q=0), indicate that there is first a re-distribution of moisture inside the solid waste pile. After approximately 20 years, the model indicates an outward flow which, however, is too small to be significant. The model was run until 25 years and no changes in these conditions were observed. Moisture content distributions inside the column at various times are shown in Figure 5.

The effect of water influx at the top of the solid waste pile was studied for various materials. For materials whose saturated value of hydraulic conductivity, K_s, is larger than the infiltration rate, Q, it was found that the infiltration rate controls the quantity of leachates exiting the waste pile and affects also, to some extent, the time at which this outflow appears.

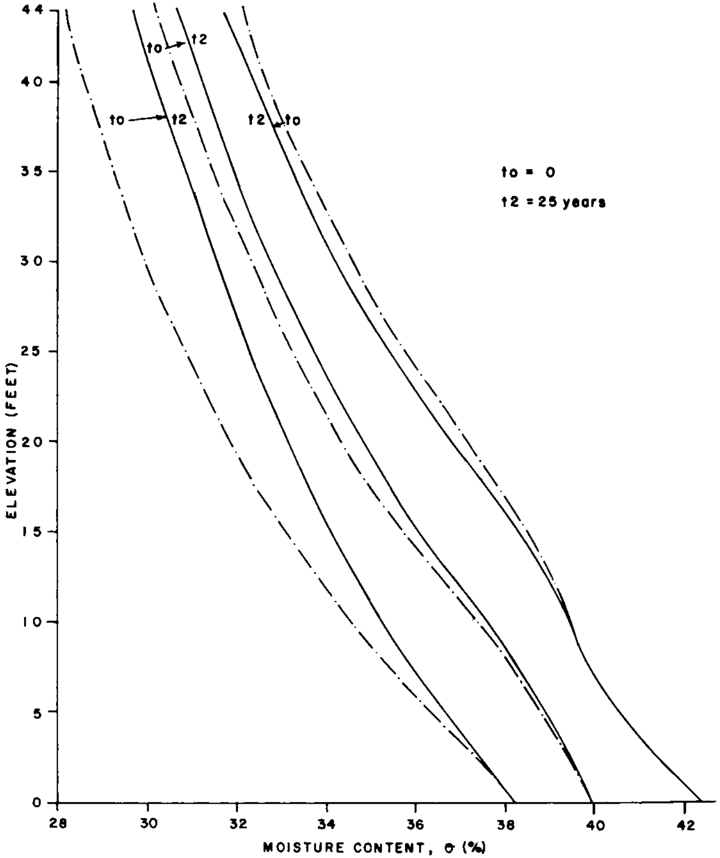
However, for cases where Q is larger than K_s the leach rate reached a steady state which is controlled by K_s and no longer by the magnitude of the infiltration rate. No ponding was allowed in these simulations.

2. Influence of Permeability. The influence of the permeability of the waste materials was studied for zero and non-zero infiltration rates. For a constant infiltration rate of finite duration, the value of the saturated hydraulic conductivity was found to have a large effect on both the time at which leachates exit the waste pile and the maximum outflow. For a fixed infiltration rate of a one-year duration, the water travel time through the waste pile was approximately ten times larger in the case of Mix B than in the case of Mix A (Figure 6).



OUTFLOW FROM SOLID WASTE PILE

FIGURE 6



EFFECT OF BOUNDARY CONDITIONS

FIGURE 7

The effect of a low-permeability layer was investigated by assuming that the last three feet of the solid waste pile consisted of a material having a saturated hydraulic conductivity equal to 10^{-9} cm/sec, a value typical of clay materials. The remainder of the column was assumed to be Mix A. An infiltration rate Q less than K_s was specified for one year. The results indicate that there is essentially no flow through the low-permeability layer.

3. Influence of the θ (ψ) and K (ψ) Characteristic Curves. The hypothetical curve labelled "sample 3" in Figure 4 was used to represent the variations of moisture content with pressure. In this case, the saturated value of θ is identical to that of the base case (θ_s = 0.389) but the moisture content decreases in a more gentle manner than in the base case (Sample 1 in Figure 4). The results obtained in this case were not significantly different from those of a reference case. Thus the actual shape of the θ(ψ) curve is not an important parameter in this analysis.

The influence of the shape of the K (ψ) curve was also studied. For this analysis, the unsaturated properties of a material having a saturated hydraulic conductivity similar to that of Mix B were obtained from the literature (1) and used in lieu of the experimental data. The steady-state results were found to be similar considering the level of accuracy appropriate to engineering applications.

4. Influence of the Initial and Boundary Conditions.
The Reeves-Duguid Model solves the unsaturated flow equation with the pressure head as the unknown variable. This implies that the initial conditions must be specified in terms of pressure; consequently, the moisture distribution in Figure 3 must be transformed into an equivalent pressure distribution using the θ (ψ) data. For the specific materials under consideration, large step changes in pressure head correspond to the specified changes in moisture content; namely, changes from 28.2% to 36.6% or 38.2% in moisture content in Mixes A and B correspond to increases in pressure head of the order of 17 to 19 m (from -2611 cm to -862 cm in Mix A and from -2611 cm to -696 cm in Mix B). Such abrupt pressure changes make the problem numerically difficult to solve; moreover, it is likely that such a sharp interface does not exist in the actual solid waste pile and that errors are introduced in field measurements of the initial moisture content.

To evaluate the effect of initial conditions, a new simulation was made in which the pressure head varied linearly from -696 cm at the bottom of the column to -2611 cm at the top of the column. The corresponding moisture content distribution varied smoothly from θ = 28.3% to θ = 38.2%. When the results are compared with those obtained with the step function input, it is found that moisture distributions at 25 years are almost identical. It appears, therefore, that if one is mainly concerned with the long-term results, the step function distribution introduces an unnecessary complexity in the model.

The effect of differing boundary conditions was studied by comparing the results obtained using constant moisture contents successively equal to 38.2%, 40%, and 42% at the bottom of the solid waste pile. In all cases the pressure head varied linearly inside the pile, yielding moisture contents equal to 28.3%, 30%, and 32% at the top of the pile, respectively. The results, shown in Figure 7, indicate that changes from the initial moisture distribution are more pronounced in cases of drier initial conditions. Moreover, in the two cases where θ equals 38.2% and 40% at the base, the column gains water while the reverse is true when θ equals 42% at the base. It can thus be assumed that there exists a critical moisture content of the lower layer, above which some outflow from the pile would occur. This critical value is between 40% and 42%; 40% represents a conservative estimate.

CONCLUSIONS

This study indicates that the saturated value of hydraulic conductivity, K_s, of the solid waste materials is an essential parameter controlling both the travel time of the water through the system (and thus the time at which leachates exit the waste pile), and the steady-state leach rate. The practical consequence of such a conclusion is that a detailed laboratory and field experimental program must be developed to provide a close estimate of K_s, possibly within half an order of magnitude. The magnitude and duration of inflow are also important and must be determined by a site-specific water-budget analysis.

The analysis of differing initial and boundary conditions shows that the model is more sensitive to the moisture content of the bottom layer (assumed constant) than to the specific initial distribution within the solid waste pile.

This study also indicates that the use of numerical models to evaluate saturated-unsaturated flow in solid waste materials is applicable even if data on properties of the unsaturated material are scarce. A catalogue of properties such as the one compiled by Mualem (1) is invaluable, and more effort should be directed to assembling experimental data from various researchers. Using numerical techniques in a parametric study serves to bound the results, which is often required in the licensing process, and to direct data gathering efforts toward the essential parameters.

The present study is only one component in the overall assessment of the impact of solid waste disposal. Figure 8, which is adapted from Reference 3, shows the flow diagram of a comprehensive environmental impact analysis of solid waste disposal. There are at least two other areas for which ground-water flow models have potential applications, namely, ground-water dispersion and immersion. Ground water dispersion refers to the transport of leachates from the waste pile through the aquifer. A two-dimensional areal model including the effects of hydrodynamic dispersion, molecular diffusion, and ion exchange is appropriate in this case. The input data required are the aquifer permeability and porosity, dispersivity, adsorption coefficients, and recharge and discharge areas.

An immersion analysis may also be required if the waste disposal site is in an area where settlement or seasonal fluctuations in the water table cause contact between the ground water and the waste pile. If the leachates exit the bottom of the waste disposal pile, then the impact of immersion may not be significant; however, if the leachates do not exit the waste pile or if their quantity is relatively small, then the immersion analysis is an important addition to the dispersion analysis.

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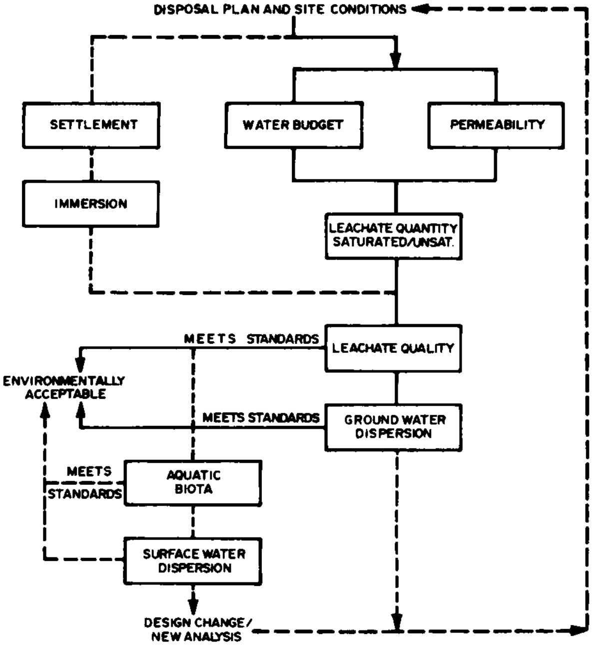

ANALYSIS FLOW DIAGRAM FOR UTILITY WASTE DISPOSAL

FIGURE 8