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# Project Summary

# Verification of the Lateral Drainage Component of the HELP Model Using Physical Models

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**The study described was conducted to verify the Hydrologic Evaluation of Landfill Performance (HELP) computer model using existing field data from a total of 20 landfill cells at 7 sites in the United States. Simulations using the HELP model were run to compare the predicted water balance with the measured water balance. Comparisons were made for runoff, evapotranspiration, lateral drainage to collection systems and percolation through liners. The report also presents a sensitivity analysis of the HELP model input parameters.**

***This Project Summary was developed by EPA's Hazardous Waste Engineering Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).***

## Purpose and Scope

This study was conducted to test and verify the liquid management technology for lateral subsurface drainage in covers and leachate collection systems. The specific objective was to verify the lateral drainage component of the Hydrologic Evaluation of Landfill Performance (HELP) Model and other regulatory and technical guidance, provisions and procedures developed by the U.S. Environmental Protection Agency (USEPA).

The HELP model is a computer model that generates water budgets for a landfill by performing a daily sequential simulation of water movement into, through and out of the landfill. The model produces estimates of depths of saturation and volumes of runoff, evapotranspiration, lateral drainage, and percolation. Lateral drainage is computed in the model as a function of the average depth of saturation above the liner, the slope of the surface of the liner, the length to the drainage collector, and the hydraulic conductivity of the lateral drainage layer. Therefore, to accomplish the objective of this study, the lateral drainage rate was measured as a function of the hydraulic conductivity, slope, length and depth of saturation of the lateral drainage layer in large-scale physical models. The measured average depths of saturation, drainage rates and drainage times in the physical models were then compared with HELP model predictions and numerical solutions of the Boussinesq equation, which applies Darcy's law to unsteady, unconfined flow through porous media.

Two large-scale physical models of landfill liner/drain systems were constructed and filled with a 3-foot (ft) sand drain layer overlying a 1-ft clay liner. A 2-inch (in.) layer of gravel was placed under the liner to collect seepage from the clay. The models were instrumented to measure the water table profile, subsurface lateral drainage rate, water application, runoff and percolation through the liner. Evapotranspiration and other water losses were estimated from the water budget for each test. The models have adjustable slope, ranging from 2 to 10 percent in this study; and different lengths, one being 26.5 ft and the other being 53.5 ft.

Several drainage tests were run on each configuration of the models by applying water as rainfall to the surface of the sand layer, and then measuring the water table along the length of the models and the lateral drainage rate as a function of time. Lateral drainage rates and water table profiles were measured during periods of increasing, decreasing and steady-state drainage rates. In these drainage tests, two drainage lengths were compared—25.4 ft and 52.4 ft. Three slopes were examined—approximately 2, 5 and 10 percent. Sands of two hydraulic conductivities were used—4 x $10^{-3}$ centimeter/second (cm/sec) (fine sand) and 2.2 x $10^{-1}$ cm/sec (coarse sand) as measured in soil testing permeameters. Four rainfall events were examined—a 1-hour (hr) rainfall at 0.50 inches/hour (in./hr), a 2-hr rainfall at 1.50 in/hr, a 6-hr rainfall at 0.50 in./hr and 24-hr rainfall at 0.125 in./hr. Also, water was applied to the sand for a long period of time (generally more than 36 hr) at a rainfall intensity which would maintain the average depth of saturation in the sand at 12 in. In addition to these drainage tests, the sand was saturated, predominantly from the bottom up for several test conditions, and then allowed to drain. In total, more than sixty tests were performed.

A complete block experimental design was used to examine the effects of drainage length, slope, hydraulic conductivity, depth of saturation, rainfall intensity and rainfall duration on the lateral subsurface drainage rates. The block design was selected because it provided the most data with the least time and expense for construction and model preparation. Several slopes and rainfall events could be examined quickly since very little time was required for changing these test conditions. Also the time requirements and costs for running an additional test with a different slope or rainfall were less than 10 percent of the requirements for preparing the model for a different sand. Additional rainfall events were examined in lieu of replicates since the lateral drainage rate as computed by the HELP model does not directly consider the effects of rainfall intensity or duration. Also, since a complete block design was used, the effect of a change in a variable is directly examined under multiple test conditions, reducing the need for replicates.

## Results of Drainage Tests

A comparison of profile shapes for the depth of saturation along the length of the drainage layer indicates significant differences between the rising saturated-depth profile (during filling) and the falling saturated-depth profile (during draining) for the same average depth of saturation ($\bar{y}$). The profiles are steeper near the drain when filling than when draining. The difference is greater for higher infiltration rates. Steady-state profiles are very similar to the profiles for draining.

The drainage rate for a given average depth of saturation was greater during the filling portion of each experiment than during the draining portion. This is consistent with the saturated-depth profiles which show steeper hydraulic gradients near the drain for filling conditions. Plots of drainage rates as a function of average depth of saturation also show that drainage continues after $\bar{y}$ has essentially reached zero. This is presumed to be drainage capillary water, commonly called delayed yield. An estimate of this capillary water volume when $\bar{y}$ had just drained to 0 in. based on an analysis of the experimental data is about 0.1 in. (cubic inches per square inch) for the fine sand and 0.3 in. for the coarse sand.

The drainage results indicated that the drainable porosity of the sands decreased with increasing depths of saturation above the clay liner. In addition, the drainable porosity at all depths was considerably smaller than the value estimated from soil moisture data and other soil properties collected on the sands. Low drainable porosity values were obtained in part due to the delayed yield and capillary effects that results from the high drainage rate. However, the presence and vertical distribution of entrapped air appear to be primarily responsible for the low drainable porosities and the change in drainable porosity with height, although no measurments of entrapped air were collected.

All parameters required to compute the drainage rate by the HELP equation except the hydraulic conductivity were measured for each drainage test. Due to variable air entrapment and differences in placement, compaction and preparation of the sand drainage media, the hydraulic conductivity measured in a permeameter in the soils testing laboratory differed significantly from the actual test values calculated from data on drainage rates and depths of saturation from the physical models. As described in the documentation report for the HELP model, the lateral drainage equation was developed to approximate numerical solutions of the Boussinesq equation for one-dimensional, unsteady, unconfined flow through porous media. Therefore, the actual hydraulic conductivity for the drainage tests was estimated by adjusting its value while solving the Boussinesq equation until the results matched the measured drainage rates and saturated depths. The hydraulic conductivity estimates are summarized in Appendix A. Determining the hydraulic conductivity in this manner provided the best estimate obtainable for each test since the Boussinesq solution is the commonly accepted representation of the actual drainage process. Comparisons were made for both steady-state drainage during rainfall and unsteady drainage following cessation of rainfall.

The computed hydraulic conductivity values differed significantly from the measured values. For steady-state drainage from the fine sand, the average computed value was only 8 percent greater than the measured value, while for unsteady drainage the average computed value was about 150 percent greater. For steady-state and unsteady drainage from the coarse sand, the average computed value was respectively 92 and 84 percent less than the measured value. For both sands, the average computed hydraulic conductivity for unsteady drainage was twice as large as the computed hydraulic conductivity for steady-state drainage.

In analyzing the computed hydraulic conductivity values, it was apparent that hydraulic conductivity decreased with increasing $\bar{y}$. This is consistent with the earlier hypothesis that the volume of entrapped air increased with increasing distance above the clay liner. A larger volume of entrapped air decreases drainable porosity and cross-sectional flow-through area, thereby decreasing hydraulic conductivity.

The computed hydraulic conductivity values varied considerably between tests on the same sand, even in the same model without disturbing the placement of the sand between tests. Considerable variability occurred between tests having exactly the same configuration of sand, slope, length, and depth of saturation, where only the rainfall intensity and duration differed. This variance was examined using an unequal three-way analysis of variance (ANOVA) test to determine whether the computed hydrualic conductivity was a function of another variable besides average saturated depth.

The test variables used in the ANOVAs included type of sand, average saturated depth, slope, drainage length, rainfall duration and rainfall intensity. No effects of rainfall duration and intensity could be discerned by inspection; therefore, the initial ANOVAs were run using depth, slope and length as the variables for data sets containing hydraulic conductivity estimates for one type of sand. These ANOVAs indicated that the computed hydraulic conductivity estimates for both sands varied as a function of average saturated depth and slope. Additional ANOVAs indicated that drainage length, rainfall intensity and duration did not significantly contribute to the variance in the computed hydraulic conductivity as a function of slope. Therefore, the variability due to slope probably arises from inaccuracies in the manner in which the effects of slope are modeled by the Boussinesq equation.

## Verification of the HELP Model

The drainage rates computed by the HELP model was compared with the results of the drainage tests in several manners. The hydraulic conductivity that was needed to yield the measured drainage rate for the same drainage length, slope, and average saturated depth existing in the drainage test was computed for several times during each test. This hyudraulic conductivity value was compared with the value measured in the soils testing laboratory and the value estimated using the Boussinesq equation. If the HELP equation accurately predicted the results of the drainage tests, the hydraulic conductivity value would agree with the measured or estimated hydraulic conductivity value for the sand. If the hydraulic conductivity value was greater than the value obtained for the sand, the HELP equation underpredicted the lateral drainage rate. Another method of comparison was to examine the effects of changing a single variable on the lateral drainage rate measured in the drainage tests and predicted by the HELP equation. The effects of drainage length, slope, average depth of saturation, and the head contributed by the slope of the liner were compared in this manner.

The hydraulic conductivity of the sand at various depths of saturation was estimated for each test using the Boussinesq solution of Darcy's law for unsteady, unconfined flow through porous media and the HELP lateral drainage equation. These hydraulic conductivity values were compared to determine the agreement between the HELP model and the Boussinesq solution. For steady-state drainage, the HELP model estimates of the hydraulic conductivity were 44 percent greater than the Boussinesq solution estimates. This result means that the HELP model underestimated the steady-state lateral drainage rate predicted by the Boussinesq solution by 30 percent. The HELP estimates were 31 percent greater than the laboratory measurements for the fine sand and 88 percent less than the laboratory measurements for the coarse sand. For unsteady drainage, the HELP model estimates were only 13 percent greater than the Boussinesq solution estimates which would underpredict the lateral drainage rate by 11 percent. The closeness of the estimates was not unexpected since the HELP lateral drainage equation was developed from numerical solutions of the Boussinesq equation for saturated unconfined lateral flow through porous media under unsteady drainage conditions. The underprediction of the cumulative lateral drainage volume would be expected to be very small since the removal rate of water from the drain layer by all other means is much smaller than the lateral drainage rate. Consequently, the effect of differences in the predicted and actual drainage times are small.

The differences between the laboratory measurement of the hydraulic conductivity and either of the two estimates computed from drainage data were much larger than the differences between the estimates. The HELP model and Boussinesq equation predicted very similar drainage rates at 2-percent slope but the HELP model predicted lower drainage rates at 10-percent slope. Unlike the laboratory measurements, the hydraulic conductivity in the drainage tests varied as a function of the depth of saturation apparently due to entrapment of air in the sand. This phenomenon makes it very difficult to model the lateral drainage process and produce good agreement between the predicted and actual results for drainage rate and depth of saturation as a function of time.

An analysis was performed to determine how well the lateral drainage equation in the HELP model accounts for the effects of drainage length, slope of the liner, average depth of saturation and head above the drain contributed by the liner in the estimation of the drainage rate. The drainage equation overestimates the decrease in drainage rate resulting from an increase in length given the same sand, slope, depth of saturation and head from the liner. Using the drainage rate for a drainage length of 25.4 ft to predict the rate for a length of 52.4 ft, the HELP model underpredicted the rate by 18 percent. The HELP equation overestimated the increase in drainage rate by 30 percent that resulted from an increase in slope from 2 percent to 10 percent. Similarly, the HELP equation overestimated the increase in drainage rate by 20 percent that resulted from increasing the height (head) of the crest of the liner from 15.3 to 30.5 in. above the drain. The effects of changes in the average saturated depth on the drainage rate predicted by the HELP equation agreed very well with the actual results.

Since the HELP lateral drainage equation was developed to approximate numerical solutions of the one-dimensional Boussinesq equation for unsteady, unconfined, saturated flow through porous media, it cannot be expected to perform any better than the Boussinesq equation. Therefore, it was necessary to compare the Boussinesq solutions to the laboratory measurements in order to form a basis for judging the significance of the differences between the HELP equation predictions and the laboratory measurements, and between the HELP equation and the Boussinesq solution.

To summarize, the Boussinesq solution after calibration still produced results significantly different from those measured in the drainage tests. The results obtained with the HELP model were generally as good or better than the Boussinesq solution. The HELP equation performed better on tests conducted with 2-percent slope and the Boussinesq solution performed somewhat better on tests conducted at 10-percent slope. The differences between predictions by the two methods for a given set of conditions were small in comparison to the range of actual results. Similarly, the differences between the predictions and the actual results were much larger than the differences between the HELP equation and the Boussinesq equation.

## Conclusions and Recommendations

The following conclusions and recommendations are made. Lateral drainage in landfill liner/drain systems is quite variable, probably due to air entrapment. The hydraulic conductivity measurement made in the laboratory is quite different than the in-place value. Consequently, the estimation of the lateral drainage rate is prone to considerable error despite having a good equation or solution method for the estimation. Neither the HELP model nor the Boussinesq solution agreed completely with the drainage results. Nevertheless, the prediction of the cumulative volume of lateral drainage is likely to be quite good since the depth of saturation will be overpredicted if the drainage rate is underpredicted and vice versa, thereby adjusting the drainage rate. However, the predicted depth of saturation will be quite different from the measured value.

Improvements should be made to improve the predictions of drainage rates resulting from changes in slope and drainage length. The drainage equation should be modified to increase its applicability to slopes as large as 30 percent and drainage lengths as large as 2000 ft.

Evaluation of the effects of drainage length, slope of the liner, depth of saturation and head above the drain on the drainage rate predicted by the Boussinesq solution should be performed to determine whether the effects observed with the HELP drainage equation are unique or derived from the Boussinesq equation. Similarly, an additional data set of drainage results should be collected to determine whether the effects are unique to this data set. Additional data should be collected for longer drainage lengths and greater slopes and from actual landfill/liner systems.

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*The complete report, entitled "Verification of the Lateral Drainage Component of the HELP Model Using Physical Models," (Order No. PB 87-227 104/AS; Cost: $18.95, subject to change) will be available only from:*

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