Accelerated Groundwater Transport Studies Using a Geotechnical Centrifuge

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The use of a geotechnical centrifuge permits the simulation of long-term groundwater flow conditions through tests on scale models. In a centrifuge, relatively large soil samples can be tested under the same stress conditions as in the prototype. This allows for a more realistic representation of field conditions than is possible in small-scale laboratory experiments. In cases of contaminant migration through relatively impermeable soils, the times of interest span decades and even centuries. The scaling relations can be utilized in solving specific problems of groundwater flow through saturated soil and also to calibrate numerical models that can then be used for prediction purposes. The scaling relationships are established and the results are illustrated through an experiment in modeling of models. Two case studies simulating long-term contaminant migration through soil are presented. In the first, the transport of radioactive contaminants through groundwater was modeled. Geiger-Mueller detectors were used to observe the migration of the radionuclides. This is a nonintrusive method of observation that does not interfere with the normal flow of water through the soil medium. The second case study deals with the behavior of different types of landfill cover materials. Specifically the long-term behavior of paper sludge as a cover material was studied. Thirty years of prototype behavior was simulated in centrifuge tests on two types of paper sludges and on a clay cover used as a control material.

Conventional field and laboratory testing procedures are often found to be inadequate for cases of long-term flow of groundwater through relatively impermeable soil layers. Also, the stress levels existing in test samples are often only a fraction of what exists in the field. In addition, the small size of laboratory samples excludes most of the heterogeneity of in situ soil conditions.

Geotechnical centrifuges can be used to perform tests on models that represent full-scale prototypes under normal field conditions. A 1/*N* scale model tested at centrifugal acceleration *N* times the earth's gravity experiences stress conditions identical with those in the prototype. Processes of groundwater flow through saturated soil—for example, in cases of consolidation and diffusionoccur N^2 times faster in a centrifuge model. This scaling permits modeling of phenomena that last extremely long prototype times. Prototype times on the order of several decades to several centuries are of interest in various problems of contaminant migration, for example, sanitary landfills and low- or medium-level radioactive waste disposal. Many geotechnical centrifuges in use today are capable of simulating more than 100 years of prototype flow by means of model tests lasting only 24 hr.

In the following sections, the concept of scaling groundwater flow processes is presented. The relationship is later utilized in two case studies related to contaminant migration through soil.

CENTRIFUGE SCALING RELATIONS

Laminar flow of fluid through a saturated porous medium is governed by Darcy's law as follows:

$$v = ki \tag{1}$$

where

v = approach velocity,
k = Darcy's coefficient of permeability, and
i = hydraulic gradient.

In a centrifuge, stress conditions that are identical with those at corresponding points in the prototype are simulated in a 1/*N* model subjected to *N g*'s when the model and the prototype have the same geometric and material properties and boundary conditions.

To understand the scaling of seepage velocity and time of flow, a conventional laboratory 1/*N* scale model at 1 *g* environment is considered. This model experiences the same acceleration field (namely 1 *g*) as the prototype but has all the linear dimensions reduced by a factor of *N*. This means that in the case of groundwater flow problems, the size of the flow paths as well as the water levels in the model will be 1/*N* times that of the prototype. The shape of flow nets will, of course, be the same as that in the prototype. Also, since both the model and the prototype are subjected to the same 1 *g* acceleration field, the velocity of flow in the two cases will be the same.

Since the length of flow paths has been scaled as 1/*N* in the model, the same velocity (as that of the prototype) will cause the time taken by the flow to be *N* times shorter than that in the model, that is,

$$\frac{t_m}{t_p} = \frac{l_m}{l_p} = \frac{1}{N} \tag{2}$$

where subscripts *m* and *p* refer to model and prototype, respectively. It should be noted that since no use has been made of Darcy's law (Equation 1) so far, Equation 2 is independent of flow conditions (laminar or turbulent).

Next, the model is considered to be subjected to an acceleration field that is *N* times the 1 *g* acceleration on the earth. The high *g*-field causes the velocity of flow to be *N* times the velocity at the 1 *g* field, that is,

$$v_m = Nv_p \tag{3}$$

Using Equation 1 to express the condition with a 1/*N* model at *N* *g*-field,

$$v_m = Nki \tag{4}$$

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Although it is easily demonstrated that the velocity scales by the same factor as the centrifugal acceleration, it is an arbitrary choice whether to consider this as due to an increase in Darcy's coefficient of permeability (*k*) or an increase in the hydraulic gradient (*i*) from the prototype to the model. Pokrovsky and Fyodorov (*1*) and Cargill and Ko (*2*) have considered the expression for coefficient of permeability,

$$k = \frac{Kg}{\nu} \tag{5}$$

where

K = intrinsic permeability,
g = acceleration due to gravity at earth's surface, and
n = kinematic viscosity of the fluid.

Thus they considered k to vary in direct proportion to g. In this case the hydraulic gradient, i, is considered constant from the model to the prototype. Schofield (*3*) and Goodings (*4*), on the other hand, consider the hydraulic gradient to change since a model experiences a drop in the full prototype head over a reduced (model) seepage path. Here the coefficient of permeability, k, is considered a material property that remains constant from prototype to model.

Tan and Scott (*5*) have suggested treating the term g in Equation 5 as a constant of magnitude equal to the usual value on the earth's surface and multiplying the whole right-hand side of Equation 1 by a necessary scaling factor when cases at g levels other than normal are considered. The other suggestion put forth by Tan and Scott (*5*) is to express Darcy's law in a pressure gradient form using the intrinsic permeability and viscosity.

Following from Equations 2 and 3 for a case in which a reduced scale model is subjected to a higher acceleration, the ratio of time in the model to time in the prototype can be written as follows:

$$\frac{t_m}{t_p} = \frac{1}{N^2} \tag{6}$$

Equation 6 represents the scaling law for time in cases of laminar fluid flow through a saturated medium.

MODELING OF MODELS AT VARIOUS *g*-LEVELS

The validity of scaling relations, as well as the performance of models at different high g-environments, can be verified by a methodology commonly referred to as modeling of models. Equation 6 was derived for a case in which where the model has a linear scale $1/N$ times that of the prototype and is subjected to an acceleration N times that of the prototype. When modeling-of-models experiments are performed, there may actually be no prototype since the same model is subjected to different acceleration levels on the centrifuge. Making the necessary modification to Equation 6 (i.e., $l_m = l_p$), the required scaling relation in this case is

$$\frac{t_m}{t_p} = \frac{1}{N} \tag{7}$$

The experimental setup shown in Figure 1 was utilized for the modeling of models. A sheetpile was embedded in the soil and the flow of water through saturated soil from one side (at higher head) to the other was observed. Ottawa sand was used as the soil medium. Colored dyes were injected on the upstream side to observe the flow lines. Three flow lines—A, B, and C—are shown. The model consisted of a 406-mm by 229-mm by 76-mm Plexiglas box containing sand to a height of 152 mm. A 100-mm long sheetpile was introduced, with 40 mm embedded in the soil.

Experiments were conducted at accelerations of 1, 20, 25, and 30 g. Water levels at upstream and downstream sides were maintained constant during the course of each experiment. The geometry of the flow paths and the time of flow were monitored during the tests.

According to Equation 7, the time for flow is inversely proportional to the acceleration during the test. So in modeling-of-model tests run at different accelerations, the time for flow to

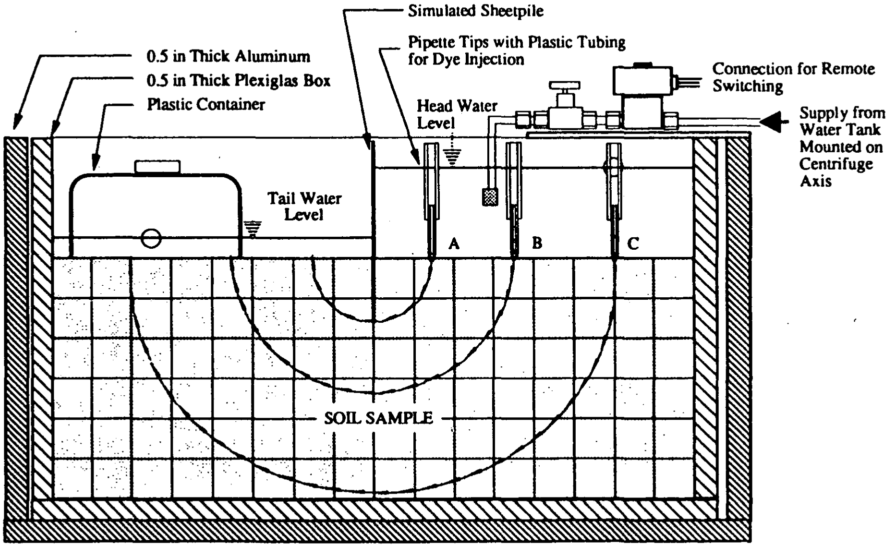

FIGURE 1 Experimental setup of model tests on simulated sheetpile.

occur will be an inverse ratio of the accelerations. That is,

$$\frac{t_2}{t_1} = \frac{N_1}{N_2} \tag{8}$$

where the subscripts indicate Tests 1 and 2. It should be noted that the same model is used in both experiments, and the time of flow between the same two points is measured in both cases. The condition of laminar flow is obeyed in both cases.

Figure 2 is a graph of the modeling validation presented above. The ratio of acceleration levels (N_1/N_2) and the inverse ratio of the time of flow (t_2/t_1) are plotted on a logarithmic scale. The points represent the ratios measured from tests with colored dyes along paths A and B at various *g*-levels. The theoretical line shown in Figure 2 is the plot of Equation 8.

It may be noted that although most points lie on or near the theoretical line, there is some deviation in the case of points representing times of travel for dye on Line A at higher N_1/N_2 ratios. These points represent the ratios from tests at higher *g*-levels (20, 25, and 30) with those from 1 *g*. The deviation may be attributed to a higher percentage of error in measuring the travel time of Line A than that of Line B. Line A is the shorter of the two lines, and at higher *g* levels the time of travel was reduced to about 1 min. The fact that the flow was observed visually and that the dye dispersed slightly in the direction normal to the flow path led to some error in the observed time of flow. Flow Line B was longer than Line A, and consequentially had a lower percentage error. This can be seen in Figure 2, where the points for Line B are seen to lie on or close to the theoretical curve.

The above application of modeling of models confirmed the scaling laws for seepage, which could then be utilized in more complex tests. Two different case studies using accelerated physical modeling will be presented here.

APPLICATION TO CONTAMINANT TRANSPORT PROBLEMS

The scaling relations for the time of seepage as the square of the scale factor (and the *g*-level) expressed in Equation 6 can be utilized to observe fluid transport phenomena that normally occur over long periods of time. Equation 6 can be used to show that a 1-day experiment on a 1/200 model at 200 *g* can model over 100 years of prototype behavior, since

$t_p = N^2 t_m$ (from Equation 6)

$= 200^2 \times 1$ days (where $N = 200$)

$= 40{,}000$ days

≈ 109.6 years

Time spans of such magnitude are commonly of interest in cases of the migration of contaminants through soils with relatively low coefficients of permeability.

Two case studies, for which experiments were performed, will be presented here. The first deals with the migration of radioactive waste materials in groundwater following a repository leakage. The second studies the long-term consolidation and seepage behavior of different types of landfill cover materials. Both experiments were performed on the 100 Gton geotechnical centrifuge at Rensselaer Polytechnic Institute.

Radioactive Waste Migration Through Soil

Much time and effort has been devoted to developing methodologies for radioactive waste disposal. Often radioactive wastes are disposed of by burial either in land-based engineered trenches or

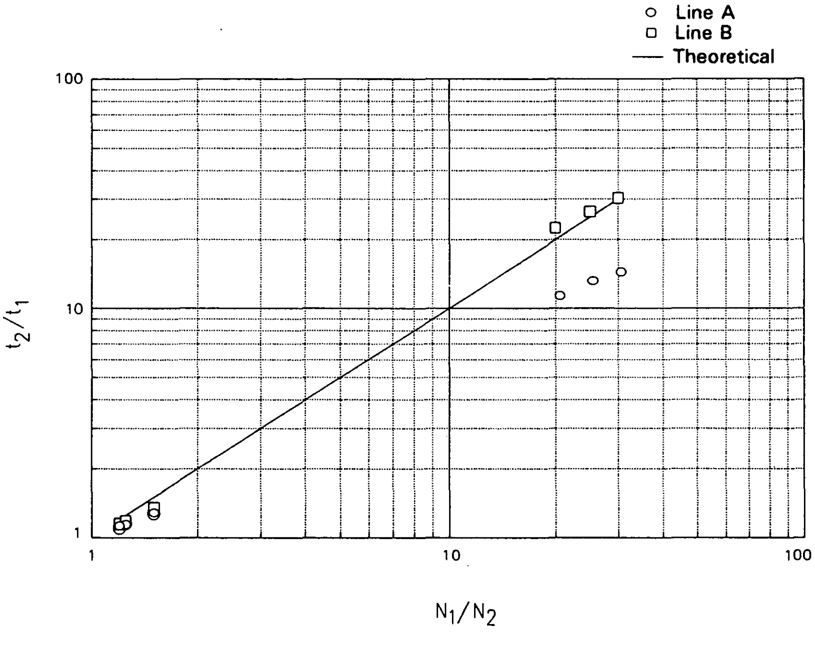

FIGURE 2 Graph showing modeling of seepage at different *g*-levels on centrifuge.

in deep ocean bed sediments (*6*). In either case, the repositories are best located in geologic deposits of low permeability. Besides the containment units, which are designed to prevent leakage, the low-permeability soil layers surrounding the repositories act as a series of barriers to the release of radionuclides into the environment.

Many radioactive waste species contain elements with very long half-lives and thus remain potentially hazardous over extended periods of time. The transport of the hazardous waste through the soil following a repository leakage is extremely slow because of the very low permeabilities of the soils surrounding the sites. Migrations of this nature can take several centuries to occur and hence make physical site observations impossible. A geotechnical centrifuge provides a suitable means for observing such long-term prototype behavior via accelerated physical modeling.

The experiments presented here were performed on a small-scale two-dimensional flow model as a pilot study to observe the technique of accelerated migration of radioactive materials in groundwater.

In the tests, radioactive species Iodine 131 (I^{131}) was allowed to migrate under a constant head through saturated silt soil that had a coefficient of permeability of approximately 5.6×10^{-6} cm/sec. The migration of I^{131} was detected using an array of nine end-window type Geiger-Mueller (G-M) tubes located on the outer side of the model box.

Figure 3 [from Zimmie et al. (*7*)] shows the cross-sectional view of the general setup of the model in a rectangular box. A two-dimensional flow condition was simulated, with the migrating species injected on the top center of the soil layer and drainage provided at the two bottom extremities. To ensure two-dimensional flow, the drains had sand cores running normal to the flow direction. Tests were run at 60 *g* for 5 hr, simulating prototype times of more than 2 years.

Besides the tests performed actually using the radioactive tracer, the flow pattern was verified visually in a separate test using potassium permanganate ($KMnO_4$) tracer as a colored dye. Figure 4 shows the flow pattern in this test and the location of the nine G-M tubes.

The G-M tubes used were of the end window type, TGM N205, with a 12.7-mm diameter thin mica window and a thickness of approximately 2 to 3 mg/cm^2. The 15-mm diameter by 41.9-mm length of completely sealed tube is filled with neon and halogen gases and is suitable for the detection of alpha, beta, and gamma radiation. This type of detector lacks the ability to provide information about the energy and type of radiation (*8*). Thus, known sources of radiation must be used as tracers. The advantages of this type of detector include insensitivity to small fluctuations in applied voltage, durability, and low cost, which make it particularly suitable for use in centrifuge experiments.

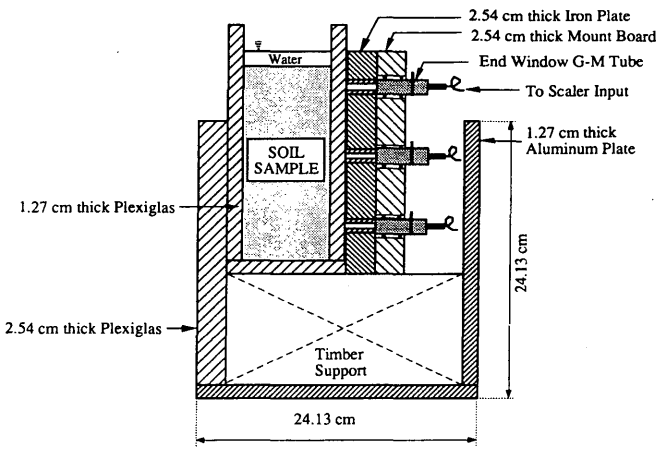

FIGURE 3 Experimental setup for tests on migration of radioactive contaminants (*7*).

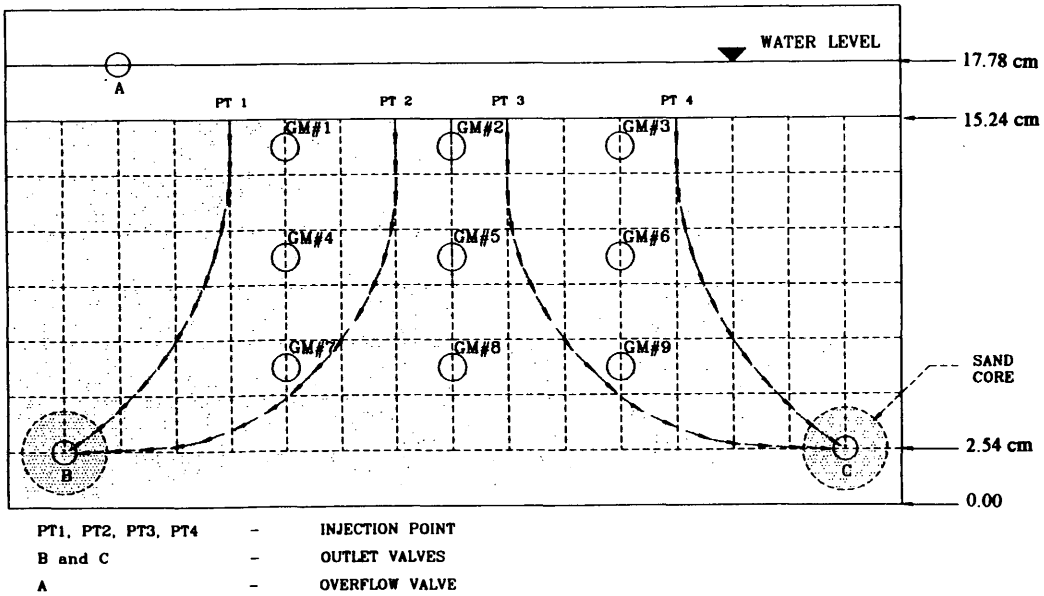

FIGURE 4 Observed flow paths of dye with respect to injection Points 1, 2, 3, and 4. Tests performed on the two-dimensional flow model at 60 *g*.

The low-voltage signals from the G-M tubes were monitored using scalers and an oscilloscope. The total counts from the tubes relative to the initial activities of the radioactive sources were plotted versus time as migration occurred. Figure 5 is a plot of the relative count with time for GM-2 and GM-7. The two points, 2 and 7, lie on the line PT 2 to B in Figure 4. The time of travel between the two points is given by the time between peaks for G-M tubes 2 and 7.

The plots in Figure 5 show some scattering. This is primarily due to the low radioactive dosage used in the study, which resulted in poor counting statistics. An initial activity of a few thousand counts per second is most desirable. However, as the counts increase, the danger from the radioactivity increases, and safety must be a consideration. Since these were pilot tests, it was not deemed necessary to use high levels of radioactivity. In spite of the low counts, the trends shown in the plots were as expected and were used to study the migration pattern of the radioactive tracer.

Good agreement between the travel times for radioactive tracer and colored dye tracers indicates insignificant sorption or attenuation of the radioactive species in the soil. A detailed description of the test process as well as discussions of the results have been presented by Mahmud (*9*).

The use of a geotechnical centrifuge in the study of contaminant migration allows the observation of behavior that spans long prototype times. Computer models used to analytically solve contaminant migration problems can be calibrated and validated using results from such experiments. The use of radioactive tracers and Geiger-Mueller detectors to observe the migration provides a means of observation that does not interfere with the natural flow pattern in the model. Such nonintrusive observation methods can be adopted for use in other studies as well. For example, to study the migration of nonradioactive contaminants, a radioactive tracer can be used to spike the pollutant of interest. After proper calibration, the measurements of tracer radioactivity can be used to determine the concentration of the migrating species. This can be done while the model is in flight, during a centrifuge test, without requiring either sample collection or chemical analyses. It is difficult to do in-flight chemical analyses.

Long-Term Behavior of Landfill Cover Materials

The long-term behavior of cover materials (impermeable barriers) for landfills was simulated in a series of experiments. The materials tested included clay, which is commonly used as the impermeable barrier layer in covers, and two different types of paper sludge, which are potential candidates for the same use.

Each test was performed at 105 *g* for a 24-hr period and, according to the scaling relations expressed in Equation 6, simulated 30 years of prototype cover behavior related to consolidation and leachate transport. The tests were conducted in a sample box 914 mm by 610 mm by 356 mm in size.

Figure 6 shows a schematic diagram of the experimental setup. The test sample consisted of a 76-mm thick layer of the cover material (clay or paper sludge) laid over a 152-mm layer of clean sand and separated from the sand by a layer of geotextile. The sand layer was compacted to nearly its maximum density and was designed to hold the leachate flowing through the cover material during the course of the experiment. The geotextile was used to prevent the clay and sludge from entering into the sand layer and clogging it. During each test, 76 mm of water was impounded on top of the cover material.

As stated previously in Equation 2, the ratio of the lengths of prototype to model is equal to the centrifugal acceleration. Accordingly, to model a typical prototype landfill cover that is 60 cm in thickness at 105 *g*, it would be necessary to build model covers about 60/105 and about 0.5 cm thick. This is not a practical thickness considering workability during model building, and the chance of leakage during the test is very high for such a thin layer. Also several liters of leachate were required to do the necessary chemical analyses. The appropriate cover thickness used in the models was selected on the basis of these criteria.

The consolidation characteristics of a soil are not functions of the thickness of the test sample. Hence in the tests performed, the coefficients of consolidation, compressibility, and volume change are not dependent on the proper scaling of cover thickness for the prototype to model.

The instrumentation on the sample consisted of linear variable differential transformers (LVDTs) on the surface of the cover and pore pressure transducers to measure the pore-water pressures at the mid-depth of the cover. The change in water level on top of the sample cover was monitored using a float mechanism attached to an LVDT. Typical settlement versus time curves (on a log scale) for the three cover materials at 105 *g* are shown in Figure 7. The spikes in two of the curves were caused when the centrifuge was stopped to add water or to correct machine imbalance, causing the surface to rebound. Once the centrifuge restarted and the model returned to 105 *g*, the settlement proceeded as a continuation of the previous curve, as can be seen in Figure 7. In case of Sludge 2, the centrifuge acceleration was reduced and maintained below 105 *g* in an attempt to reduce the machine imbalance. Following this, the machine was stopped. This explains the apparent discontinuity in the curve for Sludge 2 before and after the stoppage.

In Figure 7 the settlement reading at the beginning of the experiment at 105 *g* is taken as the initial value, and all subsequent settlements are obtained by subtracting this initial reading. This convention was followed in all the tests. As expected, the two sludges are found to be more compressible than the clay. The values of pore-water pressures at the center of the cover are plotted in Figure 8. As in Figure 7, the spikes in the curves indicate

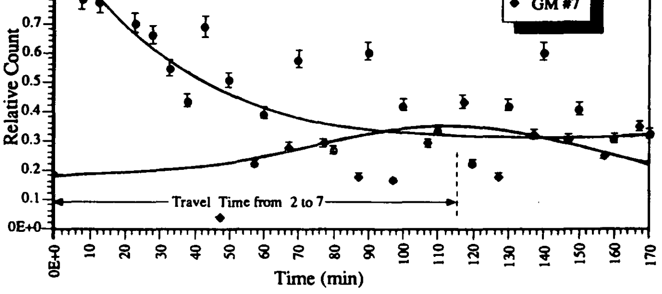

FIGURE 5 Plot of the relative counts for G-M 2 and G-M 7: distance from peak to peak denotes travel time between Point 2 and Point 7 along Flow Line 2-B; error bars represent standard deviations.

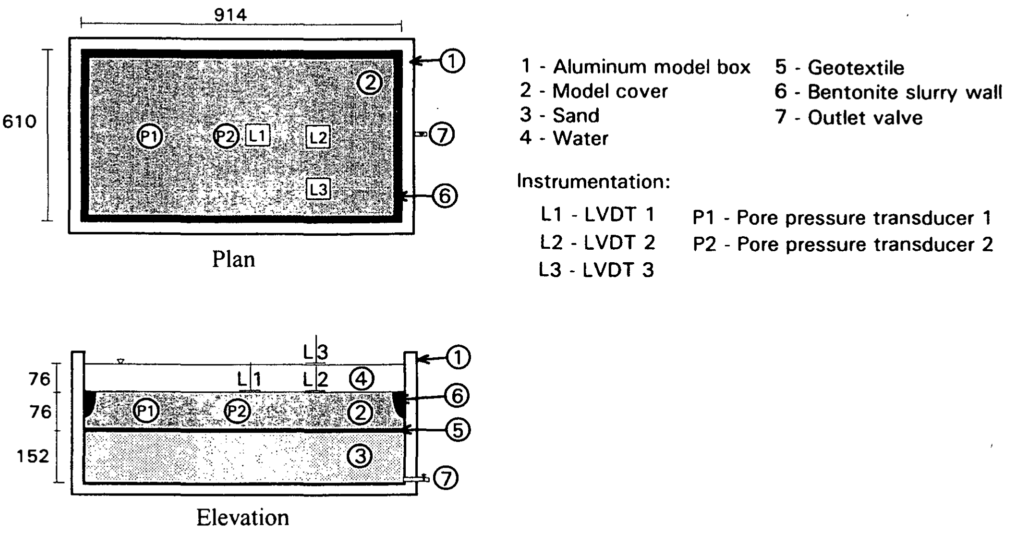

FIGURE 6 Experimental setup for tests on landfill covers.

times when the centrifuge was stopped and, consequently, the pore pressures reduced.

The change in water level on top of the cover with time indicated the rate at which water infiltrated through each of the cover materials. Some water was also lost to evaporation (since the sample rotated at about 184 rpm during the experiment). A separate test was run with only water in the box, and the drop in water level with time due to evaporation alone was measured.

Figure 9 shows changes in water level versus time, corrected for evaporation, for all three cover materials. Results from only the first 6 hr are shown.

Figure 9 may be considered indicative of the seepage characteristic of the three cover materials under identical conditions (compaction, thickness, and head of water). The clay cover is found to be the least permeable, with a coefficient of permeability of 4×10^{-8} cm/sec at 1 *g*. The plot in Figure 9 for the clay cover has an almost constant slope, indicating a constant value of permeability throughout the test. This is as expected, since there is little settlement in the clay, hence little change in void ratio.

The slopes of the curves for the two sludges shown in Figure 9 vary with time. It can be seen that at the beginning of the tests the curves for the two sludges have steeper slopes, corresponding to higher coefficients of permeability ($6\ 10^{-7}$ cm/sec for Sludge 1 and 2.5×10^{-6} cm/sec for Sludge 2). At the end of the tests the coefficients of permeability (as obtained from the slopes of the curves) are found to be 2×10^{-7} cm/sec for Sludge 1 and 4.7×10^{-7} cm/sec for Sludge 2. This demonstrates that although in the case of clay the permeability of the cover remains almost

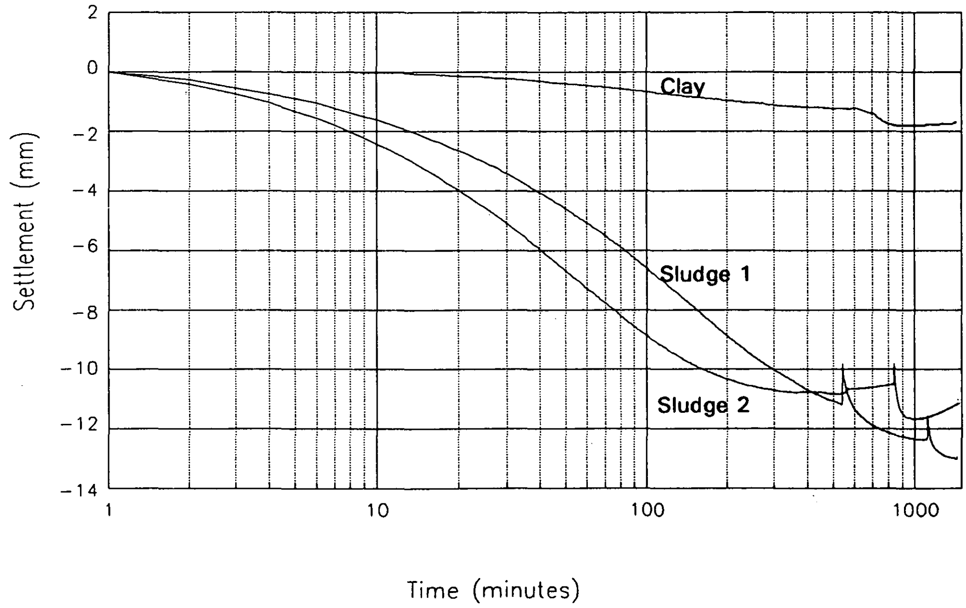

FIGURE 7 Settlement (log scale) versus time at the center of cover at 105 *g*.

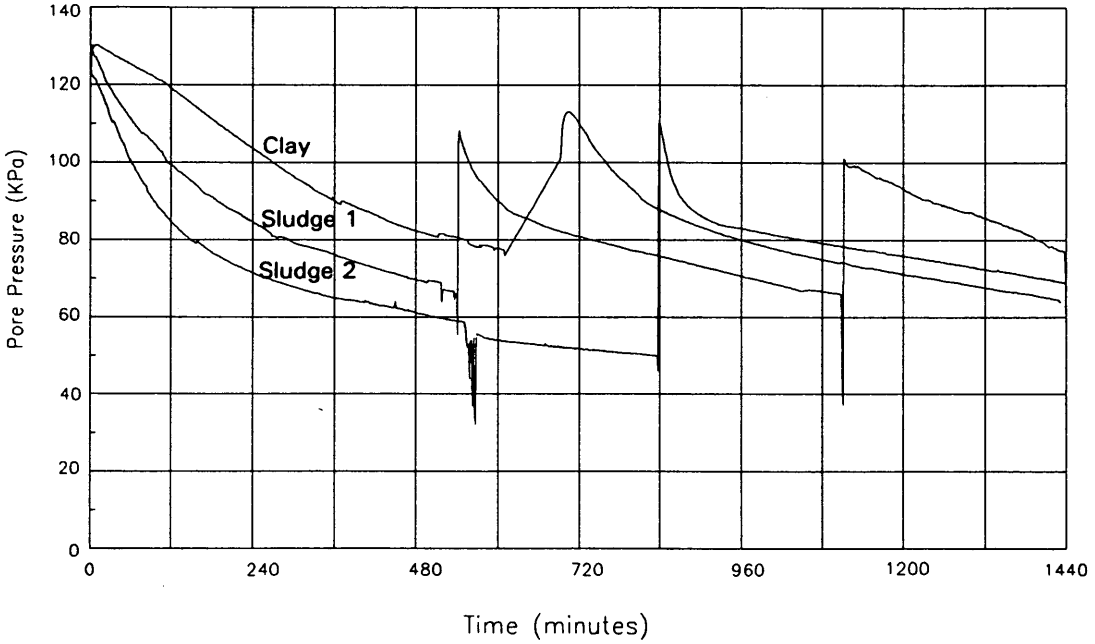

FIGURE 8 Pore-water pressure versus time at the center of cover at 105 *g*.

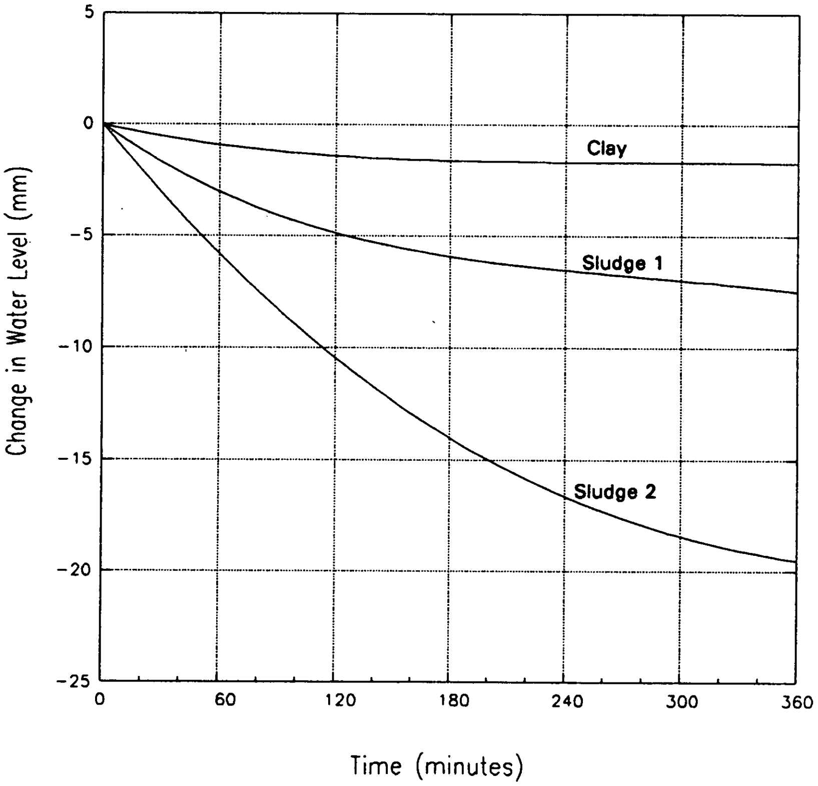

FIGURE 9 Change in water level (corrected for evaporation) (results from first 6 hr).

constant at the initial value, the coefficients of permeability for paper sludge covers tend to decrease considerably with time because of the high compressibility of the sludge, which results in large decreases in void ratio.

The biodegradation that occurs in the sludge over a period of 30 years cannot be modeled in a 24-hr test on the centrifuge. However, biodegradation causes the percentage of organics in the sludge to decrease and the paper sludge to become more soil-like in character. Because of these effects, the coefficient of permeability of the sludge decreases with the progress of biodegradation (*10*). Thus, the tests presented here are useful since they yield conservative permeability values; that is, the in situ permeabilities after 30 years are expected to be lower than those measured in the centrifuge tests.

In order to properly model flow through a saturated porous medium, it is necessary to ensure that the values for the dimensionless Reynold's and Peclet numbers are both less than 1 (*11*). In the experiments described in this paper, the values were found to be much lower than 1, and hence proper modeling of the flow was obtained.

CONCLUSIONS

The study of groundwater flow phenomena by means of accelerated physical modeling was presented in this paper. The scaling relations involved were derived and validated through the use of modeling of models. The use of the geotechnical centrifuge as a valid tool to simulate long-term contaminant migration through saturated soil and related soil behavior was demonstrated through two case studies.

In the first case study, nonintrusive Geiger-Mueller tubes were used to observe contaminant migration without interfering with the natural pattern of groundwater flow. Experiments to study the use of this method for other types of contaminants are recommended.

In the second case study, long-term tests on a relatively large landfill cover model were performed. It was possible to simulate larger prototype dimensions and to model relatively heterogeneous in situ soil. These uses can further be broadened to validate numerical and computer models, which can then be used with greater confidence in practical design.

REFERENCES

1. Pokrovsky, G. I., and I. S. Fyodorov. *Studies of Soil Pressures and Deformations by Means of a Centrifuge,* Vol. 1 (in translation). Building Research Establishment, U.K., 1968.
2. Cargill, K. W., and H-Y. Ko. Centrifugal Modeling of Transient Water Flow. *Journal of Geotechnical Engineering,* ASCE, Vol. 109, No. 4, April 1983, pp. 536–555.
3. Schofield, A. N. Twentieth Rankine Lecture: Cambridge Geotechnical Centrifuge Operations. *Geotechnique,* Vol. 30, 1980, pp. 227–268.
4. Goodings, D. J. Relationships for Modelling Water Effects in Geotechnical Centrifuge Models. In *Application of Centrifuge Modelling to Geotechnical Design* (W.H. Craig, ed.), A. A. Balkema, Rotterdam, 1984, pp. 1–24.
5. Tan, T.-S., and R. F. Scott. Centrifuge Scaling Considerations for Fluid-Particle Systems. *Geotechnique,* Vol. 35, No. 4, 1985, pp. 461–470.
6. EOS, Arctic Contamination Poses Potential Danger. *Transactions, American Geophysical Union,* Vol. 74, No. 27, July 6, 1993, p. 298.
7. Zimmie, T. F., M. B. Mahmud, and A. De. Application of Centrifuge Modeling to Contaminant Migration in Seabed Waste Disposal. *Proc., 4th Canadian Conference on Marine Geotechnical Engineering,* Vol. 2, 1993, pp. 610–624.
8. Ehmann, W. D., and D. E. Vance. *Radiochemistry and Nuclear Methods of Analysis.* John Wiley and Sons, New York, 1991.
9. Mahmud, M. B. *Geotechnical Centrifuge Modeling of Contaminant and Radioactive Waste Migration in Soil.* M. S. Thesis. Rensselaer Polytechnic Institute, Troy, N.Y., May 1993.
10. Zimmie, T. F., H. K. Moo-Young, Jr., and K. LaPlante. 1993. The Use of Waste Paper Sludge for Landfill Cover Material. *Proceedings of Green '93: Waste Disposal by Landfill Symposium,* Bolton Institute, Bolton, U.K., Vol. 2, pp. 11–19.
11. Arulanandan, K., P. Y. Thompson, B. L. Kutter, N. J. Meegoda, K. K. Muraleetharan, and C. Yogachandran. Centrifuge Modeling of Transport Processes for Pollutants in Soils. *Journal of Geotechnical Engineering,* ASCE, Vol. 114, No. 2, pp. 185–205.

Publication of this paper sponsored by Committee on Physicochemical Phenomena in Soils.