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Centrifuge Modeling of Cadmium Migration in Saturated and Unsaturated Soils

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Researchers recently have come to recognize that geotechnical centrifuge can provide a powerful experimental tool for investigating the flow and transport of inorganic contaminants in soils. Inert, non-adsorptive inorganic compounds (e.g., sodium ions) rather than adsorptive heavy metals are often used as the chemical for the investigation of pollutant transport behavior in most centrifuge modeling. To overcome the shortcomings of this approach, centrifuge tests for the study of one-dimensional pollutant migration in both saturated and unsaturated soils were designed using an adsorptive pollutant (i.e., cadmium) and conducted at two centrifugal accelerations. In this study, the concentration profile of adsorptive cadmium along the depth of soil, the moisture content varying with the soil depth and the transport behavior of the cadmium in soils were investigated. The centrifuge results show that the cadmium concentration profiles are found to be similar for the centrifuge models performed at 15 g and 20 g and the one-dimensional moisture movement in the unsaturated soil can be reproducible. The validity of centrifuge modeling of adsorptive pollutants might be affected by the g-level that, in turn, determines the centrifuge testing time and affects the sorption equilibrium.

Keywords Adsorption, centrifuge modeling, heavy metals, saturated and unsaturated soils.

Introduction

Movement of water-soluble pollutants in soils is governed by advection, dispersion, adsorption, and degradation processes. Prediction of pollutant migration in soils requires consideration of all the above processes in complex soil systems. To date, investigation of the flow and transport of contaminants in soils has used approaches such as laboratory column studies, full-scale field studies, numerical simulations, and geotechnical centrifuge modeling. While the first three approaches have been widely accepted and used for many years, all have their limitations. The laboratory column and full-scale field studies are time-consuming and complicated to perform due to little direct control over boundary conditions and the horizon of interest, which can span decades of real time. With the aid of numerical modeling, the movement of contaminants in groundwater regimes can be predicted. Unfortunately, the results of numerical modeling are dependent upon complete understanding of the fundamental processes and accurate conceptual modeling of all the relevant mechanisms. Since a geotechnical centrifuge has the ability to model the complex fluid flow

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in soils under repeatable and controlled conditions (Hellawell and Savvidou, 1994), this technique was employed in this study. The basic aim of centrifuge modeling is to recreate the stress conditions that would exist in a prototype using a model of greatly reduced scale. This is done by subjecting the model components to an enhanced body force that is provided by centrifugal acceleration of magnitude "ng," where g is the acceleration due to earth's gravity. Stress replication in an nth scale model is achieved when the imposed gravitational acceleration is equal to "ng." Due to n-fold increase in gravity in a centrifugal model, in terms of Darcy's law, the velocity of flow through soil is increased by n times and this combines with reduction in dimensions by a factor of n, resulting in reduction by a factor of n^2in the time required for flow phenomenon to occur in a centrifuge model. Due to these potential merits, the use of centrifuge for simulating contaminant transport under well-defined conditions in order to validate existing theoretical models and to get transport parameters is recently gaining great interest.

Most of the earlier research involving the use of centrifuge modeling has limited itself to assessing the migration of conservative, non-reactive inorganic pollutants (e.g., sodium chloride, lithium chloride) across saturated porous media. However, migration of contaminants is influenced by sorption processes taking place at the soil surface, thereby retarding the movement of pollutants. Migration of single, conservative, non-adsorptive pollutant species through soils using centrifuge modeling at a scale factor ranging from 1 g to 100 g was reported elsewhere (Evans *et al.*, 1994; Cooke and Mitchell, 1991; Hensley and Schofield, 1991; Hellawell and Savvidou, 1994; Hellawell *et al.*, 1993; Li *et al.*, 1994; Mitchell, 1994; Sills and Mitchell, 1995; Goodings, 1999). However, very few investigations on adsorptive pollutant (e.g., heavy metal) transport through porous media have been reported (Basford *et al.*, 2002; Antoniadis and Mckinley, 2000). Gurung *et al.* (1998) used a mini-drum centrifuge to study the migration of 200 mg/l zinc through 5 cm thick of compacted saturated sand and clay soil models with their corresponding high Peclet numbers of 29.1 and 169.7 at a scale factor of 50 g. Their findings showed that the mini-drum centrifuge could be a useful tool in modeling pollution migration problems because a good fit between centrifuge data and CXTFIT computer code data was obtained.

It is generally accepted that low acceleration scale factors should be used in centrifuge modeling to ensure the similitude of dimensionless parameters such as Peclet number (ratio of the mechanical dispersion to molecule diffusion) and Reynolds numbers (ratio between inertial and viscous forces in the fluid) that control the flow and fate of a contaminant (Mitchell, 1998). Poulose *et al.* (2000) studied moisture migration in a 6 cm unsaturated silty soil under three scale factors varying from 33.33 g to 75 g and reported that the advection in soils is dependent on the degree of saturation and highly affected by the homogeneity of the soil. Modeling of models was found to be valid only for nearly saturated soil conditions. On the contrary, Cooke and Mitchell (1991) carried out one-dimensional centrifuge modeling of sodium chloride into partially saturated fine sands. Their modeling work confirmed that one-dimensional transport of a conservative contaminant can be reproduced in centrifuge models. Mitchell (1994) studied the lateral spreading of a conservative solute in partially saturated fine sand and stated that centrifuge modeling does correctly recreate prototype transport phenomena, including transport due to matrix suction. Sills and Mitchell (1995) used a centrifuge to investigate diffusion in unsaturated soils and concluded that a geotechnical centrifuge can play a role in the testing, modeling and measurement of diffusion.

This paper reviews the scaling laws governing the centrifuge modeling of advection, hydrodynamic dispersion, and adsorption processes. The experimental conditions and centrifuge results obtained from two soil models at scale factors of 15 g and 20 g are presented. The dimensionless transport parameters and the cadmium concentration profile along the prototype soil depth are analyzed. The movement of moisture in unsaturated soils and the feasibility of using centrifuge modeling for pollutant migration in soils associated with sorption process are discussed.

Scaling Laws for Contaminant Transport

The mechanical behavior of a prototype soil mass under the earth's gravity g can be replicated in a small scale model of dimensions 1/n experiencing a centrifugal force of "ng." If the product of depth times acceleration is the same in model and prototype, the stress distribution throughout the model will be identical to that of the prototype.

The correct scaling of physical parameters relating to contaminant transport is essential for similitude of these processes in the centrifuge model and the prototype. The general scaling laws that govern the relationship between the model and corresponding prototype have been derived by Bachmat (1967) and Laut (1975) using inspectoral analysis. The dimensionless variables that are related to the migration of inorganic pollutants in saturated and unsaturated porous media are summarized as follows (Arulanandan *et al.*, 1988):

$$\pi_1 = \frac{C}{\rho_f} \quad \text{(concentration number)} \tag{1}$$

$$\pi_2 = \frac{\rho_f v d}{\mu} \quad \text{(Reynolds number)} \tag{2}$$

$$\pi_3 = \frac{v\mathrm{t}}{L} \quad \text{(advection number)} \tag{3}$$

$$\pi_4 = \frac{D_m t}{L^2} \quad \text{(diffusion number)} \tag{4}$$

$$\pi_5 = \frac{S}{\rho_f} \quad \text{(sorption number)} \tag{5}$$

$$\pi_6 = \frac{vd}{D_m} \quad \text{(Peclet number)} \tag{6}$$

$$\pi_7 = \frac{\rho_f g d L}{T_f} \quad \text{(Capillary number)} \tag{7}$$

where C is solute concentration, μ is fluid viscosity, D_m is the effective molecular diffusion, S is mass of adsorbed solute per unit volume, v is the average interstitial fluid velocity, T_f is the air-liquid surface tension, ρ_f is fluid density, g is gravitational acceleration, d is characteristic microscopic length (e.g., the mean diameter of soil particle), L is characteristic macroscopic length, and t is time.

In terms of the general scaling law (Arulanandan *et al.*, 1988), the dimensionless numbers π_1, π_3, π_4, π_5 and π_7, will be identical in model and prototype if the same porous media and fluid are used and the scaling is correct. Furthermore, if flow in model and prototype is laminar, Darcy's law is obeyed even without the equality of Reynold's number R_e. The Reynold's number π_2 describes the ratio between inertial and viscous forces in the fluid, which should be less than 1 for disregarding the inequality of Reynold's numbers in model and prototype (Goforth *et al.*, 1994).

The governing equation describing transport of dissolved contaminants is the advective-dispersive equation. The hydrodynamic dispersive process comprises a mechanical dispersion and a molecular diffusion. Since molecular diffusion is a material property, it will be the same in the model and the prototype. Mechanical dispersion, on the other hand, includes effects of both material properties and fluid velocity. With the same fluid, soil and contaminant concentration, molecular diffusion can be modeled according to the same scaling law as Darcy flow in a centrifuge model, whereas mechanical dispersion is not. In order to maintain consistent scaling law for both the advective and dispersive components, the mechanical dispersion should have negligible effect on the hydrodynamic dispersive process. The criterion is to maintain Peclet number $P_e < 1$ in the model (Arulanandan *et al.*, 1988). In general, the conditions of $R_e < 1$ and $P_e < 1$ can be met if fine-grained soils are used for the migration studies, which in fact is the case in the present study.

The migration of adsorptive pollutants is influenced by the required equilibrium time for a sorption process taking place at the soil surface. Such chemical process is at times non-instantaneous in nature and can occur in real time regardless of accelerated levels of flow. Thus, these transport mechanisms cannot be accelerated in the centrifuge. It is believed that the concentration of adsorbed pollutant can be found to be identical or very close in the model and prototype only if the same soil materials are used and equilibrium adsorption can be achieved in short time.

Soil Materials and Properties

The synthetic soils used in this centrifuge study consisted of sodium bentonite from BIOMIN Inc. (10% by weight), Ottawa sand (0.063 ∼ 0.6 mm) from U.S. Silica Company (50% by weight), 0.09 ∼ 0.15 mm fine sand (15% by weight) and 0.15 ∼ 0.3 mm medium sand (25% by weight). The adsorption of heavy metals onto sodium bentonite has been discussed by Lo and Yang (1998). Figure 1 shows the particle size distribution of the synthetic soil. The fitting line was generated by SoilVision (Fredlund *et al.*, 1997) in order to predict the soil water characteristic curve and thus the hydraulic conductivity of the unsaturated soil. The specific gravity of the soil is measured as 2.65. In this study, cadmium was selected as the heavy metal contaminant because its batch kinetic adsorption and adsorptive capacity by soils have been studied by the first author (Lo *et al.*, 2000). Cadmium solution of 100 mg/L

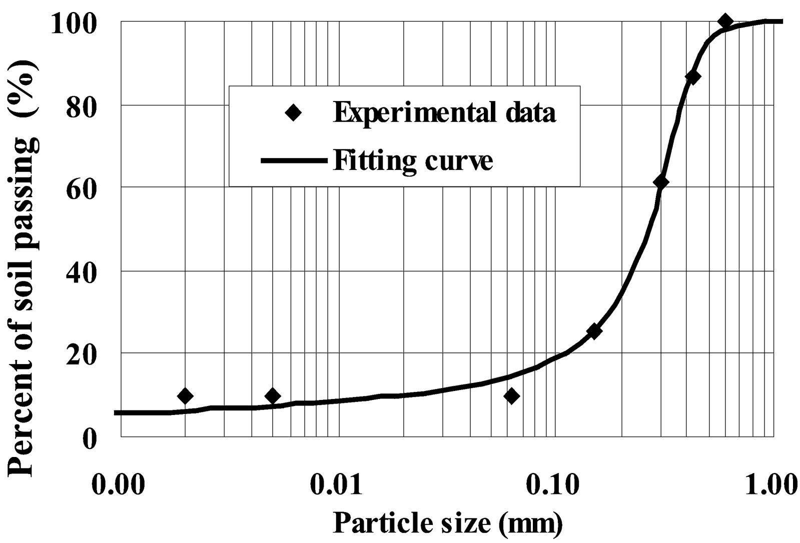


Figure 1. Grain size distribution of the synthetic soil.

was prepared using cadmium chloride ($CdCl_2$) in powder form. Sodium bentonite was used as adsorbents to remove and retard the migration of heavy metals.

The hydraulic conductivity of the saturated soil was determined as 2.5×10^{-6} cm/s in laboratory, according to ASTM D 5084 Standard Test Method for the measurement of hydraulic conductivity. Since it is very difficult to experimentally obtain the hydraulic conductivity for unsaturated soil, so computer code SoilVision was employed to assess in which the equation for determining the volumetric water content of unsaturated soil θ is based on Fredlund and Xing (1994).

$$\theta = \left[1 - \frac{\ln\left(1 + \frac{\psi}{c_r}\right)}{\ln\left(1 + \frac{10^6}{c_r}\right)}\right] \frac{\theta_s}{\ln\left(e + \left(\frac{\psi}{a}\right)^n\right)^m} \tag{8}$$

where θ_s is volumetric water content at saturation, e is natural number, 2.71828, a is approximately the air entry value of the soil, n is parameter that controls the slope at the inflection point in the soil water characteristic curve, m is parameter that is related to the residual water content, and c_r is constant related to the matrix suction corresponding to the residual water content. SoilVision is a knowledge-based database software designed to manage soil data and estimate unsaturated soil properties when laboratory data is limited. SoilVision can be used to predict soil-water characteristic curve and unsaturated hydraulic conductivity based on grain size distribution and saturated hydraulic conductivity of the soil. By using the SoilVison, the soil-water characteristic curve with residual volumetric water content of 0.09, $a = 12$, $n = 1.0$, $m = 1$, $c_r = 3000$ and the hydraulic conductivity as a function of suction pressure was produced (Figures 2 and 3). These two figures are most useful in determining the suction and the hydraulic conductivity whenever the volumetric water content of a soil is known. For instance, the suction corresponding to volumetric water content of 0.18 (or moisture content of 10%) was about 54.1 Pa according to Figure 2, and the hydraulic conductivity corresponding to a suction of 54.1 Pa was about 5.46×10^{-10} cm/s based on Figure 3.

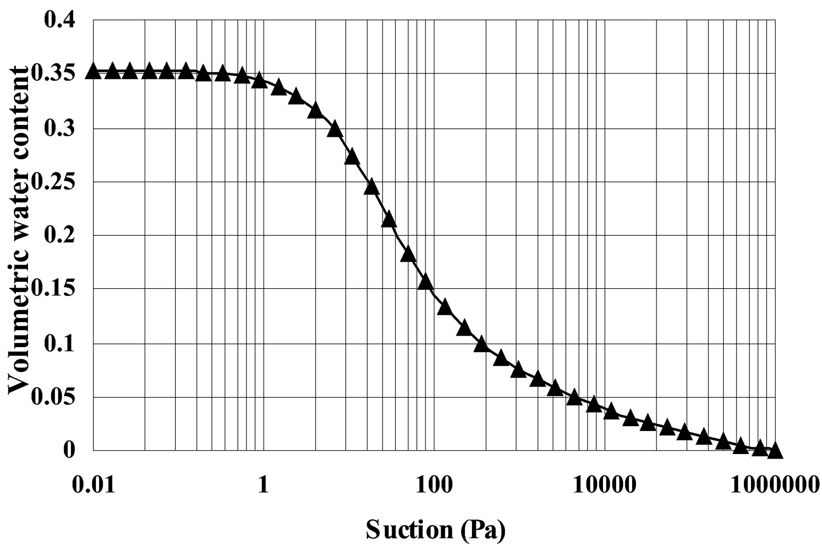


Figure 2. Soil-water characteristic curve predicted by Soil vision.

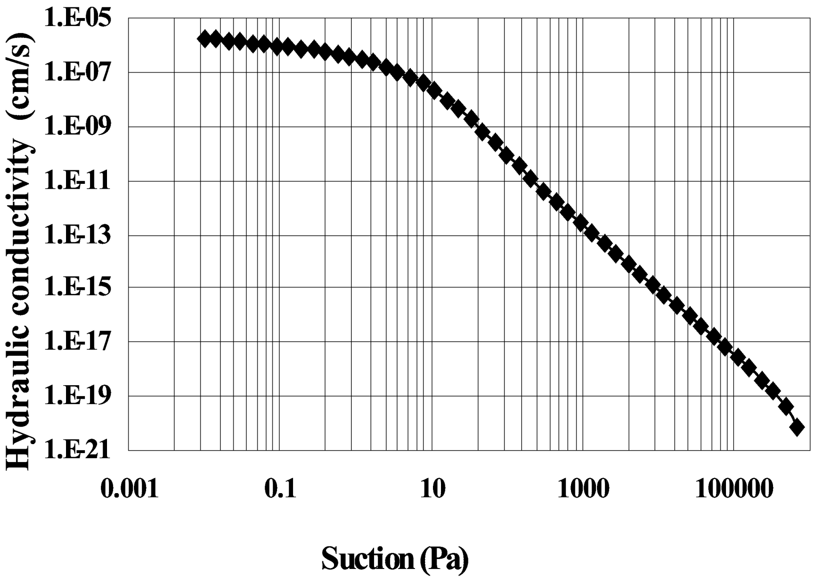


Figure 3. Hydraulic conductivity as a function of suction predicted by Soilvision.

Soil Models for Centrifuge Tests

In application of centrifuge modeling on geoenvironmental problems, it may be impossible to verify the experimental results from the centrifuge modeling against the actual field phenomenon, since reliable field data are extremely difficult to obtain due to a long time span of several decades, even centuries. For this reason, the approach adopted by this study to verify the centrifuge results is to perform centrifuge tests at two different acceleration scales, a technique known as "modeling of models." If the same phenomenon is observed at the two different scales, it is assumed that the centrifuge modeling provides an accurate representation of the prototype phenomenon. In this study, all the centrifuge model tests were conducted using a 400 g-ton centrifuge at the Hong Kong University of Science and Technology. The centrifuge has a rotating arm of approximately 8 meters in diameter and is capable of creating a gravity field of 150 times higher than the Earth's gravity for static model tests. The main features of this centrifuge have been described by Shen *et al.* (1998).

The prototype to be considered was a 340-cm-thick homogeneous soil layer contaminated by cadmium waste permeating the soil layer under a constant water head of 1241 cm. Two types of centrifuge tests were conducted to simulate the prototype at different scales, one using two saturated samples and the other using two unsaturated samples. Two soil samples with a height of 17 cm and 22.7 cm, corresponding to the centrifuge acceleration of 20 g and 15 g, were used for centrifuge tests. Table 1 shows the centrifuge modeling conditions for both saturated and unsaturated soils. The time was also scaled for the two models, as shown in Table 1.

Figure 4 shows the photo and the model setup used in tests for both saturated and unsaturated samples. The tank containing the cadmium solution has a plane size of 50 cm $\times$ 50 cm, which can effectively reduce the variation of water head or hydraulic gradient within 2% during centrifuge test due to its large surface area. The soil column, having a diameter of 10 cm, can be split into several layers of different heights in order to model the same prototype at different scale factors. Two valves above and below the soil column were used

Table 1
Experimental conditions of two centrifuge models

	Soil model 1	Soil model 2	Prototype
Height (cm)	17	22.7	340
Gravity acceleration (g)	20	15	1
Hydraulic gradient	3.65	3.65	3.65
Time (hr)	2.67	4.73	1066.7 (44.4 days)
Hydraulic conductivity (cm/s)			
Saturated soil	$6^{*}10^{-7}$	$6^{*}10^{-7}$	—
Unsaturated soil[1]	$5.46^{*}10^{-10}$	$5.46^{*}10^{-10}$	
Peclet number, P_e			
Saturated soil	0.34	0.25	—
Unsaturated soil[1]	0.0003	0.00023	
Reynolds number, R_e			
Saturated soil	$1^{*}10^{-3}$	$9^{*}10^{-4}$	—
Unsaturated soil[1]	$1^{*}10^{-6}$	$8^{*}10^{-7}$	

Note: [1]the hydraulic conductivity, Pe and Re of unsaturated soil were determined with respect to initial moisture content of 10%.

to start and stop the influent and effluent flow. An autosampling system consisting of a delivery tube and 20 effluent collection bottles was designed and mounted underneath the soil column. The autosampling system rotated at a determined time interval and the leaching solution from the soil column was delivered into solution collection bottles. This sampling process was carried out in-flight. The model setup is a closed system, with only the surface of the water in the tank and the outlet of the pipe (diameter of 5 mm) of the autosampling device, directed to the bottles for collecting the effluent, open to the atmosphere. The water heads were scaled by careful arranging of the split soil containers, and by scaling the distance between the water table in the water tank and the outlet, as shown in Figure 4. Consequently, the water pressures were identical at the corresponding points in each soil model.

Before testing, the dry soil was mixed with distilled water to a moisture content of 10% and sealed in a plastic box for at least 24 hours to allow for uniform moisture distribution. For unsaturated soil, the samples were compacted into the soil container to a bulk dry density of 1.7 g/cm^3 (a porosity of 0.359) at a moisture content of 10% by five layers using the same compactive effort as stated in a standard proctor test. For saturated models, the samples were infiltrated with water in 1g until a steady seepage was reached. Porous stones and filter papers were placed at the top and bottom of the soil column to ensure uniform flow.

In centrifuge tests, when the target centrifugal acceleration was reached, the two control valves would be simultaneously turned on and 100 mg/l cadmium solution was allowed to infiltrate into the soil during the spinning of the centrifuge. The cadmium solution of 100 mg/L was prepared from a cadmium chloride in powder form with a buffer of 0.01 M acetic acid and 0.01 M sodium acetate to maintain the solution at pH 5. At the end of the test, the valves were turned off and the inflow and outflow were stopped immediately. Though transport of cadmium during spin-down of the centrifuge may happen, the ratio between the time for spin-down of the centrifuge and the centrifuge testing time were 0.093 and 0.053, since the spin-down time in this study was only 15 minutes. The possible influence

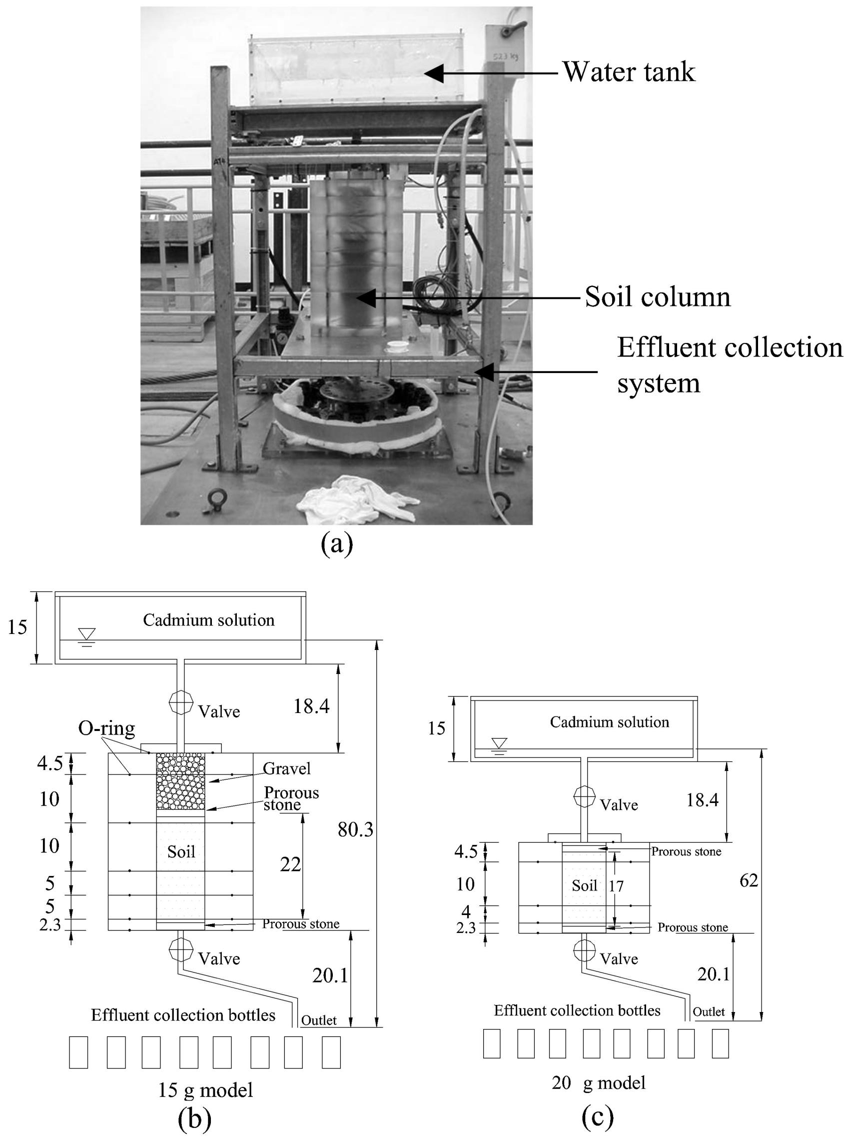


Figure 4. (a) Photo of centrifuge model setup, (b) 15 g model, and (c) 20 g model for saturated and unsaturated samples, units: cm.

of spin-down time on fluid movement in the soil column was insignificant. After the test, solution in the tank was removed, and the model was dissembled. The soil container was split into several pieces. The top 1 cm soil was removed since it was too soft. The rest of the soil was mostly divided into 5 $\sim$ 7 layers, each about 2.5 cm thick. The moisture content along the depth of the soil was determined according to ASTM method. The cadmium was extracted using 0.1 M ethylenediaminetetra acetic acid disodium (EDTA) to determine the concentration profile of cadmium along the depth of the soil. The extraction procedures were conducted based on the method mentioned by Lo and Yang (1999). The extraction efficiency of EDTA on our soil samples was first determined. One gram of soil sample prepared with a known amount of cadmium and 10 ml of 0.1 M EDTA solution were added to polyethylene centrifuge tube (Nalgene, 20 ml). The tube was sealed with a lid and rotated end-over-end for 30 minutes. The suspensions were then centrifuged at 10,000 r.p.m. for 15 minutes. After centrifugation, the supernatant was filtered and measured by AAS (Atomic Absorption Spectrophotometer, Hitachi Z-8200) for cadmium concentration. The extraction efficiency was found to be over 90%. The same procedures were used to extract cadmium from the soil samples obtained from centrifuge tests. The cadmium content in soil samples determined by EDTA extraction included the cadmium adsorbed onto bentonite as well as in pore water. The concentration of cadmium in soil was expressed as the total mass of cadmium divided by the mass of the soil. Moisture content of unsaturated soil samples was measured and plotted as a function of prototype height. The concentration of cadmium in the effluent solution was also determined by AAS.

Results and Discussion

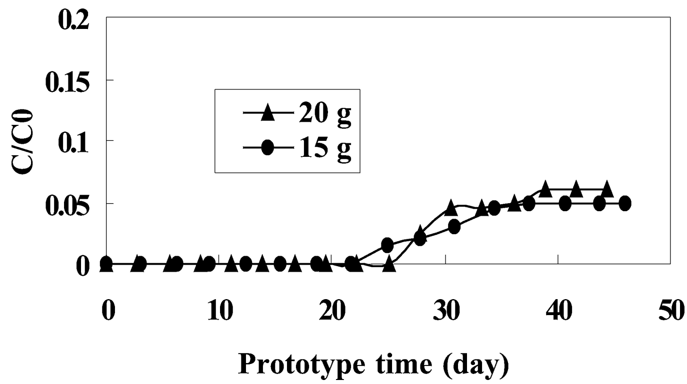
Cadmium Migration in Saturated Soils

It is widely accepted that the scaling laws for advection and dispersion process are valid for the centrifuge modeling of inorganic, non-adsorptive compounds through saturated soils (Arulanandan *et al.*, 1988; Cooke, 1991), provided that Reynolds number and Peclet number are less than 1.0. In this study, more attention has been paid to the similarity of the sorption process of the two saturated samples. The centrifuge results for the two saturated samples under 15 g and 20 g are shown in Figure 5. It can be seen that the total concentrations of cadmium in pore water and that sorbed in soil particles varies along the depth of a prototype are basically identical. To address the influence of mechanical dispersion, the Peclet numbers in centrifuge models were calculated using Equation (7). The molecular diffusion coefficient D_o of cadmium in pure water was found to be 7.19×10^{-6} cm^2/s (Yang and Volesky, 1998). The effective diffusion coefficient D_m in porous media can be obtained from the molecular diffusion coefficient by

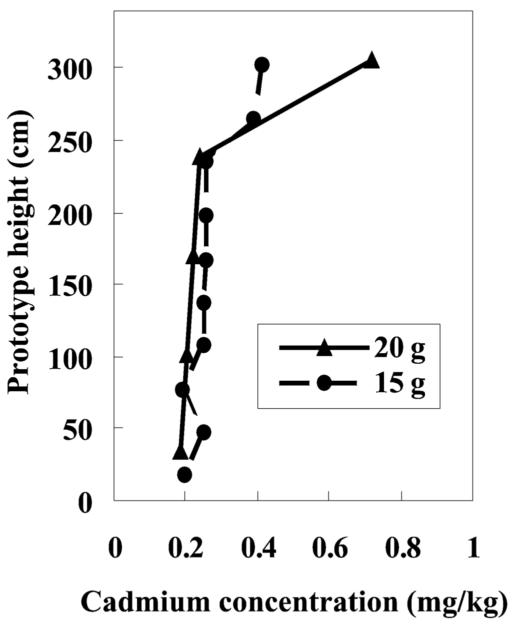
$$D_m = \tau D_o \tag{9}$$

where τ, less than 1, is the tortuosity factor that accounts for the increased distance that the contaminant must travel to get around the soil grains. In this study, $\tau = 0.5$ was used for the synthetic soil, which is based on the typical value for chemical species in geologic media (Freeze and Cherry, 1979). The calculated Peclet numbers are 0.49 and 0.3, which are less than 1, for the 20 g and 15 g centrifuge models indicating that molecular diffusion dominates the dispersion process. Therefore, the hydrodynamic dispersion process is rather independent of velocity. In addition, by using Equation (2), Reynolds numbers were calculated to be about 1×10^{-3} and 9×10^{-4} for the 20 g and 15 g models. So the flow is laminar and Darcy's law is obeyed in this study.

It is believed that similarity can be achieved if the required time for sorption is short and equilibrium is able to reach. In centrifuge modeling, sorption reactions proceed in real time, whereas the time for advection and diffusion can be accelerated by a factor of N^2. In this study, the testing times in centrifuge were 2.67 and 4.8 hours for 20 g and 15 g models, in which about 93 $\sim$ 95% of cadmium equilibrium sorption have been achieved according to the batch kinetic sorption tests conducted by Lo *et al.* (2000). Lo *et al.* found that 97% of cadmium equilibrium sorption required 10 hours of contact time and a complete equilibrium sorption required 24 hours. As pointed out by Gronow *et al.* (1988), although the centrifuge modeling might not reproduce the prototype sorption process, it can still provide useful



(a)



(b)

Figure 5. (a) Effluent cadmium concentration vs. prototype time and (b) concentration profiles in saturated soils for 15 g and 20 g models.

information on pollutant transport in soils, particularly in comparison with data from tests using conservative tracers. Based on the centrifuge findings shown in Figure 5 and the dimensionless analysis on Peclet and Reynolds numbers, it could be concluded that the centrifuge modeling for cadmium transport under these two low g-levels appears to be valid because the two saturated models gave almost the same prototype.

Moisture Movement in Unsaturated Soils

The initial moisture content and degree of saturation of the soil were 10% and 0.47 for the two unsaturated models. During the spinning of the centrifuge, no effluent solution

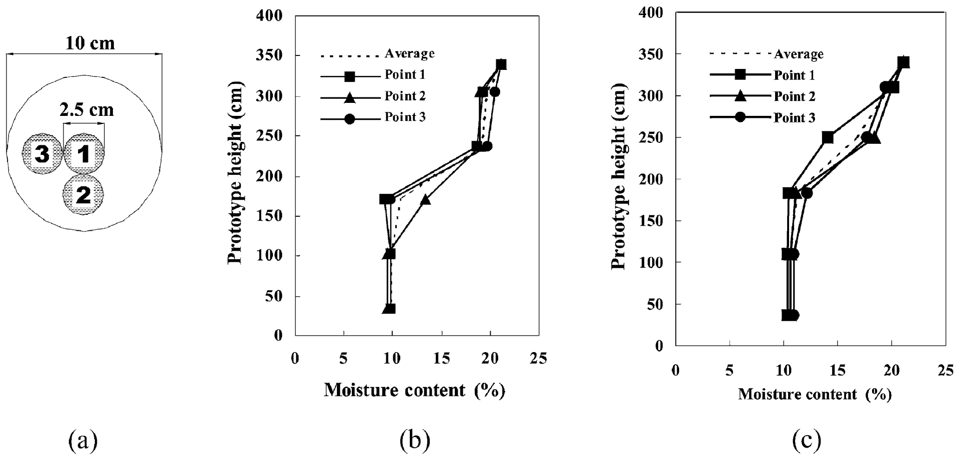


Figure 6. Moisture profile of unsaturated models: (a) sampling positions, (b) at 15 g, and (c) at 20 g.

was collected at the bottom of the soil column due to the low hydraulic conductivity of the unsaturated soil. After the centrifuge tests, soil was sliced into 5–10 layers dependent on the total height of the soil column. In each layer, samples from three positions were collected: the center position denoted as point 1, the other two positions denoted as points 2 and 3, as shown in Figure 6a. The moisture content and the total concentration of cadmium in the unsaturated soil samples were measured. The moisture contents of each soil sample as a function of prototype height and their average values based on three samples are plotted and shown in Figure 6b and 6c. It is found that the average moisture profiles of the two models show good agreement (see Figure 7), which indicates that the behavior of moisture movement along the two soil columns driven by the internal suction and gravitational gradient was similar. Figure 8 delineates that the concentration profile of cadmium from the two models determined under 15 g and 20 g are almost

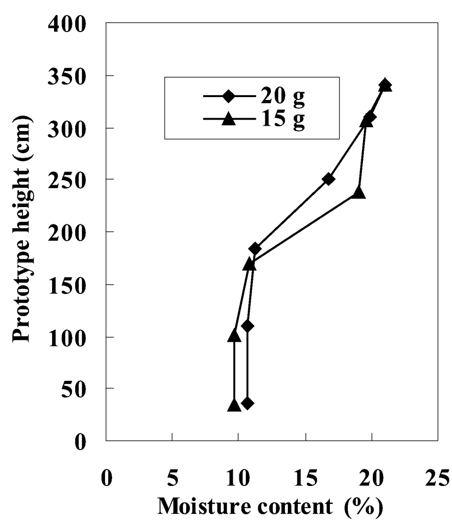
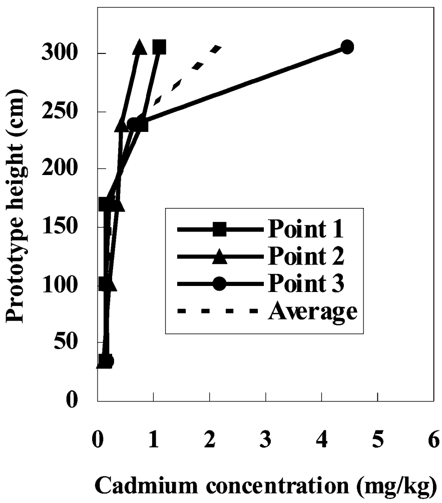


Figure 7. Comparison of moisture content of the two unsaturated models at 15 g and 20 g.



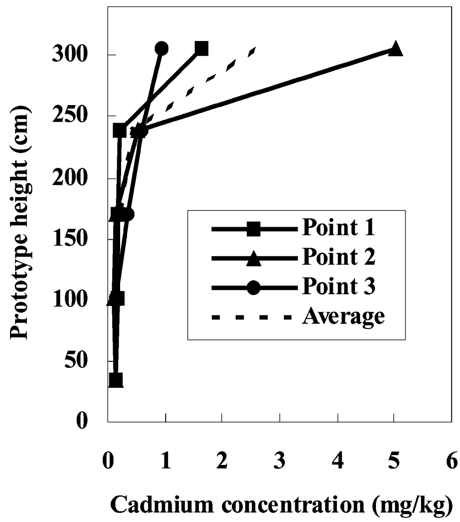


Figure 8. Cadmium concentration profiles along the soil depth: (a) 15 g model, and (b) 20 g model.

identical. The water flow process in the unsaturated soil is, therefore, found to reproduce in centrifuge.

The feasibility of using geotechnical centrifuge to study unsaturated flows is still controversial (Goforth *et al.*, 1994; Poulose *et al.*, 2000; Mitchell, 1994; Sills and Mitchell, 1995; Mitchell, 1998). By analyzing the test conditions of this study and comparing them with those conditions from literature (Poulose *et al.*, 2000), some important factors that might influence the centrifuge results are noted. In modeling of model tests, for one-dimensional migration of pollutant and moisture, model test conditions must be well controlled so that the hydraulic gradient and moisture content at the same elevation of the soil could be uniform. Side water flow along the soil column should be carefully prevented, especially when the cross-sectional area of the soil column is small and a large portion of infiltration water flows to the soil boundary. The ratio between the centrifuge testing time and the time for spin-down of the centrifuge should be kept as large as possible in order to reduce the influence of spin-down time on pollutant migration and moisture movement in the soil column. The spin-down time in this study was 15 minutes. Compared to the centrifuge testing time of 160 minutes, the spin-down is about 9.4% of the testing time, which is still acceptable.

Cadmium Migration in Unsaturated Soil

Figure 8 shows the profiles of the total cadmium concentration of the two models. Figure 9 shows the concentration profiles of cadmium in unsaturated soil, expressed in average values taken from three sampling points, for the 15 g and 20 g models. The variation of cadmium concentration with soil depth follows a clearly defined trend of high concentration on the top horizons and a fall-off with depth. The result is consistent with that found by some researchers (Adriano, 1986; Lagerwerff and Specht, 1970) for strongly polluted soils, such as industrial or mining areas, where cadmium waste was disposed of to ground surfaces. Based on the centrifuge findings shown in Figures 7 and 9, there is good agreement between the 15 g and 20 g tests on both moisture movement and cadmium transport. It can be

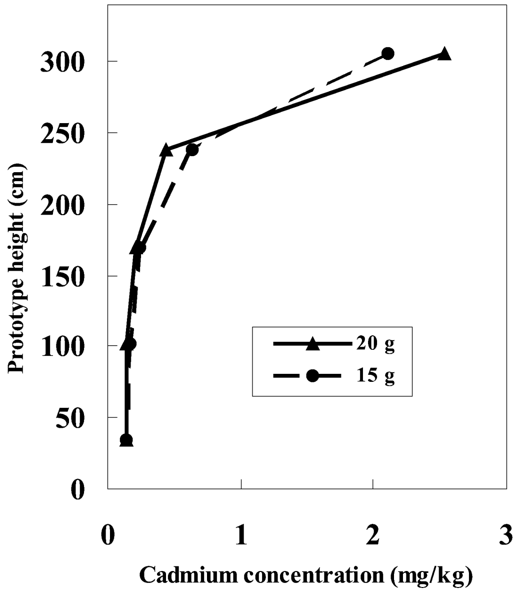


Figure 9. Comparison of the average cadmium concentration in unsaturated soil for 15 g and 20 g model.

concluded that the advective-dispersive-adsorption transport has been correctly modeled in this study. It further implies that the vertical migration of cadmium driven by gravity, suction, and concentration gradient can be investigated by centrifuge modeling.

As mentioned earlier in the section of soil materials and properties, the corresponding unsaturated hydraulic conductivity at moisture content of 10% was about 5.46×10^{-10} cm/s, and this value was used to assess the Peclet and Reynolds numbers of the two unsaturated models (Table 1). These two dimensionless numbers are so small in this study that higher gravitational acceleration might be able to use for simulation of cadmium transport in unsaturated soils. However, the maximum acceleration level must be carefully selected to make sure that the criteria of Peclet and Reynolds numbers are met and the centrifuge testing time (or the contact time between the cadmium and soil particles) is long enough for achieving an equilibrium sorption.

Conclusions

The results obtained from centrifuge model tests provided a basis for the study of the migration of adsorptive inorganic contaminants (such as cadmium) in soils. For both saturated and unsaturated soils, 15 g and 20 g models have been undertaken for modeling of model tests. The modeling of models were scaled up to prototype.

Based on the limited number of tests (4 in total), the transport behavior of cadmium as reflected by the concentration profiles along the prototype height was found to be similar for both saturated and unsaturated soils. One-dimensional moisture movement in the unsaturated soil can be reproduced in centrifuge models. It can be concluded that centrifuge modeling might be a potential tool to study the advection-dispersion-adsorption process of cadmium migration through saturated and unsaturated soils, on condition that the experimental conditions meet the requirement of Peclet number less than 1.0 and Reynolds number less than 1.0.

Since both the Peclet and Reynolds numbers are rather small when studying the cadmium transport in unsaturated soils, higher accelerated g-scale can be adopted without violating the criteria of the above two dimensionless numbers. However, the maximum gravitational acceleration must be determined carefully to ensure that this g-level is not too large for the establishment of equilibrium physical and chemical adsorption. It is because a larger g-level implies a shorter centrifuge testing time and a higher difficulty in achieving sorption equilibrium.

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