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Centrifuge Modelling of Contaminant Transport through Compacted Clay Liners

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Introduction

Physical modelling of soil behaviour has always played a pivotal role in helping the designer to acquire a better understanding of the actual behaviour under similar stress conditions in the field. In this respect, laboratory tests such as triaxial, consolidation and shear box tests are still used extensively and do provide reliable data provided that adequate testing procedures are adhered to. Centrifuge testing of soils constitutes another development in the field of physical modelling in geotechnical engineering. Centrifuge modelling is now recognised as a versatile and powerful experimental approach not only for research but also for practical purposes.

There are many everyday applications of centrifugation that could be made available to both practitioners and educators. Centrifuge modelling and testing at relatively low gravitational levels are particularly relevant to geoenvironmental practice and education. The following applications are typical (Mitchell 1998):

- centrifuge modelling to produce realistic data on the movement and fate of contaminants in groundwater for the validation or further development of numerical solutions;
- centrifuge testing for the determination of geoenvironmental properties such as hydraulic conductivities and diffusion coefficients in fine-grained soils;
- centrifuge model design using dimensional similitude for continued education and a better understanding of geoenvironmental concepts.

The transport of contaminants in subsurface flow systems is often predicted by using mathematical modelling techniques wherein the processes under simulation are modelled by a set of governing equations, which are solved using either analytical or numerical methods. Modelling results depend on a good understanding of the fundamental processes involved and the

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relevant mechanisms responsible for contaminant transport in the soil mass. To overcome shortcomings associated with the field and laboratory tests and numerical and analytical models, researchers have employed geotechnical centrifuge modelling. The usefulness and effectiveness of a geotechnical centrifuge for modelling contaminant transport mechanisms in soils have already been demonstrated and results of such studies are being used extensively for validating existing mathematical models (Hegde, 2002). It has also been demonstrated that the prototype effective stress regime can be simulated in a centrifuge model with no loss of generality (Schofield 1988; Arulanandan et al. 1988). For validation of the results obtained from centrifuge modelling various scaling laws governing a particular phenomenon have been derived. The modelling of models has also been conducted by the previous investigators to check the generality of the obtained results. If the results from a series of tests are noticed to be consistent then the modelling of model is valid. This generates high confidence in centrifuge test results. The centrifuge modelling of contaminant transport has several advantages: the time for testing soils with small hydraulic conductivity is reduced; non uniform flow is negligible due to lateral stress that results from the inertial acceleration; and the effects of *in situ* confining stresses are included in the modelling.

The existing studies on contaminant transport through fine-grained soils are carried out using large geotechnical centrifuges. Due to higher cost of modelling using larger centrifuges, the adoption of a system which is less costly and at the same time ensuring the effective and accurate modelling with an utmost satisfaction is desirable. In the present study, an attempt has been made to carry out experiments using a small geotechnical centrifuge on contaminant transport through compacted clay liners. Systematic laboratory investigations have been performed using the concept of modelling of models to verify the theoretical scaling laws for contaminant transport through the liners. The results of one-dimensional contaminant transport through clay liners are presented. It is concluded that the centrifuge models, which represent the prototype stress distribution more closely, will yield more realistic data on contaminant transport through soils and clay liners, which in turn can be used to verify mathematical models.

Contaminant Transport: Background

Contaminant transport through barriers includes contaminants carried with migrating fluid due to hydraulic gradients (advection) and molecular diffusion in response to chemical concentration gradients. The transport processes that control the flux into and out of the elemental volume are *advection* and *hydrodynamic dispersion*. Loss or gain of solute mass from the solution is governed by the processes of *adsorption* and *degradation*. In general, the transport of contaminants in soil-water system is governed by the processes of: (i) Advection, (ii) Hydrodynamic dispersion, (iii) Sorption, (iv) Volatilisation and (v) Degradation.

Transport through Compacted Clay

Compacted clay liners have been the subject of recent debate with respect to both the hydraulic conductivity that can be achieved in the field (Day and Daniel 1985; Benson and Daniel 1990) and the potential impact of soil leachate interaction upon hydraulic conductivity (Fernadez and Quigley 1985;

Bowders and Daniel 1987). The thickness of the compacted clay liner varies between 0.9 and 1.8 m. The *maximum* required hydraulic conductivity is 10^{-9} m/s (Das 1998). The use of engineered clay barriers to control the chemical flows entering the groundwater adjacent to landfill sites was discussed by Quigley et al. (1988). However, experience to date would suggest that with good engineering practice and quality control, good quality low hydraulic conductivity compacted clay liners can be constructed (Rowe 1988; Daniel 1993). An approach for analysing one dimensional contaminant transport from a landfill through a partially saturated landfill liner was described by Fityus et al. (1999). The quasi-linearised Richards equation was employed to predict the steady state, unsaturated volumetric moisture distribution throughout a soil liner. They concluded that employing a steady-state moisture distribution in the dispersion-advection equation is a reasonable approximation to make.

The rate of advective flow through clay liners depends on the hydraulic conductivity, gradient and liner dimensions. A straightforward analysis of the contaminant loading in the steady state can be made using Darcy's law and the leachate constituents concentration. The critical parameters for the analysis can be taken from the actual field problem. The hydraulic head is equal to the height of free leachate above the liner plus the thickness of the clay liner, not the height of the liner alone. The solution then is a direct application of Darcy's law to yield the flow rate. The transport can be determined as the product of the contaminant concentration and the flow rate. In the following section, the work carried out by the previous investigators relevant to the present study is presented.

Centrifugal modelling has been employed to investigate fluid flow in porous media (Alemi et al. 1976; Nimmo et al. 1987). Dimensional analysis was carried out to determine the scaling laws for centrifuge modelling of flow of pollutants in groundwater (Arulanandan et al. 1988). The validity of the scaling laws was examined by conducting modelling of model tests. A new method for measuring equilibrium distribution coefficients using a constant-head permeameter and a laboratory centrifuge was presented by Cellorie et al. (1989). Equilibrium distribution coefficients were computed from the solute equation and a least-squares parameter estimation procedure. Experimental and theoretical investigations of the progression of a contaminant pulse through a clay layer were reported by Evans et al. (1994). In the theoretical investigation, a simple model was used to predict the interstitial velocity which was then used in a simple one-dimensional, finite difference program to predict the contaminant profile in the layer.

Mitchell (1994a) has studied the lateral spread of a conservative solute (NaCl) in a partly saturated fine sand at simulated gravitational accelerations of 25 and 50g. Each section of the soil column represented 1 m of the prototype depth. Pore water contaminant analysis was carried out on all models (by dissection of models) after 2, 6 and 12 months of prototype time. Agreement between the results of the tests indicated that centrifuge modelling of advective transport (due to matrix suction and gravity) and diffusive transport is advantageous.

The development and use of a 'flexible, no lateral strain' centrifuge test cell, designed to evaluate clay liner-permeant compatibility under prototype effective-stress conditions, was presented by Mitchell (1994b). The experimental results showed that wet-compacted soils with kneading were as much as one order of magnitude less permeable than dry-compacted samples. The dry-compacted samples showed increases in hydraulic conductivity when common household chemical cleaners were used as the permeant.

Modelling of oil releases in a unsaturated sand was performed at scales of 15 and 30 (Knight and Mitchell 1995) and the results supported that a centrifuge can be used to model contaminant transport in the vadose zone. The modelling of model suggested that non-gravity dependent parameters could be modelled correctly in the centrifuge.

Rowe and Badv (1996) have performed laboratory experiments to examine the mechanism of diffusion of chloride and sodium ions through: (i) saturated compacted clayey silt, coarse sand and fine gravel; (ii) unsaturated coarse sand and fine gravel; and (iii) advective-diffusive transport through a compacted clayey silt underlain by a layer of unsaturated fine gravel. Diffusion coefficients were obtained for sodium and chloride ions from these tests on saturated fine gravel and the corresponding diffusion coefficients for unsaturated fine gravel. Theoretical predictions for diffusion in unsaturated soil were made with the diffusion coefficients and the other available data regarding the material. There was good agreement with the theoretical and observed results.

The use of centrifuge modelling as means of accessing clay liner-leachate compatibility was evaluated by Theriault and Mitchell (1997). A flexible-boundary, natural strain centrifuge permeameter was used to study the effects of permeating compacted Trail Road Landfill liner clay with three permeants: tap water, a concentrated potassium chloride solution, and a synthetic leachate. Centrifuging has been continued for up to 2 weeks to determine long-term hydraulic conductivity. Values measured in centrifuge models were in good agreement with expectations from clay-permeant compatibility theory.

Governing Equation of Contaminant Transport

The common starting point in the development of differential equations is to describe the transport of solutes in the subsurface and to consider the flux of solute into and out of a fixed-elemental volume within the flow domain. The analytical model describing advective-dispersive transport for solutes in saturated porous media can be derived from the law of conservation of mass, by assuming that the porous medium is homogeneous and isotropic, and that the flow is steady state and that Darcy's and Fick's laws are applicable. Although most barriers such as compacted clay liners are constructed in partially saturated conditions, they are often fully saturated due to prevailing high groundwater conditions and/or due to the leachate accumulated in the facility. Therefore, in most cases full saturation is a reasonable assumption. The assumption of homogeneity is also reasonable in the case of compacted clay liners. The isotropy assumption may lead to errors for natural soils. Since the flow is often one-dimensional through the barrier, the isotropy assumption will not result in significant errors (Acar and Haider 1990). A conservation of mass statement for this flow domain is given by Freeze and Cherry (1979):

net rate change of mass of
solute within the element = (flux of solute into the element) - (flux of solute out of the element) ± (loss (or gain) of solute mass due to reactions)

The solute transport equation for one-dimensional conditions is as follows:

$$n\frac{\partial C}{\partial t} = nD\frac{\partial^2 C}{\partial z^2} - n\, v_s \frac{\partial C}{\partial z} - \rho_s K_d \frac{\partial C}{\partial t} \qquad (1)$$

where
n = porosity of the soil system,
C = solute concentration at depth z (vertical position co-ordinate) at time t,
D = coefficient of hydrodynamic dispersion, which combines the effects of both molecular diffusion (D^*) and mechanical dispersion (D_m),
v_s = seepage velocity,
ρ_s = mass density of the minerals making up the soil, and
K_d = distribution coefficient of the contaminant.

The governing equation for the majority of contaminant transport models is the advection-diffusion equation defined over a specific domain. Retardation processes, particularly sorption and ion exchange, can have a significant effect on transport rates. Approach to these processes is to represent them in transport equations by introducing a retardation factor. The retardation factor R represents the average speed of contaminant transport in the subsurface environment relative to that of groundwater and is expressed as

$$R = 1 + \frac{\rho_b}{n} K_d \qquad (2)$$

where ρ_b = bulk density of the porous medium, expressed as $\rho_b = \rho_s (1 - n)$.

The quantity $\rho_s (1 - n)$ is the total mass of solids per unit volume of porous medium. The value of R can be estimated using a value of K_d and knowledge of the soil properties. The physical significance of the R is that it measures how much slower a solute migrates than that of water. A retardation factor of ten means that the average speed of solute is ten times slower than that of water.

Combining Equations (1) and (2), the governing equation for combined advection-diffusion including linear sorption becomes

$$R\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v_s \frac{\partial C}{\partial z} \qquad (3)$$

In the present study, an attempt has been made to simulate the above governing transport equation in the geotechnical centrifuge for compacted clay liners.

Principles of Centrifuge Modelling

The two basic principles of centrifuge modelling (Schofield 1988) are: (1) increase of self weight by increase of acceleration equal to the reduction of model scale and (2) reduction of time for model test as the scale is reduced. For the performance of the model to be similar to that of prototype, the soil should possess the same fabric structure, sensitivity and stress history, as well as satisfying the same loading path, boundary stress state, and pore pressure under test. It would be difficult to meet all these requirements and some deviation from similitude appears inevitable.

In centrifuge modelling, a soil column is constructed at a vertical scale of one to N so that a depth L in the model corresponds to a depth N × L in the prototype (Figure 1). In general, one can write:

$$L_m = \frac{L_p}{N} \tag{4}$$

where L is any vertical dimension and the subscripts *m* and *p* denote the model and prototype respectively. When the model is subjected to a centrifugal acceleration Ng where g = gravitational acceleration, the self weight of the model with the length L_m simulates the stress distribution in the prototype with length L_p. Figure 2 shows the plan view of the model rotating in the centrifuge (Hegde 2002). The artificial gravitational acceleration contains two components:

- the radial acceleration A_r away from the centre of rotation:

$$A_r = r\omega^2 \tag{5}$$

where r = radius (m) and ω = angular velocity (rad/s); and

- the tangential acceleration A_t perpendicular to the centre of rotation in the direction of rotation:

$$A_t = r\dot{\omega} \tag{6}$$

where $\dot{\omega}$ = angular acceleration (rad/s^2). However, the tangential acceleration can be neglected because its magnitude is small and it only exists while the centrifuge is accelerating or decelerating.

Scaling Laws

The general scaling laws that govern the relationship between the model and its prototype, with respect to transport processes in porous media have been derived using dimensional analysis (Arulanandan et al. 1988; Hensley and Schofield 1991; Cooke and Mitchell 1991). The basic assumption in this approach is that both the interstitial fluid and soil grains are incompressible. A summary of the scaling relationships relevant to the contaminant transport is presented in Table 1.

Experimental Programme

Experimental set-up consists of a small geotechnical centrifuge available at Indian Institute of Technology Bombay, as shown in Figure 3. The details of the small geotechnical centrifuge used for the present study are given in Table 2. Figure 4 depicts the experimental container set-up, which consists of an acrylic cylinder, 90 mm in diameter (internal) and 100 mm in height. The model dimensions and the corresponding prototype dimensions of silty soil, liner and steel tube (sampler tube) are given in Table 3.

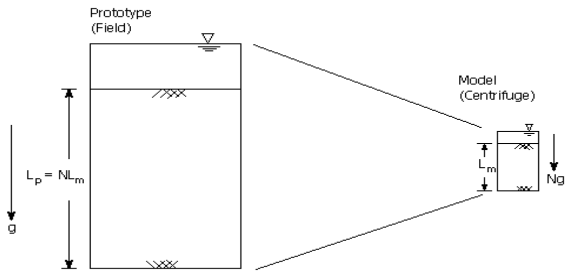

Fig. 1 Comparison of Prototype and Model

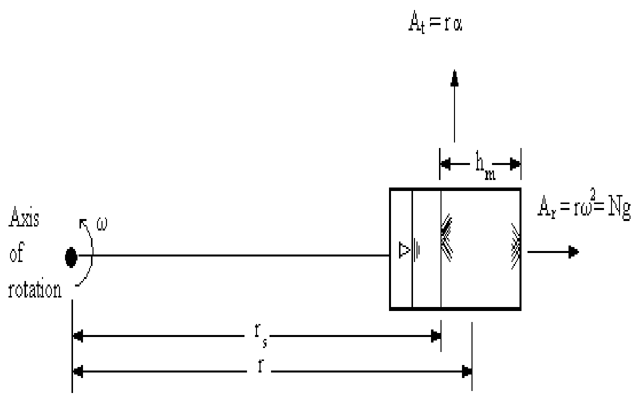

Fig. 2 Plan View of Model Rotating in the Centrifuge

TABLE 1: Scaling Relationships

Event type	Quantity	Symbol	Dimension	Scaling ratio
	Characteristic macroscopic length (sample height)	*L*	L	N^{-1}
General Processes/ Mechanisms	Area	*a*	L^2	N^{-2}
	Volume	*V*	L^3	N^{-3}
	Mass	M	M	1
	Force	*F*	MLT^{-2}	N^{-2}
	Centrifuge acceleration	*A*	LT^{-2}	N
	Interstitial flow velocity	*V*	LT^{-1}	N
Contaminant Transport Mechanisms	Concentration	*C*	ML^{-3}	1
	Hydrodynamic dispersion coeff.	*D*	L^2T^{-1}	1
	Time	*T*	T	N^{-2}

The locally available silty soil was used as subsoil. Marine clay was used to model the clay liner. A 2N sodium chloride (NaCl) solution was used to represent the model pollutant in all the experiments. Sodium chloride was selected because it is regarded as a non-reactive contaminant (McKinley et al. 1998). The various properties of silty soil and marine clay are given in Table 4.

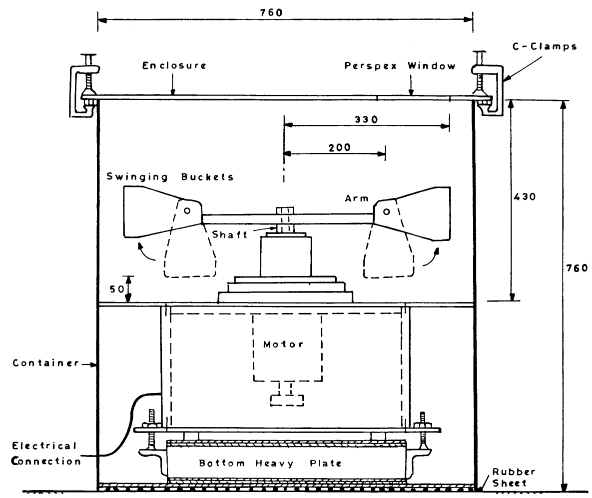

Fig. 3 Schematic Diagram of the Small Centrifuge

TABLE 2: Details of the Small Centrifuge

Parameter	Value
Type	Swinging buckets on either side of the arm
Arm Radius	200 mm
Maximum Outer Radius	315 mm
Maximum Pay Load	2.4 kg
Centrifugation Range	250-1000 rpm
Maximum Acceleration	300 g
Capacity	0.72 g-tons
Spin-up Time	5 s
Spin-down Time	30 s

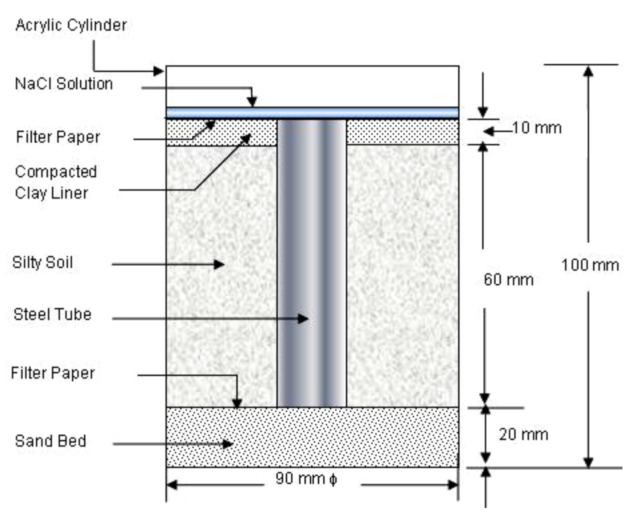

Fig. 4 Schematic Diagram of Experimental Container Set-up

TABLE 3: Model and Prototype Dimensions

Description	Model dimension		Prototype dimension	
	100g	150g	100g	150g
Thickness of Clay Liner (mm)	10.0	6.667	1000	1000
Thickness of Silty Soil (mm)	50.0	33.333	5000	5000
Height of Steel Tube (mm)	60.0	40.000	6000	6000
Thickness of Sand Layer (mm)	20.0	13.333	2000	2000

The silty soil was compacted at a dry density (ρ_d) of 1.31 gm/cc, and water content (w) of 25 % and marine clay was compacted at ρ_d of 1.24 gm/cc, and *w* of 34 % in the model container; little less than their respective maximum dry densities due to small model container. To represent the boundary conditions properly, a 20 mm (for 100g tests) thick saturated fine sand bed having a hydraulic conductivity of 4.75×10^{-5} m/s was provided at the bottom of the container. A steel tube of 24.4 mm external diameter, 1.3 mm thickness and 60 mm long, was inserted at the centre of the soil column (Figure 4) to simulate the one-dimensional contaminant transport and to extract the soil sample for chloride ion concentration determination at required levels.

TABLE 4: Soil Properties

Property	Powai soil (Silty soil)	Marine clay
Specific Gravity	2.74	2.68
Liquid Limit (%)	50	79
Plastic Limit (%)	33	40
Grain Size Distribution		
Sand (%)	39	5
Silt (%)	58	62
Clay (%)	3	33
Standard Proctor Test		
MDD (gm/cc)	1.54	1.31
OMC (%)	26.0	31.0
Hydraulic Conductivity (m/s)	3.62×10^{-8}	1.89×10^{-10}
Classification (based on USCS)	ML	CH

Equation (7) is used to calculate appropriate centrifuge speed (rpm) to attain the required level of centrifugal acceleration (N):

$$n = \frac{60}{2\pi} \sqrt{\frac{N\,g}{r_e}} \tag{7}$$

where *n* is the centrifuge speed (rpm), r_e is the effective radius and *g* is the acceleration due to gravity. The effective radius is calculated assuming that there is similarity of stresses at two-thirds model depth from the top (Taylor 1995). The experiments have been carried out with an effective radius of 233.89 mm for 75g test, 251.67 mm for 100g tests and 269.45 mm for 150g tests. The speed of the centrifuge for different acceleration level is given in Table 5.

TABLE 5: Calibration for the Centrifuge

g-level (N)	Effective radius (mm)	Speed (rpm)
75	233.89	536
100	251.67	596
150	269.45	706

For centrifuge modelling of contaminant transport, two sets of experiments are carried out. In experiment No. 1, centrifuge modelling of contaminant transport is studied using only the silty soil as a whole sub-base without the clay liner. In experiment No. 2, a 10 mm thick (prototype thickness = 1.0 m at 100g) marine clay liner is provided at the top of the silty soil. A 15 ml of 2N NaCl solution is placed at the top of the soil and the whole assembly is then mounted on one of the centrifuge baskets (buckets). After placing the counter weight on the other basket, centrifuge is started so as to allow the NaCl solution to migrate through the specimen in an elevated accelerated environment. Centrifuge is spun for 30 minutes, 60 minutes and 90 minutes (or as desired) at two acceleration levels of 100g and 150g. The steel tube with soil inside is removed from the container. The soil samples are extruded in three equal layers of 20 mm thick and stored in polythene bags. Upper layer is marked as L1, middle layer as L2 and bottom layer as L3 for further quantitative chemical analysis. The chloride ion concentration in each layer is determined using Argentometric method described below.

Sample Preparation

A 5 gm of representative air dried soil sample (extracted from the steel tube sampler) is mixed with 100 ml of distilled water and stirred for 10 minutes using a magnetic stirrer. The solution is kept for 12 hours to allow the soil particles to settle and then the upper portion of the solution is filtered with Whatman No. 542 filter paper.

Chemical Analysis

A 20 ml of filtered solution is diluted with 20 ml of distilled water and the resulting solution is used for titration. A 1.0 ml of potassium chromate (K_2CrO_4) indicator is added to this solution. The solution is titrated with 0.0139N silver nitrate ($AgNO_3$) titrant to a pinkish yellow end point.

The reagent blank value is also established using the titration method outlined above. The chloride ion concentration is estimated using:

$$\mathrm{mg\ Cl^-/l} = \frac{(\mathrm{A}-\mathrm{B}) * \mathrm{N} * 35450}{\mathrm{ml\ of\ sample}} \tag{8}$$

where A = ml titration for sample, B = ml titration for blank and N = normality of $AgNO_3$.

Results and Discussion

The study presented here demonstrated the applicability of centrifuge modelling for contaminant transport by carrying out a series of experiments using marine clay as a compacted clay liner and silty soil as a sub-base. This paper has also illustrated the use of small geotechnical centrifuge as a research tool to understand the diffusion mechanism of contaminant transport. The centrifuge tests have been performed at two inertial accelerations, 100 and 150g corresponding to rotational speeds of 596 and 706 rpm. The liner consisted of 1 m thick marine clay with a design hydraulic conductivity of 1.89×10^{-10} m/s.

In order to study the consistency of the test results, modelling of models has also been carried out at two different g-levels, i.e. 75 and 100g with clay liners. The centrifuge was spun for 106.67 and 60 minutes for 75 and 100g tests respectively, which gave a prototype time of 416.67 days. The chloride ion concentration at the upper layer L1 was found to be 206.35 mg/l and 215.80 mg/l for 75 and 100g tests respectively. The marginal difference in the chloride ion concentration may be attributed to the small difference in the hydraulic gradients at these two acceleration levels. The Peclet numbers for silty soil and compacted clay liner are much less than 0.4. Hence, the diffusion is the dominant contaminant transport mechanism. The scaling law $T_p = N^2 T_m$, where subscripts *p* and *m* stand for prototype and model respectively, used in the study is supported.

The chloride ion concentrations for different layers of silty soil with clay liner are presented in Table 6. The depth averaged values for Cl^- concentration are reported in the table. It is observed that the concentration is high in the upper layer L1. There is a considerable reduction in the pollutant (NaCl) concentration in lower layers L2 and L3. Figure 5 shows the comparison of relative concentration (C/C_0) Vs. model time at the two acceleration levels (100 and 150g). The plot of relative concentration Vs. model time for the cases with and without clay liner at an acceleration level of 150g is shown in Figure 6. The effect of clay liner in reducing the relative concentration (at a depth of 1.0 m) is illustrated with the aid of solute breakthrough curves as shown in Figure 7. Breakthrough curves are different for silty soil and silty soil with clay liner. This result is expected since the void ratio of clays and thus the permeability of clays is more sensitive to the stress level. As the stress level increases, the void ratio decreases. As the void ratio decreases, permeability also decreases. The breakthrough curve can be used to calculate the dispersion coefficient and average interstitial velocity.

Figure 8 shows the variation of relative concentration Vs. distance of travel at 100g for the case with and without clay liner. It was observed from the plots of relative concentration Vs. distance of travel that the concentration at 1 m below from the top of liner is much less as compared to the case of silty soil alone as sub-base. As the distance of travel increases the concentration further decreases but the difference in concentration levels at longer distance of travel is marginal. The effectiveness of providing clay liner is evident from Figure 8. The provision of clay liner has reduced the migration of contaminant to the lower regions by containing the NaCl solution in the liner itself. From the graph, it is possible to assess the time required for the contaminant to migrate from the buried waste to the groundwater bodies. Accordingly, the containment barrier system can be designed to contain the contaminant so as to prolong the migration time.

The chloride ion concentration results are verified using ion selective electrode (ISE) (Model 9617 BN, Thermo Orion make). There is very good agreement of results obtained by titration method and ion selective electrode. It is concluded that the centrifuge modelling is advantageous for modelling contaminant transport in fine-grained soils. Though the centrifuge modelling is advantageous, the following limitations of the study are acknowledged: (1) the variation in the applied compaction energy to the liner from model to model due to smaller model size; and (2) the sampling tube insertion may cause little disturbance to the liner and sub-base.

TABLE 6: Cl^- Concentration for Silty Soil with Compacted Clay Liner

g-level	Model time T_m (min)	Prototype time T_p (days)	Layer	Cl^- (mg/l) (Titration)	Cl^- (mg/l) (ISE)
100	30	208.3	L1	98.55	96.70
			L2	12.32	-
			L3	4.92	-
	60	416.6	L1	215.80	219.80
			L2	22.17	-
			L3	9.85	-
	90	625	L1	318.84	-
			L2	30.44	-
			L3	12.32	-
150	30	468.75	L1	238.41	242.30
			L2	27.10	-
			L3	14.88	-
	60	937.50	L1	445.94	438.5
			L2	32.17	-
			L3	12.85	-
	90	1406.25	L1	574.49	-
			L2	41.14	-
			L3	15.36	-

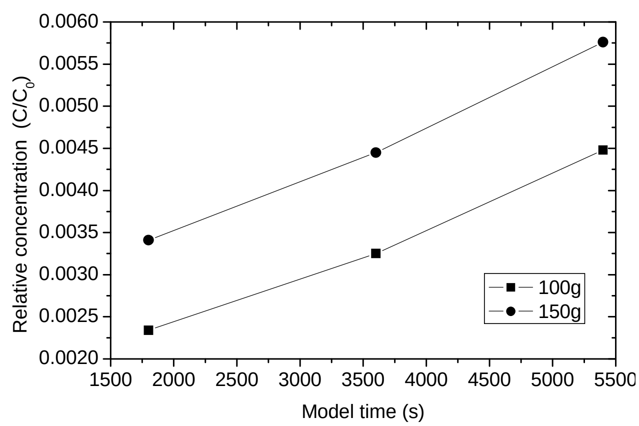

Fig. 5 Relative Concentration at 1.0 m below from the Top of Silty Soil as a Function of Model Time (Without clay liner)

Summary and Conclusions

Geotechnical centrifuges are extensively used to study different geoenvironmental engineering problems wherein it is important to understand and assess migration of contaminants and designing barriers for their containment. The centrifugal technique is advantageous for modelling solute transport in fine-grained soils since the method is quick and it is performed under bulk densities and confining stresses encountered in natural soil deposits. In the present study, the effectiveness of providing the clay liner in minimising the leachate migration through the porous media beneath the landfill is highlighted using the centrifuge modelling. The results confirmed that for a low hydraulic conductivity liner ($k < 2 \times 10^{-10}$ m/s), diffusion is the dominant migration process. The effect of self-weight on permeability was shown to be more prominent in clays. For lower hydraulic conductivities, transit time calculated solely on the basis of advective flow is unconservative. The transit time should be used in determining the required thickness of the clay liners. It is seen from the centrifuge test results that the provision of clay liner in landfills is more effective in reducing the migration of contaminants by containing the constituents of leachate in the liner itself. Equilibrium distribution coefficients (which, in turn, can be used to calculate the retardation factor) can be computed from the breakthrough curves.

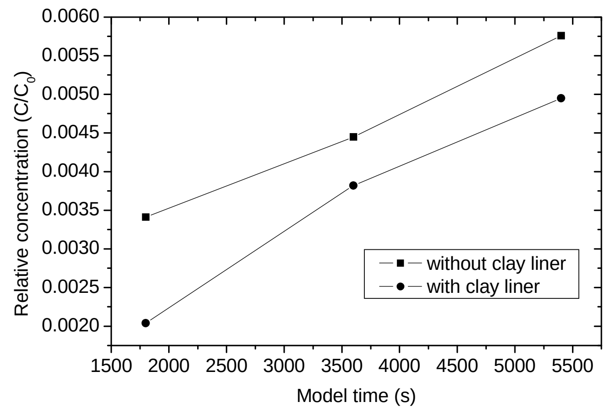

Fig. 6 Relative Concentration at 1.0 m below from the Top of Soil/Liner as a Function of Model Time at 150g

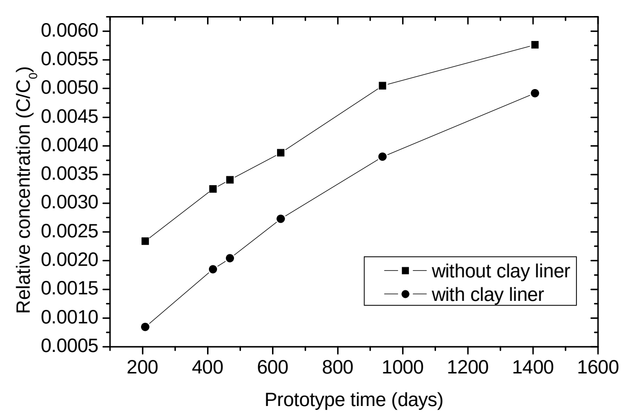

Fig. 7 Relative Concentration at 1.0 m below from the Top of Soil/Liner as a Function of Prototype Time

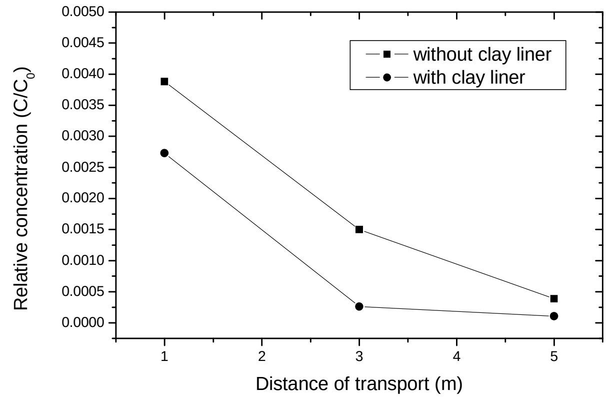

Fig. 8 Comparison of Relative Concentration Vs. Distance of Transport at 100g

It is noted that the centrifuge models, which represent the prototype stress distribution more closely, will yield more realistic data on contaminant transport. The role of centrifuge experimentation has been examined with respect to compacted clay liner and it is shown that flow from a landfill through a basal liner will reduce contaminant transport to an underlying aquifer. The centrifuge can also be used to produce data under repeatable laboratory-controlled conditions where the physical processes of advection, dispersion and adsorption occur in heterogeneous two or three-dimensional situations. For low hydraulic conductivity liners, diffusion flow mechanism should be considered in evaluating liner performance for contaminant migration.

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