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Advection Modelling using a Geotechnical Centrifuge

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Introduction

The mechanism of solute transport through soils is quite a complex phenomenon and is largely influenced by the physical, chemical and biological properties of the soil-solute system. As such, a proper understanding of the process requires its modelling, simulation and prediction. Mathematical and laboratory models have been used in the past to study and to model such interactions. However, such models lack calibration and validation. Simulation of the complexities existing in the full scale model and large time spans involved, restrict the use of laboratory models. To overcome this situation, studies can be carried out using full scale models, capable of simulating realistic prototype conditions. Such full scale models are not practically feasible because of the difficulties encountered in performing such tests, high simulation costs and large time spans involved. Most of the problems associated with mathematical models, laboratory models and full scale test models can be overcome by centrifuge modelling.

Geotechnical centrifuges have been used effectively by many researchers to study solute transport in soils. Scaling laws for the same have been derived by Cargill and Ko (1983), Arulanandan et al. (1988) and Hensley and Schofield (1991) by carrying out dimensional analysis. The validity of these laws can be checked by carrying out centrifuge modelling. The violation of some of the scaling laws have been justified in Table 1.

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Table 1
Dimensionless numbers derived for modellin solute transport

Dimensionless Number	Dimension	Evaluation
Concentration Number	$\frac{C}{\rho_f}$	Ensures similarity of concentrations at homologous points.
Advection Number	$\frac{v_s t}{l}$	Leads to kinematic similarity of motion.
Diffusion Number	$\frac{D_m t}{l^2}$	Leads to similarity of diffusion process.
Capillary effects Number.	$\frac{\rho_f g l L}{T}$	Leads to similarity of capillary effects such as height of capillary rise or flow above the ground water table.
Adsorption Number	$\frac{s}{\rho_f}$	Leads to similarity of adsorption process.
Dynamic effects Number	$\frac{g t^2}{l}$	Scaling is significant only for dynamic events like earthquakes. Not significant for solute transport.
	Discrepancies	
Reynolds Number	$\frac{\rho_f v_s L}{\mu}$	This number represents the relative importance of the inertia force over the viscous force. It is N times higher in the model. However, if Reynolds number is less than one, laminar flow occurs and scaling is not necessary.
Peclet Number	$\frac{v_s L}{D_m}$	This number represents the importance of mechanical dispersion over diffusion. It is N times higher in the model. However for low velocity flows Peclet number is less than one and dispersion is independent of velocity and can be modelled adequately.

Two dimensional studies for saturated soil conditions have been carried out by Hensley and Schofield (1991) and satisfactory results are obtained. However, the usefulness of a centrifuge to study unsaturated flows is still a matter of debate and controversy. Goforth et al. (1991) have suggested that gravity will have a negligible effect on fluid flux in relatively dry, unsaturated soils and that transport by suction flux can not be modelled to the same scale as other transport phenomena. Mitchell (1994) and Sills and Mitchell (1995) have demonstrated the usefulness of a centrifuge to create an unsaturated sample and reported that it can be used very efficiently to model permeation through unsaturated soils.

It can be noticed that most of the studies have been carried out for saturated soil conditions. However, soil rarely occurs in this state in nature and as such, there is a need for investigating the effect of soil characteristics, i.e. degree of saturation, moisture content, state of the soil, nature of the soil, particle size distribution, etc. on the transport processes in order to make more realistic predictions of solute migration within a soil mass.

An attempt has been made in the present study to briefly discuss the state-of-the-art available on the advection mechanism through the soils. A critical appraisal of such a review reveals the complexity involved in such studies, their applications in the field of environmental geotechnology along with the limitations. Some preliminary studies have been conducted to simulate moisture migration in compacted soils using the geotechnical centrifuge available in the Soil Engineering Laboratory, Indian Institute of Technology, Bombay, India. Effects of factors, viz. compaction energy, moisture content, degree of saturation and scale factor N on the advection phenomena, have also been presented.

State-of the-art on Advection Mechanisms

The modelling of advection mechanism in soils has drawn the attention of several researchers over the last few years. A chronological record of their research and findings is presented here in brief.

Laut (1975) has carried out centrifugal model tests to study the flow of water in soils. It has been observed that if centrifugal model tests involving phenomena which depend neither on surface tension nor on viscosity are performed, the centrifugal condition ($g_m l_m = g_p l_p$) suffices to secure complete equivalence between model and prototype, as long as the grain size does not influence the results.

Cargill and Ko (1983) have examined the phenomenon of transient flow in earth embankments. Theoretical scaling relations pertinent to transient flow are developed through considerations of the basic independent variables governing the flow. Experimentally derived scaling relations are found to be relatively consistent with theoretical predictions. The feasibility and validity of modelling the flow phenomenon in the centrifuge is shown.

Arulanandan et al. (1988) have carried out dimensional analysis for a problem where advection, dispersion and adsorption occur and derived the scaling laws for centrifuge modelling of these processes. The validity of these scaling laws has been examined by conducting modelling of models (models of different heights tested at corresponding g levels must yield the same extrapolated prototype result) for several types of soils (clays, sand-clay mixture, fine silts) using idealised models for one dimensional flow situations.

Conditions for satisfying the scaling laws and justifications for violating some of these have been discussed in Table 1. The influence of increased g value on the transport mechanisms has been studied. It has been observed that the effect is more prominent for clays.

Hensley and Schofield (1991) have carried out a centrifuge test simulating two dimensional migration of a conservative pollutant species from a landfill site. A large capacity centrifuge (Cambridge 10 m balanced arm centrifuge) has been used to model a well defined complex two dimensional transport problem. Results from these tests have been compared with the theoretical predictions from two existing computer codes, *Pollute* (uses semi-analytical techniques to solve the one dimensional ADE in a layered soil deposit of finite depth) and *Migrate* (to solve ADE for the case of single contaminant transport from a surface landfill site into a soil layer of finite depth under two dimensional conditions). For low seepage velocities good agreement has been observed between the experimental data gathered under one dimensional conditions and the predictions of *Pollute*. However, good agreement has not been obtained between two dimensional conditions and the predictions of *Migrate*. This may be because, one of the basic assumptions involved in Migrate that, zero surface concentration exists at all times outside the bounds of the landfill is not commensurate with the conditions of the centrifuge tests.

Goforth et al. (1991) have derived Darcy's law for a sample of soil in a centrifuge. It is observed that an interchangeable relationship exists between the pressure differential or increase in centrifugal acceleration to create the hydraulic conductivity required for causing flow. Good agreement has been obtained for intrinsic permeability measured by lg bench tests and centrifugal model tests. Tests have also been carried out for unsaturated soil conditions and it is suggested that in partly saturated soils, where suction gradients dominate fluid movement, employing a centrifuge may not be useful. However the usefulness of a centrifuge in establishing unsaturated hydraulic conductivity-moisture content relationships has been demonstrated by monitoring the change in soil suction with time as a soil column drains from an initially saturated condition.

Among the dimensionless numbers derived by Arulanandan et al. (1988), the 'capillary effects number' has a special significance for unsaturated soils. This number ensures that the moisture content profile of the model unsaturated soil column will be geometrically similar to that of the prototype. Cooke and Mitchell (1991) have examined this important precondition by comparing the centrifuge model test results with the predictions of standard extraction tests. It has also been suggested that centrifuge modelling can be used to study unsaturated flows.

Evans et al. (1994) have carried out experimental and theoretical investigations of the progression of a solute pulse through a clay layer using the type 'R Mini-drum centrifuge'. A downward hydraulic gradient has caused advective flow through a layer of clay in which water content varied with depth. In theoretical investigation, a simple model has been used to predict the interstitial velocity which is then used in simple one-dimensional, finite difference program to predict the solute profile in the layer. The theoretical prediction has been observed to be in good agreement with the experimental results.

Cooke (1994) has proposed a technique for determining the relationships among soil suction, moisture content and hydraulic conductivity using parameter estimation, based on measurement of cumulative outflow under gravity drainage from an initially saturated soil column. The results indicate that the parameter estimation aspect is particularly useful for determining the soil suction-hydraulic conductivity relationship.

Goodings (1994) has observed that for seepage governed by Darcy's law, flow velocity itself does not affect the positions of unconfined phreatic surfaces. Centrifuge models, then, can model such prototype flow events at other velocities even though velocity increases in direct proportion to N for geometrically similar boundary conditions. However, for transitional and turbulent seepage, correct modelling of head loss and the position of unconfined phreatic surfaces can only be achieved if void seepage velocities are equal in model and prototype, which can be achieved with model grain size N times smaller than the prototype. This provides new opportunities for modelling geotechnical conditions with non-Darcy flow by a factor of N in the centrifuge model flow not usually achievable in lg models.

Atkinson and Taylor (1994) have carried out centrifugal model tests to investigate drainage and moisture-suction relationships in an iron ore cargo. The study demonstrates the application of centrifuge modelling to a problem of drainage and stability in a granular material which is not strictly within the normal range of geotechnical engineering. A distinct transition was observed between the 'drier upper region' and the 'wetter lower region' and the position of this transition depended principally on the initial moisture content.

Centrifuge Modelling

Basic Concepts

Experiments are usually conducted in the laboratory to understand various phenomenon that occur in the field wherein an attempt is made to simulate the conditions of the prototype, in the models constructed in the laboratory. However, it is impossible to simulate similar conditions in the models since the body forces due to gravity play an important role. Experiments conducted to study the behaviour of the prototype indicate that it is impossible to simulate the body forces of the prototype in the model in the 1g field. These difficulties experienced in the simulation of the exact conditions of the prototype in the model may be potentially overcome by use of centrifuge for modelling as discussed by Taylor (1995).

For the sake of simplicity and accuracy in the obtained results it is desirable to construct a model with the same material properties as that of the prototype. The void ratio e, being a function of the confining stress, which directly influences the permeability of the soil mass. Kozeny-Carmen equation suggests that permeability is proportional to $\left[e^3/(1+e)\right]$, it is important to account for the stress dependence of material properties. This indicates that stresses must be similar in model and prototype giving rise to the concept of homologous points (Taylor, 1995). Therefore, the condition of identical stress is imposed on the model i.e. $\left(\sigma_m/\sigma_p\right) = \sigma^* = 1$

Stress is equal to force per unit area therefore,

$$\frac{F^*}{\left(l^*\right)^2} = \sigma^* = 1$$

Let the scale factor for length be

$$l^* = \frac{l_m}{l_p} = \frac{1}{N}$$

It follows that

$$F^* = \left(l^*\right)^2 = N^{-2}$$

Since the model and prototype are composed of identical materials, the scale factor for density is $\rho^* = 1$.

The scale factor for mass is calculated by:

$$\rho^* = \frac{m^*}{\left(l^*\right)^3} = 1$$

$$m^* = (l^*)^3 = N^{-3}$$

and the scaling factor for gravity follows from Newton's law of motion for a body at rest in a gravitational field,

$$F^* = m^* g^*$$

$$g^* = \frac{F^*}{m^*} = \frac{N^{-2}}{N^{-3}} = N$$

Therefore, if identical material is used in model and prototype, and length dimensions are reduced N times, the gravity should be increased N times in order to preserve identical stresses in model and prototype. The centrifuge is used to provide an increased acceleration field to simulate this required increase in gravitational force on the model. Thus the strong stress dependence of soil properties is accounted for in centrifuge modelling.

Scaling Laws

The general scaling laws that govern the relationship between the model and its corresponding prototype, with respect to solute transport have been derived by Laut (1975) and Arulanandan et al. (1988) using dimensional analysis. Table 2 presents a summary of the scaling relationships derived by Arulanandan et al. (1988) and Hensley and Schofield (1991).

Table 2
Summary of Scaling Relationships for Centrifuge Modelling.

Quantity	Prototype	Model
Length	N	1
Volume	N^3	1
Velocity	1/N	1
Acceleration	1/N	1
Stress	1	1
Strain	1	1
Mass density	1	1
Time (seepage)	N^2	1
Head	N	1
Pressure	1	1

Modelling of models

Prototype monitoring being often too costly and impractical, the concept of modelling of models has been evolved to provide a check on the consistency of the centrifuge model testing scheme and to validate the scaling relationships. Models of different heights when tested at the corresponding g levels must provide with similar extrapolated prototype results. This technique, known as modeling of models has been successfully used by a number of researchers to validate the results (Phillips, 1995).

Advantages of centrifuge modelling

The advantages of using a centrifuge are as follows (Taylor, 1995):

1. Time dependent problems, such as advection, can be studied in a short period of time.

2. It allows for self verification using the modelling of models technique.

3. A single model configuration can be used to evaluate many different prototype configurations by varying the acceleration level.

4. The results can be directly applied to field situations.

5. It is the only means for subjecting the laboratory model to self weight stresses comparable to those in full scale field structure.

Limitations of centrifuge modelling

Some of the limitations of modelling using a centrifuge are as follows (Taylor, 1995):

1. The acceleration level in the centrifuge varies with the radius of rotation in contrast with the essentially constant gravitational force field at the earth's surface.

2. The tangential acceleration effects may be significant if centrifuge speeds are changed too rapidly.

3. The grain size and the solute and solvent properties may differ and as such it is difficult to achieve the similarity between model and prototype.

Although these limitations are not major in nature they may affect the results upto a certain level.

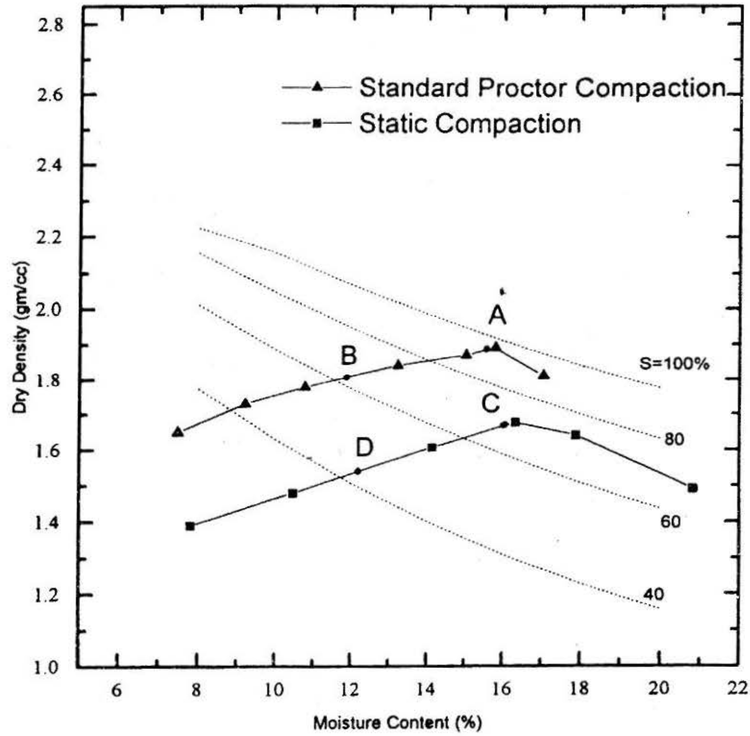

FIGURE 1 : Compaction Curves for the Soil

Experimental Investigations

Soil Properties

The soil used in the present study is a local silt with 16% clay fraction and a specific gravity of 2.75. The natural moisture content of the soil is 2.64%. The hydraulic conductivity of the soil is 1.192×10^{-4} cm/sec (as obtained from a variable head permeability test).

Compaction Characteristics

Static and Standard Proctor Compaction tests have been conducted on the soil. The compaction curves for the same are presented in Fig. 1.

On the obtained compaction curves, two points each were selected (one with high degree of saturation and the other with a relatively lower degree of saturation) on the Proctor compaction (points A and B) and static compaction curves (points C and D). These are termed as Samples A, B. C

Table 3
Details of Samples A, B, C and D

Sample Properties	Proctor Compaction		Static Compaction	
	A	B	C	D
$\gamma_{d\,max}$ (gm/cc)	1.87	1.79	1.65	1.52
Moisture Content (%)	16	12.5	16	12.5
Degree of saturation (%)	93.5	64	66	42.5

and D respectively hereafter. Table 3 presents the state of the soil at these points.

Sample Preparation

To prepare a sample, oven dry soil was taken and mixed with a predetermined amount of water (corresponding to the moisture content from the compaction curve). After mixing, the soil was transferred to an air tight polythene bag and kept for a minimum of 24 hours for ensuring proper mixing and hence to avoid non uniform distribution of the moisture. The samples were prepared in a standard permeability mould (length = 6cm, diameter = 7.98cm). The soil was divided into three parts and packed into the mould by adopting a particular compaction procedure (either Proctor or Static compaction).

This soil sample was carefully extruded on to a glass plate and small thermocol balls were fixed at 2cm intervals along the length of the sample at four points along the circumference. This is done in order to measure any change in sample height during the test and also to aid in slicing the samples after centrifugation. To verify the uniformity of moisture in the sample, after the sample is prepared, it is cut into three slices and the moisture distribution along the length is determined by taking three samples from each slice to generalize the results. It is observed that the soil samples prepared are homogeneous and almost correspond to the moulding moisture contents.

Standardization of Test Set Up

A perspex cylinder with an inner diameter of 8cm has been used. The diameters of the soil sample and cylinder are such that the sample close fits into the cylinder. A layer of sand, one centimeter thick, is placed at the bottom of the cylinder to avoid vacuum formation and to collect the outflow from the sample. The soil sample is then placed over the sand layer. A lining of bentonite slurry is provided along the sides of the soil sample to prevent leakage of the water head. The water head is then directly placed over the sample and the test

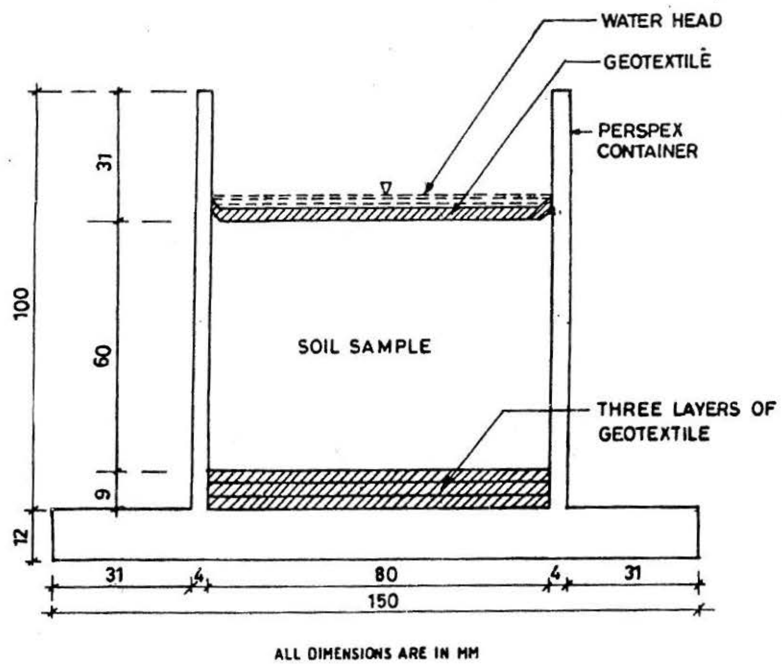

FIGURE 2 : Centrifuge Test Set-up

is carried out. It is observed that there is some loss of head indicating leakage through the sides. As such, it is required to change the setup.

In the second trial, the sand layer is replaced by three layers of sponge and instead of keeping the water head directly above the soil sample, three layers of soaked sponge are kept on the top of the sample. Due to water retention in sponge, no leakage from the sides of the sample is noticed. However, after the centrifugation is over and the sample is extruded out of the perspex cylinder, some water backflows from the bottom sponges into the soil sample.

To improve upon this, another setup is considered wherein a woven geotextile which shows better water retention properties is then tried as a substitute for the sponge. Three layers of geotextile are kept at the bottom of the perspex cylinder on which the sample was placed. A geotextile piece with a slightly larger area of cross section than the sample is placed on top to form a cup shape in which the water is held to ensure no flow occurs from the sides of the sample. This arrangement, as shown in Fig. 2, is found to be quite suitable and appropriate and as such is employed for conducting the tests in the present study.

Table 4
Details of the Centrifuge

Type	Swinging buckets on both sides of the arm
Arm Radius	20cm
Max. Outer Radius	31.5cm
Centrifuge Range	250 – 1000 rpm
Maximum Acceleration	300g
Capacity	72g tons

Centrifuge Details and Calibration

Details of centrifuge

The details of the small centrifuge available in the Soil Engineering Laboratory, Indian Institute of Technology, Bombay, India using which the studies have been conducted are presented in Table 4.

Calibration

Example: For N = 50

Speed of centrifuge, ω, (rpm) $= \frac{60}{2\pi}\sqrt{\frac{Ng}{R}}$

where

$R = [r - t - (2h/3)] = 26.3$ cm
r = radius of the arm = 31.5 cm
t = thickness of the base plate = 1.2 cm
h = height of the model = 6cm
g = 981 cm/sec^2

Substituting these in the expression; for N = 50 the speed of rotation is equal to 412 rpm. Similarly speeds for N = 33.33 and 75 have been obtained and these values have been summarised in Table 5.

Test Procedure

A water head of 0.3cm i.e.15cc in volume (sufficient enough to saturate the pores of the soil sample completely) is provided on the top of the sample. Tests have been conducted for three N values (33.33, 50 and 75) for three

Table 5
Calibration of Centrifuge

g Value	Speed (rpm)
33.33	337
50	412
75	505

different prototype times (5.2, 10.42 and 17.36 days) as presented in Table 6. After each centrifugation, volume changes in the soil samples have been observed. However, practically no volume change could be observed in any of the samples except for a very small swelling in the case of Sample D. The sample is extruded on to a glass plate and cut into 2cm slices. The moisture content of each layer is obtained by further subdividing the slices into three and taking the average of the moisture content values. Similar tests have been conducted for Samples A, B. C, D.

Results and Discussions

The moisture content has been obtained for three slices of the soil sample, after the centrifugation, and these values are presented as a variation of the normalized moisture content 'm/m_0' ('m' indicates the moisture content at a depth after time 't' and 'm_0' is the initial moulding moisture content) along the length of the sample. To study the trends of moisture migration in the soil sample, centrifuge tests have been carried out for N

Table 6
Details of Centrifuge Tests

N	Length		Time	
	Model (cm)	Prototype (m)	Model (min)	Prototype (davs)
33.33	6.0	2.0	6.70 13.50 22.50	5.20 10.42 17.36
50	6.0	3.0	3.00 6.00 10.00	5.20 10.42 17.36
75	6.0	4.5	1.33 2.67 4.44	5.20 10.42 17.36

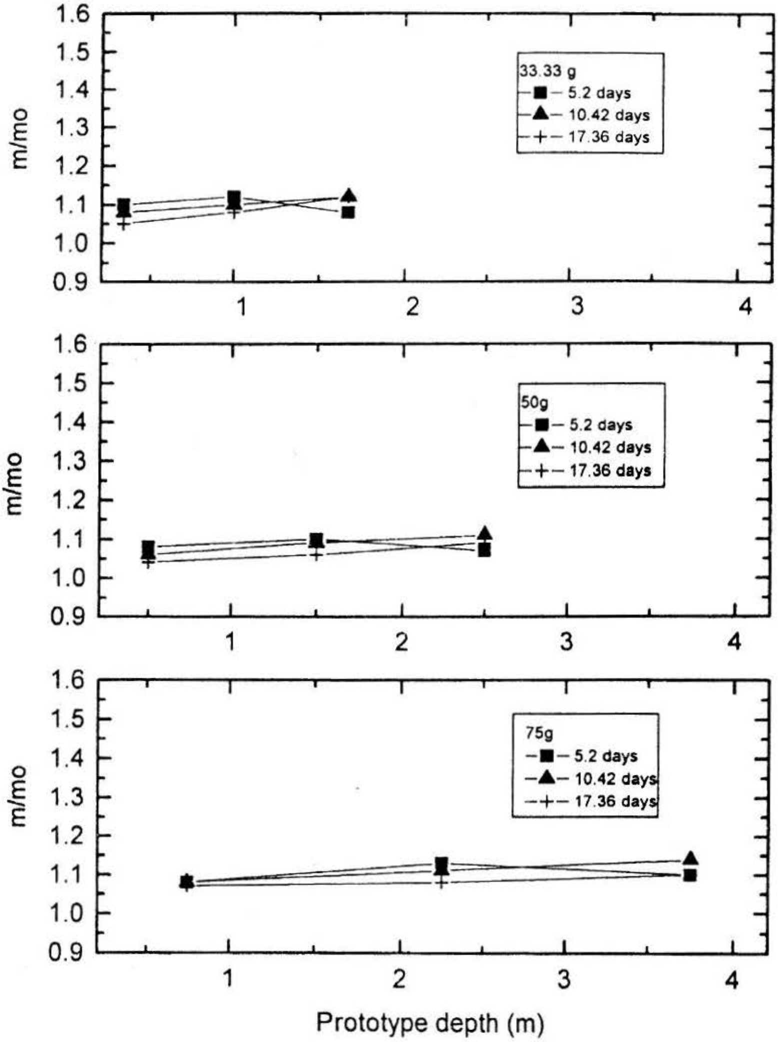

FIGURE 3 : Advection Properties at N = 33.33, 50 and 75 for Sample A

equal to 33.33, 50 and 75. Prototype times of 5.2, 10.42 and 17.36 days have been chosen for the sake of comparison. To study the effect of state of the soil sample viz., compaction energy, dry density and saturation, tests have been conducted for Samples A, B. C and D and the results are presented in Figs. 3 to 6 respectively. From these figures it is observed that in general (m/m_o) increases along the depth of the samples indicating migration of moisture from top to the bottom. This trend is much more prominent for less duration of centrifugation (i.e. 5.2 days) for all the samples studied. However,

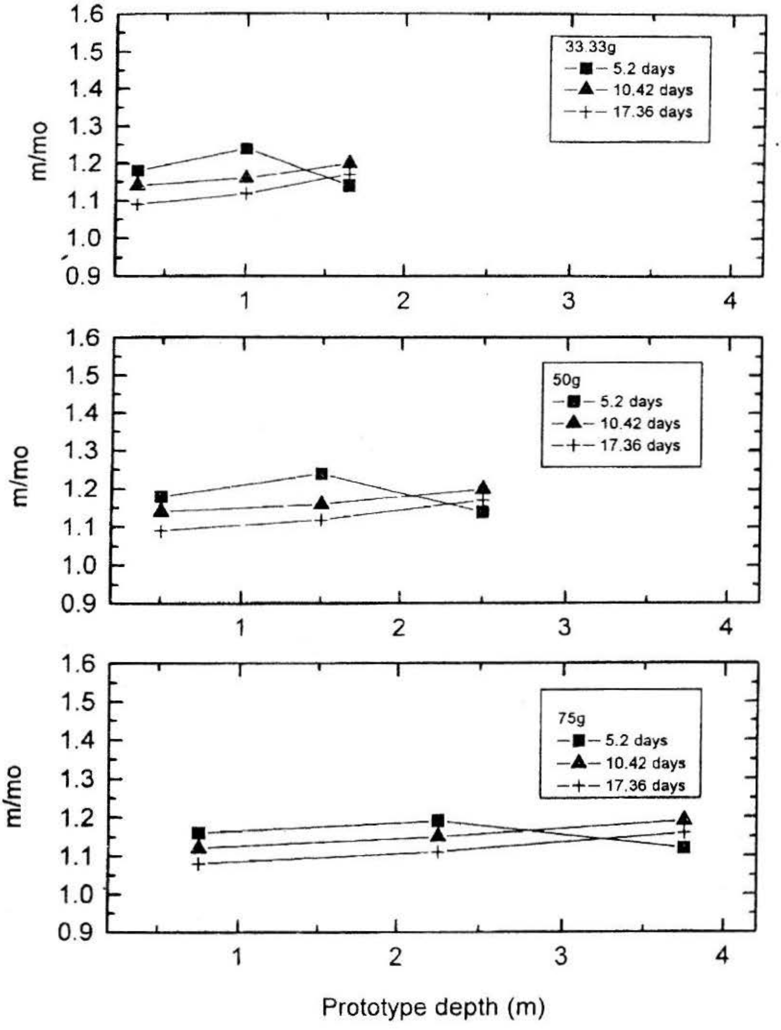

FIGURE 4 : Advection Properties at N = 33.33, 50 and 75 for Sample B

as the time of centrifugation is increased the soil samples tend to achieve almost uniform moisture throughout their length. It can further be noticed from the trends of Figs. 3 to 6, that the variation of the moisture content (m/m_o), along the length of the soil sample is almost similar for the higher saturation Samples A, B and C i.e. with $S > 60\%$. However, for the low saturations, Sample D ($S = 42.5\%$), the bottom one third portion of the soil sample shows a marked increase in the moisture content values.

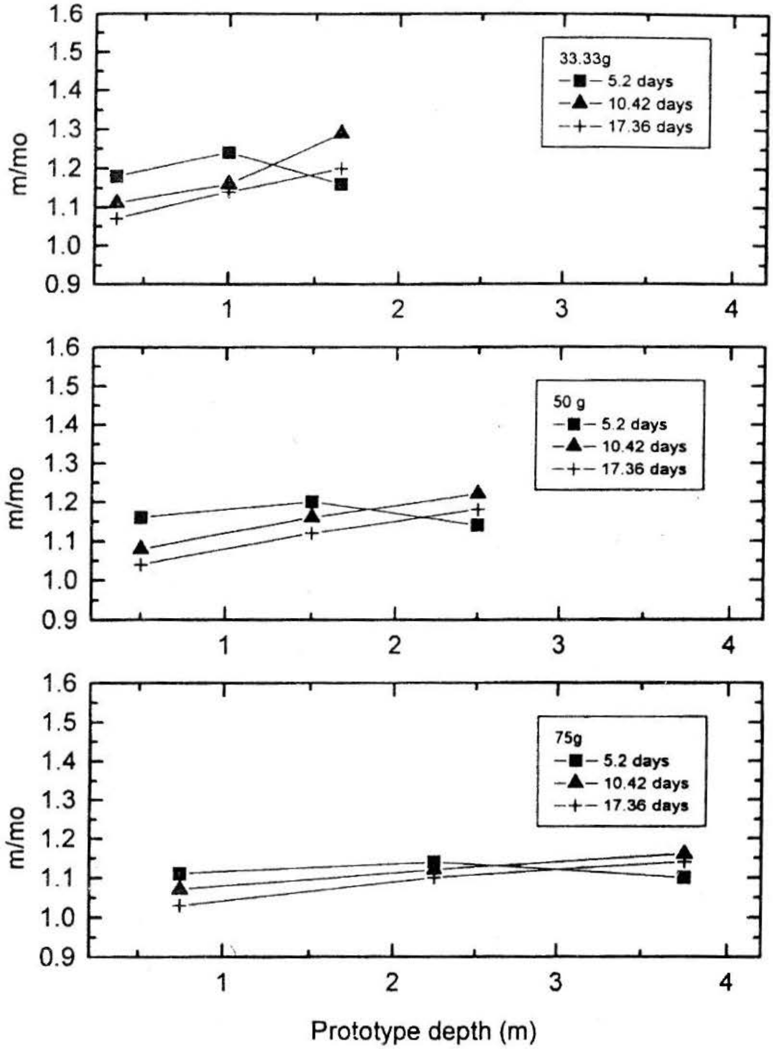

FIGURE 5 : Advection Properties at N = 33.33, 50 and 75 for Sample C

It can also be noticed that, for very high saturation values (S > 90%), Sample A exhibits equilibrium state with little variation in (m/m_o) value as a function of time along the length of the sample. However, as the degree of saturation decreases, the same phenomenon occurs with much more movement of moisture from top to bottom (as indicated by large variation in m/m_o values) in the sample as a function of time. This indicates that the equilibrium advection profile, for highly saturated soil samples, can be obtained within a short interval of time. Similar trends have been observed by Atkinson and

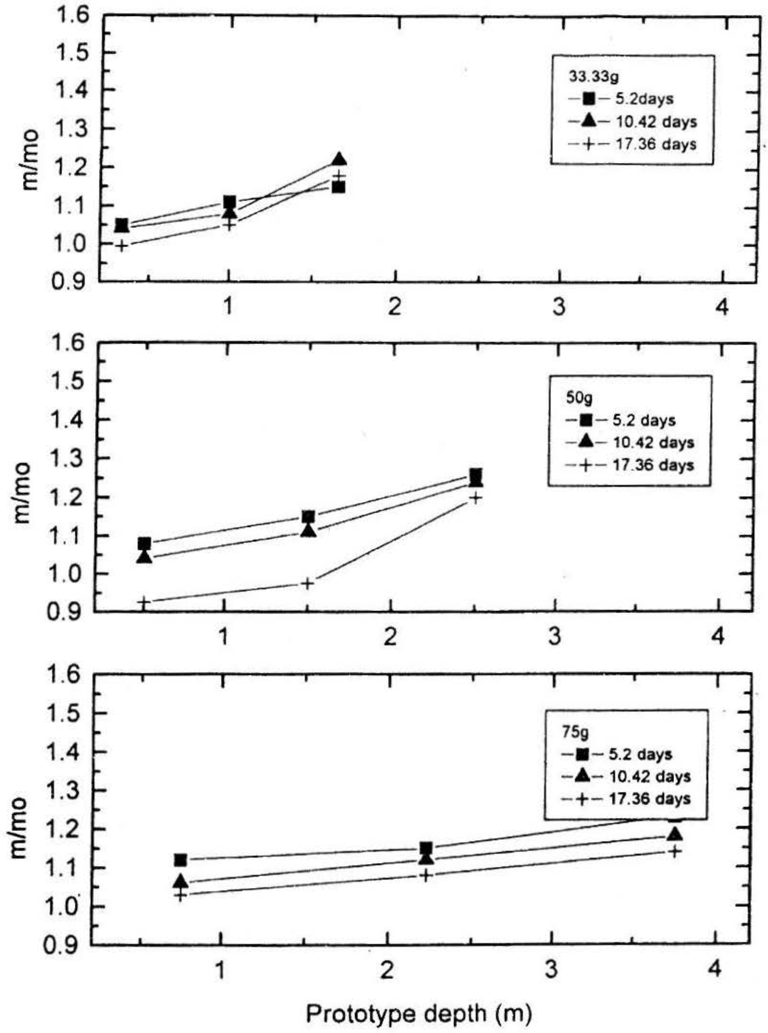

FIGURE 6 : Advection Properties at N = 33.33, 50 and 75 for Sample D

Taylor (1994) for movement of moisture in iron ore samples.

On comparing, advection profiles for Samples A and B (with same compaction efforts at different saturations) it can be noticed that Sample B (with low saturation as compared to Sample A) shows higher (m/m_o) values for the same time period as compared to Sample A (Figs. 3 and 4). Since the soil is already highly saturated, there are very little pores to be filled and as such these trends are justified. Similar comparisons for Samples A and C,

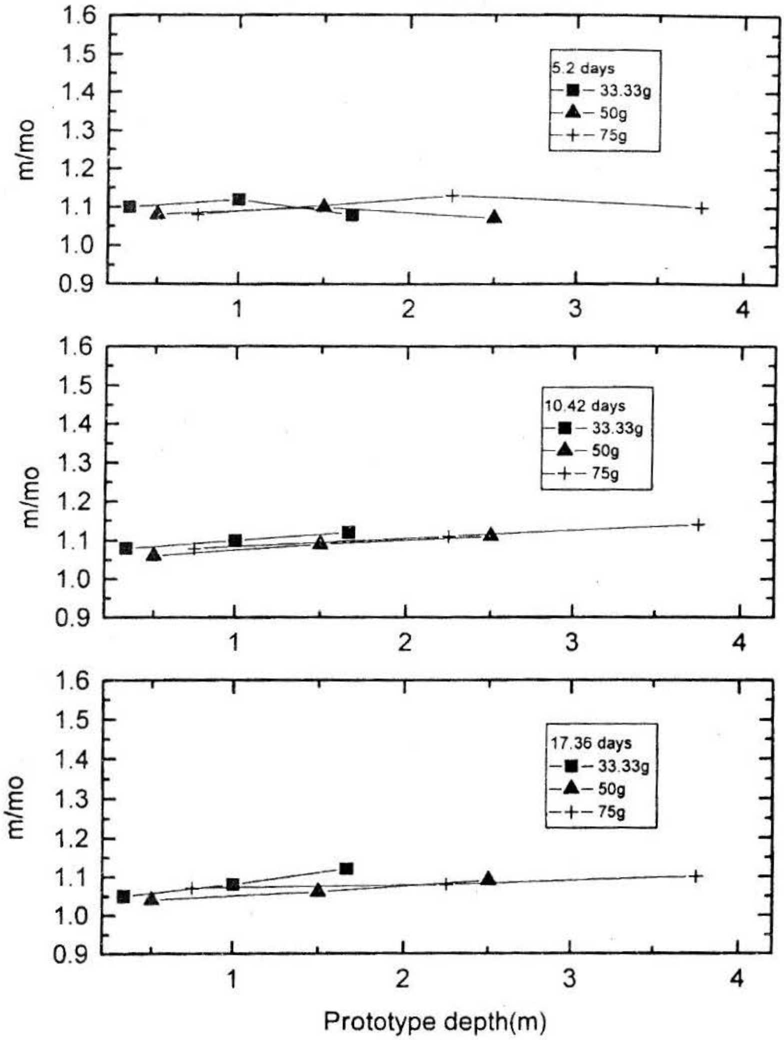

FIGURE 7 : g-Modelling for Sample A

with different compaction efforts and different saturations, indicate that for Sample C, (m/m_o) values are higher as compared to Sample A (Figs. 3 and 5). This may be due to the lower initial saturation obtained by the static compaction.

On comparing, advection profiles obtained for Samples B and C, i.e. different compaction efforts but comparable saturations, it can be noticed that (m/m_o) values are non comparable (Figs. 4 and 5). This is in accordance with the fact that for different pore structures, the advection process is different.

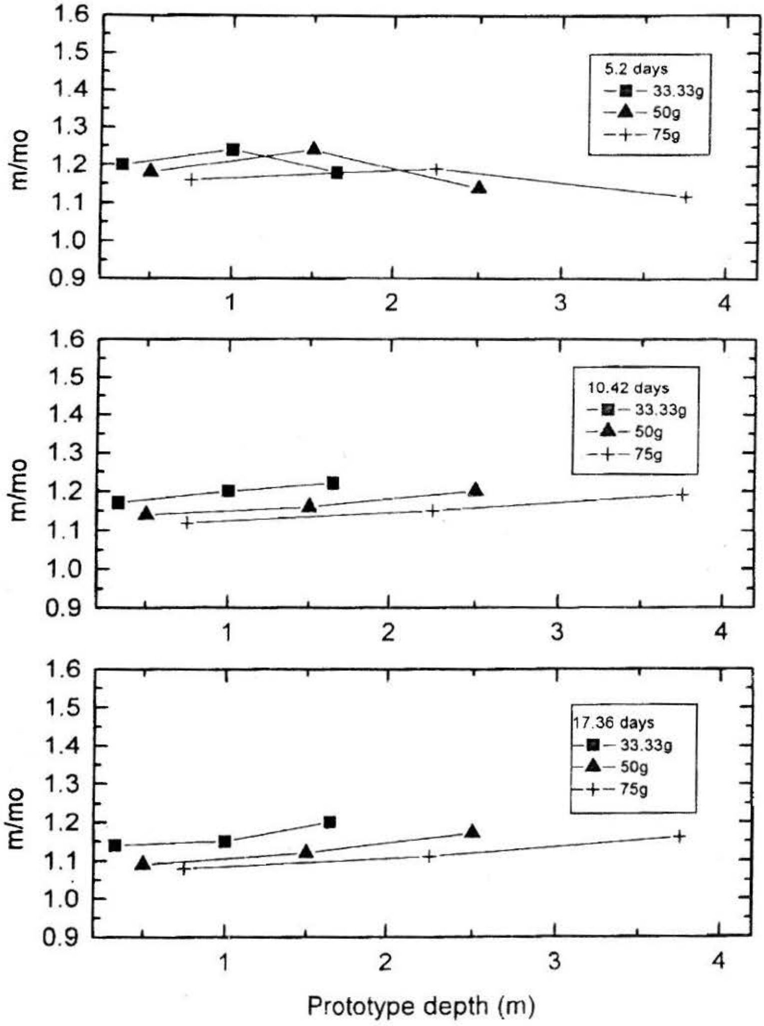

FIGURE 8 : g-Modelling for Sample

Variation of (m/m_o) over the depth of soil samples is higher for Sample D as compared to Sample C (Figs. 5 and 6) due to similar reasons. Sample D exhibits the effect of low saturation and low compaction efforts on the advection process. It is noticed that due to the lower density values, the advection process is quicker from top to bottom. This causes excessive gain in moisture content in the bottom one third portion of the sample. These trends are similar to those obtained by Atkinson and Taylor (1994).

The general trend observed from Figs. 3 to 6 is that at higher N values

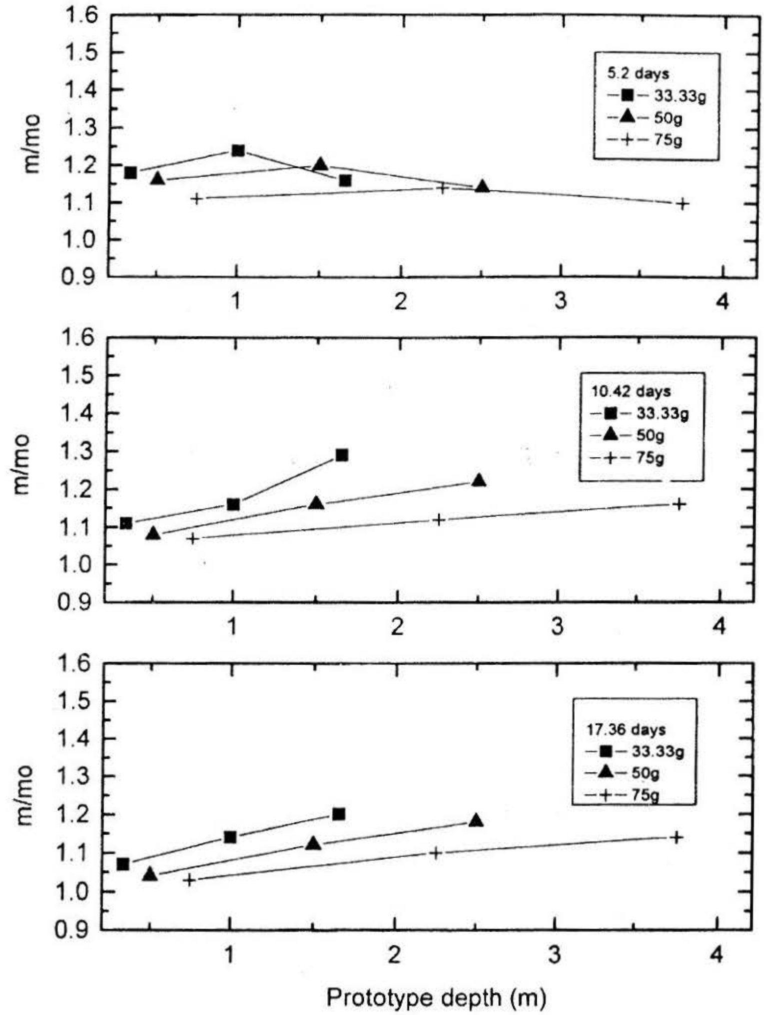

FIGURE 9 : g-Modelling for Sample C

the tendency of top two third of the soil sample, to attain an equiiibrium moisture content is much more. This in other words can be termed as the effect of centrifugal action on the advection process.

Modelling of Models

The advection profiles from Figs. 3 to 6 have been superimposed and analysed farther, to show the validity of modelling of models.

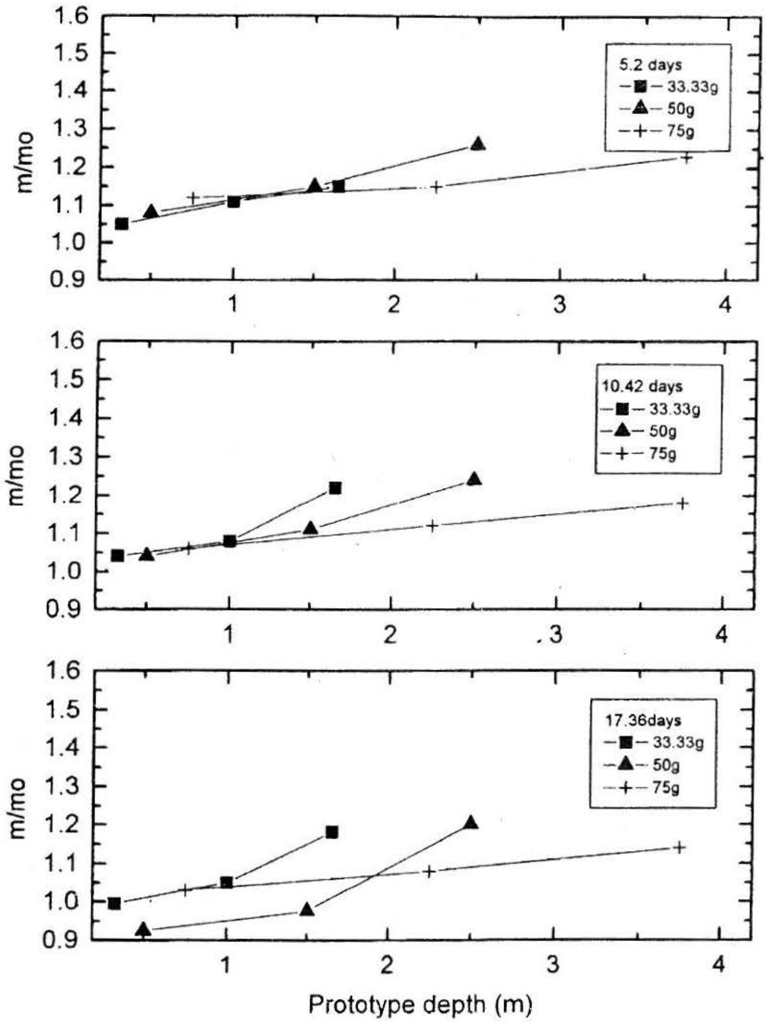

FIGURE 10 : g-Modelling for Sample D

a) **g-modelling** : Figures 7 to 10 correspond to the variation of moisture content (m/m_o) along with the prototype depth for prototype times equal to 5.2, 10.42 and 17.36 days for Samples A, B. C and D respectively for N equal to 33.33, 50 and 75g. It can be observed that for Sample A (Fig. 7), the prototype behaviour exhibited by the models at 33.33, 50 and 75g is almost similar for a prototype time.

b) **Time modeling** : Figs. 11 to 14. correspond to the variation of

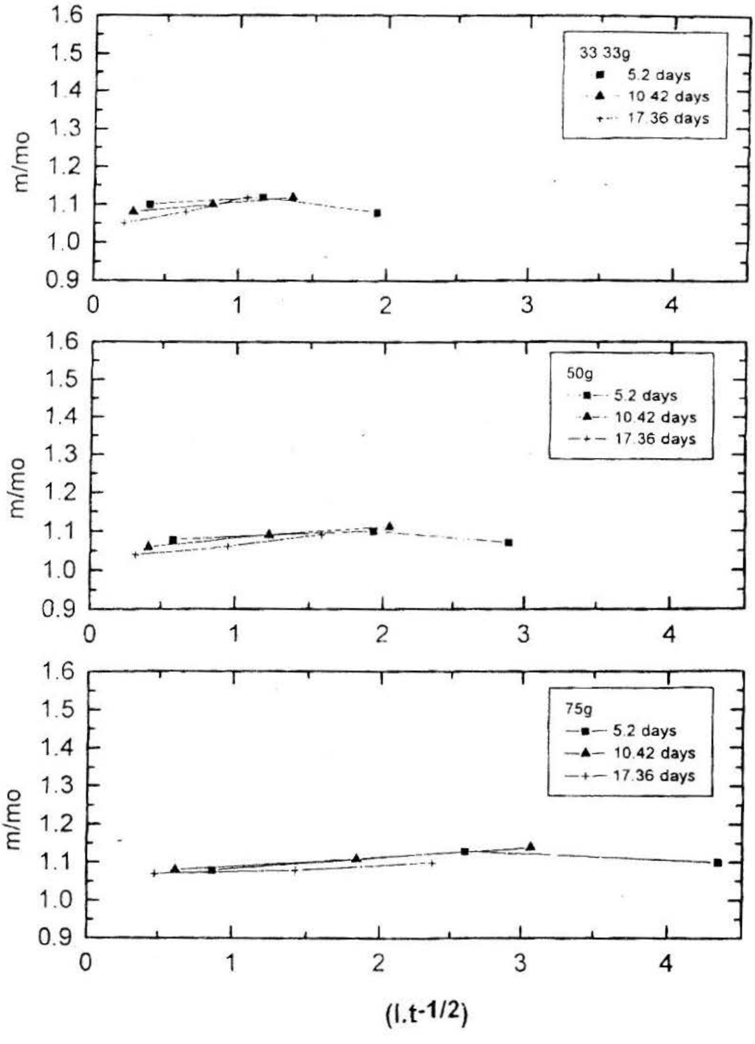

FIGURE 11 : Time Modelling for Sample A

moisture content (m/m_o) along with the non-dimensional parameter ($lt^{-1/2}$) for 5.2, 10.42 and 17.36 days for Samples A, B, C and D respectively for N equal to 33.33, 50 and 75g. It can be noticed from these figures that, for Sample A (Fig. 11), the prototype behaviour exhibited by the models at 5.2 days, 10.42 days and 17.36 days are practically the same for a particular N value.

However, for Samples B, C and D, except for some exceptions, this superimposition is not so good as shown in Figs. 8 to 10 and Figs. 12 to 14.

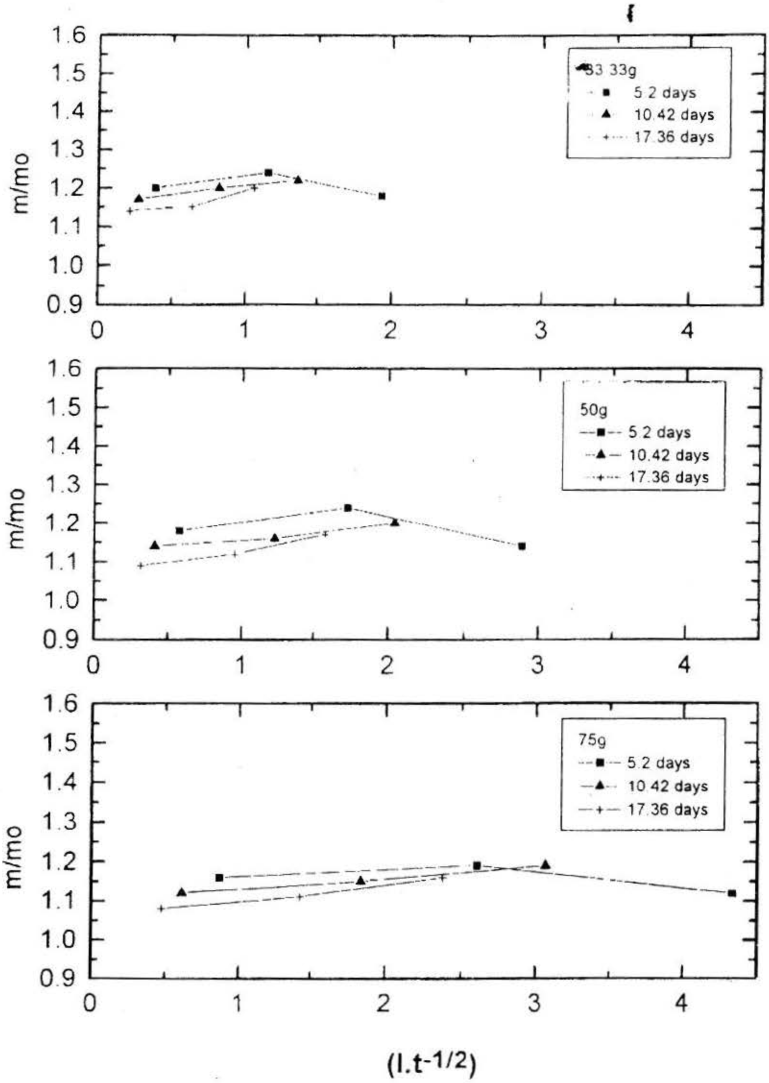

FIGURE 12 : Time Modelling for Sample B

The study reveals that modelling of models is valid for Sample A i.e. for the saturated soil conditions (S = 96%). However, the desired modelling of models (both g-modelling and time modelling) could not be achieved for unsaturated state of the soil (Samples B, C and D) as suggested by Goforth et al. (1991).

The study brings out the effect of compaction energy, moisture content, degree of saturation and scale factor N on the advection phenomena in soils.

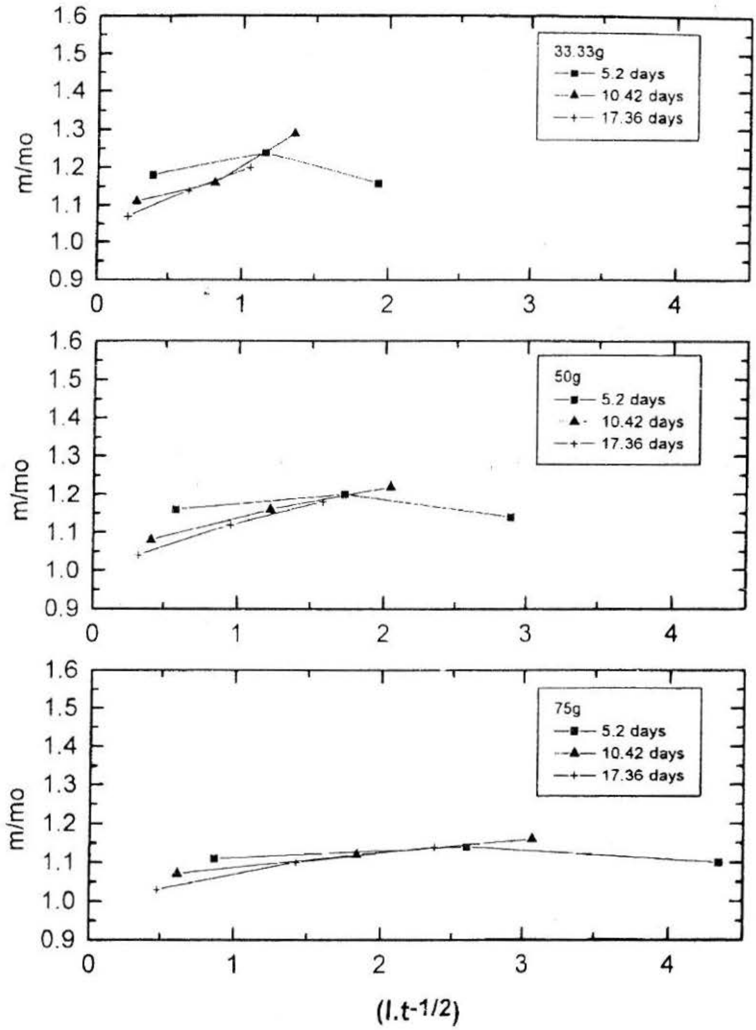

FIGURE 13 : Time Modelling for Sample C

It also indicates that small centrifuge can be utilized for modelling transport phenomenon in soils.

Conclusions

The advection mechanism in compacted soils has been modelled, using a small centrifuge, in the present study. From the results and discussions, presented in the previous sections the following general conclusions may be drawn:

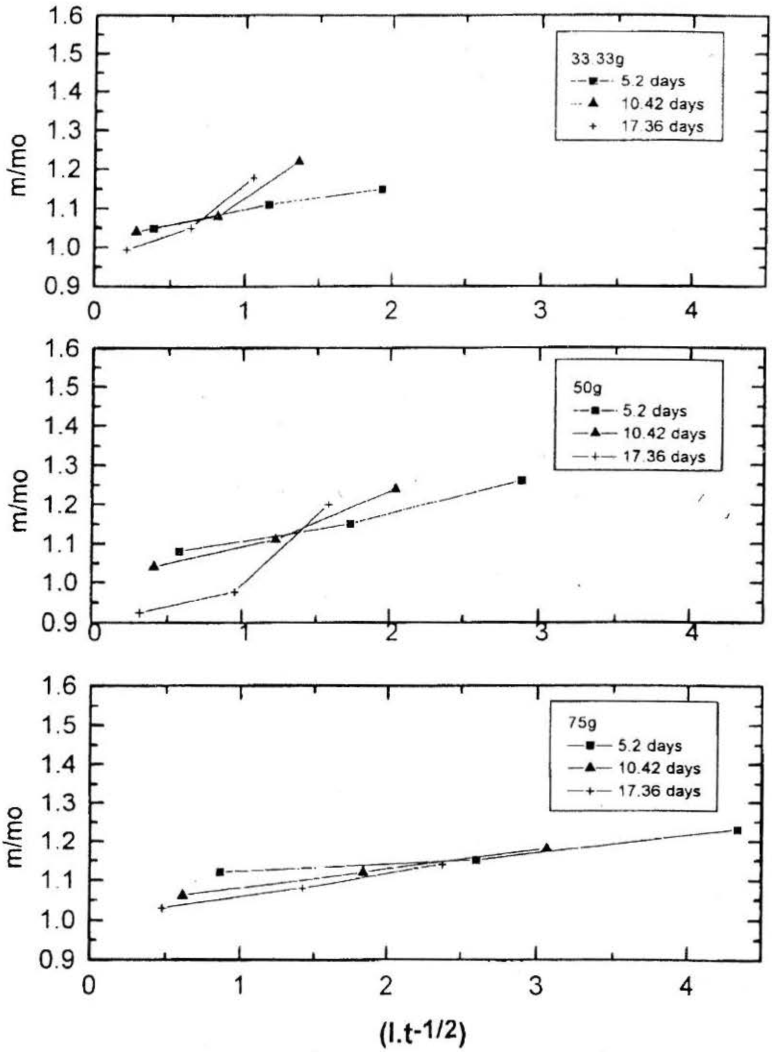

FIGURE 14 : Time Modelling for Sample D

1) Present study indicates that advection in soils is dependent on the state of the soil and a small centrifuge can also be employed to model it in an efficient manner.

2) Same soil with different states of compaction exhibits different advection profiles indicating dependence of advection on pore structure.

3) Advection increases with an increase in the degree of saturation.

4) Modelling of models is valid only for saturated soil conditions.

References

ARULANANDAN, K., THOMPSON, P.Y., KUTTER, B.L., NEEGODA N.G., MURALEETHARAN, K.K. and YOGACHANDRAN, C. (1988) : "Centrifuge Modelling of Transport Processes for Pollutants in Soils", *ASCE J. of Geotechnical. Engineering,* 114(2), pp.185-205.

ATKINSON, J.H. and TAYLOR, R.N. (1994) : "Moisture Migration and Stability of Iron Ore Cargoes", *Centriffige 94,* Balkema, Rotterdam, pp.417-422.

SILLS, B. and MITCHELL, R.J. (1995) : "A New Methodfor Studying Diffusion in Unsaturated Soils", *Geoenvironment 2000,* Vol. 1, ASCE, Geotechnical Special Publication No. 46, NewYork, pp.346-354.

BRIAN, Cooke (1994) : "Determination of Soil Hydraulic Properties", *Centrifuge 94,* Balkema, Rotterdam, pp.411-416.

CARGILL, K.W. and KO, H.Y. (1983) : "Centrifuge Modelling of Transient Water Flow", *ASCE J. of Geotechnical Engineering,* 109(4), pp.536-555.

COOKE, A.B. and MITCHELL, R.J. (1991) : "Evaluation of Contaminant Transport in Partially Saturated Soils", *Centrifuge 91,* Balkema, Rotterdam, pp.503-508.

EVANS, D.C., SAVVIDOU, C. and SCHOFIELD, A.N. (1994) : "Contaminant Migration through Clay in a Mini-drum Centrifuge", *Centrifuge 94,* Balkema, Rotterdam, pp.381-386.

GOFORTH, G.F., TOWNSEND, F.C. and BLOOMQUIST, D. (1991) : "Saturated and Unsaturated Fluid Flow in a Centrifuge", *Centrifuge 91,* Balkema, Rotterdam, pp.497-502.

GOODINGS, D.J. (1994) : "Implications of Changes in Seepage Flow Regimes for Centrifuge Models", *Centrifuge 94,* Balkema, Rotterdam, pp.393-398.

HENSLEY, P.J. and SCHOFIELD, A.N. (1991) : "Accelerated Physical Modeling of Hazardous Waste Transport", *Geotechnique,* Vol.41, pp.447-465.

LAUT, P. (1975) : "Application of Centrifugal Model Tests in Connection with Studies of Flow Patterns of Contaminated Water in Soil Structure", *Geotechnique,* Vol.25, pp.401-406.

MITCHELL, R.J. (1994) : "Matrix Suction and Diffusive Transport in Centrifuge Models", *Canadian Geotechnical Journal,* Vol.31, pp.357-363.

PHILLIPS, R. (1995) : "Centrifuge Modelling. Practical Considerations", in *Geotechnical Centrifuge Technology,* Ed. R.N. Taylor, Blackie Academic and Professional Publishers, Glasgow, pp.34-60.

TAYLOR, R.N. (1995) : "Centrifuges in Modeling. Principles and Scale Effects", in *Geotechnical Centrifuge Technology,* Ed. R.N. Taylor, Blackie Academic and Professional Publishers, Glasgow, pp.19-33.

List of Symbols

D	=	Dispersion coefficient (L^2T^{-1}).
C	=	Concentration of the solute in the pore water (ML^{-3}).
s	=	Mass of absorbed solute/unit mass of solids (M).
η	=	porosity.
v_s	=	Seepage velocity (LT^{-1}).
γ	=	unit weight of the porous medium (ML^{-3}).
t	=	time (T).
g	=	acceleration due to gravity.
T_f	=	Surface tension for pore fluid-particle interface
l	=	length of the sample.
q	=	discharge.
ρ	=	density of the soil.
ω	=	angular velocity.
r	=	radius of the centrifuge arm.
e	=	void ratio.
σ	=	Stress.
F	=	Force.
N	=	Accelerated environment subjected to.
D_m	=	Coefficient of molecular diffusion.
L	=	effective particle size.
ρ_f	=	Density of the pore fluid.
μ	=	Dynamic fluid viscosity.
m	=	moisture content of the soil sample at a given depth after centrifugation
m_o	=	moulding moisture content of the soil sample.

Notes:

1. Suffix m and p stand for the model and the prototype.
2. * on a quantity indicates the scale factor.