A Methodology to Assess the Radionuclide Migration Parameters through Bentonite-Sand Backfill in a Short Experimental Duration

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ABSTRACT

Bentonite-Sand Backfill is a part of Engineered Barrier System (EBS) widely used in a Near Surface Disposal Facility (NSDF) to delay migration of radionuclides from the disposed nuclear waste in a geo environment. Laboratory migration experiments have been conducted to understand the advection/diffusion mechanisms of various radionuclides through backfill and to evaluate their migration rates in order to assess the performance of EBS. Migration through backfill is an extremely slow process and the experiments are time consuming. Also, these experiments have limitations to simulate the field stress conditions. Various researchers have experienced the advantages of centrifuge modeling technique to model contaminant transport problems of geoenvironment. However, no such studies have been carried out adopting this technique to model the behaviour of bentonite-sand mixture as backfill in NSDF. An attempt has been made in the present study to investigate the validity of this technique to carry out such studies. Significance of geotechnical centrifuge modeling to simulate the prototype radionuclide migration mechanisms through backfill is highlighted. This paper presents the dimensional analysis of various scale factors to construct a physical model for centrifuge tests to monitor online the migration phenomena of radionuclides through bentonite-sand mixture. Studies reveal the feasibility of the technique to evaluate the migration parameters in a short experimental duration. Such studies help in improving EBS design and assessing the long-term performance of EBS in NSDF.

INTRODUCTION

Geological isolation of nuclear waste is considered worldwide as a suitable option to protect man and environment for extended period [1]. Backfill containing bentonite-sand mixture is a part of Engineered Barrier System (EBS) in Near Surface Disposal Facilities (NSDF). Under saturated conditions the hydraulic conductivity of the backfill is reduced significantly due to swelling of bentonite and thus meeting the suitable hydraulic, chemical, and mechanical properties to delay migration of waste components to far fields [2, 3]. However, adoption of bentonite as a barrier material needs an understanding of the interaction between the wastes and the bentonite. Attenuation potential of bentonite against nuclear waste components is difficult to assess, unless hydraulic conductivity, retention and strength characteristics of bentonite at soil-water conditions have been assessed for long term performance.

Usually, laboratory and field experiments are conducted to model and assess the suitability of the bentonite-sand mixture as an engineered barrier and subsequently theoretical predictions are made to assess the long term behaviour of waste disposal systems [4]. However, laboratory experiments are time consuming and suffer with the limitations to simulate the field stress conditions due to the material complexity, difficulty associated with reproduction of the boundary conditions controlling the governing mechanism(s) and the time scale used which is quite different as compared to the time required for completion of the processes in the field. Also, it is difficult to obtain the field performance of backfill media as it requires many years of field observation. The accuracy of such studies depends on the accuracy of input parameters. Earlier studies [5] reveal that values of longitudinal and transverse dispersivities in field systems are significantly large than those values obtained in laboratory experiments or on materials with simple heterogeneities. Thus, the determination of input parameters such as hydraulic conductivity and diffusion coefficients in the laboratory for use in mathematical models must be such that they represent the in-situ stress conditions which are very difficult to simulate in the laboratory. Further, there have been difficulties to verify the predicted major changes and the possible magnitude of the changes during the transport process due largely to lack of adequate data [6].

Keeping in view these problems and problems associated with the validation of the theoretical predictions, various researchers have experienced the advantages of centrifuge modeling technique to model the real life situation termed as the 'Prototype' using small scale physical models under modified gravitational field [7, 8, 9] Also, researchers [10, 11, 12] have experienced the usefulness of this modeling technique to assess the radionuclide migration phenomena. However, no such studies have been carried out adopting this technique to simulate the behaviour of bentonite-sand mixture as backfill in NSDF. An attempt has been made in the present study to investigate the validity of this technique to carry out such studies. Significance of geotechnical centrifuge modeling to simulate the prototype radionuclide migration mechanisms through backfill is highlighted. This paper presents the dimensional analysis of various scale factors to construct a physical model for centrifuge tests to monitor online the migration phenomena of radionuclides through bentonite-sand mixture. Studies reveal the feasibility of the technique to evaluate the migration parameters in a short experimental duration. Such studies help in improving EBS design and assessing the long-term performance of EBS in NSDF.

SIGNIFICANCE OF GEOTECHNICAL CENTRIFUGE MODELING

Fundamental knowledge and techniques related to physical modeling in geotechnical boundary value problems, including similitude, principles of measurement and testing methodology are important to carry out the modeling exercises to understand the usefulness of physical modeling [13]. The mechanical behaviour of a prototype soil mass under the earth's gravity, g can be replicated in a small scale model of $1/N$ experiencing a centrifugal force of Ng. If the depth times acceleration is the same in the model and the corresponding prototype, the stress distribution throughout the model will be identical with that throughout the prototype [14]. In a geotechnical centrifuge, the small scale model experiences the same magnitude and distribution of self-weight stresses as those of its prototype. The main difference between the model and its prototype is that the linear dimensions of prototype are scaled down by a factor of N, at centrifugal acceleration N times greater than g, the acceleration due to Earth's gravity. Within the sample the magnitude of stress increases with depth at a rate related to the sample density and strength of the acceleration field, *N*g. As a direct result of the increase in self weight of the permeant, i.e., 100g water weighs 100times its weight at 1g, the local seepage velocity at any point within a centrifugal model is *N* times that experienced at a similar point in the prototype. In a 1/*N* scale model, seepage-path lengths are shorter by a factor of 1/*N*, so there is a decrease by a factor of 1/*N* in the distance to be traveled by the interstitial fluid in any transient stage. It is therefore a feature of small-scale centrifuge model tests that transient processes, such as fluid motion under changing effective stresses, that occur in long prototype times can be correctly replicated in a centrifuge model in short model test times.

During operation of the geotechnical centrifuge, g along the length of the model is different due to the linear variation of the acceleration, (ω^2.r), where ω is the angular velocity and r is the (effective) radial distance of an element in the model, from the axis of rotation, and can be obtained by using the following Eq. 1 [13]:

$$r = r_t + \frac{h_m}{3} \qquad \text{(Eq.1)}$$

where r_t is the radial distance to the top of the model and h_m is the length of the model. It has also been demonstrated [13] that the maximum error due to the non-linear stress distribution is very small, for most of the centrifuges, when Eq. 1 is used.

Centrifuge model tests therefore offer a means of carrying out small scale accelerated physical modeling of geotechnical problems, at stress levels similar to those experienced by the prototype.

SIMILITUDE CONDITIONS TO MODEL RADIONUCLDE MIGRATION

The mass transport of solute through bentonite-sand backfill is influenced predominantly by processes such as molecular diffusion and/or advection. Loss or gain of solute mass from the solution is governed by the processes of sorption. Due to dominance of these processes the migration of radionuclides through backfill is complex under laboratory conditions due to swelling properties of bentonite which leads to low hydraulic conductivity [15]. Thus it is essential to establish and maintain well-controlled experimental conditions in order to study the influence of these processes on migration.

Centrifuge modeling of radionuclide migration through backfill in a NSDF (prototype) is primarily based on constructing a suitable small scale model considering various prototype conditions which control migration of radionuclides and their corresponding scale factors to maintain similitude conditions between model and prototype. Centrifuge tests provide a means of accelerating the migration processes of radionuclides through such model. Acceleration can also be achieved in a reduced-scale 1g backfill model by increasing the hydraulic gradient through the backfill [16]. However, 1g modeling techniques cannot simulate the prototype self-weight effects. Thus, it is important to consider the self weight effects in modeling to assess the performance of NSDF by physical modeling.

Scaling laws and Scale factors

Scaling laws that govern the relationship between the centrifuge model and its prototype for contaminant migration through soils have been derived on the basic assumption that the interstitial fluid and the soil grains are incompressible. Various scale factors [14] relevant to the problem of contaminant transport are summarized in Table I.

Table I. Scale factors for centrifuge modeling

Parameter	Model to prototype ratio
Length	$1/N$
Pore size	1
Porosity	1
Stress	1
Strain	1
Velocity	N
Viscosity	1
Mass	$1/N^3$
Mass density	1
Time (Seepage)	$1/N^2$
Time (diffusion)	$1/N^2$
Acceleration	N

The material properties of backfill are dependent on the confining stress and to account for the stress dependence of these material properties, stresses must be similar in model and prototype.

Scaling of stress

The scale factor (denoted with asterisk) for identical stress can be expressed as:

$$\frac{\sigma_{model}}{\sigma_{prototype}} = 1 = \sigma^* \qquad \text{(Eq. 2)}$$

In order to meet the above condition, the scale factors of the various stress dependent parameters have to be evaluated. Thus,

$$\sigma^* = \frac{F^*}{A^*} = \frac{F^*}{(l^*)^2} = l^* \qquad \text{(Eq. 3)}$$

$$F^* = m^* \times g^* \qquad \text{(Eq. 4)}$$

Where F^*, A^*, l^*, m^* and g^* represent the scale factors of force, area, length, mass and acceleration due to gravity respectively. The expressions for these scale factors can be written as:

Scale factor for length

$$l^* = \frac{l_{model}}{l_{prototype}} = \frac{1}{N} \qquad \text{(Eq. 5)}$$

Scale factor for force

$$F^* = (l^*)^2 = N^{-2} \qquad \text{(Eq. 6)}$$

Scale factor for the density and mass

$\rho^* = 1$ (for identical bentonite-sand mixture in the model and prototype) (Eq. 7)

$$\rho^* = \frac{m^*}{(l^*)^3} = 1 \text{ and} \qquad \text{(Eq. 8)}$$

$$m^* = (l^*)^3 = N^{-3} \qquad \text{(Eq. 9)}$$

Scale factor for gravity

$$F^* = m^* \times g^* \text{ and} \qquad \text{(Eq. 10)}$$

$$g^* = \frac{F^*}{(m^*)} = \frac{N^{-2}}{N^{-3}} = N \qquad \text{(Eq. 11)}$$

It can be revealed from the above scale factors that the condition to preserve identical stress in model and prototype with identical bentonite-sand mixture is length dimensions of the prototype are reduced by *N* times and subsequently the applied gravitational field is increased *N* times. Thus centrifuge tests provide the required gravitational force on the model to achieve identical stress on the materials as that of prototype.

DIMENSIONAL ANALYSIS FOR MODELING RADIONUCLIDE MIGRATION

For a problem where advection, diffusion and adsorption occur, the physical properties that define the concentration, C, of a given radionuclide may be given by:

$C = f(\mu, D_i, s, v_s, \sigma, \rho, g, l, d, t,$ bulk soil properties) (Eq. 12)

where C is the concentration of the radionuclide (M/L^3), μ is the dynamic viscosity of the fluid [M/LT]], D_i is the coefficient of molecular diffusion (L^2/T), s is the mass of adsorbed contaminant per unit-volume (M/L^3), v_s is the interstitial flow velocity (L/T), σ is the surface tension for fluid/particle interface (M/T^2), ρ is the density of the fluid (M/L^3), g is the acceleration due to the gravity (L/T^2), l is the characteristic macroscopic length (the sample height) (L), d is the characteristic microscopic length (particle size) (L), and t is the time (T).

The independent variable represented by 'bulk soil properties' can be assumed to be identical in both the model and its prototype. For the remaining ten independent variables, and one dependent variable 'C' the following non-dimensional groups can be derived [5].

$\pi_1 = C/\rho$ (concentration number)
$\pi_2 = \rho.v_s.d/\mu$ (Reynolds number, R_e)
$\pi_3 = v_s.t/l$ (advection number)
$\pi_4 = D_i.t/l^2$ (diffusion number)
$\pi_5 = \rho.g.l.d/\sigma$ (capillary effects number)
$\pi_6 = s/\rho$ (adsorption number)
$\pi_7 = g.t^2/l$ (dynamic effects number)
$\pi_8 = v_s.d/D_i$ (Peclet number, P_e)

π_1 is the dependent dimensional group, and can be written as

$$\pi_1 = f(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8) \quad \text{(Eq. 13)}$$

For similitude of transport processes through the porous media, these eight controlling dimensionless groups must be identical in both the model (m) and its prototype (p).

Scaling of fluid motion

The dimensionless group $\pi_2 = \rho.v_s.d/\mu$ gives dynamic similarity of fluid motion by ensuring that the ratio between inertial and viscous forces in the fluid remains constant. In most problems encountered in groundwater flow, the inertial forces are negligible in comparison with the viscous resistance ($R_e < 1$). In such cases, the condition that the Reynolds number remains invariant can be waived, and the equation of fluid motion may be described by Darcy's law.

Scaling of seepage

The movement of radionuclides leached by groundwater in the prototype conditions is heavily dependent on the hydraulic conductivity of the backfill. The behaviour of backfill gets altered with stress level and stress history due to self-weight effects. The achievement of identical stress at homologous points in model and prototype can therefore lead to a true distribution of hydraulic conductivity throughout the backfill. The condition $\pi_3 = v_s.t/l$ gives kinematic similarity of motion by ensuring that the ground water seepage patterns in the prototype and the model are geometrically similar. The ratio ($v_s.t/l$) remains invariant when $t_p = N^2.t_m$ i.e., the prototype time is to N^2 times that of model time

Scaling of diffusion time

Scaling of $\pi_4 = D_i.t/l^2$ leads to similarity of diffusion processes in the model and its prototype. The

Coefficient of diffusion for an ion in the porous media is a function of both the medium and the free diffusion coefficient of the ion in the solution. For an identical radionuclide and an identical backfill material, subjected to similar stress in the model and its prototype, the condition $(D_i)_m = (D_i)_p$ should arise. To maintain the ratio $(D_i.t/l^2)$ invariant, the condition $t_p = N^2.t_m$ must be met, i.e., the time required for the radionuclides to migrate by diffusion process will be N^2 times faster in the model than that of prototype. This is in agreement with the time scale function derived from π_3.

Scaling of Capillarity effects

The dimensionless group $\pi_5 = \rho.g.l.d/\sigma$ must be identical in the model as well as in the prototype to simulate the capillary effects, like the height of capillary rise or flow above the groundwater table

Scaling of linear dimensions

If the sample used for the model and its prototype is identical and the model is subjected to higher acceleration, in a spinning centrifuge, the vertical stress at a depth h_m, in the model, will be identical to that in the corresponding prototype at depth h_p. As such, for modeling of the bentonite-sand backfill of density, ρ, the vertical stress, σ_m, at a depth, h_m, in the model can be represented as:

$$\sigma_m = \rho.N.g.h_m \quad \text{(Eq. 14)}$$

Similarly, for the backfill, the vertical stress σ_p, at a depth, h_p, in the prototype would be:

$$\sigma_p = \rho.g.hp \quad \text{(Eq. 15)}$$

As such, for σ_m to be same as σ_p:

$$h_m = h_p.(N)^{-1} \quad \text{(Eq. 16)}$$

As per Eq. 16 the scale factor for linear dimensions is $1/N$. The equation states that stress similarity is achieved at homologous points in the model and its prototype by accelerating a model of scale $1/N$ to N times Earth's gravity. Since the model is a linear scale representation of the prototype, the same scale factor may be imposed to displacements also. It therefore follows that strain scales to a factor of 1. As such, the sample stress-strain properties of the model are identical to that of the prototype.

Scaling of concentration of adsorbed contaminant

Radionuclide sorption process taking place by interaction with backfill material depends on the various controlling parameters like bentonite-sand mixture ratio by dry weight, type of radionuclide, aqueous medium conditions like pH, temp etc. For similitude in the concentration of adsorbed radionuclide, s, the ratio $\pi_6 = s/\rho$ must be same in model and prototype. The above mentioned dependent sorption parameters have to be identical in the model as well as in the prototype. In addition, in order to achieve this condition rapid linear equilibrium adsorption laws have to be considered based on the value of s which is purely a function of the concentration of radionuclide in solution, C. For the cases where there is non linear equilibrium conditions there may be difficulties to model adsorption process.

The dimensional group $\pi_7 = g.t^2/l$ represents modeling of events like earthquake involving high inertial forces and $\pi_8 = v_s.d/D_i$ represents the modeling of dispersion mechanism with low (<< 1) Peclet number, P_e. These groups are not discussed in the study since, as stated above, radionuclide migration through backfill is controlled predominantly by diffusion and/or advection (advective diffusion).

PHYSICAL ASPECTS OF CENTRIFUGE MODELING

This paper describes a methodology to design and construct a small scale model for centrifuge tests simulating the backfill conditions of prototype NSDF for low level radioactive waste based on material properties, suitable scale factors in order to investigate the validity of centrifuge modeling technique.

Properties of Bentonite-Sand backfill

It is essential to account for the physical, chemical, geotechnical and hydraulic properties of bentonite, sand and their mixture to construct a model with the same material properties as those in the prototype. In this study, the properties of sodium type bentonite, Kunigel V1, Mikawa silica sand No.6, which have been used as backfill material in Japan, have been considered. The modal mineral composition and the properties of Bentonite are presented in Table II and III [17]. Due to wide range of particle sizes of backfill mixtures an attempt is made in this research to determine the particle size distribution of bentonite, sand by microscopic image analysis using Morphologi G2 particle size analyzer [18]. The results are depicted in Fig. 1. The favourable prototype condition for backfill in NSDF is to maintain the bentonite-sand ratio as 30:70 on dry weight basis [19] so that the radionuclide migration under saturated conditions of this ratio is dominated by the diffusion mechanism. However, keeping in view the design requirements for safety assessment of backfill behaviour and to understand the limitations of centrifuge modeling technique, the present study considers the ratios 10:90, 20:80 and 30:70 to conduct modeling exercises.

Table II. Modal mineral composition (%) of Sodium Bentonite Kunigel V1

Mineral	Modal %
Montmorillonite	46 - 49
Quartz	29 - 38
Feldspar	2.7 - 5.5
Calcite	2.1 - 2.6
Dolomite	2.0 – 2.8
Analcite	3.0 – 3.5
Pyrite	0.5 – 0.7
Organic matter	0.31 – 0.34

Table III. Properties of Bentonite

No.	Parameter	Value
1	Particle density (Mg/m^3)	2.79
2	Liquid limit (%)	473.9
3	Plastic limit (%)	26.61
4	Plasticity index	447.3
5	Clay(<2 μm) content (%)	64.5
6	Montmorillonite content (%)	48
7	Cation exchange capacity (meq./100g)	73.2
8	Specific surface area (m^2/g)	46-51

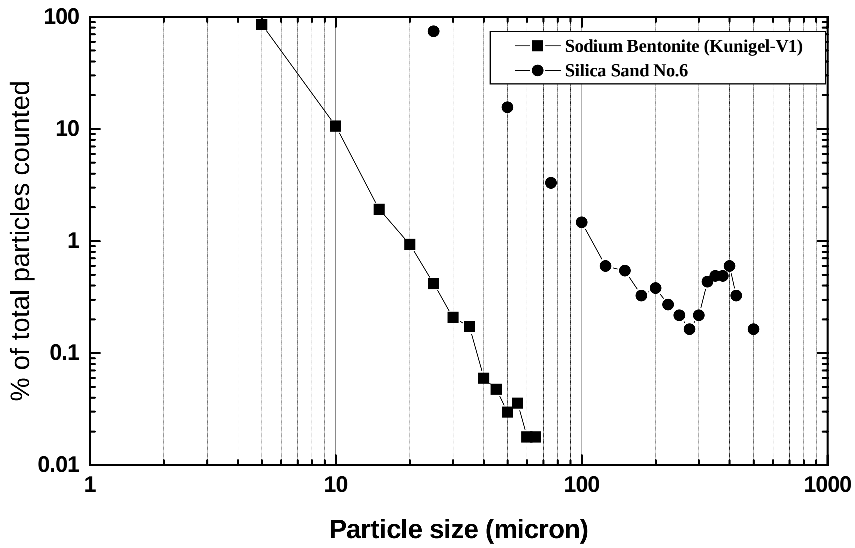

Fig. 1. Particle size distribution of Bentonite and Silica Sand

Since, the study considers the modeling of advective diffusion mechanism under saturated conditions of these ratios, the steady state saturated hydraulic conductivity of bentonite-sand mixtures is accounted to conduct preliminary investigations on migration modeling. Earlier studies carried out on the hydraulic properties of these mixtures and the results show the dependence of hydraulic conductivity on water content and dry density are presented in Table IV [17].

Table IV. Hydraulic properties of Bentonite-Sand mixtures

Bentonite content (%)	**Average soil particle density (Mg/m^3)**	**Maximum dry density (Mg/m^3)**	**Optimum water content (%)**	**Hydraulic conductivity (m/sec)**
10	2.68	1.64	17.6	2.66×10^{-10}
20	2.69	1.68	17.0	4.85×10^{-12}
30	2.70	1.72	14.6	6.87×10^{-12}

Prototype conditions

Benotnite-sand backfill conditions of Low Level radioactive Waste disposal facility [20] Japan is considered in this paper to model radionuclide migration in centrifuge. In this facility concrete trenches with wastes are sealed by backfill material covering overall area with length 191-231m, width 132-152m and depth 8-9m. This disposal facility has a cover soil with 4-9m depth from ground level. The fundamental aim of adopting centrifuge modeling technique simulating the conditions of this facility is to account for the field stress conditions in the model. Accordingly, the self-weight of cover soil and backfill depth has been considered and the length of the disposal facility is assumed as infinite length. The total vertical stress, σ_v and effective vertical stress $\sigma`_v$ levels at the top and bottom of the backfill have been calculated assuming saturated conditions of cover soil and backfill and without concrete trenches. The thickness of backfill material, z is taken as 10m whereas the thickness of overlying cover soil is taken as 10m from the ground level. The saturated unit weight of cover soil, Υ_w and bentonite-sand mixture, Υ_{sat} have been taken as 20KN/m^3 and 9.81KN/m^3 respectively. Accordingly the stress levels at the top and bottom of the backfill have been computed using the following relationship:

Total vertical stress $\sigma_v = \Upsilon_{sat}\, z \times \Upsilon_w .\, z_w$ (Eq. 17)

Stress levels at the top of backfill surface (z=10m)

- Vertical total stress $\sigma_v = 20 \text{ x } 10 = 200\text{kPa}$
- Pore pressure $u = 10 \text{ x } 10 = 100\text{kPa}$
- Vertical effective stress $\sigma'_v = \sigma_v - u = 100\text{kPa}$

Stress levels at the top of the bedrock (z=20m)

- Vertical total stress $\sigma_v = 20 \text{ x } 20 = 400\text{kPa}$
- Pore pressure $u = 10 \text{ x } 20 = 200\text{kPa}$
- Vertical effective stress $\sigma'_v = \sigma_v - u = 200\text{kPa}$

Capacity of Geotechnical centrifuge

A large capacity geotechnical centrifuge to model well-defined problems including all self-weight effects is necessary to conduct centrifuge tests. In the present study, the features of Tokyo Institute of Technology (Tokyo Tech) Mark III centrifuge [21] have been considered for its suitability as an appropriate testing apparatus to model backfill performance in NSDF. Schematic view of the centrifuge is as shown in the Fig. 2. Specifications of the centrifuge are summarized in Table V. This centrifuge is a beam type balanced-arm centrifuge having a pair of parallel arms that hold platforms on which the model container and a weight for counterbalance can be mounted. The radius of rotation is 2.45m, which is the distance from the rotating shaft to the platform base. The surface of the swinging platform is always normal to the resultant acceleration of the centrifugal acceleration, *N*g, and Earth's gravity. This would enable to incorporate inherent material heterogeneity as well as anisotropy up to a certain extent. It can be noticed from the specifications of the centrifuge that the platform dimensions and capacity of the centrifuge on payload and number of rotations are the key factors to design the model dimensions.

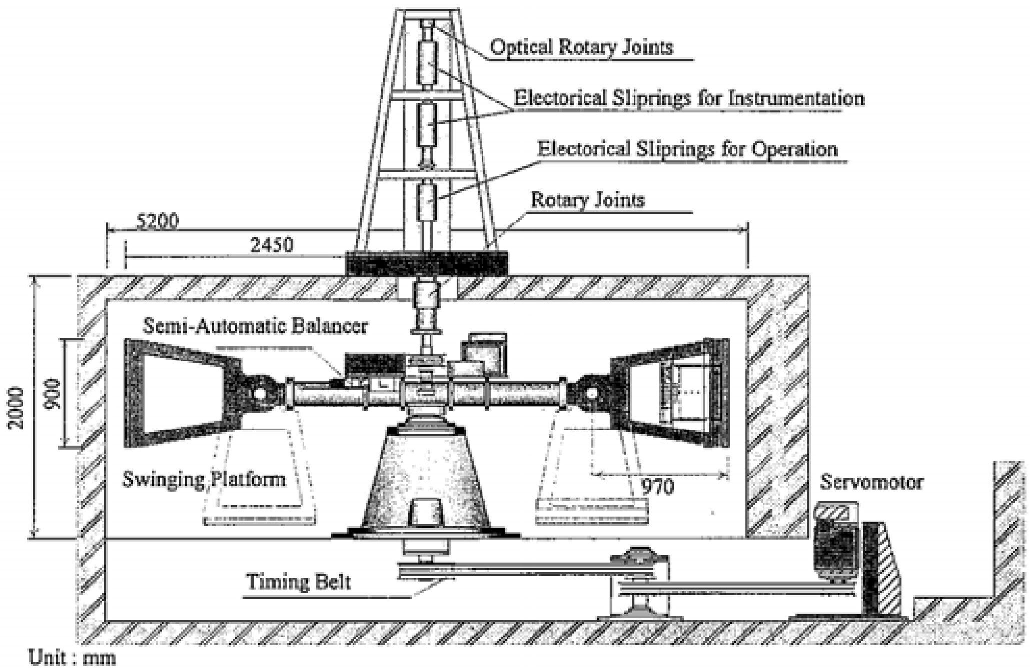

Fig. 2. Tokyo Tech Mark III geotechnical centrifuge

Table V. Specifications of Tokyo Tech Mark III centrifuge

Arm Radius	Including platform	2.45m
	Effective radius	2.0 - 2.2m
Platform dimensions	Width	0.90m
	Depth	0.90m
	Maximum height	0.97m
Capacity	Maximum payload	50g.ton
	Maximum number of rotations	300rpm
	Maximum payload at 80-g	600kg
Electrical slip rings	For operation	18 channels
Rotary joints	Number of ports for air and water	2
	Working pressure for air and water	1MPa
	Number of ports for oil	2
	Working pressure for oil	21MPa
Optical rotary joints	Number of ports	4

Description of experimental set up

In the present study, the model dimensions to conduct centrifuge tests were decided based on the properties of bentonite-sand mixture, prototype conditions, scale factors and capacity of centrifuge. Accordingly, an experimental setup has been designed as shown in Fig. 3. This setup is comprised of an acrylic column with 150mm internal diameter and 170mm external diameter and height 250mm. To simulate the prototype backfill thickness of 10m, the backfill specimen thickness 100mm can be chosen with centrifugal acceleration level 100g. Also, in order to simulate the stress levels of the prototype cover soil, 100mm thickness of sand can be provided overlying the backfill specimen as shown in the Fig. 3. This sand is also kept under fully saturated condition with source solution containing radionuclides at desired concentration level. This column is provided with top and bottom steel plates (10mm thickness) with rubber 'O' rings to seal the specimen from leakages. The top plate has provision for source solution inlet to maintain the saturated condition of overlying sand. Similarly, the bottom plate has provision for drain through porous stone. These plates have additional vent holes which can be used for inserting pore pressure transducers to monitor the pore pressure at the top and bottom of the specimen during centrifugation. The side wall of the acrylic column is provided with holes for outlet of scintillator cables. In order to monitor online the movement of radionuclides during centrifugation optical fiber plastic scintillator sensors can be placed one at the top of the backfill specimen to monitor the radioactivity levels of source solution (C_0) and the second at the bottom of the specimen to monitor the radioactivity level changes with time (C_t). The inner diameter of the acrylic column is chosen in such a way to suitably place these scintillator sensors at the top and bottom of the backfill specimen. These sensors can subsequently be connected to photomultiplier tube, amplifier and scintillator counter to measure the radiation level in terms of counts per sec.

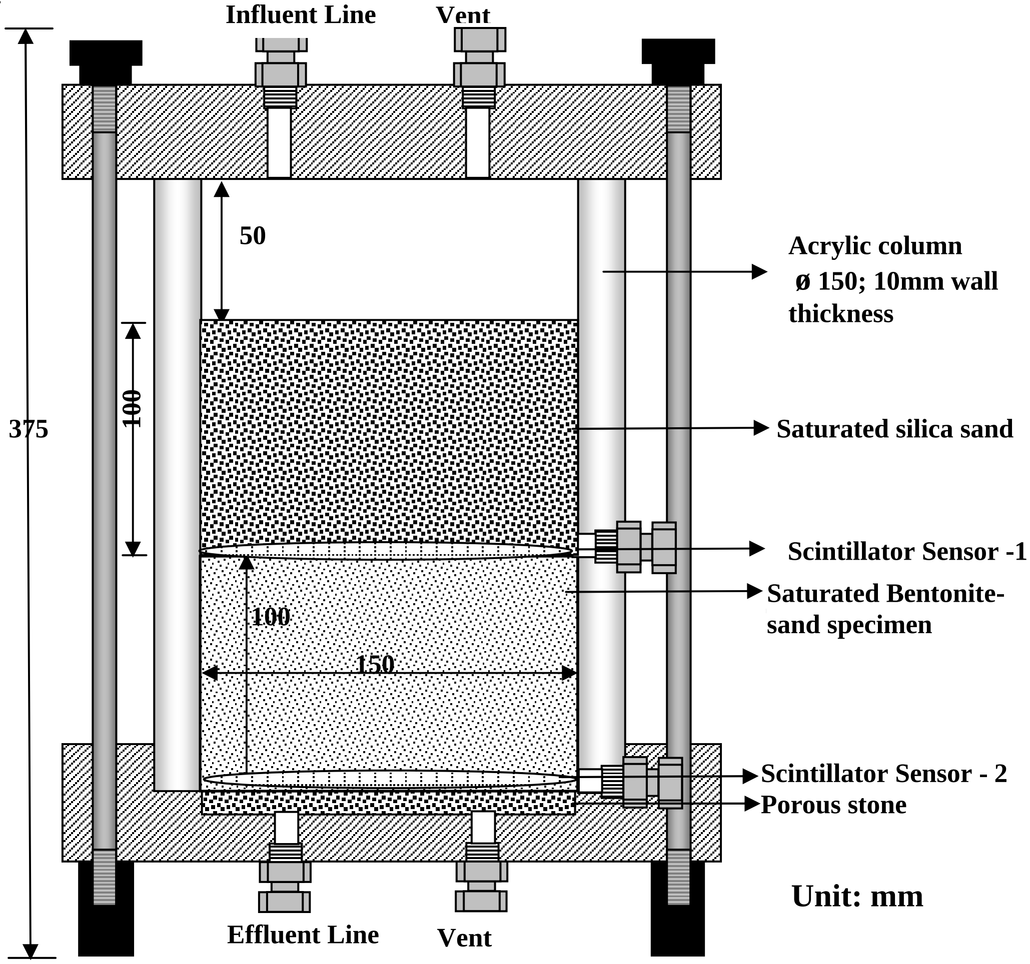

Fig. 3. Experimental setup for centrifuge tests

Calibration is done for a specific model dimension to evaluate the speed of the centrifuge to generate the desired acceleration level based on the effective radius of rotation, r, using the following relationship. r is the distance from the axis of rotation to the middle of the backfill specimen.

$$n = \frac{60}{2\pi}\sqrt{\frac{N.g}{r}} \qquad \text{(Eq. 18)}$$

Thus, for the model length of 100mm, the speed of the centrifuge, n, at the desired acceleration level of 100g to be maintained is 196 rpm. However, different thicknesses of backfill specimen can be tested simulating the entire prototype backfill thicknesses at appropriate speed levels.

Steady state saturated hydraulic conductivity of backfill specimen

As mentioned above, the study considers the modeling of advective diffusion mechanism of migration under the condition of steady state saturated hydraulic conductivity of the specimen. It is thus necessary to prepare the backfill specimen prior to conducting centrifuge tests to maintain the sample homogeneity during centrifugation efforts. This condition can be generated by saturating the model specimen by supplying distilled water at a desired pressure from the bottom of the experimental setup. During this process, the specimen is kept at constant desired volume under load equivalent to prototype stress levels. Specimen saturation can be ascertained by measuring the swelling pressure as well as the pore pressures changes at the top and bottom of the specimen. The specimen is assumed to be fully saturated when swelling pressure attains constant value as well as the pore pressures at the top and bottom of the specimen become equal. Hydraulic conductivity of the specimen can be determined in this saturated condition using the following relationship [17]:

$$\kappa = \frac{q}{A}\rho_w g \frac{H_0}{P_{in} - P_{out}}, (m/s) \qquad \text{(Eq. 19)}$$

Where q represents the average outflow quantity at unit time (m^3/s), A is the cross-sectional area, P_{in} is the water-pressure of bottom of specimen, P_{out} is the water-pressure at the top of the specimen, H_0 is the specimen height, ρ_w is the water density (kN s^2/m^4), and g represents the gravitational acceleration (=9.80665m/s^2).

In addition to maintaining the steady state saturated hydraulic conductivity, it is necessary to maintain the validity of Darcy's law (5). This can be maintained if the Reynolds number Re = $\bar{v}d/v \leq 1$, where $\bar{v}$ = interstitial velocity; d=diameter of the soil grain; and v = coefficient of kinematic viscosity. The scaling of interstitial velocity by *N* times within the model can be expressed by the following equations.

$$\bar{v}_{prototype} = \frac{\kappa}{\gamma_f n}\frac{\partial p}{\partial l} \qquad \text{(Eq. 20)}$$

$$\bar{\nu}_{\text{model}} = N\,\left(\frac{\kappa}{\gamma_f n}\frac{\partial p}{\partial l}\right) \qquad \text{(Eq. 21)}$$

DISCUSSIONS ON MODEL DESIGN AND METHODOLOGY *

The tests on particle size distribution of bentonite and sand by image analysis technique reveal that the particle size of bentonite ranges from 1.76microns to 64.10 microns and that of sand is range from 7.03 to 539.92microns. The technique is advantageous to cover wide range of sizes (0.5 – 3000microns) including colloids and the method involves particle counting to assess the size range based on their shapes. Samples can be tested in dry and wet conditions to observe the size changes due to swelling in case of expansive soils like bentonite. Also, the information on the size of colloidal particles is important to assess their mobility after interaction with radionuclides.

It can be inferred from the scaling laws and corresponding scaling factors that the feasibility of centrifuge modeling technique to model the migration of radionuclides through backfill can be established by maintaining the similitude conditions between model and prototype. These conditions reveal that the migration of radionuclides through backfill in a centrifuge model will occur at N^2 times the rate of the equivalent migration in the prototype and that concentrations will be identical in both model and prototype.

Despite the fact that the Centrifugal force provides the means of acceleration of interstitial velocity within the model specimen, there are limitations to run the centrifuge to obtain break-through of contaminant concentration changes because of very low hydraulic conductivities of backfill material. However, the changes in the concentration of radionuclides with depth in the model specimen can be accurately monitored online using optical fiber plastic scintillators to achieve steady state condition of contaminant migration. In such cases, the duration of centrifuge tests can be optimized well within the limits of centrifuge capacity for various sorbing as well as non sorbing radionuclides. Accordingly, a linear plot depicting the change in concentration with time can be plotted for various radionuclides to evaluate the migration parameter of radionuclides.

For an example, the duration of centrifuge tests evaluated applying scaling factors using the similar migration plots have been presented. The time taken by diffusion to achieve steady state migration for the non-sorbing radionuclide Iodide (I^-) and sorbing radionuclide Strontium (Sr^{2+}) through MX-80 pure bentonite [21] saturated with saline solution and compacted to dry density 1.8Mg/m^3 are shown in the Fig. 4 a & b. From the figure it can be noticed that diffusion process of I^- takes about 70 days to reach the steady state concentration of 200cps. In case of Sr^{2+}, the diffusion process takes about 15days to reach the steady state concentration of 60cps. These concentration levels would be achieved by these respective radionuclides within 10 and 2minutes of centrifugation at acceleration level 100g. Earlier studies [8] revealed that the centrifuge tests have been modeled up to 30years of pollutant transport in only 25hours of centrifuge test time. The validity of centrifuge modeling can also be established by verifying the scaling laws by conducting 'modeling of models'. This is done by testing similar models at different scales and observing similitude behaviour among models.

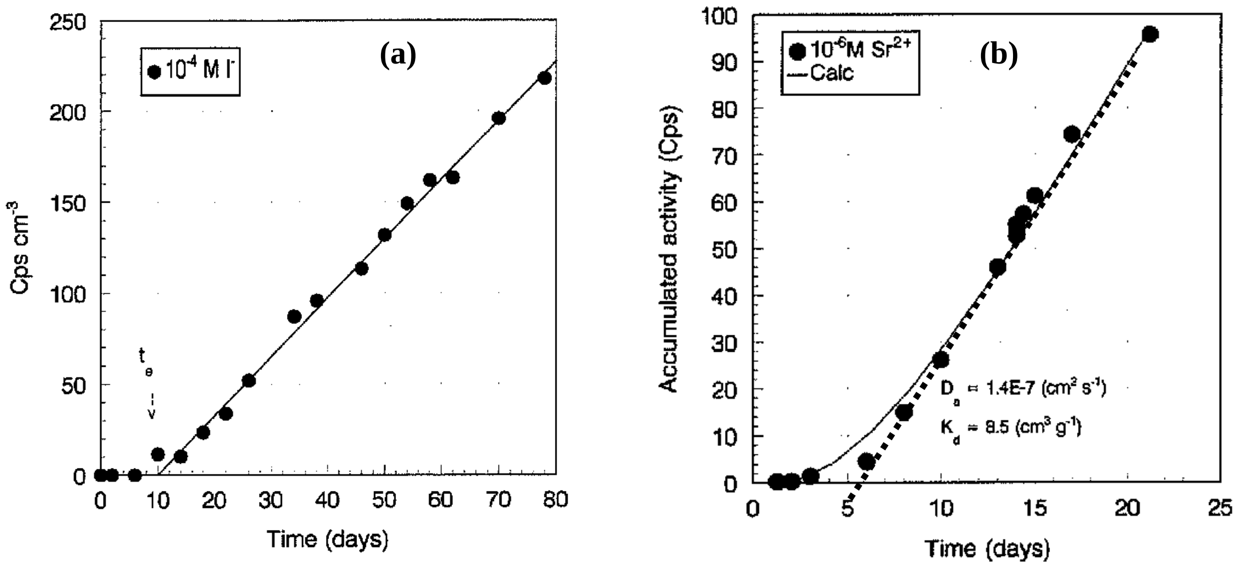

Fig. 4. Diffusion curves for I^- and Sr^{2+} through bentonite

The migration of radionuclides by advective-diffusion mechanism can be described as one dimensional contaminant transport [23] through porous media and is governed by:

$$n\frac{dc}{dt} = nD\frac{d^2c}{dz^2} - nv\frac{dc}{dz} - rK_d\frac{dc}{dt} - nlc \qquad \text{(Eq.22)}$$

Where,
c = concentration of radionuclide at depth z at time t
D = Coefficient of advective-diffusion at depth z
v = velocity of aqueous medium at depth z
n = porosity of the bentonite-sand backfill at depth z
r = dry density of the backfill at depth z
K_d = the distribution coefficient of radionuclide at depth z
v_a = nv = Darcy velocity
l = decay constant of the radionuclides

The above equation can be solved by POLLUTEv7 program subject to boundary conditions at the top and at a depth z being modeled [24]. The predictions thus obtained can be verified using the centrifuge test results for various time scales as well as incorporating heterogeneities and various test conditions like pore water quality, saline environment and temperature effects.

CONCLUSIONS

Various scaling relationships and the methodology to construct a physical small scale model indicate the validity of centrifuge modeling technique to simulate the behaviour of backfill in NSDF. However, prototype conditions and the capacity of the centrifuge are important to design and construct a model for centrifuge tests. Evaluation of migration parameters in a short experimental duration is feasible by maintaining the suitable scaling relationship between the model and prototype. Online monitoring of migration processes of radionuclides is advantageous to accurately measure the concentration changes with depth of the backfill specimen by maintaining the sample integrity.

REFERENCES

1. N.A. Chapman And I.G. Mckinley, "Geological disposal of nuclear waste," Chichester: Wiley (1987).
2. H. Komine, N. Ogata, Y. Horie, T. Ishii And S. Nishio, "Permeability and Mechanical Properties of Bentonite-Sand Mixture for Sealing LLW Repositories, SMiRT11, 271-276 (1991).
3. Satoshi Imamura, Toru Sueoka And Masashi Kamon, "Long term stability of bentonite/sand mixtures at L.L.R.W. storage", Proc. Int. Congress on Environmental Geotechnics, Osaka, Japan, November 5-8, 1996, Vol.1, 545-550 (1996).
4. IAEA, International Atomic Energy Agency, Vienna, "Final Report on Nuclear techniques in the study of pollutant transport in the environment–Interaction of solutes with geological media (methodological aspects)," IAEA-TECDOC-713 (1993).
5. K. Arulanandan, P.Y. Thompson, B.L. Kutter, N.J. Meegoda, K.K. Muraleetharan And C. Yogachandran, "Centrifuge modeling of transport processes for pollutants in soils," ASCE Journal of Geotechnical Engineering, 114(2), 185-205 (1988).
6. D.R. Lawrence, "The Lack of Technical Basis For Requiring A Ten Thousand Year Prediction For Nuclear Waste Management," Proc. Materials Research Society Symposium, Vol. 333, 193-198 (1994).
7. B. Sukh, Gurung, Hiroshi Yamamoto And Romeo I. Farcasanu, Osamu Kusakabe, Shiro Ono, "Migration of toxic chemicals through bentonite-sand layer in accelerated gravity field", Proc. Int. Congress on Environmental Geotechnics, Osaka, Japan, November 5-8, 1996, Vol.1, 521-526 (1996).
8. R.J. Mitchell, "Centrifuge techniques for testing clay liner samples," Canadian Geotechnical Journal, 31, 511-583 (1994).
9. C. Gurumoorthy, "Simulation of the radionuclide migration through the rock mass in a geotechnical centrifuge," Ph.D. thesis, Indian Institute of Technology, Bombay, Mumbai, India (2002).
10. T.F. Zimmie, M.B. Mahmud and A. De, "Accelerated physical modeling of radioactive waste migration in soil," Canadian Geotechnical Journal, 31, 683-691 (1994).
11. H. Villar And C. Merrifield, "Centrifuge modeling of radioactive waste migration through soil using radionuclides," Environmental Geotechnology, Usmen & Acar (eds), Balkema, Rotterdam, 87-92 (1992).
12. H. Villar And C. Merrifield And W.H. Craig, "Experimental aspects of modeling of migration phenomena," Centrifuge '94, Eds. Leunmg, Lee and Tan, Balkema, Rotterdam, 363-368 (1994).
13. R.N. Taylor, "Geotechnical centrifuge technology", Blackie Academic and professional, Glasgow (1995).

14. P.J. Hensley and A.N. Schofield, "Accelerated physical modeling of hazardous waste transport," Geotechnique, 41(3), 447-465 (1991).
15. H. Komine, "Simplified evaluation of hydraulic conductivities of bentonite buffer and backfill", Proc. 12th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering (CD-ROM) (2003).
16. A.N. Schofield, "Cambridge geotechnical centrifuge operations, Twentieth Rankine Lecture, Geotechnique, 30(3), 227-268 (1980).
17. Hideo Komine, "Simplified evaluation on hydraulic conductivities of sand-bentonite mixture backfill", Applied Clay Science, 26, 13-19 (2004).
18. Malvern Instruments, UK, Instruction Manual, "Morphologi G2, version 6.00", (CD-ROM) (2006).
19. JNC Report, ""H12: Project to Establish the Scientific and Technical Basis for HLW Disposal in Japan", (1999).
20. Japan Nuclear Fuel Limited Profile, "Main activities and services on disposal of low-level radioactive waste", http://www.jnfl.co.jp/english/disposal.html (2006).
21. K. Tsuno, W. Morimoto, K. Itoh, O. Murata And O. Kusakabe, " Centrifugal modeling of subway-induced vibration", Int. J. Physical Modeling in Geotechnics, Vol.5, No.4, 15-26 (2005).
22. Trygve E Eriksen And Mats Jansson, "Diffusion of I^-, Cs^+ and Sr^{2+} in compacted bentonite – Anion exclusion and surface diffusion", SKB Technical Report, TR-96-16 (1996).
23. R.K. Rowe and J.R. Booker, "1-D pollutant migration in soils of finite depth", J. Geotechnical Engineering, American Society For Civil Engineers, 111, 4, 479-499 (1985).
24. R.K. Rowe and J.R. Booker, "Modelling of 2D contaminant migration in a layered and fractured zone beneath landfills", Canadian Geotechnical Journal, Vol. 28, No. 3, 338-352 (1991).

* Experimental investigations are in progress to ascertain the safety of model design and the methodology by conducting centrifuge (*N*g) tests (in Tokyo Tech Mark III centrifuge using non-radioactive chemicals) and 1g tests using radionuclides in the radiochemical laboratory. Subsequently, the centrifuge tests using radionuclides would be carried out in the radiochemical laboratory.