Methodology for Evaluation of Hydro-Mechanical Behaviour of Clay Based Landfill Covers in a Geo-Centrifuge

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ABSTRACT

The landfill remains the most appropriate and attractive disposal technique for municipal solid waste and low level radioactive wastes. Compacted soil barrier is being used as an impervious barrier cover systems to safeguard the environment, wherever impervious soils are abundantly available. One of the predominant failures of the soil barrier is due to the occurrence of differential settlements. This paper deals with the use of centrifuge model test for evaluating the hydro-mechanical behaviour of landfill covers with and without geogrid layer at the onset of differential settlements. Motor based differential settlement simulator setup was used for inducing differential settlement at 40 gravities. The infiltration of water within the soil barrier while being subjected to differential settlements was assessed using miniature pore pressure transducers. A detailed procedure for evaluating the hydro-mechanical behaviour of soil barriers in terms of cracking pattern, water breakthrough and limiting distortion level are presented.

1. INTRODUCTION

The need for waste containment systems especially landfills is to contain solid, liquids and gases present in landfill and to discharge leachate safely for treatment. If waste containment systems are not provided, the leachate and landfill gases generated in landfills can pose a threat to the surrounding environment. Engineered landfill comprises of various layers of soil and geosynthetics, based on type of waste, thickness of waste to be contained, desirable period of post-closure monitoring, geological and geotechnical constraints etc. However, every engineered landfill should have an impervious layer (with hydraulic conductivity \( \leq 10^{-9} \text{ m/s} \)) as one of the components of lining systems. The clay-rich soil having low hydraulic conductivity is the common form of impervious layer since the early days of landfill construction. Even though newer landfills have well engineered composite lining systems with geosynthetic clay liner and / or with geomembranes, soil barriers are still commonly used in many countries of the world. Soil barriers are susceptible to cracking due to moisture fluctuations (desiccation cracks), differential settlements (mainly due to readjustments and decomposition of the contained wastes) and others. The presence of cracks in soil barrier may impair its basic function of impervious layer in landfill lining system. As the cover system is formed on unstable support (solid waste), the problem of differential settlement is more pronounced in cover system. Hence, in the present study, an attempt has been made to evaluate the hydro-mechanical behaviour of soil barrier of cover system under various magnitudes of differential settlements through centrifuge tests.

2. CENTRIFUGE MODELLING TECHNIQUE

Geotechnical centrifuge modelling can simulate the actual stress condition in the field by increasing the unit weight of a small-scaled model. In addition, the soil conditions, the loading and the response measurements can be better controlled in the centrifuge. Centrifuge modelling is now firmly established as a dependable research tool that can provide solutions to many of the hitherto intractable problems in geotechnical engineering. Application of centrifuge modelling technique to the present study is relevant because the loss of integrity of soil barrier is highly influenced by the presence of prototype stress conditions. Centrifuge scaling factors relevant to modelling of soil
barriers has been described extensively by Viswanadham & Jessberger (2005) and Viswanadham & Rajesh (2009). The centrifuge tests reported here were performed at 40 gravities. The 4.5 m radius large beam centrifuge at IIT Bombay having centrifuge capacity of 250g-ton with a maximum payload of 2.5 t at 100g and at the higher acceleration of 200g the allowable payload is 0.625 t was used (Chandrasekaran 2001).

3. MODEL PREPARATION AND TEST PROCEDURE

Model Soil Barrier Material

In the present study, it is decided to model the compacted soil material which represents a wide spectrum of material characteristics of soil barriers of landfill cover systems. Various kaolin-sand mixes were tried to achieve the ideal properties of landfill barriers, out of which kaolin-sand mix of 4 : 1 by dry weight is chosen as model barrier material. It has a liquid limit of 38%, plastic limit of 16%, coefficient of permeability of $0.4 \times 10^{-9}$ m/s, maximum dry unit weight of 15.9 kN/m$^3$ and optimum moisture content of 22% (standard Proctor compaction test).

Test Setup for Inducing Differential Settlements

A Motor based Differential Settlement Simulator (MDSS) has been custom designed and developed to induce continuous differential settlements on the soil barrier layer under high-gravity environment. It comprises of a screw jack, central platform, gear train, shafts, bearing, motor with controller, and side boxes connected to hinge plate with a mechanical hinge (Fig. 1b). MDSS system works on a simple mechanism in which the rotational movement of the motor is converted to translation movement of the central platform. The settlement rate can be adjusted by varying the speed of the motor with the help of thyristor based motor controller. The detailed specification, mechanical design and working procedure of MDSS system can be found in Rajesh & Viswanadham (in press).

Test Procedure

The MDSS system is assembled in a strong box to form a plan area of 720 mm x 360 mm (model dimensions), equivalent to 415 m$^2$ of landfill area (in prototype dimension) at 40 g. The stress concentration near the hinges is minimised by providing layer of 30 mm thick coarse sand followed by 30 mm thick fine sand layer as shown in Figure 1b. The 30 mm thick soil barrier is prepared by mixing the kaolin and sand in the ratio of 4 : 1 and moist-compacted at a moulding water content of OMC + 5% with the corresponding dry unit weight of 14.2 kN/m$^3$. Several miniature pore pressure transducers (PPTs) have been placed on top of the properly prepared soil barrier for measuring the water breakthrough and the settlement at which integrity of the barrier loses (Fig. 1a). After placing PPTs in position, calculated quantity of water and sand are kept above the soil barrier based on required overburden pressure to be simulated. In order to avoid the leakage of water between the sides of the container and the soil barrier, water tight seal made up of a thick bentonite paste has been applied all along the sides of the soil barrier, in addition to side bunds, as shown in Figure 1a. In order to evaluate deformation profiles of the soil barrier, plastic markers are embedded on the model soil barrier surface, as shown in Figure 1b. A series of Linear Variable Differential Transformers (LVDTs) are placed on the soil barrier and central platform to monitor the deformation of the soil barrier and to measure induced central settlement $a$. In the present study, central settlements are induced using MDSS continuously at 40g with a maximum central settlement of 25 mm (1 m at 40g). At the various stages of central settlements, photographs were taken using digital photo camera placed on the front side of the model and were later used for image analysis to compute deformation profiles of the soil barrier.

![Typical Views of Soil Barrier Before and After Inducing Differential Settlement](image)
4. HYDRO-MECHANICAL BEHAVIOUR OF THE SOIL BARRIER

The hydro-mechanical behaviour of the soil barrier can be evaluated using deformation profile of the soil barrier, soil strain, cracking pattern and limiting distortion level. The deformation profile and the soil strain are analysed optically by measuring the displacement z of the discrete markers which are embedded on the soil barrier. The measured co-ordinates of discrete markers are approximated with an exponential equation of the normal distribution to get the deformation profiles at various stages. The soil strain along the top fiber of the soil barrier for various stages of central settlement can be obtained from the deformation profile of the soil barrier at respective central settlement. Methodology adopted for determining deformation profiles and soil strains through image analysis were given in detail by Rajesh & Viswanadham (2009b). The deformation profile of a 1.2 m thick soil barrier having $\sigma_0 = 12.5$ kPa at various stages of central settlement (prototype dimension) is shown in Figure 2. The soil barrier has undergone uniform deformation irrespective of central settlement.

Fig. 2: Deformation Profiles of a 1.2 m Thick URSB with $\sigma_0 = 12.5$ kPa Under Various Central Settlements

The cracking pattern of the soil barrier is an important parameter in evaluating hydro-mechanical behaviour of soil barrier because integrity of the soil barrier can be lost only when crack extends to sufficient depth and width. The initiation and propagation of cracks were monitored throughout the deformation stages from $a = 0$ m to $a = 1$ m using top camera. The cracking pattern of the soil barrier (d $= 1.2$ m, 12.5 kPa) is shown in Figure 1c. Multiple cracks with few cracks extends up to full-depth of the soil barrier was developed ($a_{\text{max}} = 1$ m). The limiting soil strain at the crack initiation and water breakthrough of the soil barrier can be determined.

The performance of the soil barrier as an effective hydraulic barrier can be best illustrated through infiltration rate of permeant flow through the soil barrier. The infiltration rate is directly observed by the reduction in the volume of the water at every stage of centrifuge testing. The calculated quantity of water and several PPTs at predefined locations are placed on top surface of the soil barrier. The PPTs are calibrated and soaked in water for more than 48 hour prior to testing. The water pressure above the PPT can be determined from the pore pressure measurements. The height of water above PPTs can be determined from the pore pressure measurements. The height of water along the width of the soil barrier is assumed to be identical to that of the height of water measured at the pre-defined locations. Figure 4 shows the variation of height of water level with PPT locations in prototype dimensions i.e., water profile at various stages of central settlement (considered symmetry after validating with pilot tests). It can be noticed that water pressure forms a curvilinear shape mainly due to the radial acceleration field of the model. A distinct change in the height of water column can be noticed when the central settlement exceeds 0.2 m. Beyond $a = 0.5$ m most of the water has been depleted.

Fig. 3: Variations of Water Pressure with Time

The actual loss of water can be determined from the numerical integration of water profiles obtained at various stages of central settlement. The volume per unit width of water is equal to the area under measured water profile (i.e., numerical integration of the area). Hence, the total volume of the water present above the soil barrier can be computed by the product of the volume per unit width of the water to the width of the soil barrier. The computed initial volume of the water has been depleted.
of water was verified from the measured initial volume of water. The change in the volume of water at any central settlement can be determined from the numerical difference between the initial volume of water to the volume of water at the required central settlement. Infiltration ratio is the ratio of change in the volume of water to that of initial volume of water. The variation of infiltration ratio of the soil barrier (d = 1.2 m, 12.5 kPa) with central settlement and distortion level is shown in Figure 5. Distortion level a/l is obtained from the ratio of central settlement at any stage of deformation a to the influence length l within which differential settlement is induced. A sharp change in the curvature can be noticed between a = 0.3 m to 0.4 m which indicate that water breakthrough of the soil barrier has occurred between this central settlement. The distortion level corresponds to the water breakthrough of the soil barrier and is termed as limiting distortion level. It can be obtained from back tangent method and was found to be 0.044 as shown in Figure 5.

5. DISCUSSION

The limiting distortion level of a 1.2 m thick soil barrier with an overburden pressure of 12.5 kPa is found to be 0.044. It is also noticed that soil barrier has experienced multiple cracks with few cracks extending up to full-depth of the soil barrier. When an identical soil barrier is subjected to higher overburden pressure (25 kPa), crack dimension was found to be reduced. However, at a distortion level of 0.069, soil barrier has lost its integrity (Fig. 5). From this study, it can be inferred that with an increase in the overburden pressure, delay in the crack initiation and water breakthrough of soil barrier is observed. However, as the overburden pressure on the soil barrier of landfill cover system is limited (with a maximum value of 25 kPa), further increase in the overburden pressure may not be interesting; hence, not attempted in this study. Rajesh & Viswanadham (2009a) found a substantial delay in the crack initiation and water breakthrough when the soil barrier is reinforced with model geogrid layer. The variation of infiltration ratio of a 0.6 m thick soil barrier reinforced with very low (GR_H) and high strength geogrid (GR_R) placed at one-fourth thickness of the soil from top surface of the soil barrier is shown in Figure 5. The modelling of geogrid layer in geo-centrifuge is discussed in detail by Rajesh & Viswanadham (2009a). The limiting distortion level of the low strength geogrid layer reinforced within the soil barrier (GRSB/GR_R) was found to be 0.074. It can be noticed that even with a reduction in the thickness of the soil barrier, limiting distortion level was found to be increased, upon inclusion of geogrid layer. Interestingly, when a 0.6 m thick soil barrier was reinforced with a high strength geogrid layer, no change in the infiltration ratio was noticed, which implies, the soil barrier has not lost its integrity even at a central settlement of 1 m and distortion level of 0.125.

6. CONCLUSIONS

In the present study, the methodology adopted for evaluating the hydro-mechanical behaviour of soil barrier at the onset of differential settlement was discussed. In addition, it was demonstrated with few centrifuge model tests. From the results and discussion, it was noticed that unreinforced soil barrier (URSB) was found to lose its integrity at low central settlement and distortion levels. However, with an increase in the overburden pressure, a reduction in the magnitude of crack width and increase in the value of limiting distortion level was observed. A significant reduction in the thickness of the soil barrier with an enhanced behaviour of soil barrier was obtained when the soil barrier was reinforced with a suitable model geogrid layer.

REFERENCES


