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Studies on the deformation behaviour of randomly reinforced soil liners in a geocentrifuge

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ABSTRACT: This paper deals with the use of a geocentrifuge to model the deformation behaviour of moist compacted soil liners with and without polypropylene tape fibers. A special device for inducing non-uniform settlements during centrifuge test has been custom designed, developed and calibrated. Centrifuge tests were performed in a 4.5 m radius large beam centrifuge facility available at Indian Institute of Technology Bombay. The study is focused in understanding the deformation behaviour of moist compacted soil liners with and without randomly reinforced fibers. Three centrifuge model tests were performed on a compacted soil liner with and without fibers. The influence of the randomly reinforced fibers on the integrity of compacted soils liners at the onset of non-uniform settlements has been demonstrated through centrifuge modeling technique adequately.

1 INTRODUCTION

One of the failures associated with the performance of Compacted Soil Liners (CSL) of landfills is due to occurrence of non-uniform settlements. Excessive non-uniform settlements of this nature result in tension cracks in the zone of sharp curvatures thereby resulting in loss of integrity of the whole liner system. This problem is more pronounced in the case of a top lining system than the bottom lining system because the former is subjected to low overburden pressure as well as settlement due to readjustment and ongoing bio-degradation of the wastes that lies underneath.

A variety of research efforts have been attempted to address the problem of cracking of CSLs of liner systems due to non-uniform settlements. Very few investigators have studied the deformation behavior of soil liners subjected to non-uniform settlements (For e.g. Scherbeck and Jessberger, 1993, and Viswanadham and Jessberger, 2005). The above investigations have revealed that the loss of sealing efficiency of a CSL subjected to non-uniform settlements is reported to be influenced by the following parameters: (i) normal stress resulting from overburden, (ii) shear strength, (iii) stiffness characteristics in tension and compression, (iv) tensile strength characteristics of CSL material, and (iv) thickness of CSL.

In the recent past, the interest of using fibers has arisen to better improve compacted clay performance as hydraulic barriers without changing physical properties of soil. Past research has demonstrated that the inclusion of randomly oriented discrete fibers significantly improves the engineering response of soils (For e.g. Gray and Ohashi 1983, Maher and Ho 1994, Li et al., 2001, and Miller and Rifai 2004). This technique is being employed in road construction, strengthened backfill material, and very recently in waste containment soil liners to reduce desiccation cracking of CSLs (Miller and Rifai 2004). Current information related to fiber use to reduce or to restrain the tensile cracking of CSL at the on-set of non-uniform settlements is very limited. Hence, this forms the research interest of current context. Figure 1 shows a schematic cross-section of top lining system along with a deformed fiber reinforced soil liner at the onset of non-uniform settlements of varying degree of curvature radii with central settlements equal to Δs_1, Δs_2. Randomly distributed fibers can provide isotropic strength to soil and avoid the existence of potential planes of weakness. As the problems associated with desiccation cracking and cracking to excessive non-uniform settlements occur to the same liner material, the present study aims at understanding the deformation behaviour of soil liner with randomly reinforced discrete fibers at the onset of non-uniform settlements.

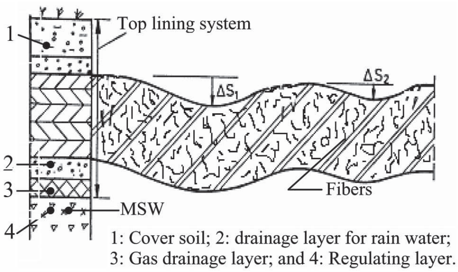

Figure 1. Deformed fiber reinforced CSL.

Centrifuge model tests were performed at 40 g by keeping the thickness and moulding water content of soil liner as constant and without any overburden. The influence of aspect ratio of the fibers was studied by mixing the 0.25% of polypropylene fibers randomly.

2 CENTRIFUGE MODELING OF RANDOMLY REINFORCED SOIL LINERS

The centrifuge modeling technique in geotechnical engineering can be extended to study the response of fiber reinforced soil liners subjected to continuous non-uniform deformations created artificially in the centrifuge. Centrifuge modeling was essential in this regard because the cracking of the soil liner and fiber-soil interaction is highly influenced by the presence of prototype stress conditions. Hence, the application of this technique to the present context of study is regarded to be more relevant.

The 4.5 m radius large beam centrifuge at Indian Institute of Technology Bombay (IIT Bombay), India was used in the present study. The centrifuge capacity is 250 g-ton with a maximum payload of 2.5 t at 100*g* and at higher acceleration of 200*g* the allowable payload is 0.625 t.

Several investigators have used fibers made of polypropylene, polyester, polyaramid, fiberglass, etc. These fibers come in two different styles: (i) plain and (ii) fibrillated types. The volume fraction and aspect ratio of fibers were also varied to evaluate their influence on the engineering behaviour of fiber-reinforced soil.

By adopting suitable scaling considerations, ultraviolet stabilized polypropylene plain tape fibers of 1.2 mm width, less than 0.02 mm thick and having tenacity equal to 6.5 g/denier are used. Keeping in view of the results reported in the literature, the volume fraction of fibers equal to 0.25 % is selected along with two aspect ratios 15 and 30 respectively. Miller and Rifai (2004) have reported about an increase in hydraulic conductivity with increasing volume fraction of fibers and it was of the order of 1×10^{-9} m/s up to 0.5% fibers.

2.1 *Model preparation and test procedure*

A large container having internal dimensions of 720 mm in length, 410 mm in depth and 450 mm in width was used in the present study. A view of the test set-up used in the present study is illustrated schematically in Fig. 2. By this arrangement it was possible to model a landfill area as large as 520 m^2 in the prototype scale and simulates the ongoing non-uniform settlements undergoing over large areas of landfills. Non-uniform settlements were induced to the liner continuously with the help of a hydraulic cylinder with an average settlement rate of 0.85 mm/min. Before placing the 30 mm coarse sand layer followed by 30 mm fine sand layer, horizontal surface with the hinge doors and piston assembly was maintained. These sand and gravel layers are referred herein as sacrificial layers and are required to induce smooth continuous non-uniform settlement profile to the soil liner, when the trapdoor plate settles.

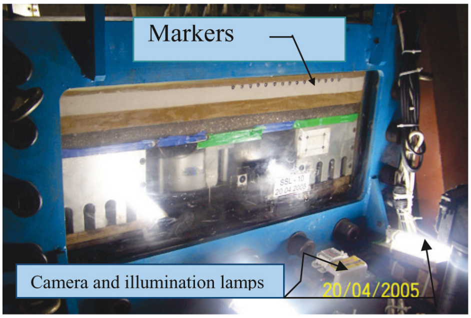

Figure 2. View of the model test set-up.

In the present study, kaolin-sand mixture was selected as a model liner material with the following properties: liquid limit = 38%; plasticity Index = 16%; and maximum dry unit weight = 15.9 kN/m^3 and optimum moisture content = 22% (standard Proctor compaction). The kaolin-sand mixture was mixed at its maximum dry unit weight and its optimum moisture content with proper care to make a liner of thickness 30 mm (Model SSL-4). For two other models SSL6 and SSL6a, a liner thickness of 30 mm is maintained but it is made with randomly reinforced discrete Polypropylene fibers with 0.25% volume fraction of fibers. For SSL6, an aspect ratio of 15 and 30 for SSL6a was selected. The details of the centrifuge tests presented in this paper are summarized in Table 1.

The model was prepared at 1g with the cylinder at its full stoke under an operating pressure of 500 kN/m^2. Desired settlement control rate was achieved by withdrawing the air pressure in the tank in steps and allowed the oil to flow out of the cylinder through a needle flow control valve. Markers were inserted along the cross section at every 20 mm centre to centre distance and 5 mm below the top surface of the model

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Table 1. Details of centrifuge model tests.

	SSL-4		SSL-6		SSL-6A	
	M	P	M	P	M	P
d	30 mm	1.2 m	30 mm	1.2m	30 mm	1.2 m
$a_{max.}$	25 mm	1 m	25 mm	1 m	25 mm	1 m
w_c (*)	4.5 mm	0.18 m	5.1 mm	0.204 m	4.5 mm	0.18 m
d_c (*)	30 mm	1.2 m	30 mm	1.2m	30 mm	1.2 m
ε_c	0.65%		0.82%		0.89%	
R (#)	4.25 m	170 m	2.85 m	115 m	2.5 m	100 m
$\varepsilon_{of\ (max)}$ (**)	3.53%		3.62%			3.56%

M: Model; P: Prototype; Thickness of CSL d; Max. central settlement $a_{max.}$; Average crack width w_c ; Average crack depth d_c; Cracking Strain ε_c; Radius R; Maximum outer fibre strain $\varepsilon_{of\ (max)}$; $^{\#}d_p = Nd_m$; *Measured at the end of centrifuge test; **computed for $a_{max.}$ = 25 mm (1.0 m); #Radius at the zone of max. curvature; Scale factor or g-level N = 40;

soil liner to measure the settlement contours during various stages of the test (Fig. 2). Also 20 mm square grids of markers were placed on the model soil liner surface along the zone of maximum curvature.

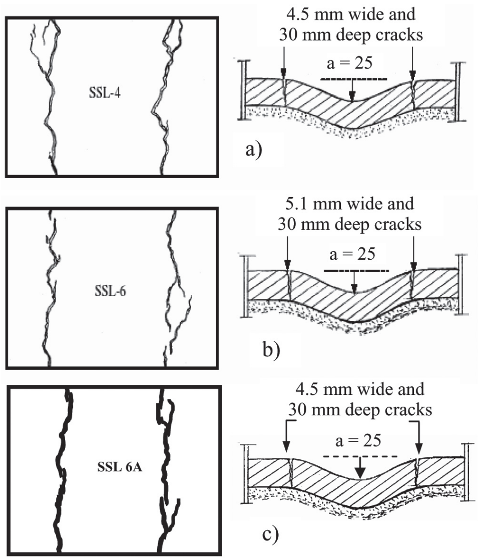

Figure 3. Tested models at the end of the centrifuge test.

3 RESULTS AND DISCUSSION

The centrifuge model tests reported in this study were conducted at 40 gravities to study the influence of randomly reinforced discrete fibers on the deformation behaviour of compacted soil liner at the onset of non-uniform settlements. Settlement contours during various stages of the centrifuge tests were obtained with the help of LVDTs placed on the surface and as well as markers embedded within the soil liner. Figure 3 shows status of all the models (SSL-4, SSL-6, SSL-6A) at the end of centrifuge test. As can be seen from the Fig. 3a, cracks penetrating up to full depth of the liner thickness was noticed for the model SSL-4, SSL-6 and SSL 6a at all investigated cross sections and along the zone of maximum curvature. Similarly, models SSL-4, SSL-6, and SSL-6a are experienced to have single and wide cracks (Fig. 3b and 3c). The cracking pattern in fiber-reinforced liners was found to be more or less identical to an un-reinforced soil liner. This shows that a compacted soil liner with and without fibers of 1.2 m thickness in field will be subjected to wide and deep cracks extending up to full depth, if it is subjected to 1.0 m central settlement over a period of time.

Markers placed over the top surface of the liner at the zone of maximum curvature were analyzed to obtain the top surface strain distribution during various stages of centrifuge tests. Figure 4 gives the variation of maximum surface strain at the zone of maximum curvature with ratio central settlement *a* to the maximum central settlement $a_{max.}$ As obtained in Fig. 4, a delay in the initiation of cracking of fiber reinforced soil liner can be noted.

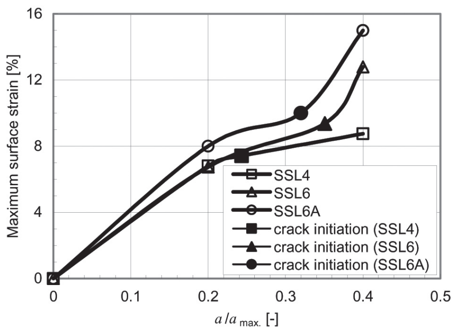

Figure 4. Variation of Maximum surface strain with a/a_{max}.

Variation of maximum outer fibre strain with radius at the zone of maximum curvature is shown for SSL-4, SSL-6 and SSL-6A in Fig. 5. Figure 5 reveals that a 1.2 m thick liner (model SSL-4) experiences initiation of cracking strain equal to 0.65% at radius equivalent to 170 m. Whereas, fiber reinforced liners experiences initiation of cracking strain in the range of 0.82 – 0.89% at radii of the order of 100 – 115 m (models SSL-6 and SSL-6a). To some extent, this indicates the role played by these fibers in restraining the cracking of compacted soil liner. The difference in deformation behaviour could be attributed to an increase in the tensile strength of the fiber reinforced soil material due to the presence of randomly distributed fibers within the soil liner compacted at its maximum dry unit weight and optimum moisture content. Evaluation of tensile strength-strain behaviour of the compacted soil liner material with and without fibers is beyond the scope of the present study.

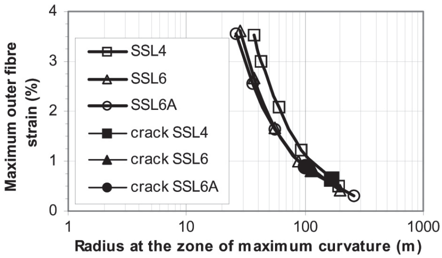

Figure 5. Variation of maximum outer fiber strain with radius at the zone of maximum curvature.

As discussed above, the observed distinct mechanism by which incorporation of fibers improves the performance is by subjecting fibers to relatively high tensile stresses and interfaces being held together by the fibers. Increasing pre-cracked strength requires that fiber be rigidly bonded, there being no relative displacements between them. Increasing post-cracked strength will depend upon the extent and type of bonding between fiber and soil. If there was no bonding, then the soil would pull off the fiber-hence, the fiber would be of no use. For both the models SSL-6 and SSL-6a, the compacted soil at the onset of non-uniform settlements, it was observed to pull off of the fiber. This could be attributed to inadequate: (i) aspect ratio and (ii) bond between soil and fibers. For the model SSL-6a, with an increase in aspect ratio, the exhumed fibers were found to be distorted and split. This indicates the participation of fibers in restraining cracks at the zone of maximum curvature before subjecting to pull-out of the surrounding soil. Further studies are being focused to evaluate the influence of some of the parameters like: (i) aspect ratio and (ii) bond on the deformation behaviour of compacted soils liners at the onset of non-uniform settlements.

4 CONCLUSIONS

Based on the analysis and interpretation of centrifuge model test results, the following conclusions can be drawn:

(i) The inclusion of fibers as a reinforcing material affected the deformation behaviour of compacted soil liner compliance to non-uniform settlements. The improved soil-fiber mix enhances the function of soil liners and covers as hydraulic barriers for waste containment systems of landfills by decreasing the cracking potential.

(ii) By considering fibers as discrete elemental inclusions within the soil, the scaling considerations adopted in this study implies that identical fibers with more or less similar engineering properties shall have to be used in the field. However, further studies are required to evolve further on the deformation behaviour of randomly reinforced compacted soil liners.

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