Geofiber reinforced slopes subjected to seepage: Centrifuge study

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ABSTRACT: The main objective of this paper is to simulate seepage induced slope failure using a centrifuge modelling technique and to explore the influence of discrete and randomly distributed flexible polymeric fiber inclusions on the stability and deformation behaviour of slopes. This paper presents the behaviour of 2V:1H slopes with and without geofibers tested in a large beam centrifuge at 30 gravities. All the models were thoroughly instrumented to measure pore water pressures at the onset of raise of water table and displacements during centrifuge test. The stability analyses of both slopes with and without fibers were carried out using SLOPE/W software. Based on the analysis and interpretation of centrifuge model test results, significance of fiber reinforcement on the stability and deformation behaviour of slopes was presented. The performance of geofiber reinforced slopes subjected slopes was found to be superior to the tested un-reinforced slope. Results of this study indicate that the homogeneously mixed geofiber reinforced soil (GRS) can be an alternative fill material for constructing levees, earthen dams, and other irrigation structures.

1 INTRODUCTION

Failure of geotechnical structures, such as levees, dams, vertical cuts, embankments etc. is very common and in most of the cases causative force behind these is seepage. The term ‘seepage’ usually refers to situations where the primary driving force is gravity controlled, such as establishing seepage losses from a reservoir, where the driving force is the total hydraulic head difference between the entrance and exit points. In maximum cases, these slope failures occur due to raising water table either by rainfall, flood, snow and drawdown etc. So, analysis of effects of these events on the slope will give better understanding on seepage induced slope failure. Due to raise of ground water table, pore water pressure increases or it can be said that the negative suction in the soil decreases and consequently shear strength of soil slope decreases. Therefore it is extremely important to evolve at a proper slope stabilization technique to protect these geotechnical structures. With an aim to develop an alternative fill material using a soil prone to seepage, use of discrete and randomly distributed fiber inclusions to restrain seepage induced slope failure is explored. Several researchers, like Gray and Ohashi, 1983, Sivakumarbabu and Vasudevan, 2008a, 2008b, Das, 2009, Das et al. 2009) studied effect of discrete and ran-domly distributed geofibers (flexible polymeric fibers) on engineering properties of soils through experimental investigations. Earlier studies indicate that fibers improved the soil strength characteristics but there must be an optimum fiber content and length. Like strength property, seepage behaviour of soil i.e. permeability, piping resistance, seepage velocity also get changed by the fiber inclusion (Sivakumarbabu and Vasudevan, 2008b; Furumoto et al. 2002; Das et al. 2009). Though the efficacy of fiber reinforced soil was established by many researchers, still very few researchers have explored fibers through physical model tests especially at high gravity environment. Only reported fiber reinforced soil modelling in a geotechnical centrifuge was done by Li et al. (2001) and Viswanadham et al. (2009). The aim of the present study is to understand the effect of discrete and randomly distributed geofibers on the stability and deformation behaviour of a slope subjected to seepage through a centrifuge model study.

2 MODEL MATERIALS AND ITS PROPERTIS

There are two main model materials used throughout the present study, soil and fiber. Influences of geofiber on shear strength characteristics of soil was also carried-out apart from centrifuge model studies and are used to analyse centrifuge models.

2.1 *Soil*

Previous researchers suggest that silty-sand types of soils are more prone to seepage-induced failure, hence properties of a silty-sand was achieved by mixing 80% locally available fine sand and 20% commercially available kaolin by dry weight and that soil was used as model soil for the present study. The soil used in the present study has sand size particles of 80%, silt size particles of 10 % and clay particles of 10 %. An average particle size d_{50} equals to 0.25mm. According to Unified soil classification system (USCS) it is classified as SM type soil. The maximum dry unit weight (MDD) and optimum moisture content (OMC) of a soil were found to be 18.75kN/m^3 and 8% according to standard Proctor compaction. The cohesion and angle of internal friction angle of soil compacted at MDD and OMC were found to be equal to 11.6 kPa and 27° and were determined according to direct shear test conducted on saturated soil samples. In the case of fiber reinforced soil, the presence of fibers were found to have negligible effect on compaction characteristics (Das, 2009) and hence same MDD and OMC as that of an un-reinforced soil were maintained.

2.2 *Fiber*

Polyester fibers were used in the present study. Polyester fibers are commercialized under the brand name "Recron 3s". It has a triangular cross section for better anchoring with other ingredients of the mix. Specific gravity of polyester fibers was 1.33 and a tensile strength of 600 MPa. The fibers were found to have 10 denier and an equivalent diameter in the range of 33-55 μm.

2.3 *Shear strength properties of soil with and without geofibers*

Shear strength of both reinforced and un-reinforced soil was determined through a series of Direct Shear Tests on saturated soil samples. These results were used to perform the stability analysis of seepage induced slope models with and without fibers. During the sample preparation, fibers were weighed according to the prescribed fiber content and mixed into the dry soil in small increments until all of the fibers were effectively distributed within the soil. Proper care was taken while the mixing, so that fibers do not get accumulated. After achieving the uniform dry mix, water equivalent to OMC was mixed and then compacted at MDD according standard Proctor compaction.

Direct shear tests on saturated soil samples were conducted for different fiber contents (0.05%, 0.1% and 0.25%) having 25 mm length. Each combination of fiber soil mix was also tested under three different normal stresses, 50kN/m^2, 100kN/m^2, and150kN/m^2 at a strain rate of 0.25 mm/min. Shear stress vs. shear strain curves were plotted for three different normal stresses applied during direct shear tests. τ-σ plots were plotted using a shear stress value correspond to 10% strain and are shown in Fig. 1. It is clear from Figure 1 that the soil strength parameters have increased with the increment of fiber content.

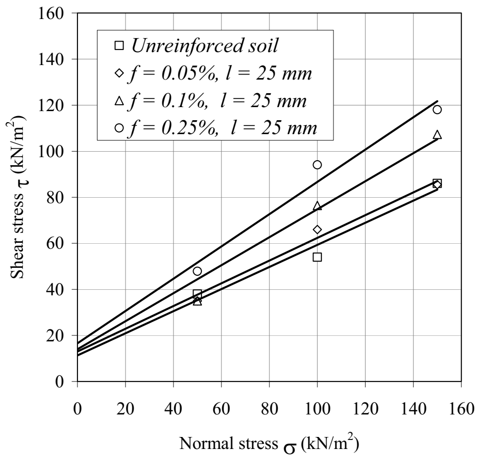

Figure 1. τ – σ plot for model soil unreinforced and polyester fiber reinforced soil having fiber length *l* = 25 mm.

3 CENTRIFUGE MODEL STUDIES

Geotechnical centrifuge modelling is a technique in which small scale geotechnical models are subjected to centrifugal acceleration by rotating about a vertical axis in a horizontal plane, which is many times higher than the earth gravitational acceleration. Size of the model or the reduction scale should be in a same proportion to the chosen acceleration field to earth's acceleration due to gravity. To study the deformation and stability of seepage induced geofiber reinforced soil slope, centrifuge modelling is one of the viable alternatives as the response of seepage induced slope failures is highly dependent on simulation of body forces. Study of seepage induced slope failure was done in Indian Institute of Technology Bombay large beam centrifuge having 4.5 m radius and 250 g ton capacity. The specifications in detail were given by Viswanadham et al. (2009).

3.1 *Scaling considerations*

Scaling relationships are extremely important in centrifuge modelling. The basic advantage of using centrifuge modelling is that prototype stress level can be achieved through this technique. Scale factors used in a centrifuge model study have been elaborated by Schofield (1990). While modelling of fiber reinforced soils in a centrifuge, the scaling considerations of the fibers are very important. For centrifuge modelling the scaling consideration of the fibers can be adopted as Viswanadham et al. (2009) similitude condition of the tape fiber, i.e. that both in case of model and prototype same fiber (similar length, diameter, and type) can be used.

3.2 *Preparation of slope models*

The slope model was prepared within a metal strong box having internal dimensions 760 mm x 200 mm x 410 mm with one side made up of a thick acrylic sheet to observe the slope model during the centrifuge test. The slope model was prepared considering a half portion of an embankment. The prototype dimensions were: height of slope 7.2 m, crest width 7.5 m and inclination of slope 1H: 2V at 30 gravities. The dimensions were so chosen that it will represent an embankment which at just stable condition with a factor of safety (FOS) around 1 without any rise in the ground water table for the soil parameters given in section 2.1. Detailed description about seepage flow simulator was given elsewhere by Das (2009). For simulating the water seepage from the side of the slope, a water-tank (80 mm x 360 mm x 200 mm), made up of a 10 mm thick acrylic sheet, was kept inside the strong box. One face of the water tank was perforated to allow the water pass through the slope. To monitor the settlement and pore water pressure changes during the centrifuge tests, three Linearly variable differential transformers (LVDTs) at the top of the slope and five miniature pore pressure transducers (PPTs) were used. PPTs were placed at the toe level horizontally.

3.3 *Test programme*

After completion of the entire setup the model test package was mounted on the swing basket of the centrifuge. The test was performed at a g-level of 30. After a ramping time, centrifuge was rotated at 81 rpm i.e. at 30g. After attaining 30g, water seepage was allowed through the slopes by switching on a solenoid valve connecting surge tank with seepage simulator. The water was allowed to flow within the model slope until the global or localized failure occurred. In this paper, results of two centrifuge tests are reported. They are: model ADF2 and model ADF1. Model ADF2 is in un-reinforced and model ADF1 is reinforced with polyester fibers having fiber content equal to 0.1% and length of 25 mm. The cohesion and angle of internal friction angle of polyester fiber reinforced soil compacted at MDD and OMC were found to be equal to 14 kPa and 32°.

3.4 *Test results*

A global failure was observed for an un-reinforced slope at the onset of seepage, as shown in Fig. 2a for model ADF2. Failure was observed to initiate with formation of tension cracks at the crest and followed by a typical circular failure surface. In comparison, geofiber reinforced slope with the same boundary conditions, was found to be stable even after subjecting to seepage of 20days, as shown in Fig. 2b for model ADF1. Some localized failures were noted to take place near the toe of the slope for model ADF1.

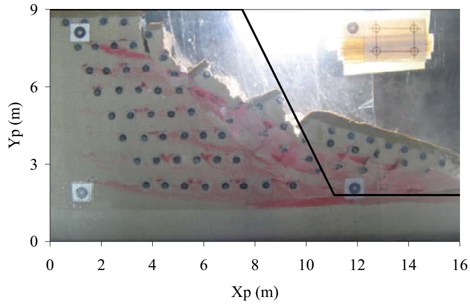

Figure 2a: Slope profile after centrifuge model tests for unreinforced slope ADF2 (prototype dimensions)

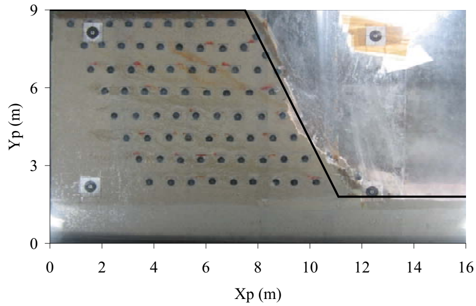

Figure 2b. Slope profile after centrifuge model tests for fiber-reinforced slope ADF1 (prototype dimensions)

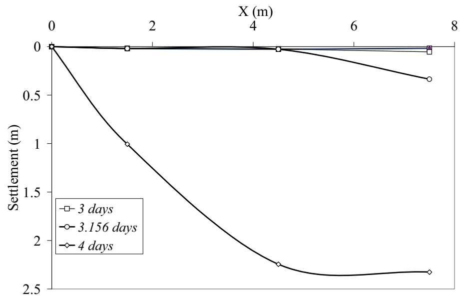

Figure 3a. Variation of surface settlement with horizontal distance from the crest of the slope for an unreinforced slope ADF2 (prototype dimensions).

Failure pattern and crest settlements were measured from the LVDT recorded data. Figures 3a-3b show the settlement plots for un-reinforced and geofiber reinforced slopes. Maximum settlement for an un-reinforced slope (model ADF2) was around 2.3 m which is about 32% of the slope height (7.2 m). On the other hand geofiber reinforced slope was found to undergo (model: ADF1) only 0.7% of slope height. This brings out the significance of discrete and randomly distributed geofibers on the stability and deformation behaviour of a soil slope at the onset of seepage.

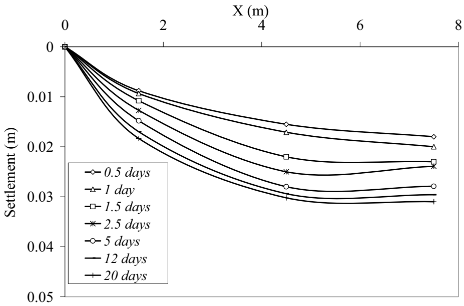

Figure 3b. Variation of surface settlements with horizontal distance from the crest of the slope for a reinforced slope ADF1 (prototype dimensions).

3.4 *Stability analysis*

Stability analysis of the seepage induced slopes was carried out using limit equilibrium based software package SLOPE/W using ordinary Bishop's method of slices. During stability analysis, the position of phreatic lines was plotted directly from the measured PPT data obtained from the centrifuge model tests (Das, 2009). Factor of Safety (FOS) was calculated for each stage of seepage. Initially when the pore water pressure kept on increasing FOS remained constant up to a certain limit. After that it gradually dropped as the pore water pressure increased considerably. For an un-reinforced slope ADF2, FOS dropped below 1 at normalized pore water pressure ratio of about 0.45. In the case of ADF1, FOS started decreasing at pore water pressure ratio 0.36 but it never dropped below 1, as shown in Figure 4. Pore water pressure ratio (u/γh) is the ratio of pore water pressure measured by a PPT placed at half distance from the crest of the slope horizontally from the seepage tank simulator to unit weight times height of the slope. This indicates that fibers can hold soil particles, restrict their movement and consequently increased the FOS, even at very high pore water pressures. Identical behaviour was observed through physical centrifuge model tests.

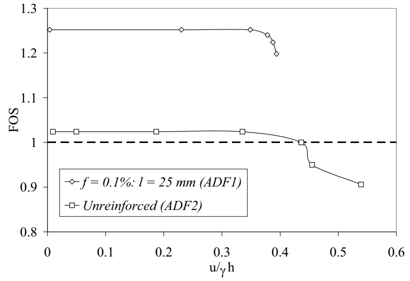

Figure 4: Variation of FOS with normalized pore water pressure

4 CONCLUSIONS

Direct shear test results showed that inclusion of fibers increased the soil shear strength. Maximum increment was around 40% to 50%. Centrifuge model tests showed that geofiber reinforcement is effective in reducing the slope settlements and enhancing the stability. Catastrophic failure was observed in the case on an un-reinforced slope (ADF2) at a pore water pressure ratio of 0.43, whereas almost no movement was observed in the case of a reinforced slope. Finally it can be concluded that geofiber reinforcement inclusions were found to be effective in mitigating seepage induced slope failures due to raising ground water table and increase the slope stability. Therefore, the use of geofiber reinforcement inclusions is a viable option for improving stability of man-made slopes (like levees, embankments and ash pond dams) and GRS can be considered as an alternative fill material with an appropriate mixing method in the field.

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