Centrifuge Modeling of Wrap-around Geogrid-reinforced Soil Walls

Mane, Abhinav
Research Scholar
e-mail: abhinav.mane@iitb.ac.in

Viswanadham, B.V.S.
Professor
e-mail: viswam@civil.iitb.ac.in

Department of Civil Engineering, IIT Bombay, Powai, Mumbai

ABSTRACT

This paper addresses the static response of wrap around geogrid reinforced soil walls resting on a firm foundation to the self weight loading imposed in a geotechnical centrifuge at pre-failure and at failure. A short series of centrifuge tests were carried out on model geogrid-reinforced soil walls with two different spacing’s of reinforcement layers. A wrap around technique was used to represent a flexible facing in order to initiate failure in reinforcement layer; ratio of the length of the reinforcement to the height was maintained at 0.85. Reinforced soil wall models were subjected to varied g-levels (in steps of 5g from 10g onwards) up to the maximum target g-level of 75g or to collapse whichever occurs first. A digital image analysis technique was employed to arrive at the displacement vectors of markers glued to the reinforcement layers. These displacements were used to compute and analyze the strain distribution, and to identify the peak strain distribution at pre-failure and at failure.

1. INTRODUCTION

Various studies have been made on reinforced soil structures which includes laboratory model studies (Juran and Christopher 1989, El-Emam and Bathurst 2005) field studies (Benjamin et al. 2007, Tatsuoka et al. 2009, Yang et al. 2010) and centrifuge small scale model studies (Porbaha and Goodings 1996, Zornberg et al. 1998, Zornberg and Arriaga 2003, Viswanadham and Mahajan 2007). Though various field instrumentation techniques are evolved to monitor behaviour of prototype reinforced soil wall structures the cost associated with them is significant, resulting in limited scope for field prototype studies. Centrifuge modelling technique in geotechnical engineering provides a tool to investigate the behaviour of prototype structures by increasing acceleration by N times to a model scaled down by 1/N times that of the prototype. Increase in acceleration on scaled down model results in achieving identical stress level as that of prototype. It was noted that very few investigators studied reinforced soil walls behaviour with geogrid as a reinforcement material in a centrifuge. As a part of this investigation, two model geogrid reinforced walls constructed with dry sand as a backfill are tested in a geotechnical centrifuge by increasing gravity in intervals of 5g from 10g up to failure. By keeping the reinforcement type, length of reinforcement, slope inclination and slope height as constant, spacing of reinforcement layers was varied. A slope inclination of 84° with horizontal was adopted. The focus of the study is to identify the pattern of strain distribution in reinforcement layers, and surface settlements of the soil wall model with respect to variation of g-levels and vertical spacing of the reinforcement layers.

Reinforced Soil Wall Models

In this paper, results of two centrifuge tests on geogrid reinforced soil wall models are presented with the model wall height of 270mm, sloping inclination of 84°, foundation layer thickness of 30mm and vertical reinforcement spacing Sv of 20mm for model ARS1 and 30mm in model ARS2 respectively. The results of stability analysis and deformation of behaviour of two model geogrid reinforced soil walls constructed with flexible facing was presented. In order to induce failure within the reinforced zone, Length of reinforcement normalized to slope height was adopted as 0.85.

Model Materials

Soil

The sand used was dry Goa sand, composed of rounded and sub-rounded particles, and classified as SP in the Unified Soil Classification System. The maximum and minimum void ratios for this type of sand were 0.895 and 0.597. The corresponding unit weights were 13.6 kN/m$^3$ (minimum) and 16.4 kN/m$^3$ (maximum), respectively. The effective particle size, $d_{10}$ of the sand is 0.13 mm. Angles of internal friction
determined by conducting direct shear tests on dry sand placed at 55% and 85% relative densities were found to 33° and 38° respectively (Viswanadham and Mahajan, 2007).

Geogrid
Contrary to soils, the similitude condition does not allow the use of identical geogrid materials in model and prototype studies. In the present study, a fine model geogrid was selected such that it satisfies the scaling considerations presented by Rajesh and Viswanadham (2009). The scaling of frictional bond behaviour and tensile load-strain behaviour of the geogrid are considered to be the two basic requirements for modeling geogrid. The scaling of frictional bond behaviour was ensured by ensuring that the percentage open area of the model geogrid is in the band width of percentage open area of commercially available geogrids. The selected model geogrid (MG1) was found to have a tensile load of 0.23 kN/m at an ultimate strain of 10.9%. (based on wide-width tensile tests in the cross-machine direction, which is nothing but laying direction of the model geogrid).

The percentage open area of the model geogrid was found to be 90% and is found to be close to the upper limit of the range of percentage open area f of commercially available prototype geogrids. Further, the results of zero-grip tensile tests conducted close to the procedure outlined by Porbaha and Goodings (1996) yield a tensile load at break of 0.45 kN/m.

2. MODEL PREPARATION AND TEST PROCEDURE
The 4.5m radius large beam centrifuge facility available at IIT Bombay was used in the present study. The specifications of centrifuge equipment are discussed by Viswanadham and Mahajan (2007).

Model Container
The schematic cross-section of the model geogrid reinforced slope model test package is shown in Figure 1. The test set-up consists of a strong box having 760 mm in length, 200 mm in breadth, and 410 mm in height (internally). The front wall of a model test package is formed with a thick Perspex sheet which enabled to view the model during flight. The front and rear walls were coated with a thin layer of white petroleum grease and polythene sheet strips of 100 mm width were placed to reduce boundary friction effects.

3. CENTRIFUGE TEST RESULTS
Figures 3-4 present the variation of measured surface settlements for models ARS1 and ARS2 with time in model (Viswanadham and Mahajan, 2007). In order to view front elevation of the model during flight, a digital photo camera is mounted along with the model test package. The photo camera was triggered by accessing a central process unit through a computer in the control room.

Before placing polythene sheet strips, a rectangular grid of permanent markers were placed on the inner side of Perspex sheet. After placing polythene sheet strips, a 30 mm thick foundation layer was placed at a relative density of 85% to represent a firm foundation. In order to get desired slope inclination, a formwork was placed temporarily within the strong box. For each model, desired numbers of geogrid layers were placed one by one and dry sand was pluviated using a raining technique to achieve a relative density of 55%. This was selected to induce failure to model geogrid reinforced soil walls and to represent poor compaction conditions. In order to trace the movement of geogrid layers at the onset of increasing gravity level and to compute strain distribution along reinforcement layers, L-shaped plastic markers were glued on to model geogrid layers. One leg of plastic marker was glued to model geogrid layer and other portion was applied white petroleum grease layer to facilitate movement. All geogrid layers were numbered from in increasing order from toe to the slope crest. Geogrid markers were placed on each layer of geogrid in model ARS2 and on alternate layers in the case of model ARS1. Four numbers of Linear Variable Differential Transformers (LVDTs) were placed at crest (L1), 70mm (L2), 170 mm (L3) and 270 mm from the crest (L4) of the soil wall to measure the surface settlements of the soil wall during test (Fig. 1). The data from these transducers was acquired by using an on-board data acquisition system. Figure 2 shows the perspective view of geogrid reinforced soil wall model. In order to arrest escaping of soil particles through model geogrid openings, a thin non-woven geotextile layer was placed on the outer side and edges were coated with a thin layer of bentonite. A variable g-level technique was used to induce failure to the reinforced soil wall models. The g-level was increased in steps of 5g from 10g to 75 g or up to failure, whichever occurred first. During each g-level, a waiting period of 2 minutes was maintained. This was maintained to prevent creeping of model geogrid reinforcement layers.

Fig. 2: Perspective View of Model Geogrid Reinforced Soil Wall Before Centrifuge Test (Model: ARS2)
dimensions along with corresponding g-levels. As can be noted, both the models experienced a catastrophic failure. Model ARS 1 reinforced with 12 model geogrid layers (MG1) experienced a failure at 45g. In comparison, model ARS2 reinforced with 8 model geogrid layers (MG1) was observed to experience failure at 30g itself. Table 1 summarises salient observations made in two models.

Table 1: Summary of Centrifuge Test Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ARS 1</th>
<th>ARS 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geogrid type</td>
<td>MG1</td>
<td>MG1</td>
</tr>
<tr>
<td>Wall Inclination (degrees)</td>
<td>84</td>
<td>84</td>
</tr>
<tr>
<td>Vertical spacing $S_v$ (mm)</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>$L_r$ (mm)</td>
<td>230</td>
<td>230</td>
</tr>
<tr>
<td>g-level at failure $N_f$</td>
<td>45</td>
<td>30</td>
</tr>
<tr>
<td>$H_f$ (m)</td>
<td>12.15</td>
<td>8.1</td>
</tr>
<tr>
<td>$h(S_c/H)_f$</td>
<td>0.048</td>
<td>0.063</td>
</tr>
<tr>
<td>Failure mechanism</td>
<td>Catastrophic</td>
<td>Catastrophic</td>
</tr>
</tbody>
</table>

*Height at failure in prototype dimensions $H_f = N_f H_m$; $S_c$/Height at failure.

Figure 5 presents the variation of surface settlements with the horizontal distance from the crest of the geogrid reinforced soil wall for model ARS1. The normalized crest settlement with slope height at failure ($S_c/H$) was found to be 0.048 for model ARS1 and 0.063 for model ARS2. This is attributed to farther spacing of reinforcement layers in model ARS2.

Digital Image Analysis

A series of images were captured during centrifuge tests and the displacements of geogrid markers were calculated with the help of image analysis software (Viswanadham and Mahajan, 2007). Figure 6 shows front elevations of model geogrid reinforced soil wall at 1g and 40g for model ARS1. A distinct development of failure surface can be noted from Fig. 6b. Figure 7 gives the displacement vectors of markers stuck on to geogrid reinforcement layers shown in model ARS1 from 1g to 40g. Horizontal and vertical axes shown in Figure 7 can be converted to corresponding prototype dimensions by multiplying corresponding gravity level. Figure 8 gives strain distribution within the model geogrid reinforced soil wall for model ARS2. Observed failure surface along with locations of the zone of observed ruptures in exhumed model geogrid layers were depicted in Figure 8.

Observed failure surface was found to be in good agreement with zone of peak strains along geogrid reinforcement layers. Figure 9 presents the variation of peak strain with normalised wall height for models ARS1 and ARS2. Peak strain $\varepsilon_p$ is defined as the maximum value of strain along a particular geogrid reinforcement layer. Maximum peak strain $\varepsilon_{p_{max}}$ within the geogrid reinforced soil wall was found to be 14.2% and 17.2% and located at 0.4H and 0.33H (from the top surface of the foundation layer) for models ARS1 and ARS2 respectively. This implies that for same wall inclination and reinforcement type, with an increase in geogrid reinforcement spacing, location of $\varepsilon_{p_{max}}$ was observed to shift downwards vertically. In the
case of geosynthetic reinforced slopes with 63.4° inclination, \((\epsilon_p)_{\text{max}}\) was observed to be at mid-height of the slope (Zornberg et al. 1998 and Viswanadham and Mahajan, 2007). All reinforcement layers exhumed from models ARS1 and ARS2 were found to show clear breaks and is found to consistent with observed strains and measured ultimate strain of the reinforcement material. Modified Bishop simplified method of slices (SLOPE/W) was used to calculate variation factor of safety of the reinforced soil wall with g-level. Figure 10 shows variation of factor of safety with g-level for models ARS1 and ARS2. The results of stability analysis were found to be in agreement with physically observed centrifuge model test results.

![Fig. 8: Strain Distribution in Reinforcement Layers of Geogrid Reinforced Soil Wall Model (Model: ARS2)](image)

![Fig. 9: Reinforcement Peak Strain Distribution at the End of Centrifuge Test](image)

![Fig. 10: Variation of Factor of Safety with g-level for Models ARS1 and ARS2](image)

4. CONCLUSIONS

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

- Catastrophic failure was observed in both the model walls at the onset of increase in g-level. This indicates that the failure of the reinforced soil wall is mainly dependent on tensile load-strain characteristic of reinforcement layers.
- For a geogrid reinforced soil wall with 84° inclination with the horizontal, maximum peak strain was observed to locate within bottom half portion of the wall. This was further observed to shift downwards with an increase in spacing of reinforcement layers.
- The results of global stability analysis of reinforced soil walls were found to be in agreement with physically observed centrifuge test results.

However, further investigations are warranted in order to understand the stability and deformation behaviour of geogrid reinforced soil walls.

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REFERENCES


