USE OF ANCHORED GEOSYNTHETIC SYSTEM FOR SHORE PROTECTION: CENTRIFUGE STUDY

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ABSTRACT

In recent years, new dangers to coastal areas have emerged as a consequence of climate change and rising sea levels. This necessitated a need for developing alternative shore protection measures. Anchored geosynthetic systems (AGS) were evolved as a technique for stabilizing slopes at or near failure state as well as erosion control. This paper evaluates influence of the AGS system on stability and performance of a 12 m high silty sand slope subjected to seepage by using centrifuge modeling technique. Seepage condition was simulated using a seepage flow simulator causing to rise in phreatic surface level at 50g. In this paper, results of two centrifuge tests carried-out on 1V:1H slopes are presented to bring-out the efficacy of AGS system in ensuring slope stability and improving the performance during centrifuge tests. Based on scaling relationships, anchors and geosynthetics were scaled-down and were modeled as pre-tensioned anchors and a geocomposite layer, respectively. An anchor inclination of 15° with the horizontal was adopted for AGS slope model. Nine numbers of anchors were spaced in a square grid of 3 m centre to centre both in horizontal and vertical direction on the slope surface. Both the centrifuge models were instrumented with linearly variable differential transformers (LVDTs) and pore water pressure transducers (PPTs) to measure surface displacements from crest of the slope and development of phreatic surfaces within the slope. Digital image analysis technique was employed to trace the movement of plastic markers embedded within the slope body as well along the slope face at the onset of seepage. In addition to substantial effect of employing AGS on slope stability, ability of centrifuge modeling in rendering reasonable results, concerning AGS slopes under seepage condition are addressed.

Keywords: Centrifuge modeling, seepage, anchored geosynthetic system, image analysis, shore protection.

INTRODUCTION

In recent years, instability of infrastructures due to events resulted from climate change has received much attention. In general, two methods named structural and nonstructural have been utilized to decrease instability and erosion of coastal areas. Recent techniques developed to mitigate the erosion of coastal areas utilize mostly geosynthetic materials. In this respect, geotextiles wrap around revetment (Recio-Molina and Yasuhara 2005; Yasuhara and Recio-Molina 2007; Faure et al. 2010) or geotextiles containers (Saathoff et al. 2007; Lee and Douglas 2012; Yasuhara et al. 2012) have been employed.

A system named anchored geosynthetic system (AGS) was introduced by Koerner (1984) and Koerner and Robins (1986) to stabilize slopes and for controlling erosion. In the system, a geosynthetic fabric such as geotextile, geonet or geogrid is draped on the ground surface and then anchored to underlying hard soil/rock layers via small diameter metal rods. The geosynthetic fabric is provided with reinforced openings on the given grid pattern to facilitate driving of the anchors through them into underlying soil mass. The anchors are first driven to approximately 75 to 90 percent of their designed depth and then fastened to the geosynthetic fabric. In next stage, the anchors are driven to their final depth. After installation of AGS, the fabric is tensioned, curvature is imparted to the soil-geosynthetic interface, and compressive stresses develop on the slope surface. The stresses applied on the surface result in increase in confining pressure followed by enhancement of shear strength of the soil. The exposed geosynthetic fabric can be protected against ultravoilet radiation exposure with covering with the soil along with a layer of armor stone. However, if geogrids or geonets are used, AGS can be combined with biotechnical stabilization techniques giving more shear resistance.

Further studies were performed by Hryciw (1990, 1991), Vitton (1991), Hryciw and Haji-

Ahmad (1992), and Hryciw and Irsyam (1992). Ghiassian et al. (1997) presented an analytical solution along with experimental results to evaluate stability of infinite slopes reinforced by AGS under uniform seepage conditions. Ghiassian et al. (2009) reported that in the case of infinite slopes, limit equilibrium method assuming a circular arc or composite failure surface predict reasonably good results.
This paper presents results of centrifuge model tests conducted on AGS slopes to understand stability and deformation behavior of AGS slopes under seepage conditions. Two centrifuge model tests on unreinforced and reinforced slope with AGS having inclination of 1Vertical:1Horizontal were carried-out to examine effectiveness of the system on the stability of slopes having silty sand type soil subjected to seepage.

CENTRIFUGE MODELING

Geotechnical centrifuge modeling is testing of a 1/N scale model in a centrifugal acceleration field of N times the normal gravity, so that self-weight stresses are identical at corresponding points in the model and in the field. Since behavior of AGS slopes are strongly influenced by surface loading and boundary conditions, centrifuge modeling technique is useful for understanding the actual performance of AGS slopes.

The large beam centrifuge facility having 4.5 m radius available at the Indian Institute of Technology Bombay (IITB), India was used in the present study. The centrifuge has a capacity of 2500 g-kN can carry a maximum payload of 25 kN at 100 gravities. Specifications of the centrifuge were given elsewhere by Rajesh and Viswanadham (2009).

Scaling Considerations for Centrifuge Modeling of AGS Slopes

Centrifuge test data are related to the corresponding prototypes through scaling relationships established between the centrifuge model and prototype. In AGS slopes, the scaling relationships pertaining to anchors and geosynthetic layer are required to be specified.

In stability analysis of AGS slopes, bending and shearing resistance of the anchors are conservatively ignored. Therefore, in the centrifuge modeling, only pull-out strength and axial stiffness are adopted for similarity considerations.

The anchor loads in AGS are transferred on the slope surface through the geosynthetic fabric. Further, in order to prevent movement of soil particles at the onset of seepage, the fabric must be fine enough to act as a filter. Consequently, reinforcement and filtration functions were selected to establish scaling relationships between model and prototype geosynthetic.

In order to provide the functions anticipated from the geosynthetic, a geocomposite layer composed of a non-woven geotextile and a geogrid was adopted for modeling the geosynthetic fabric in AGS slopes. Scaling considerations presented by Viswanadham and König (2004), Rajesh and Viswanadham (2009), Izawa and Kuwano (2010) and Rajesh and Viswanadham (2011) were used to achieve the modeling considerations for the reinforcement function of geogrid component of the geocomposite. Characteristics of opening sizes and cross-plane flow of the geotextile were selected as criteria for filtration function of non-woven geotextile component of the geocomposite. Accordingly, equivalent opening size (EOS) and permittivity (ψ) were used to obtain scaling factors for filtration functions as indices for opening sizes and cross plane flow characteristics, respectively. Detailed discussion on the scaling considerations for AGS slopes was given by Rajabian et al., (2012). Table 1 presents a summary of scaling relationships for centrifuge modeling of AGS slopes.

Table 1 A summary of scaling relationships for centrifuge modeling of AGS slopes

Quantity	Prototype	Model
[a]Anchor parameters		
Length, l_a(m)*	N*	#1
Axial stiffness AE_a/l_f (kN/m)*	N	1
Pull out strength, F_a (kN)*	N^2	1
Geosynthetic parameters		
Tensile strength, T_g(m)*	N	1
Secant stiffness , J_g (kN/m)*	N	1
Percentage open area, f*(%)	N^2	1
Interface friction angle, δ_{sg}*	1	1
[a] Permittivity, ψ*	1	1
[a]Equivalent opening size	1	1

*E_a: Elasticity modulus of tensile element of anchor; l_f: Free length of anchor; $f = a_l a_t/[(a_l+b_l)(a_t+b_t)]$, where a_l and a_t are grid opening sizes in longitudinal and transverse directions and b_l and b_t the widths and ribs in longitudinal and transverse directions, respectively; N: scale factor or g-level, $\#(l_a)_p/(l_a)_m = N$, $(l_a)_p$ and $(l_a)_m$ are length in prototype and model dimensions, respectively.

Model Soil

The slope models were made using a blend of locally available fine sand from Goa state of India and commercially available kaolin in 4:1 ratio (by dry unit weight). The sand can be classified as SP according to Unified soil classification system. Kaolin was found to have 58 % silt and 42 % clay size particles. The liquid limit and plasticity index of kaolin used in the present study are 42.6 % and 18.4 %, respectively and is classified as CL according to Unified soil classification system. The model soil was classified as SM according to USCS. A compaction test (standard Proctor) was conducted on the tested soil and showed that soil has a maximum dry density of 18.75 kN/m^3 at optimum moisture content of 9%. By performing direct shear tests at three normal stresses 50 kN/m^2, 100kN/m^2 and 150 kN/m^2, soil was found to have friction angle and cohesion of 27° and 11.6 kN/m^2, respectively. Permeability Coefficient of 1.54×10^{-6} m/s was achieved from conducting falling head test on the tested soil.

Model Anchor

The anchor used in the present study represents active anchors (or pre-tensioned anchors). Purposefully, this type of anchor was selected to apply desired load to the anchor.

Bt following scaling considerations, polyester strands were selected to model the anchors. Breadth and thickness of polyester strands including thickness of polyvinyl chloride coating are 3 mm and 1 mm in model dimensions, respectively. Average results of tension tests executed on five polyester strands samples revealed that a single polyester strand has a tensile strength of 0.032 kN at 2 mm elongation (i.e. 2 % strain) and an ultimate tensile load of 0.211 kN at an ultimate strain of 6.8%. The strand was found to have an axial stiffness of 16.125 kN/m.

Figure 1 shows details of model anchors designed in the present study. The length of bond portion of the anchor was designed as 60 mm. The free length was intentionally designed as 160 mm to cross the observed failure surface in the case of an unreinforced slope. In order to prevent the polyester strand from coming in contact with the soil in the free length portion, a thin plastic tube of 5 mm diameter was used. A uniform blend of epoxy resin and coarse quartz sand (having particle sizes ranging from 0.5 mm to 1 mm) was used to grout the strand.

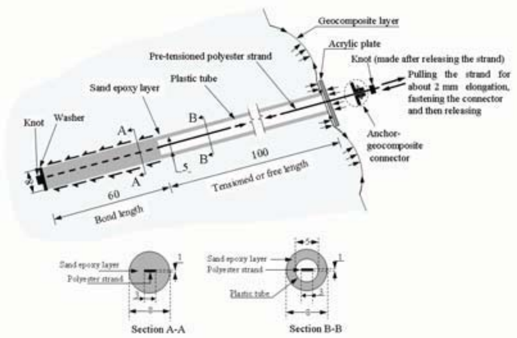


Fig. 1 Schematic diagram showing details of anchors of AGS (all dimensions are in mm)

Model Geosynthetic

As described, a non-woven geotextile and a scaled-down model geogrid were combined to make a geocomposite as AGS fabric. Specifications of non-woven geotextile and geogrid are given by Rajabian et al. (2012). Results of wide width tensile tests (ASTM D-4595, 2005) on model geocomposite revealed that the geocomposite has an average ultimate tensile load of 1.22 kN/m at an ultimate strain of 15%.

A connection system including custom made L-shaped connectors and a 6 mm thick acrylic plate having 198 mm in length and 30 mm used for holding the anchor loads and transferring the anchor loads to the geocomposite (Fig.1).

Model Preparation and testing program

A strong box having internal dimensions of 760 mm in length, 200 mm in width and 410 mm in height was used to construct the model in the present study. In order to observe model status during the flight, front wall of the container is made of a thick transparent Perspex sheet. The other walls of the container are made of well-machined mild steel plates. Both internal sides of walls were covered with a thin layer of white petroleum grease and thin polythene sheet strips of 100 mm width to limit influence of friction on the behavior of the models. With this arrangement, the friction effects can be reduced, and plain strain conditions can be approximated (Deepa and Viswanadham, 2009). Figure 2 presents the cross-section of an AGS slope model set-up developed in present study.

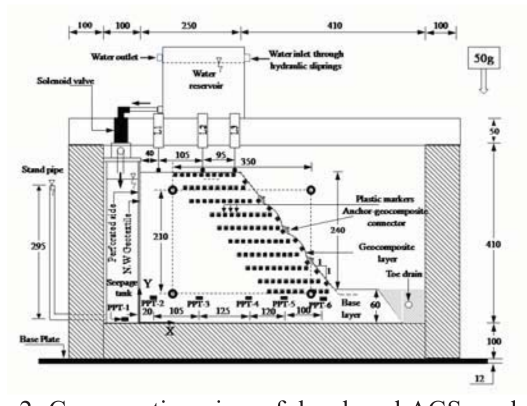


Fig. 2 Cross-section view of developed AGS model set-up (all dimensions are in mm)

Before lubricating the inner side of the Perspex sheet, a rectangular grid of permanent markers were placed as benchmarks to trace the movement of markers embedded in the front face of unreinforced as well as AGS slopes through image analysis. A seepage simulator developed at IIT Bombay was used and it includes seepage tank, water reservoir tank and solenoid valve to simulate rising of ground water table with in the model slope body. One of the walls of the seepage tank in contact with the slope was provided with 2 mm diameter pre-punched holes and covered with a thin non-woven geotextile layer to facilitate water flow during the test without washing of fine particles.

Slope models with height of 240 mm and inclination of 45° were built on the base layer of 60 mm thickness. A toe drain was provided towards the right end of the container to permit drainage at the downstream end. The models were instrumented with three linear variable differential transformers (LVDTs) from crest of the slope to measure surface settlements, as shown in Fig. 2. For measuring the pore water pressure during the tests, six miniature pore water pressure transducers (PPTs) were used and located at specified positions, as shown in Fig.2.

All models were constructed in 30 mm thick layers using moist-compacted at its optimum moisture content and maximum dry unit weight (standard Proctor compaction). A temporary wooden support was placed for achieving slope inclination at normal gravity. After completion of each layer, ten L-shaped plastic markers (placed 20 mm centre to centre) were placed on each compacted soil layer to track the displacement of the soil during different stages of the test. One side of the markers in contact with inner side of the Perspex sheet were lubricated with white petroleum grease to minimize the friction and facilitate free movement of markers. Further, a red colored food dye was placed at selected locations to trace the movement of water within the slope body. Figure 3 shows a view of developed AGS model placed on swing basket along with the accessories at 1g.

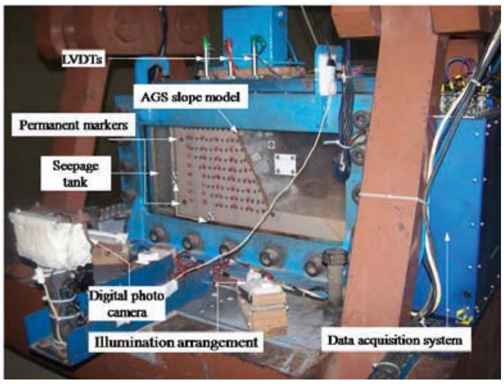


Fig. 3 View of developed AGS model before centrifuge test

After preparing the slope model, the slope face was shaped with a slightly curved surface to facilitate transferring of the anchor load onto the slope surface. Then geocomposite layer provided with pre-punched holes was laid on the surface of the slope. Further, adequate anchorage was provided to geocomposite layer at the toe and the crest of the slope. With the help of a specially designed wooden template, the anchors were installed at 15° inclination with horizontal. In order to install the anchors, holes having same diameter as the anchors were augered from the slope face into the slope. The strands were passed through the geocomposite and acrylic plates. In order to apply the anchor loads, the anchors were pulled for about 2 mm elongation (corresponds to 32.1 N according to tension test results on polyerster strand). By holding the tensioned strand, connectors were placed on the tensioned strands and tightened. A knot was made to the exposed portion of the strand to prevent slippage of pre-tensioned anchors. With this arrangement a perfect contact is made between geocomposite and soil. Additionally, the anchor load was applied on the slope surface by tensioning the geocomposite.

In this paper, two slope models with inclination of 1V:1H were examined. One test was performed on an unreinforced slope and the other on an AGS slope model. Table 2 gives details of AGS slope model discussed in this paper.

Table 2 Details of AGS slope model

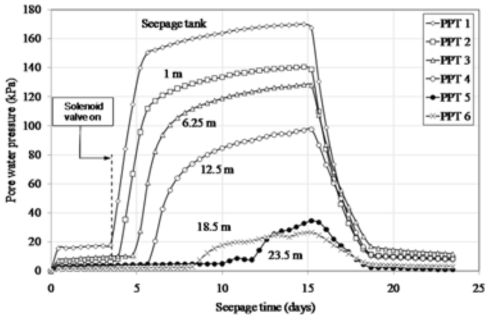
Parameters	**1g**	**50g**
Slope height(mm)	240	12000
Slope inclination(β)	45°	45°
[a]Anchor inclination(α)	15°	15°
S_V(mm)	60	3000
S_H(mm)	60	3000
No. of anchors	9	9
Anchor length(mm)[L_b+L_f]	160[60+100]	8000[3000+5000]
Anchor load(kN)	0.032	80

[a]With horizontal; S_V: Vertical spacing of anchors; S_H: Horizontal spacing of anchors; L_b: Bond length; L_f: Free length

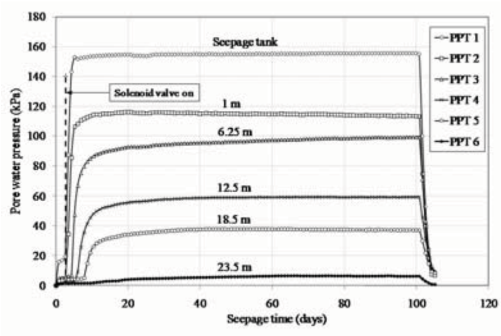
Centrifuge model tests were subjected to seepage at 50g acceleration while the model is subjected to rotation under a constant angular speed of 104 revolutions per minute. Status of front elevation of the model was recorded by using a digital photo camera mounted along with the model. Each test lasted for about 1 hour unless failure with arge deformations occurred in the model or otherwise. This corresponds to a seepage time of 104 days in prototype dimensions at 50g. All datas from LVDTs and PPTs were recorded at one second intervals through the data acquisition system mounted on right hand side of the basket (Fig. 3).

RESULTS AND DISCUSIONS

Figures 4a,b present measured variation of pore water pressure with seepage time in days for unreinforced and AGS slope models. For the AGS slope model, steady-state seepage conditions were observed to develop within 5 to 6 days of seepage. Figure 5 shows the front elevation of the slope models during penultimate stages of centrifuge tests at 50g.

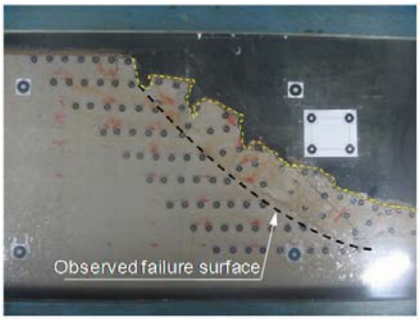


a) Unreinforced slope

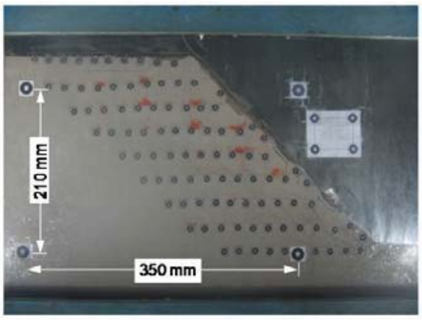


b) AGS slope

Fig. 4 Variation of pore water pressure with seepage time (in prototype dimensions)



a) Unreinforced slope model

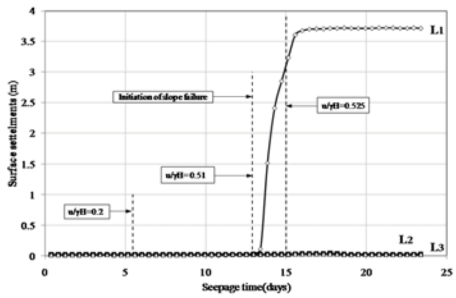


b) AGS slope model

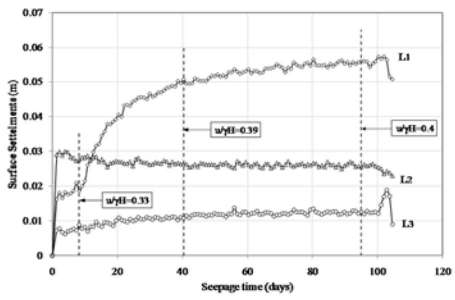
Fig. 5 Front elevations of the slope models during penultimate stages of centrifuge tests at 50g

As can be noted, the unreinforced slope model was observed to be stable at 50g before the onset of seepage. However, it underwent catastrophic failure once pore water pressures within the slope increased. In comparison, AGS slope model was found to undergo very negligible surface settlements and withstood the effect of raising ground water table very effectively. This shows the efficiency of AGS technique to enhance stability and erosion resistance

Figure 6 presents variation of surface settlements with seepage time in prototype dimensions. Variations of normalized pore water pressure measured with PPT3 (u/γH) were marked for each model during the process of seepage. The normalized pore water pressure (u/γH) is defined as the ratio of measured pore water pressure obtained from PPT3 placed at 125 mm (6.25 m) from crest of the slope to the product of bulk unit weight of the soil and height of the slope H.



a) Unreinforced slope

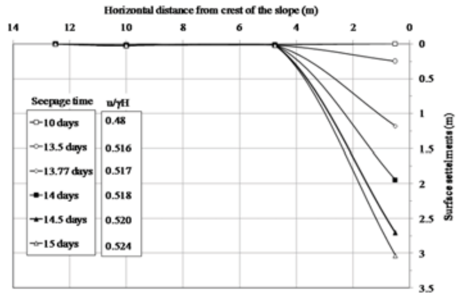


b) AGS slope

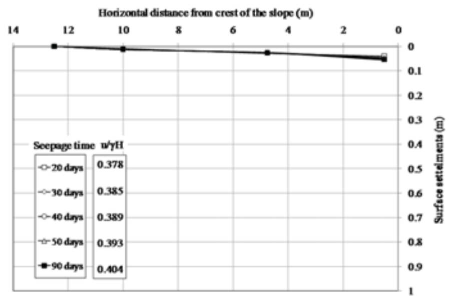
Fig. 6 Variation of surface settlements with seepage time in prototype dimensions.

Figures 7a,b present the variation of measured surface settlements with the horizontal distance from crest of the slope for different seepage times and values of u/γH for unreinforced and AGS slope models in prototype dimensions. Seepage time was referred herein as time in days after attaining 50g. In Figs. 6 and 7, increase in the settlements with development of pore water pressure is noticeable.

The unreinforced slope model was observed to undergo a catastrophic failure at u/γH = 0.51 and showed a maximum surface settlement of 3.03 m (which is 25.2% of the height of the slope) for LVDT L3 placed at the crest corresponding to a seepage time of 15 days in prototype dimensions. In comparison, the AGS slope model showed a marginal increase in surface settlements of only up to 0.057 m (which is 0.475% of the height of the slope) even after subjecting to 102 days of seepage. This shows the significance of AGS slope in improving the performance at the onset of seepage.



a) Unreinforced slope



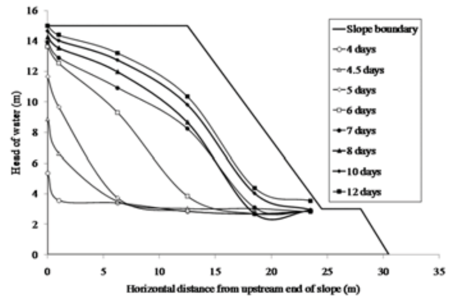
b) AGS slope

Fig. 7 Variation of measured surface settlements with the horizontal distance from crest of the slope (in prototype dimensions)

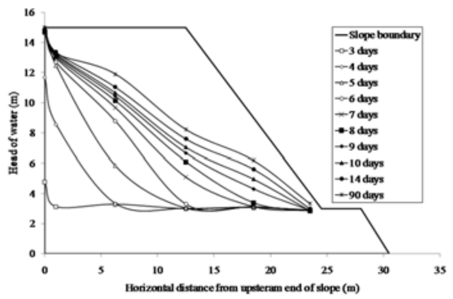
Figures 8a-b present the developed phreatic surfaces at various seepage times for both unreinforced and AGS slope models obtained from measured PPT data in prototype dimensions. These phreatic surfaces are used in stability analysis of slope models.

IMAGE ANALYSIS

Digital image analysis technique was used to monitor and quantify movements and deformations of the slope models. With the help of fixed coordinates of permanent markers the captured images were scaled and calibrated. Digital image analysis was performed using GRAM++ software (Gram ++ 2004). For selected images captured during centrifuge test at 50g for the various seepage times, displacement vectors of markers were obtained. Figures 9a-b show the plot giving displacement vectors from the moment solenoid valve was set to on and to penultimate stages of the test in prototype dimensions for two models. As can be noted from Fig. 9, slope reinforced with AGS has shown very negligible movements. With the help of image analysis, face movements of the slope surface normalized to the height of the slope (S_f/H) for AGS model at different seepage times were plotted. AGS slope model was found to have S_f/H = 0.025 at the bottom of the slope after subjecting to seepage of 100 days emphasizing effectiveness of AGS in improving the deformation behavior of slopes under seepage conditions.



a) Unreinforced slope

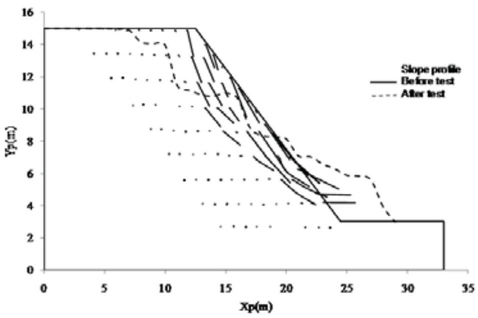


b) AGS slope

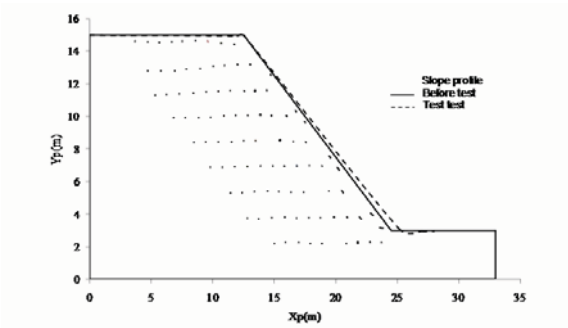
Fig. 8 Developed phreatic surfaces at various seepage times (in prototype dimensions)

STABILITY ANALYSIS

The stability analysis of reinforced and unreinforced slope models was carried-out at various seepage times in prototype dimensions. Slide software (Rocscience, 2005) was used in the present study. AGS slope was modeled as an unreinforced slope along with uniform external forces applied at 15° orientation on the slope surface. In the stability analysis, the load corresponding to ultimate strain of strands was adopted as AGS loads. Summation of this load for all anchors was distributed uniformly on the slope face. The variation of factor of safety with u/γH for unreinforced and AGS models is plotted in Fig. 10. As can be noted, results of limit equilibrium analysis are in a good agreement with physically observed centrifuge test results.



a) Unreinforced slope



b) AGS slope

Fig. 9 Results of image analysis for unreinforced and AGS slope

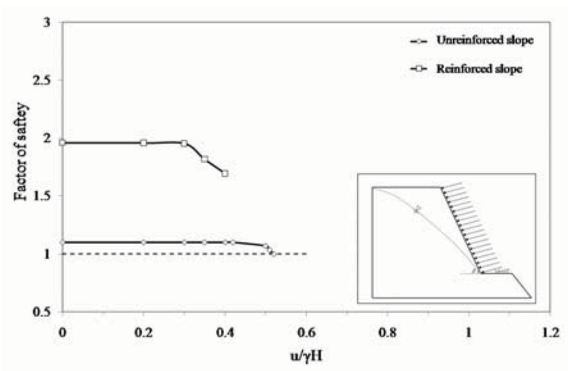


Fig. 10 Variation of factor of safety with u/γH

CONCLUSIONS

In this paper, results of two centrifuge model tests on unreinforced and reinforced slope with AGS are reported. Based on analysis and interpretation of centrifuge model tests, the following conclusions can be drawn:

1. Unreinforced slope with an inclination of 45° and 12 m height was found to be stable without rising of ground water table. However, it underwent seepage induced failure once the value of u/γH equal to 0.52. In comparison, reinforced slope with AGS having inclination of 45°, height of 12 m and nine number of polyester strand anchors in a square grid of 3m x 3m was found to be stable. This shows effectiveness of AGS in ensuring the stability of slopes under seepage conditions.
2. The unreinforced slope and AGS slope with nine number of polyester strand anchors experienced maximum crest settlement of 3.03 m (0.252 H) and 0.05m (0.0042H) during penultimate stages of the test, respectively. These results indicate that using AGS deformation behavior of slopes under seepage conditions can be improved.
3. Comparison of stability analysis results with those of centrifuge shows that the results are in good agreement with physically observed centrifuge test results.

Further studies are warranted to understand the deformation behaviour of AGS slopes subjected to seepage by varying anchor orientation and anchor type and layout.

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