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A new method for remediation of sandy slopes susceptible to seepage flow using EPS-block geofoam

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ABSTRACT

Using expanded polystyrene (EPS) geofoam (geofoam block) in slope remediation projects has drawn interest from the civil engineering sector for its ease of application and budget saving features. According to design precedence, all slope remediation applications that use geofoam blocks should incorporate permanent drainage systems to prevent instability of the lightweight geofoam blocks due to hydrostatic and seepage pressures. In this study, a new method for slope remediation using geofoam blocks was tested through physical laboratory experiments. For this purpose, a total of 24 lysimeter (dimensions of 60 cm height, 20 cm width, and 200 cm length) experiments (including duplicates) were conducted in which seepage through a geofoam block slope system were generated with three different constant water levels in the water reservoir of the lysimeter. Geofoam blocks (dimensions of 2.5 cm height, 5 cm width, and 15 cm length) were assembled to form embankment type configuration at the toe section of the sandy slopes. This study also included coupled numerical model simulations that were comprised of variably saturated flow modeling and slope stability modeling which could be implemented successfully for the global static failure analysis of the geofoam block slope system comprised of two mediums with different geotechnical characteristics. In addition to global static stability failure analysis, which involved conventional limit equilibrium analysis for the geofoam block slope system, hydrostatic sliding mechanism was investigated which provided insight into using an overburden concept to increase the resistance against horizontal driving forces. Experimental and numerical modeling results showed that the geofoam block slope system was stable even though the phreatic surface was above the bottom of the geofoam block assemblage. For this reason, the embankment type configuration tested in this study can be considered a viable remediation technique where seepage induced deep-seated global stability and hydrostatic sliding failures are a concern.

1. Introduction

There are several factors that can trigger slopes to fail. Steep slopes, low strength slope materials, weak foundation conditions, and earthquakes are major factors affecting slope instability. Seepage is another primary cause of slope instability for both manmade and natural slopes (Fox and Wilson, 2010). Leaky pipes, irrigation, snowmelt, thawing ice lenses, runoff from uphill sources, the clogging of a drain, or shutting off a near-surface well might produce mounding of the phreatic surface within the slope above its steady-state position (Schmertmann, 2006). When this infiltrated water enters a slope faster than the excess pore-water pressures can dissipate, stability will be significantly reduced. Pore-water pressure accretion is the most prevalent of failures on natural hillslopes (Sidle and Ochiai, 2006).

The cause and nature of a slope failure must be understood before designing slope remediation systems (Duncan and Wright, 2005). Fay et al. (2012) listed the essential elements of slope stabilization as proper planning and site investigation, understanding the soil, and knowing the surface and subsurface water conditions. Since every slope repair project has unique causes, numerous types of remediation techniques have been developed (Dronamraju, 2008; Shah, 2008; Fay et al., 2012). These remediation techniques can be categorized in four different groups: mechanical stabilization techniques, earthwork techniques, erosion control techniques, and bioengineering techniques (Fay et al., 2012).

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In addition to these listed slope stabilization categories, reducing the driving force is a viable alternative (Elragi, 2000). However, since the resisting forces along the failure surface are also dependent on the weight of the slope (resisting forces are proportional to normal stresses), the factor of safety against global stability failures (instability along rotational failure surfaces) can only be increased if the reduction of the driving forces is greater than the reduction in the resisting forces. In order to reduce the driving forces in slopes, engineers have used several lightweight fill solutions (e.g., pumice, shredded tires, expanded polystyrene (EPS) geofoam (geofoam block), and tyre bales). Among these lightweight fill materials, a geofoam block has high strength to density ratio (Elragi, 2000; Stark et al., 2004). Due to this property, durability and ease of installation in the field, geofoam block has been gaining popularity since it was first used as a lightweight embankment fill by Norwegian Public Roads Authorities in 1972 (Aabøe, 2011).

In addition to its application as a lightweight embankment fills for roadways, geofoam blocks were used for slope stabilization projects in Japan largely in the mid-1980's to the mid-1990's (Tsukamoto, 1996). Geofoam blocks have been used by Reuter and Rutz (2000), Reuter (2001), Mann and Stark (2007) in slope remediation projects in United States. Even though geofoam blocks have experienced wide-spread use in slope stabilization and rehabilitation projects, there were no formal design guidelines or procedures until 2011. Arellano et al. (2011) developed a design guideline, which was funded by the National Cooperative Highway Research Program (NCHRP), to use geofoam blocks for slope stabilization and repair projects. In this design guideline, Arellano et al. (2011) presented design procedure algorithms which were based on conceptual failure modes. This design guideline is based on the recommendation that all geofoam block slope systems incorporate a drainage system since many of the geofoam block slope case histories evaluated as part of the NCHRP 24-11(02) research included use of underdrain systems below geofoam blocks to prevent water from accumulating above the bottom of the geofoam block assemblage. Also, in some cases, drainage systems were incorporated between the adjacent upper slope material and geofoam blocks to collect and divert seepage water and thereby alleviate seepage pressures.

Even though the design procedure recommends permanent drainage systems, the groundwater table may rise in the long-term due to clogging of the drainage pipe as a result of improper design and/or poor construction in the field. As a result, the groundwater table may rise above the bottom of the geofoam blocks which may cause global stability failure of the slope and/or hydrostatic sliding failure of geofoam block assemblage. The behavior of geofoam block slope systems for remediation of sandy slopes with seepage was first studied by Akay et al. (2012, 2013) using scaled physical slope experiments for marginally stable sand slopes. Based on an extensive laboratory testing program, Akay et al. (2013) concluded that in comparison with the results obtained from the non-remediated slope ("Matrix" configuration), the geofoam block configurations ("One Row" and "One Row Partial Bottom") could be considered as a viable alternative remediation technique for shallow-seated failures; however, they seemed to be ineffective to prevent deep-seated global stability failures of a marginally stable steep sandy slope under seepage. Therefore, Akay et al. (2013) recommended that various geofoam block configurations be investigated to evaluate the use of geofoam block for remediation of sandy slopes that experience deep-seated global stability failures under seepage.

The overall objective of this study was to evaluate a geofoam block configuration in order to remediate a 1:1 sandy slope with a deep-seated slip surface with seepage. In general, geosynthetic reinforcements are used to remediate/construct 1:1 or even steeper sandy slopes (Benjamim et al., 2007; Portelinha et al., 2013). In this study, the possible use of geofoam blocks as a remedial geosynthetic alternative for steep sandy slopes subjected to seepage was investigated. For this purpose, a small scale (1:20) laboratory, physical-slope modeling techniques (1-g model test) were utilized. This laboratory method has been successfully performed to model not only the behavior of geofoam block slope systems with seepage forces (Akay et al., 2012, 2013), but also to model various geotechnical systems such as stone columns (Deb et al., 2011), geogrid reinforced foundations (Latha and Somwanshi, 2009), footing on geogrid reinforced clay slope (El Sawwaf, 2007a), geogrid and geotextile reinforced sand slopes (Lee and Manjunath, 2000; Yoo, 2001), geogrid reinforced flyash slope (Choudhary et al., 2010), horizontal anchor plates (El Sawwaf, 2007b), and geocell reinforced foundations (Dash et al., 2003). When compared to the field prototype, the main drawback of the 1-g small scale laboratory model is the differences in the stress levels between the 1-g model and field prototype (Akay et al., 2013; Choudhary et al., 2010; Latha and Somwanshi, 2009). However, the results of this research are relevant to revealing insights of using the proposed geofoam block configuration for remediation of sandy slopes susceptible to seepage forces at 1:20 scale.

This study also included numerical model simulations that were comprised of variably saturated flow modeling and slope stability modeling. The model results were utilized in the determination of the factor of safety against prevailing failure mechanisms observed during laboratory lysimeter experiments. Therefore, the factor of safety against global stability failure (FS_{GL}) of the slope and the factor of safety against hydrostatic sliding of the geofoam block assemblage along the interface of the bedding level and the bottom of the embankment (FS_{SL}) were calculated for the quantification of the performance of the geofoam block configuration.

2. Materials and methods

2.1. Laboratory lysimeter studies

A total of 24 lysimeter experiments (including duplicates) were performed in this study. Following Fox et al. (2006), Wilson et al. (2007), and Akay et al. (2013), the lysimeter was constructed using 1-cm-thick Plexiglas and had the dimensions of 200 cm length, 20 cm width, and 60 cm height (Fig. 1a). In addition to the soil compartment, the lysimeter had a water reservoir located at one end that generated the necessary hydraulic gradient for seepage to occur through the constructed slope. The constant water level in the reservoir was adjusted to be higher than the base of the slope (25 cm, 38 cm, and 50 cm water pressure head). A stainless steel mesh having an opening size of 0.063 mm (equivalent to No. 230 sieve size) and a perforated 1-cm-thick Plexiglas plate with 8-mm-diameter holes was placed between the reservoir and the soil compartment of the lysimeter. The back-slope was uniformly compacted into the soil compartment of the lysimeter in 2.5 cm lifts to obtain a homogeneous domain with a dry density of 14 kN/m^3. The constructed slope had a side-hill with a 45° angle (1:1 horizontal:vertical). In order to mimic field conditions in which the failed mass of the slope displaced at the toe provides resistance to subsequent failures, the slope was packed only to a length of 100 cm. The slope height and width was 55 cm and 20 cm, respectively (Fig. 1a).

Data collection during an experiment included the pore-water pressures (h) developed inside the slope that were measured by 22 pencil-size tensiometers (Soil Measurement Systems, Tucson, AZ, USA) which were found to be successful at monitoring water pressure dynamics during previous soil column and lysimeter studies (Akay and Fox, 2007; Akay et al., 2013). The numbering and