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Conventional reinforcement as a potential prevention measure against piping

Renforcement conventionnel en tant que mesure de prévention potentielle contre la tuyauterie

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ABSTRACT: Piping is one of the main failure mechanisms that can affect the safety of water-retaining structures. A phenomenon that can occur when a local disruption of water structure caused sand erosion and concentration of seepage flow at that location. This entails sufficient hydraulic gradient resulting in the formation of shallow pipes in the sand layer. There are number of methods to increase the factor of safety against piping. An effective technique is soil reinforcement. The soil reinforcement can be performed by the inclusion of elements (strips, bars, etc) within the mass of soil in a preferred direction. Geogrids can be used as a convenient reinforcement material for improving the behaviour of the soil because of the high tensile resistance and significant friction in the soil. This paper presents laboratory experiments that were performed on unreinforced and reinforced soil samples. Reinforcement was done using different types of geogrid in different layers of the soil sample to investigate the effect of this method and arrangement of the geogrid sheets on the critical hydraulic gradient and resistance against piping. Subsequently, the results demonstrate that reinforcement increased the critical hydraulic gradient up to 75% compared to the value in unreinforced soil. The amount of improvement of the critical gradient is dependent on the arrangement and type of the geogrid.

RÉSUMÉ: La tuyauterie est l’un des principaux mécanismes de défaillance pouvant affecter la sécurité des structures de retenue d’eau. Un phénomène qui peut se produire lorsqu'une perturbation locale de la structure de l'eau a provoqué une érosion du sable et une concentration du flux d'infiltration à cet endroit particulier. Cela implique un gradient hydraulique suffisant entraînant la formation de tuyaux peu profonds dans la couche de sable. Il existe de nombreuses méthodes pour augmenter le facteur de sécurité contre la tuyauterie. Une technique efficace consiste à renforcer le sol. Le renforcement du sol peut être effectué par l’inclusion d’éléments (bandes, barres, etc.) dans la masse du sol dans une direction privilégiée. Les géogrilles peuvent être utilisées comme matériau de renforcement commode pour améliorer le comportement du sol en raison de la résistance élevée à la traction et du frottement important dans le sol. Cet article présente des expériences de laboratoire réalisées sur des échantillons de sol non renforcés et renforcés. Le renforcement a été effectué à l'aide de différents types de géogrille dans différentes couches de l'échantillon de sol afin d'étudier l'effet de cette méthode et de la disposition des feuilles de géogrille sur le gradient hydraulique critique et la résistance à la tuyauterie. Par la suite, les résultats démontrent que le renforcement a augmenté le gradient hydraulique critique jusqu’à 75% par rapport à la valeur obtenue dans le sol non armé. L'amélioration du gradient critique dépend de la disposition et du type de géogrille.

Keywords: Piping; soil reinforcement; geogrid; critical hydraulic gradient

1 INTRODUCTION

When water flows through a soil there is a transfer of energy to the soil which causes a seepage force. The seepage force may result in a significant reduction in effective stress, which in extreme cases, may lead to erosion of the soil. When the flow direction is upwards, with sufficient hydraulic gradient, the effective stresses will be zero. The value of hydraulic gradient corresponding to zero resultant body force is called the critical hydraulic gradient. In this case the contact force between soil particles will be zero and soil will have no strength which leads to fluidization of the soil. There are different erosion processes which are studied by different researchers including Niven and Khalili (1998), Gallo and Woods (2004), Zoueshtiagh and Merlen (2007), Philippe and Badiane (2013) and aslo other researchers including Sherard et al. (1984), Sellmeijer (1988), Ojha et al. (2003), etc. In general these processes are called piping.

The actual word 'piping' refers to the development of channels at the downstream side of the structure where the flow lines converge which leads to the occurrence of high seepage pressures (Sellmeijer, 1988). It is noticeable that 'Backward erosion piping' is a different mechanism, which is specifically for the process of pipe formation in uniform granular materials in the opposite direction to the water flow, whereas, 'piping' is considered as a more general term for the formation of pipes (Van Beek, 2015). Ojha et al. (2003) reported that piping is a kind of seepage erosion and involves the development of subsurface channels in which soil particles are transported through the porous medium. Foster et al. (2000) and Ojha et al. (2003) indicated that piping erosion occurs in structures that are made up of loose soil with relatively high permeability. The phenomenon of piping for loose soils is a common problem in downstream of earth embankments under the influence of upward seepage (Sherard et al. 1984).

Therefore, the hydraulic structures should be protected against piping by using appropriate techniques to increase the factor of safety. These include widening of the dike, inclusion of sheet pile, impervious clay blanket, cut off, filters, etc.

One of the effective techniques for improving the mechanical behaviour of granular soil is soil reinforcement. Reinforcing of soil can be performed by inclusion of reinforcing elements (strips, bars etc) within the mass of soil in a preferred direction which is termed conventional reinforcement. In 1960s, Vidal (1978) invented this technique by using galvanized steel strips in granular soil. Since 1970s, the use of geotextile for mechanical reinforcement has gained increasing popularity due to the more satisfactory performance compared with metal reinforcement (Gray and Ohashi, 1983). Geotextiles are reinforcing materials that increase shear strength and ductility, and provide smaller loss of post peak strength in reinforced sand in comparison with unreinforced sand.

The effect of this method on stress-strain behaviour and mechanical behaviour of soil has been studied by many researchers, but there has been limited study for understanding the performance of conventional reinforced soils against piping. Therefore the aim of this research study is to investigate the effect of this method on the resistant of sandy soil against piping.

2 EXPERIMENTAL SETUP AND TEST PROCEDURE

Based on the apparatus that was designed and fabricated by Skempton and Brogan (1994) for studying the piping phenomenon and also the considerations followed by previous researchers, a simple setup was used for conducting one dimensional piping tests. A schematic illustration of the set-up is shown in Figure 1.

This setup consisted of two transparent cylinders placed on an acrylate base that were connected to each other through a transparent tube with a valve. The wall of one of the cylinders is perforated at distances of 2 cm to allow for various head differences. Thus, the hydraulic gradient is applied by means of an upstream reservoir and a downstream overflow with adjustable head difference.

The second cylinder is consisted of three different sections. Above the first section, which is attached to the base, there is a perforated disc and a mesh on the disc which is used to provide uniform distribution of the flow through the sample and also prevents downward migration of the soil sample. The middle section is used as a container for a compacted soil sample of 100 mm height and 50 mm diameter. The top section is a cylinder, which is perforated to create the desired head of water on the soil sample.

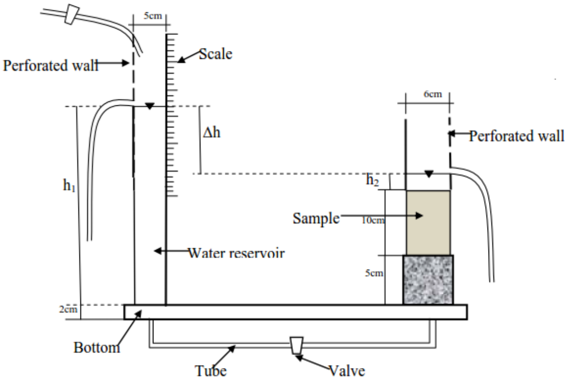

Figure 1. Schematic illustration of experimental setup

In this research study, the experiments were conducted on natural soil samples and geogrid reinforced samples. Initially standard compaction tests were performed for each condition of reinforced and unreinforced samples to determine the maximum dry unit weight and optimum water content. Consequently, it was decided to use water content and dry unit weight equal to 10% and 16.0 KN/m^3 for preparing piping samples. These samples were prepared by using static compaction.

In the sample preparation, the soil was mixed with an amount of water corresponding to a water content equal to 10%. The moist soil was kept in a closed plastic bag and allowed to cure for 12 hours. Then, compaction was done in a special mould by applying a static pressure in three layers, using a compression loading frame. Each layer was compacted at a fixed displacement rate of 1.5 mm/min until the maximum dry unit weight was achieved.

Preparing geogrid reinforced samples was done by using circular geogrid sheets with diameter slightly less than 50 mm (cylinder diameter) that were prepared from the main geogrid sheets. The geogrid was placed in different locations of the mould (see Figure 2), and the soil was applied and densified by compaction, following a procedure similar to the one used for the unreinforced sample.

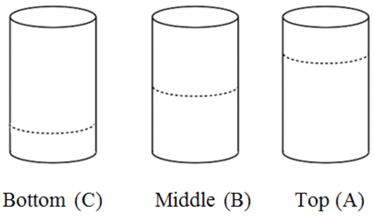

Figure 2. Geogrid sheet arrangement in the soil sample

After preparing the soil sample the mould containing the sample was placed in the apparatus (in the middle section of the setup). The sample was saturated for 12 h without applying a hydraulic head. Afterwards, the initial hydraulic head difference of 0 cm is increased in steps of 2 cm. This process is repeated until failure occurred in the sample, which was identified by formation of local boiling.

3 RESULTS

In this study, all the experiments were conducted by using one type of soil which consisted of 90% sand and 10% silt with the d_{50} of 0.25 mm (d_{10}= 0.075, d_{30}= 0.18 and d_{60} = 0.3 mm). According to the Unified Soil Classification System (USCS), the soil is classified as poor graded silty sand (SP-SM). The grain size distribution of this soil is shown in Figure 3.

Two different geogrid sheets were used in this study with the names Fiberglass and Polypropylene (see Figure 4) and three tests were done by using each type of these geogrids. The mesh size of these geogrids is 4 mm for fiberglass and 6 mm for polypropylene. Based on the information obtained from the manufacturer, these geogrid sheets are resistant to the acidic and basic environment, and their water absorption is negligible.

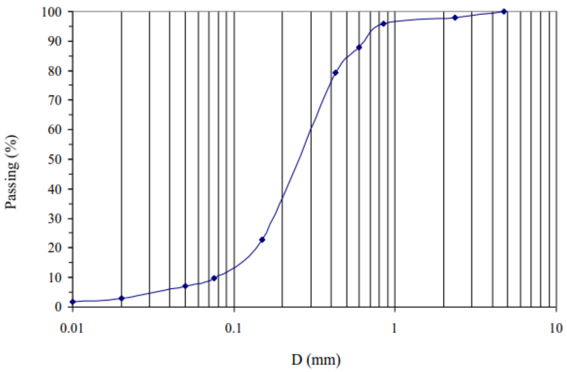

Figure 3. Grain size distribution of soil used

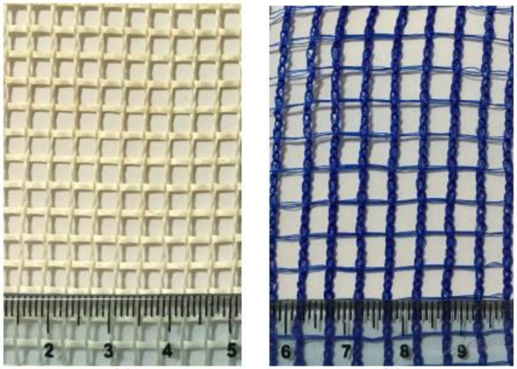
(a) (b)

Figure 4. Geogrid sheets ((a):Fiberglas, (b):Polypropylene)

During the experiments, the volume of the discharge water was measured in every step after increasing the head of water in the reservoir which leads to the hydraulic gradient increment. Therefore, by using discharged water the seepage velocity for each value of hydraulic head was calculated through the following equations:

$$v = k.i \tag{1}$$

$$i = \Delta h/L \tag{2}$$

$$vs = v/n \tag{3}$$

Where v, k, i, Δh, L, and vs are discharge velocity (m/s), coefficient of permeability, hydraulic gradient, head difference, length of sample (m) and seepage velocity (m/s) respectively. n is the porosity of sample which is calculated using equation that was suggested by Zornberg et al. (2002):

$$n = Vv/(Vs + Vf + Vv) \tag{4}$$

Where Vv, Vs, and Vf are volumes of voids, soil solids and geogrid respectively.

Therefore, the hydraulic head and discharge values were measured for each step and then the required values were calculated. Some of the results are presented here. The course of the seepage velocity as a function of hydraulic gradient for different arrangement of fiberglass and polypropylene sheets is presented in Figure 5 and 6. As can be seen in these figures, each graph consist of two linear parts. The onset of the steep change in the gradient of the seepage velocity-hydraulic gradient curves was assumed to estimate the critical hydraulic gradient by drawing two tangent lines as used by Sivakumar et al. (2008).

As shown in Figure 5, the value of hydraulic gradient for the natural soil is 0.8, whereas, reinforcing the sample with the fiberglass sheet results in higher hydraulic gradient. When the fiberglass is located at the bottom of the sample, (C in Fig.2) the hydraulic gradient indicates a significant increase by changing from 0.8 (natural soil) to 1.4 showing 75% increase compared to the unreinforced soil. This value changed to 1.2 because of reinforcing soil by using fiberglass sheet in the middle and top of the sample (B and A in Fig.2) demonstrating 50% increase compare to the natural soil.

The variation of seepage velocity as a function of hydraulic gradient for the samples reinforced with polypropylene layers are shown in Figure 6. In these experiments, the critical hydraulic gradient for the reinforced soils in the arrangements of bottom, middle and top of the sample (C, B and A) are 1, 0.8 and 0.76 respectively. Comparison between these values and critical hydraulic gradient of natural soil leads to the consequence that the critical hydraulic gradient raised in the order of 25% in the bottom arrangement.

These plots indicate that higher gradients can be obtained by reinforcement of soil with geogrid sheets and this increment in the hydraulic gradient depends on the arrangement of geogrid layer and type of geogrid sheet. For comparison the critical hydraulic gradient in the samples with fiberglass is considerably higher than the same samples with polypropylene. In addition, in both tests, the highest critical hydraulic gradient is achieved where the geogrid sheet is located at the bottom of the sample.

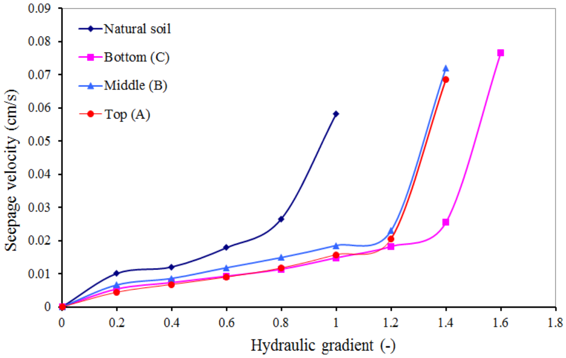

Figure 5. Seepage velocity as a function of hydraulic gradient for fiberglass sheets

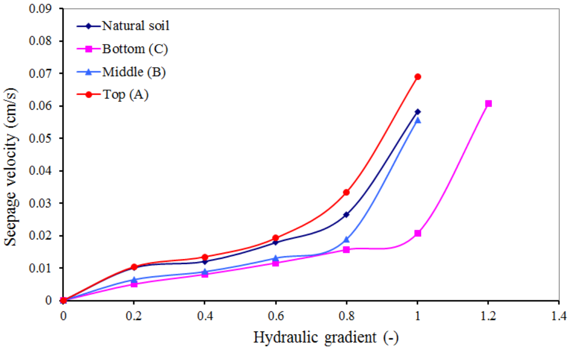

Figure 6. Seepage velocity as a function of hydraulic gradient for polypropylene sheets

4 DISCUSSION AND CONCLUSIONS

The basic mechanism of soil reinforcement is based on the effective stresses and friction forces between the soil and the geogrid which increases the strength of the composite material against applied load. Furthermore, the reinforcement has the ability to unify the mass of soil that would otherwise part along a failure surface.

As indicated in Figure 5 and 6, the highest critical hydraulic gradient is obtained when the layer of geogrid is placed at the bottom of the sample (C in Fig.2). In this arrangement, the geogrid layer subjected to the compaction pressure three times for three compacted layers during the preparation, whereas, in other arrangements, the compaction pressure is only applied once or twice (arrangement A and B). Therefore, this enhanced embedment and contact of geogrid with soil particles leads to more friction and consequently higher critical hydraulic gradient.

These experiments show that the permeability of reinforced samples is less than natural soil which leads to the consequence that even the open geogrid reinforcement reduces the permeability. According to these results, the samples with the lowest permeability have the largest resistance. Due to the presence of geogrid in the sample, displacement of fines before fluidization of the sand below the geogrid is more difficult than above it. This will result in a relatively high hydraulic gradient in the lowest part of the sand and a lower hydraulic gradient in the sand above the geogrid. Therefore, at a gradient of one, there are still effective stresses in the upper part of the sample. The sand from below the geogrid pushes against the sand above the geogrid, resulting in wall friction above the geogrid which consequently proved the possibility of gradients above one.

Comparison between the results of two different types of geogrid demonstrates that the maximum critical hydraulic gradient is obtained in the experiments with fiberglass. When the soil is reinforced with one layer of fiberglass at the bottom of the sample, the value of critical hydraulic gradient is 1.4 while for polypropylene it is 1. Although in both cases the openings are much larger than the grain size, it is likely that some arching occurs below the geogrid, preventing the fluidization of the sand below the geogrid. This arching will be more effective below the stiff fiberglass with openings of 4 mm than below the more flexible polypropylene with openings of 6 mm. Arching only results in a higher overall gradient if the permeability of the sand above the geogrid is larger than the permeability below the geogrid and in this way some effective stresses and wall friction is created above the geogrid. This may easily occur when some fines are washed out from the sand above the geogrid.

Therefore, this analysis leads to the consequence that soil reinforcement increased the critical hydraulic gradient up to 75% compared to the unreinforced soil. This improvement of the critical gradient and soil resistance depends on the arrangement and type of the geogrid.

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