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Research Paper

Models for predicting the seepage velocity and seepage force in a fiber reinforced silty soil

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ABSTRACT

Randomly reinforced soil is used in hydraulic projects such as temporary canals, earth dams, stream restoration and so on for controlling seepage. This paper presents an investigation into the effect of random reinforcement on the seepage velocity and seepage force in a silty soil. Experimental tests were carried out on randomly reinforced samples with two types of fiber at different lengths and percentages. The results show that the random reinforcement of soils with fiber is an effective technique in controlling the seepage velocity and seepage force. Regression models were developed based on the experimental data for determination the seepage velocity and seepage force. The proposed models include the length of fiber, fiber content of soil and hydraulic gradient. Comparison between the model predictions and the experimental results shows that the proposed models can satisfactorily predict the seepage velocity and seepage force for a randomly reinforced silty soil. Analysis of the results of the proposed models shows that the seepage velocity increases with increasing the hydraulic gradient but decreases with increasing fiber length and fiber content. In addition the seepage force increases with increasing the fiber length and fiber content of the soil.

1. Introduction

Water can flow in a soil mass under a hydraulic gradient. When water flows through a soil its energy is transferred to the soil skeleton and this leads to a seepage force applied to the soil skeleton. When the flow of water is in the upward direction the seepage force tends to lift the soil mass by reducing its effective weight. If the seepage force exceeds the weight of the soil the resultant force will be acting upward and soil would become unstable. In this condition the erosion would progress backward along the flow line until an erosion path, nearly in pipe shape is formed. This kind of soil erosion is termed piping. During piping the hydraulic gradient reaches to a value that is termed critical hydraulic gradient (i_c). Piping is a common problem in earth embankments [1]. Brown and Graham [2] reported the failure of a number dams in the USA and concluded that the failure of them was due to the occurrence of piping. It has been reported that failure of embankment dams due to piping is about 0.5% and about 1.5% of them experience the piping phenomenon [3]. Foster et al. [3] and Ojha et al. [4] state that piping usually occurs in earth structures that are made up of loose soil with high permeability. Failure of hydraulic structures such as irrigation canals, temporary check dams and soil structures has been attributed to seepage-induced piping [5]. Ubilla et al. [6] investigated the failure of the levees and flood wall protecting New Orleans, Louisana, USA and surrounding areas during Hurricane Katrina. They concluded that one of the main reasons for the failure was piping. It is therefore necessary to reduce the energy of flow of water and control the seepage force in order to increase the safety of hydraulic structures against piping. There are many methods to prevent from piping failure and to increase the piping resistance of the soil such as using cut off walls, trenches, sheet piling, blankets of impervious material and pressure relief wells.

Randomly reinforcement soil is one of the mechanical methods that has been used to improve the mechanical properties of soil. In this method soil is mixed with randomly distributed discrete fibers. One of the main advantages of using randomly distributed fibers is that they are deposited in a mass independent of each other and have an equal probability of occurrence in any portion of the composite mass [7]. They have an equal probability of making all possible angles with an arbitrarily chosen axis [8]. The majority of previous research work has been done on the

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strength of granular soils randomly reinforced with fibers [9–12]. The results of these research works have shown that reinforcing soil with randomly distributed fibers increases the strength of the soil. Furumoto et al. [13] introduced, for the first time, the randomly reinforced soil in the downstream of hydraulic structures to resist against piping. Furumoto et al. [13] conducted laboratory and field tests on randomly reinforced soil (for application in river levee) and concluded that the use of randomly reinforced soil is an effective method for stabilization of soil against piping. Sivakumar Babu and Vasudevan [5], Das et al. [14] and Das and Viswanadham [15] performed experimental tests on reinforced soil samples in a special apparatus that simulates the upward flow of water. They found that soil reinforcement is a suitable method to control piping. The previous investigations on the use of reinforced soil to improve the resistance of soil against piping are limited to very small diameter fibers (in the range of μm) that could be impractical in field applications. Estabragh et al. [16] conducted experimental tests on two types of fiber (polyester and polyethylene) with large diameters (0.2 and 0.28 mm) and different percentages for improving piping resistance and controlling the seepage velocity of a sandy silty soil. The main aim of this work is carry out statistical analysis of the experimental results that were presented by Estabragh et al. [16] and develop a suitable regression model to describe the piping behavior. In development the regression relationships fiber length, fiber content of soil and hydraulic gradient were considered as the key parameters that have significant effect on piping.

2. Experimental tests

2.1. Apparatus

Skempton and Brogan [17] designed and fabricated an apparatus for studying the piping phenomenon in sandy gravel material. After that researchers such as Furumoto et al. [13], Sivakumar Babu and Vasudevan [5], Das et al. [14] and Das and Viswanadham [15] used an apparatus, almost similar to the Skempton and Brogan's apparatus. By studying the apparatuses that were used by the above researchers a simple apparatus was designed and fabricated for conducting one dimensional piping tests as shown in Fig. 1. The main function of this apparatus is to simulate the upward seepage through the soil sample as discussed by Estabragh et al. [16]. In the apparatus the sample can be subjected to an upward flow of water under different hydraulic heads. The hydraulic gradient (i) can be determined at each stage of the test by the following relationship:

$$i = \Delta h / L \tag{1}$$

where Δh is the differential head between in the beginning and at the end of the sample, L is the length of the sample.

2.2. Material

2.2.1. Soil

A silty sand soil consisting of 77% sand and 23% silt was used in this work. The physical and mechanical properties of the soil are shown in Table 1. This soil can be classified as SM (sand with silt) according to the Unified Soil Classification System.

2.2.2. Fiber

Polyethylene and polyester fibers in filament form with diameters of 0.28 and 0.20 mm were used in this work. The strength characteristics (tensile strength and elastic modulus, measured in the laboratory) and the other properties of fibers (obtained from the manufacture) are summarised in Table 2

2.3. Sample preparation

Fibers with lengths of 5, 25, 35 and 50 mm and percentages of 0.5%, 0.75%, 1% and 1.5% (weight of air dry soil) were used in this work. The mixing of fiber and the soil was done according to the methods that was used by researchers such as [18,9]. Compaction tests were performed on the natural soil and the reinforced soil according to the ASTM standard. In the preparation of the samples for natural or reinforced soil they were mixed with an amount of water corresponding to optimum water and mixing was done by hand. Preparation of the samples was done by static method in a special mould in three layers [19] by a loading machine. The samples were compacted at their optimum water content to attain the maximum dry unit weight according to their compaction curve. The samples had diameter and length of 50 and 100 mm respectively.

2.4. Testing program

After preparing the samples the mould containing the sample was placed in the apparatus. The samples were saturated under $\Delta h = 0.0$ for a duration of 24 h. The piping test was conducted by increasing the head of water in the reservoir (hydraulic head) at increments of 20 mm while the level of water above the sample was kept constant at 50 mm (see Fig. 1). The duration of each increment was about 10 min and during this time the discharge water from the sample was collected and its volume was measured when the rate of discharge was stabilized. The increasing of the level of water in the reservoir was continued until piping occurred in the sample. The piping was observed as the formation of small bubbles and local boiling. Seepage velocity was calculated by the Darcy's equation:

$$v = k \cdot \Delta h / L \tag{2}$$

where v and k are discharge velocity and coefficient of permeability respectively. Seepage velocity (v_s) was calculated using the following relationship:

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

where n is the porosity of sample. For calculation of the porosity of the reinforced sample, the fibers were considered to be similar to soil solid particles. The porosity was calculated as:

$$n = V_v / V \tag{4}$$

where V_v and V are the volume of voids and total volume of the soil.

Critical hydraulic gradient (i_c) is defined as the ratio of head of water at which the soil particles start to lift due the upward flow of water (Δh_c) to the length of sample (L):

$$i_c = \Delta h_c / L \tag{5}$$

As the water flows through the soil a force is applied to the soil particles which is referred to as seepage force. The seepage force at critical gradient can be calculated by the following relationship:

$$P = \gamma_w * \ i_c * V \tag{6}$$

where P is the seepage force at critical gradient (i_c), γ_w is unit weight of water and V is the volume of soil sample.

3. Results and discussion

Typical results of variations of seepage velocity with hydraulic gradient for the natural soil and the soil reinforced with 35 mm polyethylene fibers at different percentages are shown in Fig. 2. Fig. 3 shows similar results for a constant percentage of fiber (0.75%) and different lengths of polyethylene fiber (5, 25, 35 and 50 mm). Figs. 4 and 5 show the similar results as Figs. 2 and 3