Available online at www.sciencedirect.com

ScienceDirect

Soils and Foundations xxx (2018) xxx–xxx

www.elsevier.com/locate/sandf

Laboratory testing for evaluation of the influence of a small degree of internal erosion on deformation and stiffness

Mari Sato [a,*], Reiko Kuwano [b]

[a] Academic Assembly, Shimane University, Japan
[b] Institute of Industrial Science, The University of Tokyo, Japan

Received 21 February 2017; received in revised form 26 December 2017; accepted 30 January 2018

Abstract

Suffusion is a type of internal erosion, namely, the transportation of soil driven by the seepage force of finer fractions within coarser fractions. The present work uses triaxial confining compression tests to study how a small degree of suffusion affects soil stiffness and deformation. This approach allows the suffusion inside a specimen to impose a downward seepage flow. Although a small degree of suffusion is not detectable, it can lead to the deterioration of earth structures. Linear displacement transducers and clip gages were attached to specimens to accurately measure the localized strain rates. In addition, the turbidity of the discharged water was evaluated. Following the downward seepage, each drained specimen was monotonically compressed. The experimental results show that cohesive soil undergoes suffusion and that most of the clay fractions bonding the sand particles erode. At intermediate strain, the deviator stress decreases in proportion to the degree of suffusion, but this decrease ceases at the critical state. Anisotropic behavior is observed and is tentatively attributed to the disruption of the soil texture, which is qualitatively monitored by scanning electron microscopy. Finally, a simple formula is proposed for evaluating the decrease in stiffness due to suffusion.

Keywords: Internal erosion; Suffusion; Cyclic loading; Confining compression test

1. Introduction

Internal erosion is the migration of soil brought about by a seepage force in the ground; it sometimes contributes to ground disasters such as landslides and sinkholes. Internal erosion can be divided into four types: concentrated leak erosion, suffusion, contact erosion, and backward erosion. Concentrated leak erosion mainly occurs in cores having finer fractions and low permeability at dam sites; it is the phenomenon of soil drainage between cracks (see, e.g., Sherard et al., 1984b; Wan and Fell, 2004; Haghighi et al., 2013). Contact erosion occurs at the interface between soils of differing grades where finer soils are entrained into the gaps between coarser soils (Wörmen and Olafsdottir, 1992). Backward erosion, or piping, is the eroding of the surface soil due to localized upstream flow; it leads to the disappearance of the effective stress in the ground. Foster et al. (2000) reported that about half of all dam failures are caused by internal erosion, which is far greater than the number of dam failures caused by sliding.

The present study focuses on suffusion in which finer soil fractions are transported among the voids of coarser soil fractions. Previous studies have proposed various criteria to define the onset of the suffusion of cohesionless soil (see, e.g., Terzaghi, 1926; Bertram, 1940; U.S. Army Corps of Engineers, 1953; Sherard et al., 1984a, 1984b;

Peer review under responsibility of The Japanese Geotechnical Society.
* Corresponding author.
E-mail addresses: maris@life.shimane-u.ac.jp (M. Sato), kuwano@iis.u-tokyo.ac.jp (R. Kuwano).

https://doi.org/10.1016/j.sandf.2018.01.004
0038-0806/

Vaughan and Soares, 1982), which can be separated into various distributions of soil grades and hydraulic conditions. Soil grade distributions allow the transportation of finer particles of diameter d between the voids of coarser particles of diameter D. Suffusion is relevant to dams because dam cores consist mainly of finer particles, whereas dam filters consist mainly of coarser particles. Based on slot tests and slurry tests, Sherard et al. (1984b) proposed that $D_{15}/d_{85} > 9$ is an appropriate design criterion for both cores and filters. Kenney and Lau (1985) and Kenney et al. (1985) reported that the constriction size in filter voids could be determined from the specimen length and the ratio D_{60}/D_{10} which, in turn, could be obtained from the grading distribution. Hydraulic criteria for suffusion are based on both the critical hydraulic gradient (see, e.g., Skempton and Brogan, 1994; Wan and Fell, 2008) and the critical flow rate (see, e.g., Ke and Takahashi, 2012). Critical values are influenced not only by the magnitude of the water pressure and the flow rate, but also by the magnitude of the confining stress. Based on one-dimensional seepage tests, Moffat et al. (2011a), Moffat and Fannin (2011b) suggested that hydraulic conductivity at the onset of instability and vertical effective stress are linearly correlated. Thus, recent research has elucidated the factors that trigger suffusion and its progression.

Some studies have proposed that internal erosion influences stiffness and deformation (e.g., the decrease in ground stiffness and the increase in void ratio). For example, Sato and Kuwano (2015a) obtained the decrease in penetration resistance in suffused soil. Chang and Zhang (2013) induced internal erosion inside a specimen by applying confined compression under isotropic or anisotropic conditions to simulate the seepage flow at a dam site. By subjecting a suffused specimen to various levels of stress, they found that the anisotropic conditions further favored the rapid progression of erosion, leading to the reconstitution of the force chains. Kelly et al. (2012) and McDougall et al. (2013) verified the effect of particle loss in soil by mixing salt particles into specimens and subjecting them to triaxial compression tests. By compressing the specimen after the dissolution of the salt particles, they found that the loss of larger particles induces more contraction during confined compression because of the collapse of the soil texture. Single salt particles, ranging from 0.063 to 1.0 mm, were transported, and the ratio of the mass of the salt particles in the whole specimen ranged from 2% to 15%. This means that they simulated both small and large ratios of erosion. Ke and Takahashi (2014) deduced that the amount of eroded fines is proportional to the initial amount of fines and that suffusion decreases the soil strength at the major stage of drained confined compression. The influence on the mechanical consequences of suffusion was also described by a comparison with the well-known theory for a ground without suffusion. Maeda et al. (2012) used the discrete element method (DEM) to simulate the removal of particles from the ground by a repetitive increase in monotonic loading and the removal of the finer fractions. They concluded that the removal causes an increase in the void ratio, a contraction because of the confining pressure, and poor grading. In addition, the peak stress vanishes following the removal of the fines. Hicher (2013) proposed a new model for the suffusion effect and related the evolution of ground deformation to the confining stress and the ratio of erosion. This formula indicates that the amount of eroded soil is proportional to the deformation, especially under high confining pressure, and that erosion decreases the internal friction angle.

In the present study, a triaxial compression testing apparatus is employed to examine how a small amount of suffusion, which is a type of internal erosion, affects the strength and deformation characteristics of well-graded natural sand containing plastic clay with drained confined compression. In addition, several sensors are attached to the soil specimen to measure the local strain during the experiment. The specimen is subjected to small cyclic loads to determine Young's modulus and Poisson's ratio. Thus, this study addresses the lack of recent studies that examine quantitatively how a small degree of suffusion affects soil stiffness and the deformation of cohesive, natural sand. Suffusion leads to the deterioration of earth structures and can even lead to their complete destruction during earthquakes and heavy rain. For example, the Great East Japan Earthquake of 2011 led to the failure of a great number of soil structures (see, e.g., Kazama and Noda, 2012). Many studies have simulated suffusion by using noncohesive sand with artificially mixed silt fractions (see, e.g., Ke and Takahashi, 2012, 2014; Sato and Kuwano, 2015a, b; Kondo et al., 2013). Based on the proposals by Haghighi et al. (2013), Yokoyama (2002), and Osanai et al. (2006), whereby the progression of erosion is related to turbidity, the turbidity of discharged water is examined to evaluate the amount of eroded soil. Following the confined compression of the specimen, the micro-disturbance of the soil skeleton is observed by scanning electron microscopy (SEM).

The present paper is organized as follows: First, the procedure for using the triaxial testing apparatus and the conditions that induce suffusion inside the specimen are presented. Second, the test results are described by separating the specimen's behavior into that which occurs during suffusion and that which occurs during confined compression. Next, the cross-sectional images of the specimen acquired by SEM and the influence of suffusion on deformation and soil stiffness are quantitatively discussed. Finally, the concluding remarks of this study are given.

2. Testing method

2.1. Testing apparatus

Sato and Kuwano (2015b) described the details of the testing apparatus. Fig. 1 shows a schematic diagram of the confining compression test apparatus for inducing internal erosion. Fifty-two holes, 5 mm in diameter, were

Please cite this article in press as: Sato, M., Kuwano, R., Laboratory testing for evaluation of the influence of a small degree of internal erosion on deformation and stiffness, Soils Found. (2018), https://doi.org/10.1016/j.sandf.2018.01.004