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Suffusion and clogging by one-dimensional seepage tests on cohesive soil

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Abstract

The factors of suffusion progression due to a series of one-dimensional laboratory seepage tests on cohesive soil were investigated. Suffusion is the transportation of finer fractions between larger fractions with seepage force. It has been studied for noncohesive soil because suffusion often takes place in filter zones at dam sites. However, other soil structures containing cohesive soil are also threatened by suffusion, particularly in grounds imposed by a high and concentrated seepage force. Following the seepage tests, a series of laboratory penetration tests was conducted to measure the strength of ground-induced suffusion. We proposed that the potential for the onset of suffusion was governed by the gradation curves of the materials and the pore size of the outlet due to the results of seepage tests and the synthesis of previous studies. Both suffusion and clogging take place at high hydraulic gradients. Suffusion is initiated over the critical pore velocity and depends on the material properties. Namely, if suffusion is allowed in the ground and the soil is allowed to outflow from the outlet, suffusion will be initiated. If either one of these is not allowed, clogging will occur and that will lead to a reduction in hydraulic conductivity. The penetration resistance decreased in proportion to the progression of suffusion despite the fact that the absolute amount of suffused soil was subtle. This implies risks of the promotion of vulnerability in practical grounds by continuous and invisible suffusion. In addition, the turbidity of the discharged water proved that by measuring the preferential migration of finer fractions through the soil specimen, it may be possible to monitor the onset of suffusion.

Keywords: Suffusion; Cohesive soil; Erosion; Laboratory test; Seepage; Dams; Embankments; Penetration resistance

1. Introduction

Internal erosion is the transportation of soil particles inside the ground. It accompanies the seepage force and sometimes induces the collapse of dam dikes and levees. Despite various filter and core design criteria that have been proposed to prevent the failure of ground structures (e.g., Terzaghi, 1926; Bertram, 1940; Sherard et al., 1984a; Vanghan and Soares, 1982), internal erosion has sometimes been reported as the cause of ground disasters. For example, sinkholes appeared in the W.A.C. Bennet Dam, in Canada, whose core material was eroded to the filter zone. The grading distribution in the core zones was investigated by Stewart and Garner (2000) after sinkhole accidents occurred. They obtained the loss in finer fractions by comparing that during construction with that at failure. Internal erosion from the core zones also took place in the El Batan Dam, in Mexico, and was detected from the leakage of turbid water close to the outlet pipe. Berrones et al. (2011) stated that the grading of the soils in the filter zones of the El Batan Dam did not satisfy the recent criteria stated by Sherard and Dunnigun (1989). Furthermore, a steep-sided trench induced the formation of differential settlements in the ground surrounding the outlet conduit.

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Previous studies (e.g., Fell and Fry, 2007; Bonelli, 2012) classified internal erosion into four groups according to the different initiation mechanisms: a) concentrated leak erosion, b) backward erosion and piping, c) contact erosion and d) suffusion. Concentrated leak erosion is the enlargement of cracks due to erosion from the surface of the cracks, mainly occurring in the cohesive soil of core zones (e.g., Sherard et al., 1984b; Wan and Fell, 2004; Haghighi et al., 2013). Consideration of not only the particle size distribution of the core materials, but also that of the filter materials, is crucial to prevent concentrated leak erosion, since the finer fractions of cores are retained in the granular matrix of the filters. This phenomenon is called filtration or self-filtering, and studies on the computation of the voids of the matrix of the granular soils are widely known (e.g., Cividini and Gioda, 2004; Reboul et al., 2010). Backward erosion and piping signify the eruption of erosion along the direction of the water flow. This eruption of erosion eventually leads to the formation of shallow pipes to the surface at the exit of the seepage (e.g, Richards and Reddy, 2012). Contact erosion occurs at the interface between the fine soil and the coarser soil due to the pulling of the fine soil into the gaps of the coarser soil (e.g., Wörmen and Olafsdottir, 1992). Suffusion is the movement of finer fractions among the voids of courser fractions with the seepage force; it is primarily studied in filter materials. The aim of most of the previous studies has been to obtain the conditions of the onset of suffusion on cohesionless soil; the conditions were separated into grading distributions and hydraulic criteria. Grading distributions govern the void size in the specimen and the soil particles passing through the filter pores. For example, Sherard et al. (1984b) carried out *slot* tests and *slurry* tests. They found that the boundary range of the filter size was closely related to the filter size, D_{15}. Kenny, Lau. (1985b) evaluated the *constriction size*, namely, the pore size through which the soil particles are capable of passing. The constriction size is obtained by the specimen length and the value of D_{60}/D_{10}. The hydraulic criteria on suffusion were grouped into critical hydraulic gradient (e.g., Skempton and Brogan, 1994; Wan and Fell, 2008) and critical pore velocity (e.g., Ke and Takahashi, 2012). In addition, critical values were related to confining stress. The *critical value* commonly indicated the value at the onset of suffusion, for example, the critical hydraulic gradient or the critical velocity. Moffat et al. (2011a, 2011b) conducted one-dimensional seepage tests which were able to control the confining stress on the specimen, presenting novel insight into the evolution of internal instability, including suffusion. Moreover, they proposed a linear correlation among hydraulic conductivity at the onset of instability and vertical effective stress. Ke and Takahashi (2012) mentioned that the linear proportion of the hydraulic gradient to the average flow velocity inflected after the gradient reached the critical value. Moreover, they revealed that the cone tip resistance was decreased by high hydraulic gradient-induced erosion. Therefore, the onset of suffusion on cohesive soil can be triggered by various parameters and is influenced by the soil strength.

This paper describes one-dimensional seepage tests on cohesive soil. Seepage induces an invisible, subtle degree of suffusion, although suffusion principally has been taken into account for cohesionless soil applied to filters and just a small degree of it has been thought not to affect the ground. We suspect that not only cohesionless soil, but also cohesive soil, contains the risk of the initiation of a small degree of suffusion where the concentration of seepage has occurred (e.g, Kuwano et al., 2012). The turbidity of the discharged water was measured during the experiments to evaluate even small amounts of suffusion, since the validation of the erosion progress was able to be monitored with the turbidity of the leaked water at practical sites, as suggested by Yokoyama (2002) and Osanai et al. (2006). The initiation of the muddiness of the drained water has empirically been known to take place prior to ground disasters.

In addition, we investigate the strength of a ground imposed with suffusion due to a series of laboratory penetration tests, following the one-dimensional seepage tests. Sato et al. (2014) revealed in laboratory model tests that the descent of the penetration resistance was attributed to the suffusion on noncohesive soil. We suspect that a small degree of suffusion may invisibly deteriorate ground structures, consequently promoting ground disasters. From numerical analyses, Maeda et al. (2012) and Hicher (2013) proposed that erosion causes an increase in the void ratio and a decrease in stiffness. However, this has yet to be confirmed in laboratory experiments on natural sand.

The contents of this paper are as follows. The paper initially provides the results of a series of laboratory one-dimensional seepage tests which monitored the turbidity of drained water. The influence of the seepage conditions, for example, the difference in hydraulic gradient and the materials, are examined by the seepage tests. Secondly, the strength of the soil specimens, in which erosion is induced, is evaluated from a series of laboratory penetration tests. Our aim is to understand the comprehensive influence of internal erosion on cohesive soil, the factors of the onset of internal erosion and the variation in stiffness of the ground subjected to internal erosion. An evaluation of the vulnerability brought about by internal erosion is important because many ground structures have been threatened by collapse due to earthquakes (e.g., Kazama and Noda, 2012). Following the discussion on the laboratory test series, we finally conclude the paper with a summary of the processes of suffusion progression and clogging.

2. Testing Method

2.1. Test apparatus

Fig. 1 illustrates the testing apparatus, which includes a soil chamber and a water tank. The soil chamber consists of an acrylic cylinder and top and bottom plates, fixed by four metal rods. The chamber is 80 mm in diameter and 310 mm in height. The inlet tube is mounted on the water tank; it is capable of applying high hydraulic gradients. The bottom plate has 52 holes, 5 mm in diameter, on which a thin filter, with a mesh size of 1 mm or 4 mm, is placed. This filter allows for the drainage of both soil and water from the specimen. The discharged soil and water are collected in a bowl set below the soil chamber.