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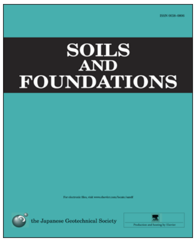

Suffusion-induced change in spatial distribution of fine fractions in embankment subjected to seepage flow

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Abstract

Suffusion describes the phenomenon whereby finer particles are eroded through the voids of coarse particles by the seepage flow. This may cause the deterioration of the hydraulic structure and, in the worst case, result in the failure of the hydraulic structure. The suffusion process is presented in this paper in an embankment under transient and steady seepage conditions. A series of physical model tests on seepage-induced suffusion on a small-scale model embankment is performed under constant boundary head conditions. A binary mixture, consisting of two Silica sands (Silica sands Nos. 3 and 8), which is categorized as "internally unstable material" by several previous criteria for the seepage-induced internal stability, is used for the model embankment. The cumulative eroded soil mass and the discharged rate of water are recorded during the seepage tests. The spatial extent of the variation in erosion-induced fines contents is discussed through sieve analyzes on subdivided areas of the model embankment after seepage testing. The test results reveal that a decrease in fines propagates along the phreatic surface from downstream in the embankment. Below the phreatic surface, the eroded fines not only move laterally by the seepage flow, but also vertically due to the gravitational force, and are deposited in the foundation. This deposition of the fines results in the expansion of the fine-rich region in the foundation and causes a decrease in the permeability of the whole embankment.

Keywords: Suffusion; Internal erosion; Seepage; Physical model tests

1. Introduction

Erosion induced by seepage inside embankments is called internal erosion. This phenomenon is known to be one of the causes of the deterioration of hydraulic structures and, in severe cases, triggers the failure of the structures (*e.g.*, Foster et al., 2000; Richards and Reddy, 2007; Fry et al., 2012). Ground disasters caused by this phenomenon have not only occurred in hydraulic structures, but also in reclaimed land (Khomenko, 2006; Kuwano et al., 2012).

Types of internal erosion include concentrated leak erosion, contact erosion, backward erosion, and suffusion (Fry, 2012; Fell and Fry, 2013). Concentrated leak erosion is driven by the seepage flow in the opening (crack or cavity). It detaches particles from the sides of the opening. Contact erosion is the erosion of particles at the interface between fine and coarse layers due to a quasi-horizontal groundwater flow. Backward erosion describes the erosion of soil particles at the exit end of a seepage path, such as leaking through the downstream surface due to a high exit velocity or hydraulic gradient. Suffusion describes the phenomenon whereby finer particles are eroded through the voids between the coarse particles by the seepage flow. It is also described as "a special case of backward erosion peculiar to gap-graded soil"

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(Richards and Reddy, 2014). This paper focuses on the suffusion phenomenon.

The process of dam failure by internal erosion and piping is classified into four phases: the initiation of erosion, the continuation of erosion, the progression to form a pipe, and the formation of a breach (Foster and Fell, 1999). Foster and Fell (1999) described this erosion process by detailed event trees. Some of the steps of this process show how failure initiated due to suffusion in an embankment or its foundation; this is the target of the present study.

Moffat et al. (2011) defined suffusion as the phenomenon whereby "the finer fraction of an internally unstable soil moves within the coarser fraction without any loss of matrix integrity or change in total volume," whereas with suffosion, "particle migration yields a reduction in total volume and a consequent potential for collapse of the soil matrix". In this paper, the widely accepted term "suffusion" is used.

Suffusion develops in the first two phases, namely, the initiation of erosion and the continuation of erosion, in the failure scenarios initiated by suffusion. This phenomenon is a potential risk to the long-term stability of hydraulic structures over a period of years. During these phases, the performance of a hydraulic structure, *e.g.*, the hydraulic and mechanical characteristics, might deteriorate progressively. On the other hand, the time scale for the third and fourth phases related to piping, namely, the progression to form a pipe and the formation of a breach, are relatively short, compared with the time scale for the first two phases. In other words, the hydraulic structure is in the phases of the initiation or the continuation of erosion for most of its service life. Therefore, this study focuses on the suffusion development phase and includes the initiation of erosion and the continuation of erosion phases.

For the initiation of erosion phase in the failure process of embankment dams, many research works have been conducted on suffusion and internal instability based on one-directional upwards or downwards seepage experiments; the initiation of this phenomenon depends on the particle size ratio between the finer fraction and the coarse fraction (*e.g.*, Honjo et al., 1996; Terzaghi, 1939), the particle size distribution (*e.g.*, Kenney and Lau, 1985; Li and Fannin, 2008; Wan and Fell, 2008; Chang and Zhang, 2013; Moraci et al., 2014), the particle shape (Marot et al., 2012), the confining pressure (*e.g.*, Bendahmane et al., 2008; Moffat and Fannin, 2011), the hydraulic gradient (*e.g.*, Skempton and Brogan; 1994, Sterpi, 2003), the flow velocity (Perzlmaier et al., 2007), and the seepage angle (Richards and Reddy, 2012, 2014), among other factors. Richards and Reddy (2014) suggested a methodology based on kinetic energy to predict suffusion and the backward erosion initiation potential and performed analyses of the factors of safety against these phenomena for a homogenous embankment model with a foundation.

For the continuation of erosion phase, the development of erosion depends on the presence or absence of an adequate filter or transition zone (Foster and Fell, 1999). Moffat et al. (2011) showed the spatial and temporal progression of seepage-induced internal instability, which included suffusion and suffosion from the initiation to the progression phases in a one-dimensional seepage field. They observed the conditions of the specimen through a transparent wall and measured the local hydraulic gradient in the specimen. Luo et al. (2012) described the evolution of suffusion in pore scale as: "fine particles migration → pores clogging → pushing out clogging pores → fine particles remigration." These observations were made in the laboratory in a relatively short period, *i.e.*, days. However, the time scale for the initiation and the continuation of suffusion phases in a real embankment or foundation is very slow, *i.e.*, from months to years (Fell et al., 2003).

Most of the above-mentioned suffusion studies focused on the phenomenon in a uniform one-dimensional seepage field, while the seepage flow in a real structure is more complex and so is the suffusion progress. However, there are few studies which consider the effect of the geometry of a real structure on suffusion in the initiation and the continuation phases. The laboratory experiments of Lindow et al. (2009) suggested that the failure mechanism due to seepage is dependent on the slope angle. Sterpi (2003), Cividini and Gioda (2004) and Cividini et al. (2009) carried out finite element analyses to examine the spatial and temporal distributions of fines under seepage with a phreatic surface by modifying the erosion model proposed by Sterpi (2003). Uzuoka et al. (2012) and Zhang et al. (2013, 2014) demonstrated the temporal change in fines within the "geometry" of the embankment by means of numerical simulations.

Experimental studies on internal erosion have been conducted for large-scale contact erosion (Beguin et al., 2012). To the authors' knowledge, studies based on physical model tests for suffusion are limited (Saito et al., 2012). Saito et al. (2012) provided eight hours of water supply, 16 h of drainage and 180 repetitions to a physical model, which was made of pit sand to imitate a levee. After seepage testing, the fines content was examined at four locations within the model levee.

In this paper, a series of physical model tests is performed on a small-scale model to examine the seepage-induced suffusion process in an embankment during the phases of the initiation and the continuation of erosion.

2. Experimental apparatus and procedure

2.1. Material

To simplify the phenomenon, a mixture of fine and course fractions, namely, a gap-graded soil, is used for the model. This type of gap-graded soil exists in the glacial tills of Canada and New Zealand, but sometimes is used as material for filling. To use a dredged soil as a fill material, its workability is improved by mixing in cement or pit sand. Typically, the latter is a gap-graded soil. Although use of such a material can exaggerate the test results, it allows (a) easy distinction between the base and the erodible materials and (b) easy observation of the fines migration in a short period.

Based on the works by Ke and Takahashi (2012, 2014), Silica sands Nos. 3 and 8 are used as the model materials. Silica sand No. 3 is applied to model the soil skeleton, while Silica sand No. 8 is applied as the erodible fines particles in the voids of the coarse skeleton. Hereafter, Silica sand No. 8 is referred to as fines for simplicity, even though Silica sand No. 8 is not strictly classified as