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Experimental investigations on suffusion characteristics and its mechanical consequences on saturated cohesionless soil

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Abstract

The characteristics of suffusion and its mechanical consequences on saturated cohesionless soil with different initial fines contents at various stress states are presented in this paper. A series of seepage tests is performed by constant-flow-rate control mode with the measurement of the induced pore water pressure difference between the top and bottom of the tested specimen under the isotropic confining pressure. Back pressure is maintained constant in the tested soil specimen to ensure fully saturated soil condition. Cumulative eroded soil mass is continuously recorded by a consecutive monitoring system. Suffusion induced axial strain and radial strain of the 70mm-in-diameter and 150mm-in-height specimen is recorded during the seepage tests. The gap-graded cohesionless soil, which are assessed as internally unstable by existing evaluation methods, are tested. The mechanism of suffusion is demonstrated by the variation of hydraulic gradient, hydraulic conductivity, percentage of cumulative fines loss and volumetric strain during suffusion. The parametric study on the influence of two variables, effective stress level and initial fines content, on the mechanism of suffusion is elaborated. The mechanical consequences of suffusion are evaluated by conducting monotonic drained compression tests on the eroded specimens. Companion specimens without suffusion are tested for comparison purpose. The test results reveal that with the progress of suffusion, hydraulic gradient would drop and hydraulic conductivity would increase. Large amounts of fines are eroded away and correspondingly, contractive volumetric strain occurs. The larger effective confining pressure would lead to the less extent of suffusion. With larger initial fines content, more fines would be eroded away. The monotonic compression tests indicate that suffusion would cause the reduction of the soil strength at the major stage of drained shearing.

Keywords: Suffusion; Gap-graded cohesionless soil; Triaxial test; Saturated; Deviator stress

1. Introduction

Significant damage to the high embankments of mountain-side roads was observed during Noto Peninsula Earthquake of Japan in 2007: the road facilities in approximate 80 places have been damaged (Sugita et al., 2008). Significant damage was done to the flow slide of embankments constructed on catchment topography, such as swamps and valleys, which is usually accompanied with a large volume of fresh water. It is possible that those earth structures had suffered from years of erosion, which chronically loosened the soil packing, making it vulnerable to seismic shaking. Indeed, numerous soil structure failures reported in the literature have been attributed to soil erosion. Crosta and di Prisco (1999) presented a slope failure along an old fluvial terrace in Italy. By site investigation and numerical analysis, the authors concluded that seepage erosion, the tunnel scouring in the superficial layers, and the seepage

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Notation

D'_x	Grain size for which x% mass passing is finer of the coarse fraction of a grading curve (mm)
d'_x	Grain size for which x% mass passing is finer of the fines fraction of a grading curve (mm)
D_x	Grain size for which x% mass passing is finer of the filter (mm)
d_x	Grain size for which x% mass passing is finer of the base soil (mm)
e_0	Initial void ratio after saturation
e_c	Void ratio of the suffusional specimen without volumetric deformation
e	Post-suffusion void ratio
ε_v	Suffusion induced volumetric strain (%)
FC	Initial fines content by mass (%)
ΔFC	Cumulative fines loss by mass (%)
k	Hydraulic conductivity (m/s)
p'	Mean effective stress (kPa)
q	Deviatoric stress (kPa)
Q	Inflow rate (m^3/s)
v	Darcy velocity (m/s)
V_f	Volume of fines
V_c	Volume of coarse grains
ΔV_f	Volume of eroded fines
ΔV	Intergranular re-arrangement induced volume change
Λ	Ratio of the increments of void volume to that of solid volume due to particle removal (McDougall and Pyrah, 2004; McDougall et al., 2013)

erosion at the slop toe were the vital factors triggering the failure. Muir Wood (2007) reported that the two large sinkholes formed by internal erosion at the crest of the W.A.C Bennett Dam in Canada presented a significant threat to the dam safety. Richards and Reddy (2007) concluded that approximately half of the world's dam failures have been related to soil erosion. The main triggers for soil erosion are the piping of soil grains through concentrated leaks, backward erosion, suffusion and dispersion. To clearly recognize the seepage-induced internal instability of soil, the clarity of each term by definition is necessary: (1) piping refers to the phenomenon that underground water flows along continuous openings such as cracks, and the soil on the wall of the tubular "pipe" is progressively washed away with the seepage flow, forming several large and instable soil channels which results in a significant loss of soil integrity; (2) backward erosion indicates the erosion of soil grains at the exit of a seepage path, such as the downstream face of a homogeneous embankment, where the erosion resistance of the soil is highly dependent on the hydraulic gradient and the soil stress state; (3) suffusion describes the phenomenon that fine soil grains are eroded through the voids between the coarse grains by seepage flow, usually accompanied by seepage flow over the years; (4) dispersion results from the chemically induced erosion of clay soils which is mostly observed in rainfall erosion. Recent studies revealed that the initiation and progression phases of piping and soil internal erosion may be classified into four mechanisms: (i) suffusion, (ii) contact erosion, (iii) backward erosion, (iv) concentrated leak erosion (Fry, 2012; Fell and Fry, 2013).

This paper focuses on the characteristics of suffusion. At the beginning of the twentieth century, Russian researchers published a comprehensive study about the selective erosion phenomenon of fine grains through a coarse matrix (Goldin and Rumyantsev, 2009). The fine grains are transported through the voids between the larger grains by seepage flow. This phenomenon is referred to as "suffusion" in hydrology or "percolation" in the power industry. It develops chronically with quantities of seepage flow over a period of years. Kovacs (1981) divided suffusion into two subcategories: internal suffusion and external suffusion. "Internal suffusion" occurs when the hydrodynamic forces are large enough to move fine grains from soils, affecting the local hydraulic conductivity. In contrast, the "external suffusion" occurs at the surface of a soil layer, which is "when the volume of the solid matrix is reduced, accompanied by an increase in permeability, but the stability of the skeleton composed of the coarse grains is unaffected". Recently, refinement of the definition is presented. Moffat and Fannin (2006) separated the phenomenon as "suffusion" and "suffosion". They noted that "Internal instability describes the migration of a portion of the finer faction of a soil through its coarser fraction. Redistribution of the finer fraction, termed suffusion, may yield a loss of grain and instigate a process of undermining, termed suffosion." Richards and Reddy (2007) clearly defined suffusion as "the phenomenon that 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 suffosion, "on the other hand, means the erosion of grains would 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.

Soils vulnerable to suffusion are often considered internally unstable, indicating that the constrictions formed by coarser fractions which constitute the soil skeleton are sufficiently large to allow the free passing of fines. A variety of empirical methods have been proposed to assess the instability potential for a soil (U.S. Army Corps of Engineers, 1953; Istomina, 1957 [Ref. Kovacs (1981)]; Kezdi, 1979; Kenney and Lau, 1985, 1986; Burenkova, 1993; Mao, 2005; Chang and Zhang, 2013b; among others). Those investigations introduce the "filter" concept whereby coarser fractions serve as a filter if water flows through. Whether or not the finer fractions would be potentially flushed off depends on the effective grain size ratio between the filter and fines. The ratio should not exceed an empirically derived threshold. The frequently used representative grain sizes are D'_{15}, D'_{85} of the coarse fraction, and d'_{15}, d'_{85} of the fines fraction in a soil. The effective grain size