Suffusion-induced change in spatial distribution of fine fraction in embankment subjected to steady and unsteady seepage flow

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ABSTRACT

Suffusion is the phenomenon that fine particles are detached from the solid matrix by seepage flow and are transported through the pores formed by coarse particles in the ground. This may cause deterioration of soil structures and, in the worst case, resulting in failure of the soil structures.

In this paper, to examine the seepage-induced suffusion process in embankments, a series of physical model tests on seepage-induced suffusion on small-scale model embankments are presented. Binary mixtures consist of two Silica sands (Silica No.3 and No.8), having different dominant particle sizes, were used for the model embankment. The spatial extent of erosion-induced fines content variation is discussed through sieve analyses on subdivided areas of the model embankment after seepage testing. In particular, effects of seepage duration and unsteady seepage flow on soil erodibility and migrating of fines in embankments are discussed.

The results of these experiments show that the temporal suffusion development under the steady seepage flow depends on balance between dislodgement of erodible fines from embankment and its deposition into the base in the early stage. After a certain elapsed time, suffusion may develop backward along the phreatic surface from downstream in the embankment. It was also observed that the erodible fines may not only move laterally by seepage flow but also move vertically due to the gravitational force and are deposited in the base. This deposition of the fines resulted in the expansion of the fine-rich region in the base and may have caused decrease in the nominal hydraulic conductivity of the embankment. When the unsteady seepage flow was adopted, changes in the spatial distribution of fine fraction were exaggerated and the downward movement of the fines became prominent.

Keywords: internal erosion, suffusion, seepage, physical modeling

1 INTRODUCTION

Erosion induced by seepage inside embankments is called internal erosion and may cause the deterioration of the soil structure, in severe cases, triggering the failure of the soil structure (Foster et al., 2000, Fry et al., 2012). Types of internal erosion include piping, backward erosion, contact erosion and suffusion, etc. Suffusion is the migration or transport of fines inside the voids of a coarse skeleton. The development of this is relatively slow (Fell et al., 2003).

A review of existing research on one-directional upwards or downwards seepage experiments show that the initiation of this phenomenon depends on the particle size distribution (e.g. Kenney and Lau, 1985), particle shape (Marot et al., 2012), hydraulic gradient (e.g. Skempston and Brogan, 1994), and the confining pressure, (e.g. Bendahmane et al., 2008) among other factors.

However, there is little study considering the geometry of a real structure on suffusion. The laboratory experiments of Lindow et al. (2009) suggested that the failure mechanism due to seepage was dependent on slope angle.

Sterpi (2003) proposed an empirical law based on results of upward erosion tests. Cividini and Gioda (2004) and Cividini et al. (2009) carried out finite-element analyses to examine spatial and temporal distribution of fines under seepage with phreatic surface by use of the modified erosion model. Uzuoka et al. (2012) and Zhang et al. (2012, 2014) demonstrated the temporal change fines within the “geometry” of embankment by numerical simulations.

Experimental studies for internal erosion have been conducted on contact erosion (Beguin et al., 2012) at large-scales. 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 hours of drainage, and 180 repetitions.
for the physical model, which was made of pit sand mimicking levee. After seepage testing, the fines content was examined at four locations within the model levee.

In this paper, to examine the seepage-induced suffusion process in an embankment, a series of physical model tests were performed on small-scale models. The spatial change of fines content is discussed through comparisons of sieve analyses in different areas of the model embankments after seepage testing.

2 EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Material

Based on the works by Ke and Takahashi (2012, 2014), Silica sand No. 3 and Silica sand No.8 are used as the model materials. Silica sand No. 3 modeled the soil skeleton, while Silica sand No.8 is used as the erodible fine particles in the voids of the coarse skeleton. Hereafter, the Silica No. 8 is referred to fines for simplicity even though the Silica No. 8 is not strictly classified as fines. The chosen fines content of the mixture is 15 %. The grain size distribution curves of each sand and the mixture and basic properties of the mixture material are shown in Fig. 1 and Table 1, respectively. According to several criteria on the seepage-induced internal instability (Chang and Zhang, 2013, Wan and Fell, 2008, Li and Fannin, 2008), the mixture of this study is categorized as internally unstable and is vulnerable to suffusion if seepage takes place.

![Grain size distribution curves of silica sand and their mixture](image)

**Fig. 1. Grain size distribution curves of silica sand and their mixture.**

| Fine content of mature (%) | 15% |
|---------------------------|-----|
| Median grain size $D_{50}$ (mm) | 1.78 |
| Effective grain size $D_{10}$ (mm) | 0.138 |
| Uniformity Coefficient $C_u$ | 13 |
| Curvature coefficient $C_c$ | 7.9 |
| Specific gravity | 2.645 |
| Maximum void ratio, $e_{max}$ | 0.79 |
| Minimum void ratio, $e_{min}$ | 0.53 |
| Void ratio range ($e_{max}$ - $e_{min}$) | 0.26 |

2.2 Experimental apparatus and procedure

Figure 2 shows side view of experimental system. The box has two tanks on both sides, namely the “water supply tank” and the “drainage tank”. The vertical sidewalls between the drainage tank and embankment model contain metal mesh so that only water and fines less than 0.25 mm can flow through.

To prevent material separation during preparation of the model embankment, partially saturated soil is used. The sand is compacted by layers with the thickness of 20mm where sensors are not located. The target dry density is 1.560 g/cm³. The model ground is scraped off with a shaped frame and formed to be a 260.5 mm high embankment. The breadth of model is 150mm.

By pouring water into the water supply tank, seepage flow in the ground can be modeled. After the beginning of the pouring of the water, the boundary head reaches 190 mm and 40 mm at the upstream and downstream side, respectively, in around 30-40 minutes in each test case.

Two parameters (elapsed time of seepage and number of repeated water infiltrations) were examined by physical model tests. The details of the test conditions are summarized in Table 2. Elapsed time was started from the pouring of water into the water supply tank.

In Case St1, the water supply was shut off promptly after a near-steady state, confirmed by stable pore water pressure inside the model embankment. In the other cases, the seepage was continued for a prescribed time with keeping the water heads at the boundaries constant.

![Side view of experimental system](image)

**Fig. 2. Side view of experimental system.**

| Case | DD (g/cm³) | RCSD | ST | SedM | SedR |
|------|------------|------|----|------|------|
| St1  | 1.559      | 1    | 0.58 | 22.8 | 0.76 |
| St20 | 1.562      | 1    | 20  | 32.4 | 1.09 |
| St24 | 1.560      | 1    | 24  | 34.9 | 1.17 |
| St48 | 1.567      | 1    | 48  | 28.0 | 0.913 |
| St96RS4 | 1.560   | 4    | 96  | 44.6 | 1.20 |
| St96RS8 | 1.560   | 8    | 96  | 43.1 | 1.48 |
| St280 | 1.560      | 1    | 280 | 154.7 | 5.19 |
| St280RS40 | 1.559 | 40   | 280 | 234.8 | 7.89 |

DD: Dry density, RCSD: Repeat count of supply and drainage, ST: Seepage time, SedM: Sediment mass, SedR: Sediment Ratio
Case St96RS4 consisted of 1440 minutes of water supply, 1440 minutes of drainage, and four repetitions to the physical model. Case St96RS8 were provided repeated water penetration in eight cycles of 720 minutes duration. In this case, the value of the pore water pressure transducer at P1 in Fig. 2 showed a maximum head fluctuation of plus or minus 30 mm due to complications in the experimental system. In Case St280RS40, the repeated water penetration times are random. Water resupply points in these cases are plotted on the results of the eroded soil mass change described in Section 3 (Fig. 3). Sieve analyses in each area of the embankment were carried out to estimate the extent of erosion-induced fines content variation.

3 RESULTS AND INTERPRETATION

3.1 Characteristics of erosion in model embankment

Figure 3 shows evolutions of the cumulative eroded soil mass for all the cases, except Case St1. Water resupply points in Case St280RS40 are indicated by square dots in Fig. 3. In Case St48 the data were not collected continuously. Changes in the discharge rate of water at the toe with the exception of Cases St1 and the calculated discharge with a homogenous distribution of fines ($FC = 15\%$) by finite-element analysis are shown in Fig. 4. The total eroded soil masses are summarized in Table 2. Figure 5 shows the total head measured by pore water pressure transducers located near the upstream boundary against time as a measure of the water pouring into the water supply tank. It is a rough standard value because it includes the effect of suffusion at the location.

As shown in Fig. 3, major fines erosion took place in the early stage of the seepage tests. In this period, the discharge rate is relatively large (Fig. 4). After that, the erosion rates get smaller and the discharge rate also gradually decrease with time to 0.4 to 0.6 L/min. This indicates that the erosion rate correlates with discharge rate. In other words, the hydraulic conductivity of the entire embankment correlates with suffusion. Luo et al. (2012) describe that the evolution of suffusion in pore scale “relates to fine particles migration → pores clogging → pushing out clogging pores → fine particles remigration”. Several one-directional seepage tests showed decreasing in hydraulic conductivity with elapsed time (e.g. Bendahmane et al., 2008, Marot et al., 2012, Lafleur, 1999). The decrease in hydraulic conductivity indicates in some cases that suffusion leads to clogging in the soil specimen. Lafleur (1999) showed that the variations in general hydraulic conductivity of specimen depend on spatial distribution of fines in specimens in interpretation for downward filtration tests on geotextiles and cohesionless soils. If this interpretation is applied to the geometry of a real structure, general hydraulic conductivity of an embankment depend on spatial distribution of fine fraction in embankment.

Some discrepancy in the cumulative eroded soil mass exists, i.e., the eroded soil mass is relatively large in Cases St280 and StRS40 and the discharged rate is also large in these cases, compared to the other cases. The exact causes are unclear, but the authors infer the occurrence of a relatively strong flow between the sidewall and soil in these cases. However, as the spatial distributions of fine fraction at the middle cross section in these cases show coherent trend, compared with the other cases, these test results are also used to discuss about the progress of suffusion in the following subsections by treating this result as increased suffusion phase.
3.2 Change in spatial distribution of fines in embankment after seepage testing

Changes in spatial distribution of fines are calculated by assuming that the initial fines content is the same in all parts of model embankment before the seepage tests. Distributions of changes in the fines content normalized by the initial value are plotted in Fig. 6 for Case St1. In this figure, it can be seen that the fines decreases throughout the model, especially at the bottom of the base near the downstream boundary (Fig. 6 at A). This change of spatial distribution indicates changes until reaching a near steady state.

The outline of the phreatic surface before the end of seepage testing is indicated by a solid line and the calculated phreatic surface with a homogenous distribution of fines ($FC = 15\%$) by the finite-element method is indicated by dashed line in Fig. 6.

To understand progress of the suffusion in the embankment under the constant seepage flow, an attempt is made to visualize the change of the fines content distribution using the tests having different seepage time. Assuming all initial test conditions and erosion process are the same, the tests are arranged by ascending order of the seepage time or cumulative eroded mass. To eliminate the fines content change during the transient stage, i.e., before the seepage flow becoming stable, incremental change of the normalized fines content with time is plotted in Fig. 7 by making Case St1 as a reference.

In the slope zone and at the top of the base, no marked change in fines content was observed in the early stage of the constant seepage (Fig. 7(a)-(c)).

![Fig. 6.](image)

Fig. 6. Percentage change in spatial distribution of fines in embankment for Case St1

However, results of Case St280 which much fines eroded out to outside of model induced by relatively strong flow or long term seepage, a large reduction occurred at Area B near the toe and Area C near the phreatic surface in the slope zone (Fig. 7(d)).

An increase in fines can be observed in the bottom of the base around horizontally 0-40 mm and 315-385 mm distant locations from the toe of the slope after 20 hours of seepage under constant head (Fig. 7(a)). These fines increased areas develop in the horizontal direction with time and amount of eroded soil mass (Fig. 7(b)-(d)).

As the seepage flow is mostly horizontal at the base, leftward horizontal migration of the fines is expected. However, the decreasing rate at element A is relatively small, compared with an increasing rate at the further downstream locations in the bottom of the base. A possible explanation for this is the migration of fines in the other directions. Namely, the eroded fines move not only by seepage flow but also by gravitational vertical force and deposit in the base.

![Fig. 7.](image)

Fig. 7. Incremental change of normalized fines content with time by making Case St1 as a reference, - St20 (20 hours) (a), St24 (24 hours) (b), St48 (48 hours) (c), St 280 (280 hours) (d)
increased area is grown to be relatively-rapid channel part of matrix flow extended from the downstream to upstream.

4 CONCLUSIONS

In this paper, a series of physical model tests on seepage-induced suffusion in levee are conducted. By examining effects of seepage time and repeated water infiltration on soil erodibility and migrating of fines, the seepage-induced suffusion process in embankments is examined and the following conclusions are drawn:

1. In the early stage of the process, the change in the fines content in the embankment is affected by transportation of fines with the seepage flow and sedimentation of fines into the base.
2. After a certain elapsed time, suffusion may develop backward along the phreatic surface from downstream in the embankments.
3. The erodible fines may not only move laterally by seepage flow but also move vertically due to the gravitational force and are deposited in the base. This deposition of the fines resulted in the expansion of the fine-rich region in the base and may have caused decrease in the hydraulic conductivity of the whole embankment.
4. The repeated water infiltration leads to the prominent vertical transportation of fines from the slope zone to the base zone.

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