International Journal of GEOMATE, March, 2025 Vol.28, Issue 127, pp.121-128
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.127.g14317
Geotechnique, Construction Materials and Environment

VISUALIZED EVALUATION OF INTERNAL EROSION PROGRESS UNDER DIFFERENT SEEPAGE FLOW HISTORIES

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*Corresponding Author, Received: 06 Jan. 2025, Revised: 16 Jan. 2025, Accepted: 20 Jan. 2025

ABSTRACT: In Japan, the frequency of torrential rain events has increased yearly, and many embankment structures have often failed. With age, many embankment structures have lost their original stability. The seepage history of rain and groundwater has caused the migration of fine particles within the soil, whereby the mechanical properties of the embankment may have changed. Current guidelines for the construction and maintenance of embankment structures often assume that the structures are made of uniform materials and rarely consider the deterioration of the soil materials. Therefore, systematizing our understanding of the effects of embankment inhomogeneity on stability dynamics is essential. In this study, visualization of fine particle migration was performed using transparent soils. The influence of different seepage histories on the process of internal erosion was then evaluated. Once soil particles moved significantly, subsequent movement was small, even when the hydraulic gradient was changed. However, at a certain time, after the water table dropped and then rose again, fine particles would again mobilize significantly. Furthermore, this study suggests that the water table fluctuation may weaken the soil.

Keywords: Seepage, Internal erosion, Refractive index matching, PIV, Hydraulic gradient

1. INTRODUCTION

In recent years in Japan, there have been many cases of embankment failures of structures such as levees and earth dams due to events such as heavy rainfall [1]. Levee failure-induced piping is also considered dangerous following the Yabe River levee failure [2-4]. According to a survey of levees along the 10050 km length of the major rivers in Japan, about 40% are at a hazard of seepage failure and piping failure [5]. While reasonable controls against this damage are essential, many embankments need reinforcement throughout Japan. Local failure of the embankment slopes is particularly likely to occur in weak areas, and evaluation and maintenance methods for medium to long-term changes over time are required.

The migration of soil particles within the ground due to the seepage accompanying rain and groundwater is known as “internal erosion”, whereby changes in the mechanical properties (e.g., permeability and shear strength) of embankment occur. Because the progression of internal erosion may ultimately affect embankment dynamics, such as deformation and failure, several replicate experiments and analyses have been performed. The causes of internal erosion have been investigated in recent decades, as mentioned by Horikoshi and Takahashi [6]. Although the causes of internal erosion have been clarified, they have only been identified from the case studies conducted under specific material and hydraulic conditions. To elucidate the effect of internal erosion on the macroscopic behavior of soil structures, investigation of mechanical characteristics of the eroded soils is essential under scenarios as illustrated in Fig. 1. Sato and Kuwano [7] investigated the deformation of sand specimens after internal erosion due to seepage flow. Suzuki et al. [8] conducted a triaxial test on soil specimens to investigate the strength reduction of embankment due to internal erosion. To implement these findings in society as disaster countermeasures, however, understanding how internal erosion progresses in time and space is essential. It is possible to visually assess the progress of internal erosion with numerical simulation (*e.g.* Nguyem and Indraratna [9]); nonetheless, the experimental data for validation of numerical models are lacking. Therefore, a benchmark on internal erosion behaviour

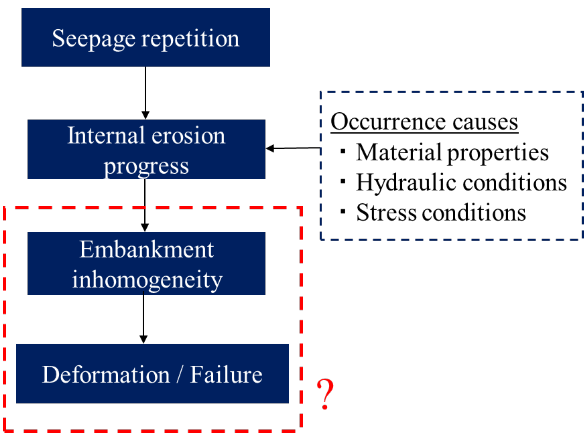


Fig. 1 Scenarios of embankment instability

experimentally is required.

To evaluate the process of internal erosion progression, an approach that visualizes the soil interior is desirable. Nguyen et al. [10] conducted the suffusion test, and visually investigated the strain changes due to the internal erosion progression by X-ray tomography. Nakashima et al. [11] conducted the seepage tests using sand specimens, and confirmed from CT images that heterogenization of soil is more likely to occur in the lower density zone. Internal visualization using X-ray CT images is often useful, although it requires expensive equipment. In addition, because it often takes time to compose an X-ray CT image, an object to be imaged must be stationary. In other words, to evaluate the movement of soil particles, the interval between image acquisition must be set as short as possible. Therefore, more efficient experimental methods are required. In comparison, refractive index matching is useful for evaluating movement of granular material. Sanvitale and Bowman [12] investigated internal behaviour of saturated granular free-surface flows in the context of high-speed movement. It is expected that this technique has the potential to be applied to visualizing internal erosion.

In this study, using a simulated soil prepared by a refractive index matching, internal erosion of the soil is visually and quantitatively evaluated by tracking the finer particles that move due to seepage. Firstly, a selection of tracer particles was carried out. This is essential for quantitative assessment of particle migration. Secondary, a series of seepage tests were conducted, and the internal erosion behavior was evaluated by analyzing images captured during the test. The soil heterogeneity caused by internal erosion progress is a long-term phenomenon and may depend on the seepage history that the soil has undergone in the past. Therefore, assessment of internal erosion with a focus on the seepage conditions are important. However, there has been few previous research on this issue. This study investigated the effects of different seepage histories on the progress of internal erosion to organize the migration of fine particles during seepage. Finally, the relationship between seepage history and internal erosion progress was systematically summarized.

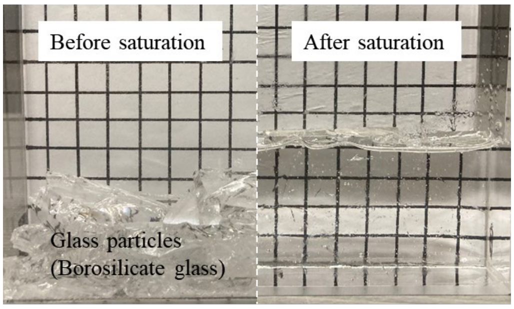


Fig.2 Refractive index matching

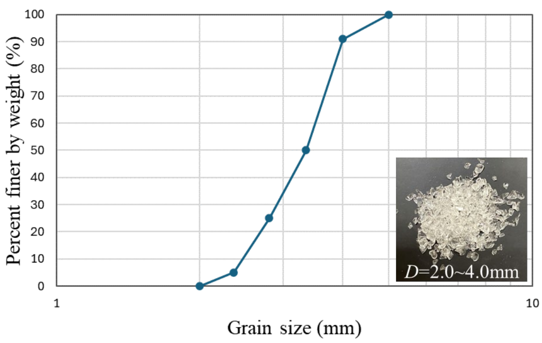


Fig.3 Particle size distribution curve

2. RESEARCH SIGNIFICANCE

Developing an experimental method that can visually evaluate the internal erosion behavior of fine particles is essential to theoretically systematizing the instability of the embankment structures. Assessing the instability of embankment structures from the microscale has important engineering implications. Furthermore, clarifying the internal erosion behavior due to differences in seepage history leads to prediction of embankment structures inhomogeneity caused by expected seepage conditions. This study improves the visualization method of internal erosion using refractive index matching techniques, and contributes to elucidating the process of internal erosion.

3. EXPERIMENTAL STUDY

3.1 Refractive Index Matching

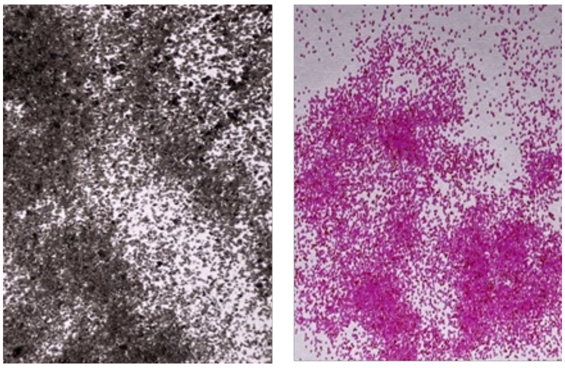
By matching the refractive indices of different substances (*e.g.* solids and fluids), transparent materials can be produced, as shown in Fig. 2. Changing the refractive index of the substance to be tracked allows their visualization. Alternatively, the interior of transparent materials can be visualized by sheet laser irradiation, a technique referred to as LAT (Laser-Aided Tomography) [13]. Saomoto et al. [14] performed PIV (Particle Image Velocimetry) analysis on the images captured by LAT, and quantitatively investigated the mutual movement of particle and pore fluid.

In this study, borosilicate glass (refractive index: 1.47~1.48) was used as a solid, and sodium iodide solution (refractive index: 1.48) adjusted to a 60% mass percent concentration was added as a liquid. Since the refractive indices of borosilicate glass and sodium iodide solution are almost the same, transparent materials could be prepared. Borosilicate glass plates were crushed mechanically and sieved through a 2~4 mm sieve to simulate soil particles. Fig. 3 shows the particle size distribution curve of the sieved material.

3.2 Tracer Particle Selection

At first, a permeability experiment was conducted to select fine particles to be tracked. In this study, colored sand and luminescent particles were examined. The colored sand was prepared by coloring No. 7 silica sand with black spray (Fig. 4). Luminescent particles were prepared by soaking the crushed glass, adjusted to the average particle diameter of No. 7 silica sand (D_{50} = 0.25 mm), in rhodamine solution. The fine particles were mixed to a content of 1% of the mass of the coarsely crushed glass. Rhodamine emits light in response to the wavelength of a green laser (532 nm). Fig. 5 shows the inside of the sample irradiated by a YAG (Yttrium Aluminum Garnet) laser. Using this material makes it possible to track the movement of fine particles in response to fluid movement.

Fig. 6 illustrates a configuration of the test equipment. Test materials were installed in an acrylic column at a relative density of 60% while applying vibration with a mallet. The test materials were then saturated with sodium iodide solution. A granular filter was placed at the bottom of the column to uniformly apply the water pressure on the specimen.



(a) Colored sand (b) Luminescent particles

Fig.4 Tracer particles

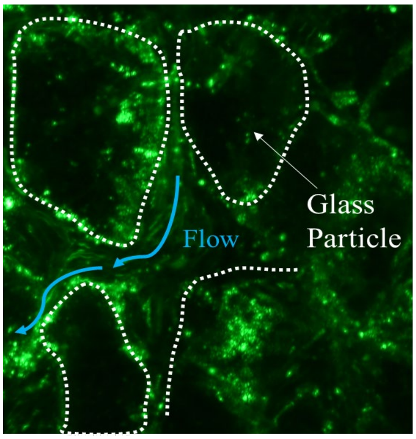


Fig.5 Visualization inside test material using YAG laser

Additionally, mesh filters were set above and below the specimen to allow the washing away of fine particles. After saturation, the hydraulic gradient was changed by raising the upper tank. A preliminary test was conducted in which the hydraulic gradient was increased in the order of 0.5, 0.7 and 1.0, at 10-minute intervals. During the experiment, the side of the specimen was photographed with a digital camera at intervals of 1 second, as shown in Fig. 7, and PIV analysis [15] was performed on the photographs to evaluate the migration of fine particles. In image analysis, to clarify the movement of fine particles following the flow of pore fluid, it is necessary to be careful not to include the movement induced by the movement and rotation of coarse particles. Therefore, an acrylic block was placed on the top of the specimen to restrain the upper movement of coarse particles.

Fig. 8 shows the results of PIV analysis. The figures show composite vector contours, with red areas indicating large particle movements. Each result for hydraulic gradients is shown. When colored sand was used, there was no significant relationship between the magnitude of the hydraulic gradient and the amount of particle movement. On the other hand, the results of the test using luminescent particles under similar hydraulic conditions show that the area where internal erosion occurs widens when the hydraulic gradient is increased. This indicates the possibility that the internal erosion can be evaluated

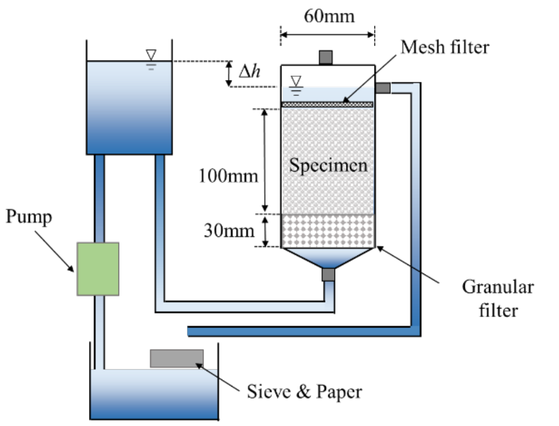


Fig.6 Configuration of test equipment

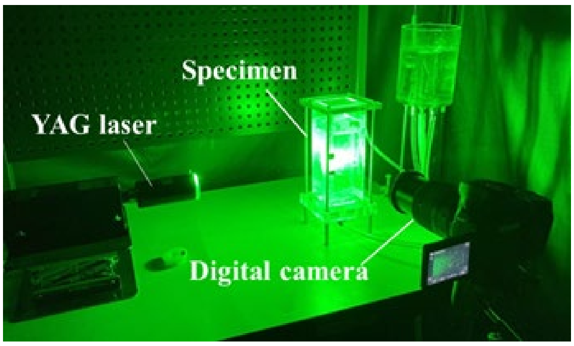
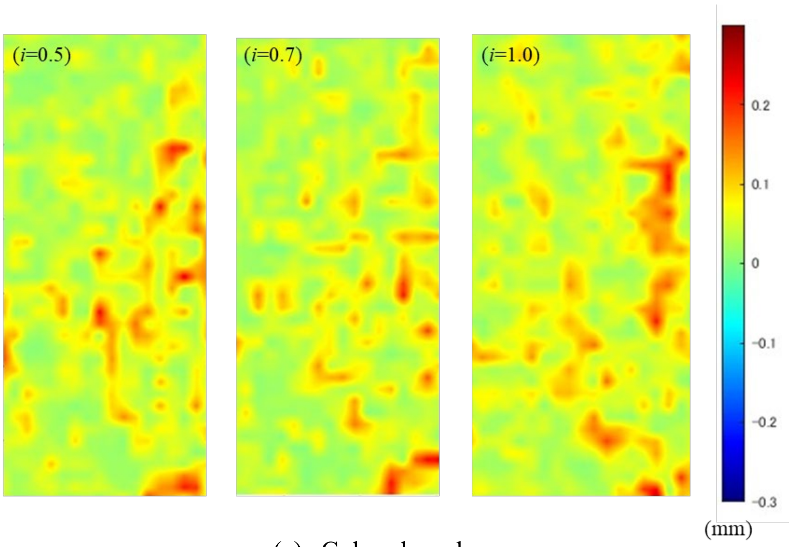
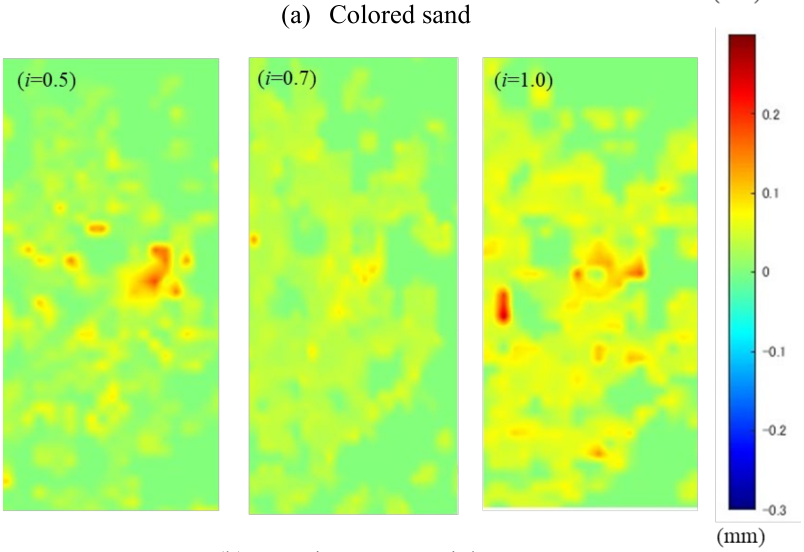


Fig.7 Overview of test equipment



(a) Colored sand



(b) Luminescent particles

Fig.8 PIV analysis with different tracer particles

more accurately with luminescent particles than with colored sand. The magnitude of movement of the fine particles was almost the same in both cases, which can be said that the effect of the type of tracer particle on this is small.

3.3 Test Procedures

Based on the preliminary experiments, luminous particles were employed as tracer particles for tracking and were applied at different permeability histories, as shown in Fig. 9. In Case 1, the hydraulic gradient was kept at 2.0 for 120 min. In Case 2, the hydraulic gradient was increased from 0.5 to 1.5 in steps and then maintained at 2.0 for the remaining time. In Case 3, the hydraulic gradient was increased from 0.5 to 1.5; then the fluid was drained, and the same hydraulic gradient conditions were applied again, with the hydraulic gradient set to 2.0 at the end of the second cycle. In Case 4, the hydraulic gradient was increased from 0.5 to 1.5 for three cycles in total, and the hydraulic gradient was set to 2.0 at the end of the third cycle. The hydraulic gradient was increased by 0.5 every 15 minutes in Case 2 and Case 3, and every 10 minutes in Case 4. The drainage process also

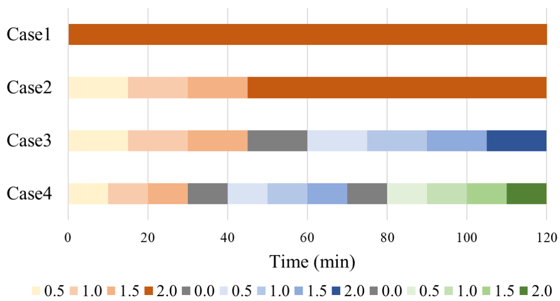


Fig.9 Test procedures
(Legend indicates hydraulic gradient)

took 15 minutes in Case 3, and 10 minutes in Case 4. Case 1 and Case 2 simulate monotonic water level increases, while Case 3 and Case 4 simulate repetitive water level fluctuations.

4. TEST RESULTS

Figs. 10 to 13 show the results of the composite vector contours in each test case. In Case 1, the fine particles moved most significantly at 30~45 minutes and hardly moved thereafter. In Case 2, the largest movement of fine particles was observed at a hydraulic gradient of *i*=1.0. After that, when the hydraulic gradient was increased, the fine particles moved slightly, but the change was smaller than the result for a hydraulic gradient of *i*=1.0. In Case 3, the fine particles moved significantly at a hydraulic gradient of *i*=1.0 in the first cycle, and the movement was small thereafter, as in Case 2. In the second cycle, there was almost no movement up to a hydraulic gradient of *i*=1.5, but when the hydraulic gradient was increased to *i*=2.0, the fine particles moved significantly again. In Case 4, there was some movement of fine particles at a hydraulic gradient of *i*=1.5 in the first cycle. The fine particles started to move at higher hydraulic gradients compared to the other cases. This may be due to a shorter permeability time at each hydraulic gradient than in the other cases, but further investigation is needed. The overall movement was still observed at a hydraulic gradient of *i*=0.5 in the second cycle. Thereafter, the movement of fine particles was small even when the hydraulic gradient was changed. Even in the third cycle after drainage, there was a slight movement at a hydraulic gradient of *i*=0.5, and the movement settled down at a hydraulic gradient of *i*=1.0. The movement was large at a hydraulic gradient of *i*=1.5 in the third cycle, and the movement of fine particles continued even after the gradient was increased to *i*=2.0.

5. DISCUSSION

From the above experimental results, the relationship between seepage history and fine particle behavior can be summarized as follows. Once the fine particles move significantly, the movement cannot be observed, even if the hydraulic gradient is increased, such as in Case 1 and Case 2. However, as observed in Case 3 and Case 4, when the hydraulic gradient is increased through the drainage process, there is a condition in which the fine particles move again. Furthermore, comparing the results of Case 3 and Case 4, as the number of seepage cycles increases, the hydraulic gradient at which the movement of fine particles begins again becomes smaller. This implies that water table fluctuation may intensify soil heterogeneity and weaken the geotechnical structures. Fig. 14 illustrates the kinetic behavior of fine particles following seepage flow. Once the fine particles flow out, the flow concentrates in the gaps that have been formed (Fig. 12 (a)). This means that the pore fluid

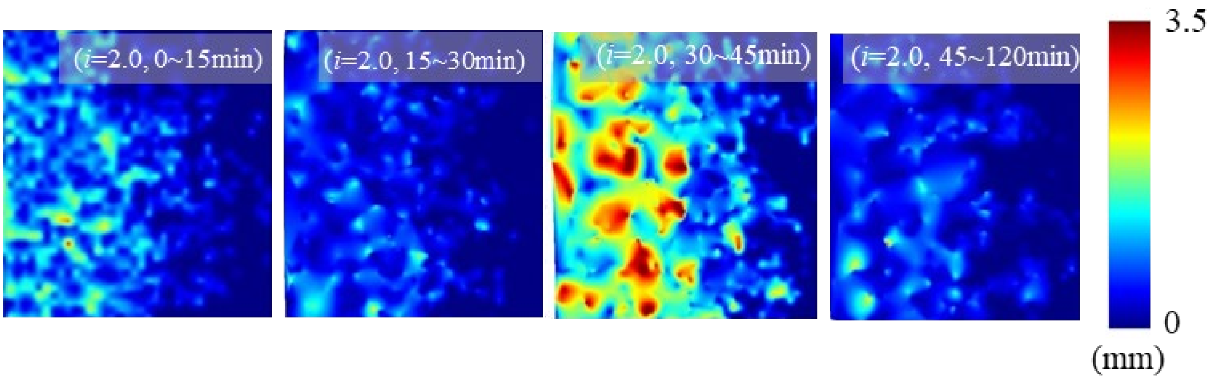


Fig. 10 Fine particle migration (Case1)

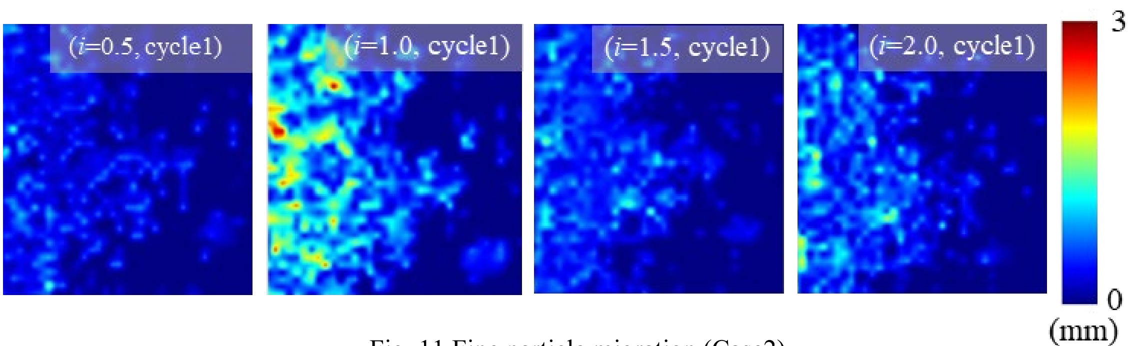


Fig. 11 Fine particle migration (Case2)

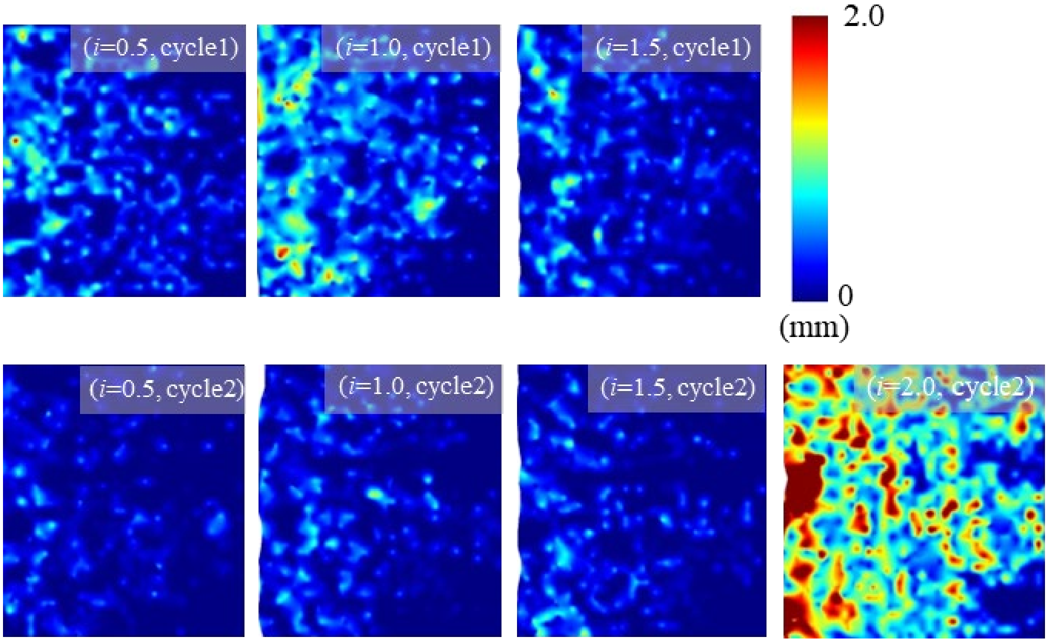


Fig. 12 Fine particle migration (Case3)

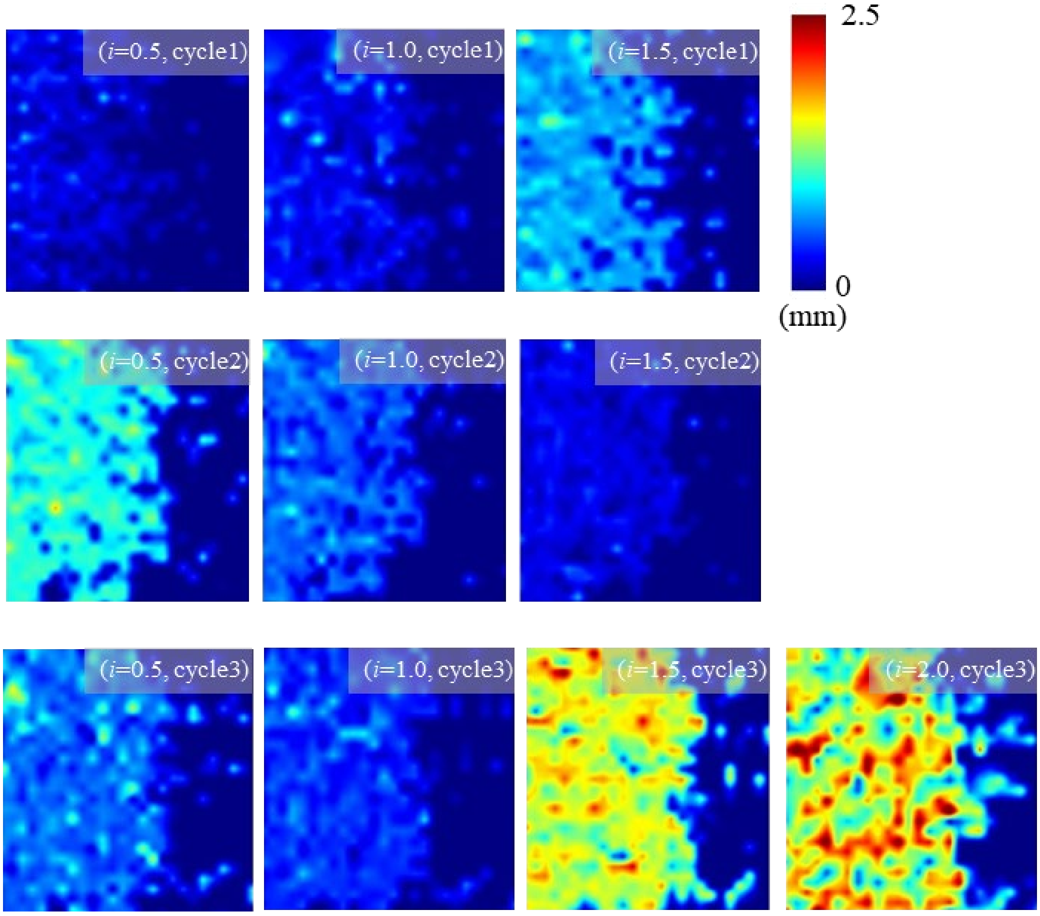


Fig. 13 Fine particle migration (Case4)

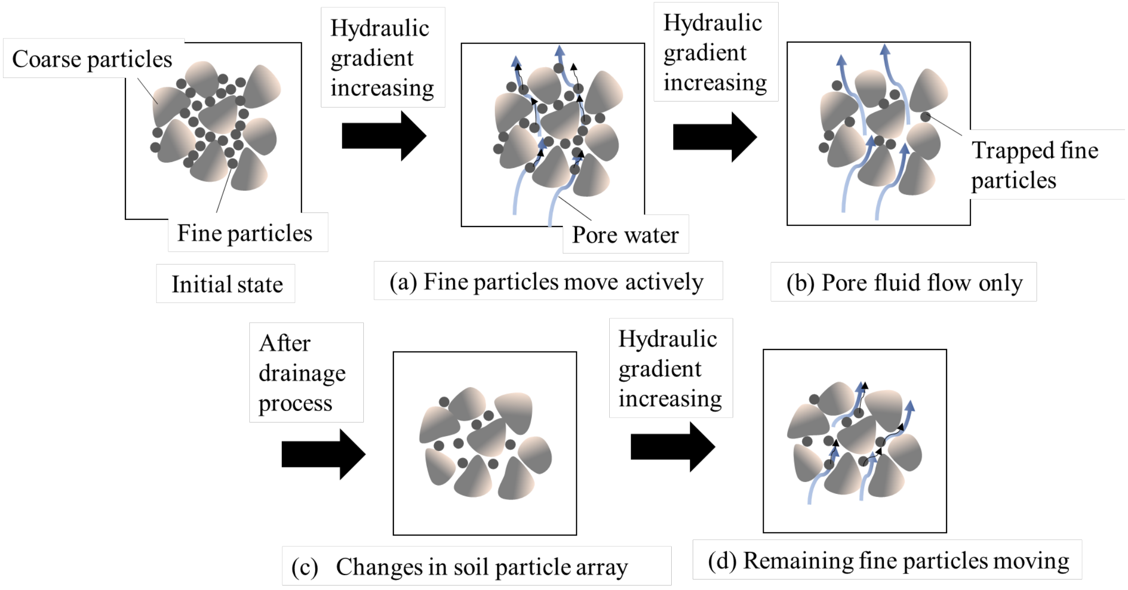


Fig. 14 Relationship between seepage history and kinetic behavior of fine particles

selectively flows in areas where it is easy to flow, and it is thought that once the fine particles have moved significantly, the amount of change becomes smaller because there are no fine particles remaining in the flow path (Fig. 12(b)). On the other hand, if the soil undergoes a drainage process (water level fluctuation), the soil skeleton deforms to fill the gaps created by the outflow of fine particles (Fig.12 (c)), and the fine particles that did not flow out during the previous seepage can move again (Fig.11 (d)). The previous study reported that the initiation and continuation of erosion increase the risk of embankment structures [16]. The findings of this study indicate the possibility of evaluating these behaviors, and contribute to the systematization of the internal erosion process.

6. CONCLUSION

In this study, the seepage history and the progression of internal erosion were examined using transparent specimens prepared by index matching. Fine particle movement was simulated by luminescent particles. The following conclusions were drawn:

1) Once fine particles moved significantly, the subsequent movement was small, even if the hydraulic gradient was increased.
2) When the hydraulic gradient increased after drainage, fine particles migrated significantly again.
3) As the number of water level fluctuations increased, the hydraulic gradient at which the fine grains began to move again became smaller. This suggests that water table fluctuation may weaken the soil.

7. ACKNOWLEDGMENTS

This work was supported by Grant-in-Aid for Scientific Research (21K14244).

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