Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-2357

Effects of fluctuated hydraulic gradient in high-cycle range on suffusion process and soil strength properties

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ABSTRACT: Suffusion is a type of internal erosion in which only fine particles move and flow out of the soil due to seepage flow through soil structures. This phenomenon affects the permeability, strength, and deformation properties of the soil. Waterfront embankments, such as river embankments and reservoir embankments, are subjected to fluctuations in seepage flow due to the changes in water storage levels caused by rainfall and agricultural activities. However, the behavior of suffusion when the hydraulic gradient is varied and its effect on the strength properties are often unclear. In this study, one-dimensional upward water-passing experiments were conducted using a cylindrical column. Changes in the fines content and density of the soil specimens, subjected to suffusion under conditions for which the hydraulic gradient was varied up to 100 cycles, were investigated. In addition, consolidated drained (CD) triaxial compression tests were conducted on the specimens sampled after the water-flow experiments to determine how the strength and dilatancy properties were affected by suffusion. The results showed that the effects of the fluctuated hydraulic gradient on the progression of suffusion were different for the two soil samples with different particle size distributions. Furthermore, the effects of suffusion on the strength and dilatancy properties also varied with the particle size distributions. Based on the results of a series of experiments, the process of suffusion and the subsequent changes in strength were discussed in terms of the role and the mode of existence of the fine particles.

KEYWORDS: internal erosion, suffusion, embankment, triaxial tests.

1 INTRODUCTION

Suffusion is a type of internal erosion in which only fine particles move and flow out of the soil due to seepage flow through soil structures. Recent studies have shown that suffusion affects the permeability, strength, and deformation properties of the soil (Sarmah & Watabe, 2023). As shown in Figure 1, embankment structures at the waterfront, such as river embankments and reservoir embankments, are subjected to fluctuations in seepage flow due to the changes in water storage levels caused by rainfall and agricultural activities. In this study, one-dimensional upward water-passing experiments were conducted with a cylindrical column to investigate the distributions of the fines content and density of soil specimens subjected to seepage flow under a variation in hydraulic gradient of up to 100 cycles. Furthermore, consolidated drained (CD) triaxial compression tests were conducted on specimens sampled at the upper and lower parts of the cylindrical column to evaluate how the strength and dilatancy properties changed due to suffusion. Based on the results of the series of experiments, the process of suffusion and the subsequent changes in strength were discussed in terms of the role and the mode of existence of the fine particles.

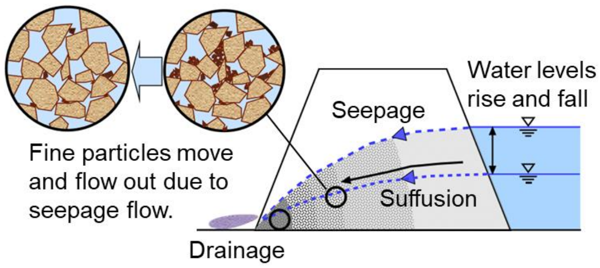

Figure 1. Conceptual diagram of suffusion.

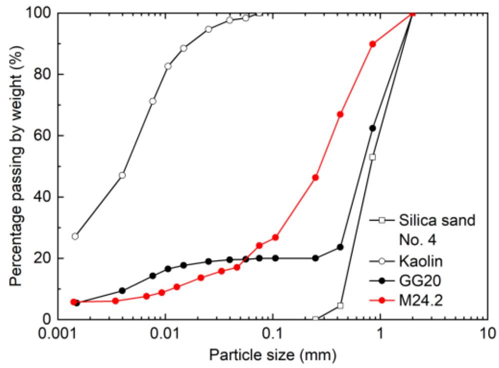

Figure 2. Particle size distributions of soils used in the experiments.

2 EXPERIMENTAL SAMPLES USED IN THIS STUDY

Figure 2 and Table 1 show the particle size distributions and physical properties of the soil samples used in the experiments, respectively. The soil samples were a mixture of silica sand No. 4, with kaolin at 20% by mass (named GG20), and decomposed granite soil collected in Ube City, Yamaguchi Prefecture, Japan (named M24.2). The soil samples were passed through a sieve with an aperture diameter of 2 mm. Soil with a particle size distribution in which the intermediate particle sizes are removed (called "gap-graded soil") and soil with a convex particle size distribution (called "upwardly concave" or "soil with flat tail in finer") are generally prone to suffusion (Foster & Fell, 1999). GG20 corresponds to the former, while M24.2 corresponds to the latter.

Table 1. Physical properties of soils used in the experiments.

Soil code	GG20			M24.2
		Silica sand No. 4	Kaolin	
Fines content F_c %	20.0	0.0	100	24.2
Specific gravity G_s	2.653	2.675	2.646	2.634
Plasticity index I_P	—	NP	24.3	NP
Optimum water content w_{opt} %	13.0	—	—	13.4
Maximum density ρ_{dmax} Mg/m^3	1.860	—	—	1.700

3 OVERVIEW OF EXPERIMENTAL APPARATUS AND EXPERIMENTAL METHOD

Figure 3 presents a schematic diagram of the cylindrical column device used in this study. The soil specimens were all cylindrical with an inner diameter of 100 mm and a height of 200 mm. By keeping the water level in the water supply tank and the water level in the reservoir above the specimen constant through overflow, the hydraulic gradient could be given as the arbitrary difference in water head. The float switch and the solenoid valve were connected to a microcomputer and timer relay to automatically control the water level in the reservoir above the specimen.

A sample in a moist state, whose water content had been adjusted to have an optimum water content ratio, was tamped every five layers to produce each specimen. The soil samples were tamped while controlling the height of each layer to achieve the target degree of compaction. After preparing the specimens, they were passed through carbon dioxide for 1 hour and then permeated with deaired water for 24 hours to sufficiently increase the degree of saturation.

After that, two patterns of upward water-passing experiments were conducted. Pattern C is the case in which the hydraulic gradient was increased in steps, and then the water was allowed to flow at a constant hydraulic gradient for 24 hours. After connecting the specimen to the water supply tank, the tank was raised to initiate the water-passing in an upward direction at a hydraulic gradient of 0.2. After increasing the hydraulic gradient, the flow rate of the overflowing water from the reservoir above the specimen was measured every 5 minutes to confirm that the flow rate remained constant. Then the hydraulic gradient was increased by 0.1. This process was repeated. After the hydraulic gradient reached approximately 0.9 times the critical hydraulic gradient i_c for quicksand, the water-passing was continued for 24 hours, keeping the hydraulic gradient at that level or reducing it to a predetermined value. The hydraulic gradient of $0.9i_c$ may seem large when compared to the average hydraulic gradient of actual embankment structures based on disaster experience. However, the localized hydraulic gradients of the small cracks inside embankments, around pipe breaks and near seepage outlets, may achieve high hydraulic gradients of 1.0 or higher. A case study has been reported to corroborate this. In the case of the Gouhou Dam, which was concluded to have collapsed due to suffusion, an infiltration analysis showed localized hydraulic gradients of up to 1.49 (Zhang & Chen, 2006). After the experiment, the water-passing was stopped and the pore water in the specimen was drained from the bottom at a very slow rate using a peristaltic pump. Two acrylic molds (inner diameter of 50 mm, height of 100 mm, and thickness of 5 mm (tapered at the tip)) were then press-fitted into the center of the specimen and hollowed out into a cylindrical shape with a diameter of 50 mm (Figure 4). The triaxial specimens (50 mm in diameter and 100 mm in height) were sampled at two locations (upper and lower parts) without disturbing the soil structure after suffusion by detaching the connecting portion of the molds. Soil was also sampled from locations other than the area where the mold was press-fitted, and the distributions of the fines content and water content were measured for seven layers in the vertical direction.

Pattern R is the case in which suffusion occurred due to fluctuations in the hydraulic gradient. In the same manner as Pattern C, the hydraulic gradient was increased until it reached $0.9i_c$. Then the hydraulic gradient was varied repeatedly such that the lower and upper limits were 0.4 and $0.9i_c$, respectively. The direction of the water-passing was not changed. The number of cycles was set to five patterns of 10, 30, 50, 80, and 100. After the experiment, triaxial specimens were sampled and their fines content and water content were measured as in Pattern C.

Next, consolidated drained (CD) triaxial compression tests were conducted on the specimens sampled from the water-passing experiments to investigate the mechanical properties of the soil affected by suffusion. After covering each specimen with a rubber sleeve and setting it in the triaxial testing apparatus, the specimen dimensions were measured with calipers. After replacing the air inside the specimen with carbon dioxide gas, deaired water was injected to saturate the specimen. After applying back pressure of 100 kPa, the B value was confirmed to be 0.95 or higher. Consolidation was performed at an effective confining pressure of 50 kPa. After confirming that consolidation was completed, the specimens were sheared under drained conditions until the axial strain reached 15%. The specimens were collected and their dry masses were measured after shearing.

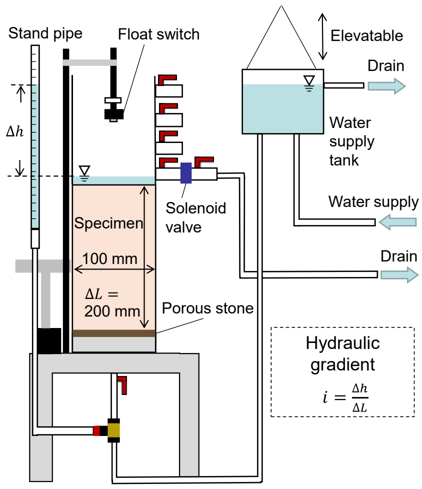

Figure 3. Schematic diagram of cylindrical column device used in this study.

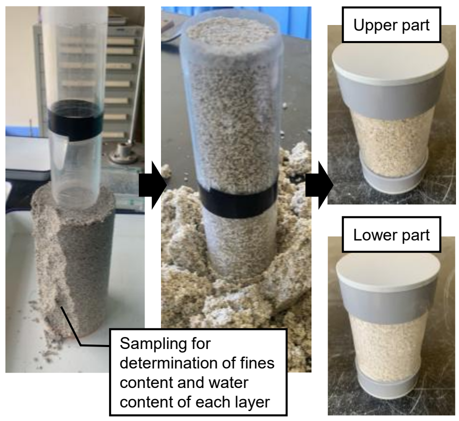

Figure 4. Preparation procedure of triaxial specimen after water-passing experiments.

4 EXPERIMENTAL RESULTS

4.1 *Results of one-dimensional column water-passing experiments*

Figure 5 shows the distribution of fines contents for each layer after the completion of the water-passing experiments. Here, the experiment ID for Pattern C represents [soil sample name - (target compaction) - C - final hydraulic gradient], while the experiment ID for Pattern R represents [soil sample name - (target compaction) – R number of variations]. Figure 5 shows the results of the experimental cases using GG20. In all cases and in all layers, there was a decrease in fines content from an initial fines content of 20%. Suffusion occurred throughout the entire layer, and the difference between the layers with large and small fines contents in the same specimen was about 3% at most. Although there was some variation, the overall fines content decreased as the number of hydraulic gradient variations increased.

Figure 6 shows the results for the experimental cases using M24.2. The fines content was significantly lower with Pattern R than with Pattern C. It was also found that the experimental case with 50 variations in hydraulic gradient had the highest overall decrease in fines content, although the overall variation was large. In the case of GG20, a large quantity of fine particles had already moved and flowed out at the stage of constant hydraulic gradient flow. Only a small quantity of fine particles moved and flowed out due to fluctuations in the hydraulic gradient. On the other hand, M24.2 was found to be a sample that was strongly affected by fluctuations in the hydraulic gradient, since suffusion was unlikely to have occurred due to the water-passing with a constant hydraulic gradient.

4.2 *Results of consolidation drainage (CD) triaxial compression tests*

Figures 7 and 8 show the relationship between the degree of compaction and peak strength for the cases with GG20 and M24.2, respectively. The characters at the beginning of the experimental ID indicate the specimen sampling position (U: upper part, L: lower part). The results are also shown for a specimen prepared by 5-layer compaction in a metal mold for comparison with the case without suffusion (Pattern B). The experiment ID represents [soil sample - target degree of compaction - B]. It is noted that some experimental cases are missing due to an experimental error. The dry density of the triaxial specimens was calculated from the volume of the specimen at the stage when it was set in the testing machine and the dry mass of the specimen measured after the triaxial test was completed. The degree of compaction is considered to reflect the influence of the volume of fine soil particles that flowed out and the volume change due to collapse subsidence and other factors.

In the case of GG20, the data for Patterns C and R were distributed in the upper part compared to Pattern B, where there was no suffusion. When suffusion occurred, the degree of compaction decreased and the peak strength also decreased, but the degree of decrease was smaller than that of Pattern B. Based on the results of Pattern B, it can be said that the strength did not decrease as much as expected from the degree of compaction. On the other hand, the data for M24.2 showed the opposite trend. In the case of M24.2, in some cases, the degree of compaction increased from the initial level due to volumetric shrinkage during the water-passing. In any case, the strength of the compaction was lower than that expected from the degree of compaction when subjected to suffusion.

Figure 9 shows the relationship between the degree of compaction and the dilatancy coefficient at failure. The dilatancy coefficient at failure is the ratio of micro-volumetric strain $d\varepsilon_v$ to micro-axial strain $d\varepsilon_a$ at the onset of peak strength; it is the slope of the tangent line at failure in the axial strain-volumetric strain relationship. The positive and negative values are reversed so that the positive values represent positive dilatancy. The strength of coarse-grained soils is derived from the frictional resistance between the particles and the resistance due to the dilatancy. The higher the dilatancy coefficient, the more the dilatancy contributes to the strength. In the GG20 specimens subjected to suffusion, the dilatancy coefficient at failure did not change much even though the degree of compaction decreased from the initial 90%. The fine particles are thought to have been involved in interlocking between contact points. The main skeletal structure, consisting of coarse particles and fine particles between the contact points, still maintained D_c = 90% of the state even after the outflow of fine particles. Fine particles that moved and flowed out would not have contributed to the skeleton.

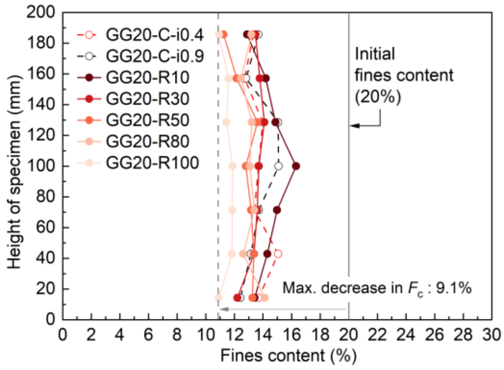

Figure 5. Distributions of fines contents of specimens after water-passing experiments (Case with GG20).

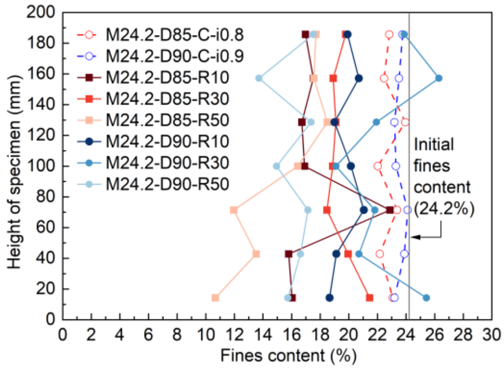

Figure 6. Distributions of fine grain contents of specimens after water-passing experiments (Case with M24.2).

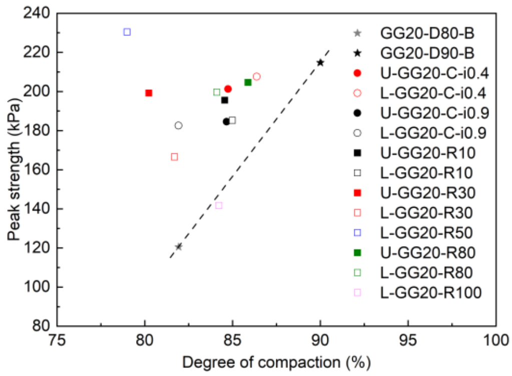

Figure 7. Relationship between degree of compaction and peak strength (Case with GG20).

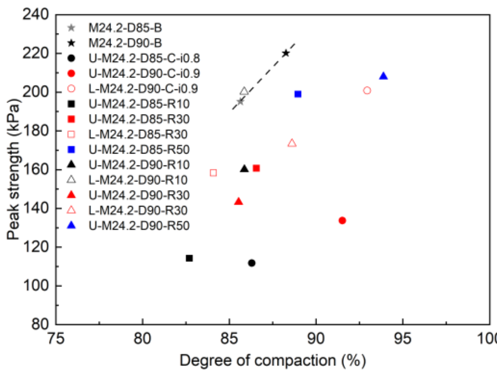

Figure 8. Relationship between degree of compaction and peak strength (Case with M24.2).

On the other hand, the dilatancy coefficient of M24.2 at failure was lower than that of the specimen that was not subjected to suffusion. The decrease in strength of M24.2, with the loss of fine particles and without a change in density, as mentioned above, is a result of the suppression of dilatancy. In other words, the fine soil particles that initially contributed to the main skeletal structure and played a role in the strength development may have migrated or flowed out.

5 DISCUSSION

Based on the results of the one-dimensional column water-passing experiments and the consolidated and drained triaxial tests, the process of suffusion and the subsequent changes in strength were discussed in terms of the role and the mode of existence of the fine particles. Figure 10 shows a conceptual diagram organizing these considerations. Mehdizadeh et al. (2021) proposed the following three types of fine particles in soil depending on the difference in effective stress transfer: active fine particles (Afp), semi-active fine particles (S-Afp), and free fine particles (Ffp). Afp are fine particles that receive stress transfers from the coarse particles and contribute completely to the skeleton of soils. Ffp are fine particles that are suspended and deposited in the voids formed by the coarse particles and are easily moved by permeation forces. S-Afp are in between Afp and Ffp, and can be regarded as fine particles that begin to move with a certain degree of loading (in this study, e.g., fluctuations in hydraulic gradient).

As shown in the results of the one-dimensional column water-passing experiments, in the case of GG20, a large quantity of fine particles moved and flowed out when subjected to a constant hydraulic gradient. When the hydraulic gradient was varied, fine particles did not move or flow out much. In the case of M24.2, fine particles did not move and flow out much during the phase when they were subjected to a constant hydraulic gradient. However, as the hydraulic gradient was varied, more fine particles moved and flowed out. This suggests that the Ffp were more abundant in GG20 than the S-Afp, while the S-Afp were more abundant than the Ffp in M24.2. Assuming that all the fine particles discharged by the constant hydraulic gradient flow were Ffp and that all the fine particles discharged by the fluctuating hydraulic gradient were S-Afp, the ratio of Ffp to S-Afp in the soil was roughly estimated as shown in Figure 11.

The difference between the results of GG20 and M24.2 in the triaxial tests can be attributed to the difference in the proportions of Ffp and S-Afp. GG20 has more Ffp that are not involved in dilatancy and do not lose much strength when Ffp are lost. M24.2 has more S-Afp that are involved in dilatancy and the loss of S-Afp is responsible for the significant decrease in strength. Thus, the effect of suffusion on the strength of the soil varied greatly depending on the role originally played by the eroded soil particles.

6 CONCLUSIONS

The results obtained in this study are as follows.

1. M24.2, which is soil with upwardly concave particle size distribution, is more sensitive to a fluctuated hydraulic gradient than GG20, which is a gap-graded soil.
2. The strength of GG20, which was subjected to suffusion, was greater than that estimated from the degree of compaction. M24.2, which was subjected to suffusion, was smaller than that estimated from the degree of compaction. This difference in results may be attributed to the different effects of suffusion on the dilatancy properties of each sample.

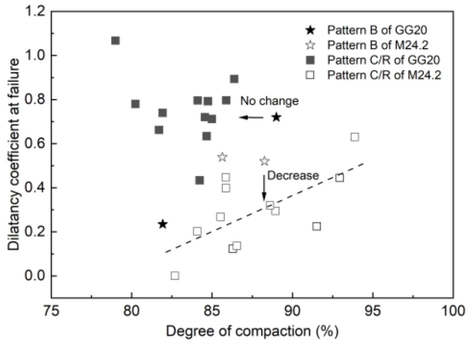

Figure 9. Relationship between degree of compaction and dilatancy coefficient.

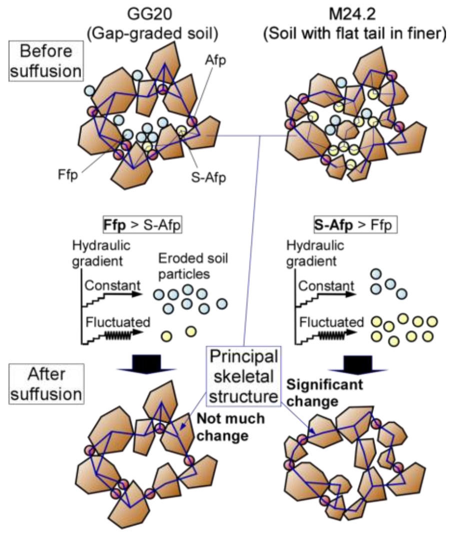

Figure 10. Conceptual diagram of role and mode of existence of fine particles based on the results of the experiments.

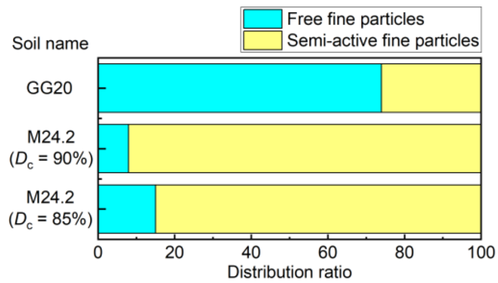

Figure 11. Ratio of Ffp to S-Afp particles in soils estimated from the results of the experiments.

3. The differences in the process of suffusion and its effect on the strength of GG20 and M24.2 could be interpreted in terms of the role and the mode of existence of the fine particles.

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