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공학석사 학위논문

Suffusion Sensitivity of Earth-fill Dam soils in Korea through Seepage Tests

실내 침투 시험을 통한 국내 댐 제체 재료의

suffusion에 대한 안정성 평가

2019년 **8**월

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지도 교수 정 충 기

이 논문을 공학석사 학위논문으로 제출함

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김인현 석사 학위논문을 인준함

2019년 8월

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Abstract

Suffusion Sensitivity of Earth-fill Dam Soils in Korea through Seepage Tests

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In Korea, most of the dams are fill dams, which is made of ground material decomposed from rocks, mostly granite. Such hydraulic earth structures can undergo different kinds of damages and result in several failure modes.

Among these, internal erosion, overtopping and slope instability are the major possible failure modes. From the dam failure cases abroad, it is shown that internal erosion turned out to be the most responsible failure mode that can lead to a dam breach.

Suffusion is the process by which finer soil particles are moved through constrictions between larger soil particles by seepage forces and it is the phenomenon responsible for internal erosion.

If suffusion takes place, the permeability of the soil will change sharply, and this can induce a reduction of the shear strength. It can also lead to clogging by the fine particles in the downstream side of the dam and can develop excessive pore pressure causing slope instability or render the filter less effective in protecting the core materials.

The phenomenon of suffusion has been studied by a number of researchers and

based on the analysis of laboratory suffusion test results they have proposed criteria on grain size distribution to evaluate the internal stability of the soils.
The suffusion test conducted by several researchers, however, are different in terms of the testing methods. Such discrepancies in suffusion test methods lead to the problem of applicability of the existing criteria on dams.
Therefore, the means of applying the criteria in evaluating the internal stability of domestic dams is insufficient, and the surest method is to conduct a laboratory suffusion test together with the consideration of influential factors of the tests.
In this study, the existing criteria for assessing the internal stability of the soils are introduced and applied to 9 different domestic fill dam materials. Suffusion tests are conducted on well-graded silty-sand, which has a representative grain size distribution of earth-fill dams in Korea. Based on the test results, suffusion sensitivity is evaluated. The influential factors are also considered and evaluated.

Key words: Suffusion, Internal erosion, Internal stability. Suffusion test, Fill dam materials, Failure mode, Grain-size distribution

Student Number: 2017-22346

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Chapter 1 Introduction

1.1 General

Hydraulic earth structures, such as levees and dams, can undergo different kinds of damages. Among these, internal erosion, overtopping and slope instability are the major possible failure modes.

The dam failure cases abroad are well summarized in the research of Foster and Fell (2000b) and according to the statistics, 57 of the 126 cases of the dam failure abroad were caused by internal erosion, accounting for 45% of the total number of failures. The two other major failure modes, overtopping and slope instability accounting for 44 and 4% respectively. Hence, internal erosion is one of the two main causes of damage in hydraulic earth structures.

The phenomenon of internal erosion is not limited to a particular point of the dam body, but can be observed in several locations, such as in the embankment itself, in the foundation, from the embankment through foundation and between the base materials in the embankment body and the filter materials.

Suffusion is the process by which finer soil particles are moved through constrictions between larger soil particles by seepage forces (Wan and Fell, 2008) and it is the phenomenon responsible for internal erosion.

Since, suffusion can be associated with other major failure modes, based on the study of Foster (1999), it becomes more clear that the internal erosion is one of the most important factors affecting the overall life expectancy of embankment dams or levees.

The problems associated with the phenomenon of suffusion are as follows:

1) Increase in local permeability of the soil inducing a reduction of shear strength leading to piping (Chang and Zhang, 2013)
2) Generates more voids in the foundation leading to settlement of the crest and cause overtopping
3) Increase in pore pressures and loss of strength in the embankment or foundation leading to a downstream slide (CFGB, 1997)

In Korea, 17,310 out of 17,493 dams are fill dams (National Disaster Management Research Institute, 2013) and they mainly serve as an agricultural purpose. Fill dams in Korea are made of ground materials decomposed from rocks, particularly well-graded silty-sand, thus having broad range of grain size distribution. Korea Rural Community Corporation (KRCC) has reported that only 10 out of 107 cases of dam failure were caused by internal erosion accounting for 9% of the total failures.

Based on the research conducted by Foster and Fell (2000a) and Wan and Fell (2008), dam materials having broad range of grain size distribution are known to be susceptible to suffusion and also shows the highest frequency of internal erosion failure. However, the number of dam failures, caused by internal erosion is relatively small in Korea and this is inconsistent with the investigation results abroad.

The explanation for this contradiction could be at least two fold. First, there is a lack of expertise in internal erosion in Korea. This can be drawn from the fact that except for the filter design and piping criteria, there are insufficient criteria for suffusion in designing fill dam guidelines in Korea.

Second, criteria for internal stability of the soils are based on the experimental investigations, which was conducted mostly on gap-graded soils. Hence, due to the discrepancy in soils used in the tests, the internal stability of domestic fill dams could not be properly evaluated.

Even though, there are some criteria considering the fine fraction of the soils, the soils tested was artificially blended, which is also different from the actual materials used in the domestic fill dams. Additionally, depending on the investigators, experimental program was different in terms of the details, which again lead to the poor evaluation results. Hence the problem of applicability of existing criteria still remains.

Generally, suffusion test is conducted by using 1-axial seepage cell and introducing water across the specimens. Through the suffusion tests, the internal stability of the soils is evaluated. In interpreting the test results, the amount of soil discharged, color of the effluent, hydraulic gradient and flow rate are often assessed.

Based on the analysis of laboratory suffusion test results, criteria on grain size distribution for evaluating the internal stability of the soils have been suggested by many researchers.

Most of the criteria however, may not be applied and evaluate the internal stability of domestic fill dam materials properly due to the aforementioned discrepancies in testing methods in detail, such as soils, relative density, filter system, hydraulic gradient and vibration,

Therefore, in evaluating the internal stability of domestic fill dam materials, the influential factors which affect the results of the suffusion tests should be considered and suffusion test should be conducted on the materials that can represent the fill dam materials in Korea, since suffusion test is the surest method to evaluate the internal stability of soils.

In this study, existing criteria for assessing internal stability have been introduced and the methods are applied to domestic fill dam materials in order to verify its applicability. Also suffusion test has been conducted on well-graded silty-sand, having representative grain size distribution of domestic fill dams. Based on the test results, change in hydraulic conductivity, the amount of soil discharged and post-test grain size distribution were assessed and the suffusion sensitivity on domestic fill dams have been evaluated.

During the suffusion tests, influential factors, such as, soils (fines content), relative density, filter system, hydraulic gradient and vibration, were also considered and evaluated.

1.2 Aim and Scope of the Study

In this study, internal stability of domestic fill dams in Korea were evaluated. Laboratory suffusion tests were conducted on natural well-graded silty sand, which has the representative grain size distribution of the fill dams in Korea, and the suffusion sensitivity was evaluated with the influential factors.

In verifying the applicability of existing criteria for evaluating the internal stability of soils, widely used criteria of Kenny and Lau (1985) and Wan and Fell (2008), have been applied to 30 grain size distributions.

24 out of 30 grain size distributions were obtained from 6 different reservoirs or embankments which have not gone through any internal erosion failures: the Sanchuck reservoir, the Bokgu embankment, the Jiseul reservoir, the Songnae reservoir, Udong reservoir and the Daesong embankment. 6 grain size distributions were obtained from 3 different embankments which have gone through internal erosion failure (4 grain size distribution from the Dasan embankment): the Dasan embankment, the Youei embankment and the Daegok embankment.

Suffusion tests were conducted on Gwanak weathered residual soils (GW soils), which is included in the range of grain size distribution obtained from 9 different fill dams. In evaluating the effect of the fines content in the suffusion tests, GW soils with adjusted fines content of 25 and 10% (AG25 and AG10) were also used as a test specimen.

Influential factors in suffusion test were evaluated by differing the properties of the soils (fines content), relative density, filter system, hydraulic gradient, and applying vibration.

1.2 Outline

Chapter 2. Literature Review

Earlier investigations on internal stability are introduced and discussed. Widely used criteria of Kenny and Lau (1985) and Wan and Fell (2008) are addressed with the experimental program

Chapter 3. Assessment on Internal Stability based on the Existing Criteria

The internal stability of fill dam materials obtained from 9 different fill dams are evaluated based on the existing criteria with the discussion of the results.

Chapter 4. Laboratory suffusion tests

The experimental program in this study are introduced. Properties of the tested soil specimen (GW, AG25 and AG10 soils) are presented and the means of interpreting the suffusion test results are explained.

Chapter 5. Suffusion test results

The results of the suffusion tests considering the influential factors are shown with the results of the amount of soils discharged and variation in hydraulic conductivity. At the end of the chapter the test results are summarized.

Chapter 6. Analysis of the Test Results

The results of the suffusion tests are presented. By interpreting the results, the internal stability of domestic fill dam materials is evaluated with the influential factors.

Chapter 7. Conclusions

A summary of this paper is given with the consideration of the internal stability of the domestic fill dam materials and influential factors. The directions for further study are proposed.

Chapter 2 Literature Review

2.1 Investigations on internal stability

US Army Corps of Engineers (USACE) has firstly used the term ‘inherent stability’ and ‘internal stability’ in order to address the problem of internal erosion that can occur in the drainage system of the dams. In their research, they stated suffusion as a subcategory of internal erosion and defined as a selective erosion of finer particles from the matrix of coarser particles, leaving behind a soil skeleton formed by the coarser particles.

The problems caused by suffusion, are well described in the study of early researchers. According to the study of Chang and Zhang (2013), if suffusion takes place the permeability of the soil will increase locally and this could induce a reduction of shear strength leading to piping.

Moreover, the occurrence of suffusion can be associated with other major dam failure modes, such as piping, crest overtopping and slope instability.

Dam failures that are associated to suffusion are described in the study of Foster (1999). According to its study the dam failure can be described in four stages and the phenomenon of suffusion can be regarded as an initiation stage that can lead to another dam breach (figure 2.1).

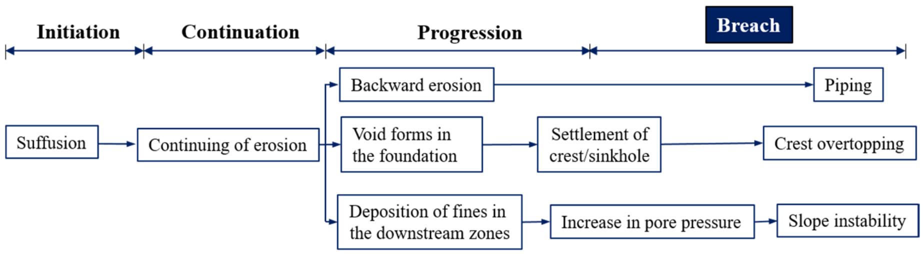

Figure 2. 1 Suffusion associated dam breaches (adapted from Foster, 1999)

If continuous erosion takes place due to the phenomenon of suffusion, it can cause backward erosion, formation of voids in the foundation and clogging of the fines in the downstream zones. Eventually, this progression can lead to dam breaches such as piping, crest overtopping due to the settlement of the crest or sinkhole and slope instability due to the increase in pore pressure in the downstream side of the dam. Therefore, the phenomenon of suffusion can be regarded as one of the most important factors affecting the overall life expectancy of embankment dams.

In order to evaluate whether the dam or levee is susceptible to suffusion, the phenomenon of suffusion has been studied by several researchers based on the laboratory suffusion tests. (Kenny and Lau, 1985; Sun, 1989; Burenkova, 1993; Skempton and Brogan, 1994; Wan and Fell, 2004; Fernanda and Spitia, 2017).

Since the occurrence of suffusion is often difficult to observe and may take considerable time to observe in the field, most of the studies are based on the analysis of grain size distribution according to the laboratory suffusion tests.

Based on the test results, they have proposed criteria to evaluate the internal stability of soils.

Generally, suffusion test is conducted by using 1-axial seepage cell and introducing water across the specimens. In interpreting the test results, the amount of soils discharged, color of the effluent, and measured hydraulic gradient and flow rate are often considered.

It should be noted that the suffusion tests conducted by each of the researchers are different in details, such as soils used in the test, relative density of the soils, filter system, flow direction, hydraulic gradient and the presence of vibration. The details of the suffusion tests conducted by the previous researchers are summarized (table 2.2) and will be discussed later.

Among the differences in detail, soil types and properties plays the most important role in evaluating the suffusion sensitivity. The soil used in the previous suffusion tests were mostly narrowly graded soils (USACE, 1953; Kenny and Lau, 1985; Skempton and Brogan, 1994; Fernanda and Spitia 2017), such as clay-sand to sand-gravel mixtures, which are well-known to be vulnerable to suffusion.

Narrowly graded soils have been frequently used in the suffusion tests, because the laboratory suffusion test is less time-consuming and the phenomenon of suffusion itself can be clearly detected.

Soils with a relatively broad range of grain size distribution, such as silt-sand-gravel to clay-silt-sand gravel, are rarely used in the suffusion tests (Sun, 1989; Burenkova, 1993; Wan and Fell, 2008). For these tests, soils corresponding to each particle size distribution were artificially blended to reach the desired range of grain size distribution.

In this chapter, the research on suffusion conducted by Kenny and Lau (1985) and Wan and Fell (2008) will be introduced. Their methods have been widely used in several organizations and guidelines to determine if the soil is sensitive to suffusion. Although the suffusion tests performed by Kenny and Lau (1985) were conducted only on sandy-gravel mixtures, the criteria appear to be frequently adopted, due to their application convenience and their conservative internal stability assessment results. The criteria suggested by each of the researchers are applied to domestic fill dam materials and discussed in the later chapter.

2.1.1 Kenny and Lau (1985)

Kenny and Lau (1985) used the concept of constriction size which serve as a window for movable fine particles. It is suggested that the size of the predominant constrictions in a void network of a filter is approximately equal to one quarter the size of the small particles making up the filter. Therefore, the particle of size D (at any given particle size), can migrate when the filter is consisting of materials of size 4D and larger. On the contrary, when the filter is consisting of materials of size between D-4D, due to its relatively smaller constriction size, the particle of size D, will not be able to migrate though there are sufficient seepage force.

This theory can be expressed in $\mathrm{H/F}$ shape curve, in which H stands for mass fraction of particles between sizes D and 4D, and F stands for the mass fraction smaller than D. Figure 2.3 shows the example of $\mathrm{H/F}$ shape curve for a random grain size distribution.

Based on the $\mathrm{H/F}$ shape curve, conditions related to the migration of soil particles can be expressed. When, $(\mathrm{H/F})_{min}$ is larger than 1.0, since there are enough materials of size D-4D, the migrations of particles of size D, are limited and can be evaluated as stable gradings.

If $(\mathrm{H/F})_{min}$ is smaller than 1.0, particles finer than grain size D would likely to be eroded since there are deficiency in the number of particles in the size range D-4D. Thus the soils corresponding to this condition can be evaluated as unstable grading.

This theory was verified based on the laboratory suffusion tests. And the experimental program was followed after the experiments held in the study of USACE (1953).

Initially, 16 sandy-gravel mixtures with different grain size distributions were used in the suffusion tests. The soil specimens were compacted in a seepage cells of either 245 mm or 580 mm diameters. The thickness of compacted soil specimen was 580 mm for the smaller seepage cell, and 860 mm for the larger seepage cell. Information about the relative density was roughly described for only a few specimens and it has not been further considered in evaluating the internal stability of soils.

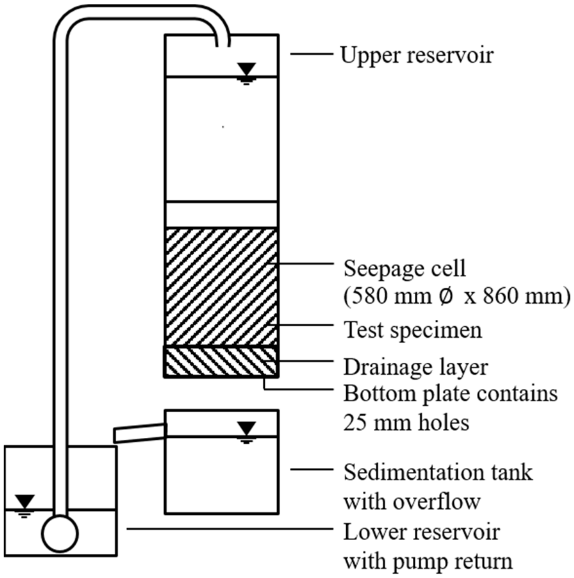

Figure 2. 2 Suffusion test apparatus based on the study of Kenny and Lau (1985)

For the filter, from which the soils are discharged, a perforated bottom plate with 25-mm-diameter holes was used (figure 2.2). This is to duplicate the constrictions formed by the filter materials.

Water was introduced downward, and the concept of unit flux, discharge per unit area, was used instead of the hydraulic gradient. The maximum unit flux varied from 0.37 to 1.67 cm/s, which corresponds to the hydraulic gradient of approximately 5-60 (Hans Rönnqvist and Peter Viklander, 2014).

During the experiment, the soils were vibrated manually using a rubber hammer for effective particle movement. Based on the authors' experience, the application of vibration in the laboratory suffusion test shortens the experiment time, but at the same time leads to a conservative assessment result, since the vibrational force accelerates the migration of the soil particles.

In determining whether the soil is internally stable or unstable, post-test grain size distribution analysis was conducted. It is believed that the loss of fines from throughout the specimens, due to the suffusion process, results in the development of different grain size distribution across the specimens. The tested specimens were divided into several layers and sieve analysis was conducted. Through a comparison of the initial and the post-test gradings, the internal stability of the soil was determined and by extending the post-test gradings to match the initial gradings, the amount of loss of fines was estimated.

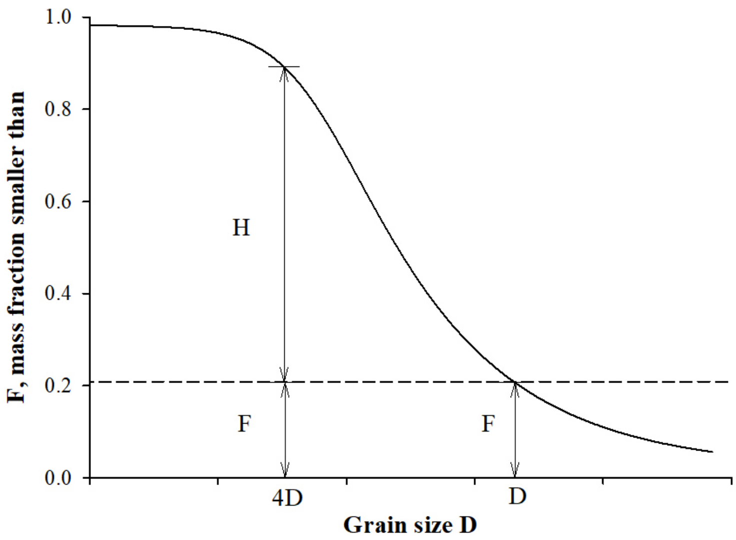

Figure 2. 3 H/F curve criteria proposed by Kenny and Lau (1985)

In analyzing the results, Kenny and Lau (1985) proposed the proportion of a shape curve that is relevant to the boundary line of F, the portion of the loose particles. For widely graded soils, the maximum range for loose particles is F = 0-0.2, and soils with narrowly graded grain size distribution, the maximum range for loose particles is F = 0-0.3.

The H/F shape curve (figure 2.3) was applied upon the 16 tested soil specimens and based on the test results, it was concluded that the boundary for internal stability corresponds to H=1.3F and later it has been revised as H=1.0F (Kenny and Lau, 1986).

2.1.2 Wan and Fell (2008)

In the research of Wan and Fell (2008), suffusion tests were conducted on 20 different samples and the internal stability of the soils were evaluated based on the methods of Sharard (1979), Kenny and Lau (1985), and Burenkova (1993).

Based on the evaluation results, Wan and Fell (2008) stated that the method of Sherard (1979) and Kenny and Lau (1985), shows conservative results, that most of the samples are predicted as internally unstable. And the Burenkova (1993) method describes better predictions but not so accurate.

Due to the poor predictions of existing criteria for evaluating the internal stability of the soils, Wan and Fell (2008) used statistical methods, varying the combination of particles size parameters, and compaction density. And in order to enlarge the volume of the data-set, other laboratory test data have been included in their work.

Based on the modifications on the method of Burenkova (1993), the boundaries of the equal probability of the suffusion test results were obtained through logistic regression. In the Burenkova (1993) method, d90/d60 and d90/d15 ratios were used. The d90/d60 ratio represents the slope of the coarser part of the grain size distribution, and higher value represents single size coarse materials, forming larger constrictions. The d90/d15 ratio describes the filter action between the coarser and finer particles.

Later through experience in using modified Burenkova (1993) method, alternative method for evaluating the internal stability of the soils was suggested. Based on trial and error, the grain size distribution with a steep slope on the coarse part and a flat slope on the fine part are likely to be internally stable. Therefore, the ratios of d90/d60 and d20/d5 were considered, and the likelihood of internal instability was described using two boundaries generating three zones, stable zone, transition zone and unstable zone (figure 2.4).

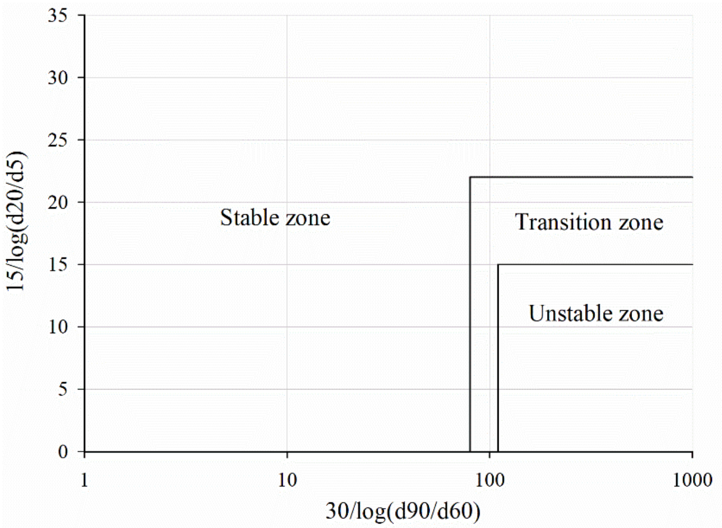

Figure 2. 4 Criteria for internal stability of the soils based on the modified coefficient of uniformity (Wan and Fell, 2008)

In the experimental program, suffusion tests conducted on 20 soil specimens are introduced to describe its distinctiveness and features. The specimens were formed by blending the soils with a particular grain size (clay-silt-sand-gravel) to reach the desired grain size distribution.

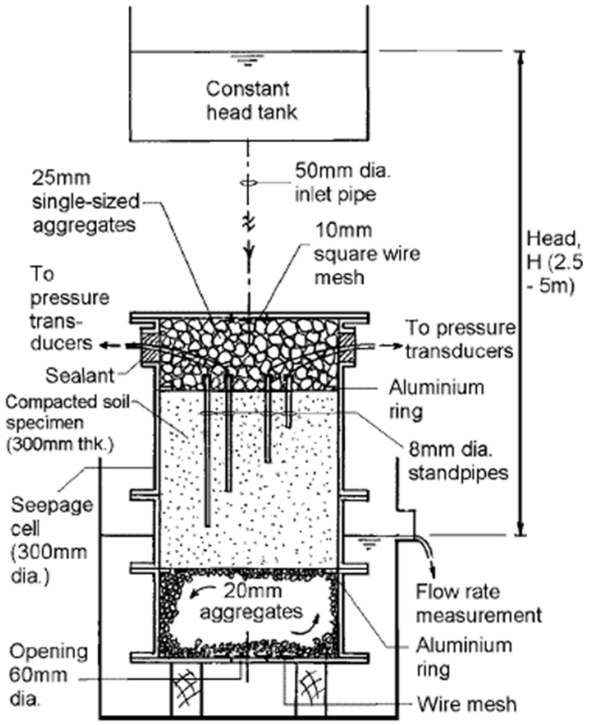

Figure 2. 5 Suffusion test apparatus used in the study of Wan and Fell (2008)

The term, relative compaction, was used instead of, relative density, and the soil samples were compacted in two different compaction densities: 90 and 95%, in a seepage cell with diameter size of 300 mm. The thickness of compacted soil specimens was 300 mm.

As shown in figure 2.5, drainage layer was installed at the bottom of the seepage cell with 20-mm-aggregates, which served as a filter material corresponding to the constriction size of 2-5 mm. At the same time, a bottom plate with a 60 mm opening was installed, to hold the aggregates in the right position.

Both the downward and upward water flow tests were conducted to investigate the internal stability of the soils and to determine the hydraulic gradient, at which the internal erosion of the fines content is initiated. During the experiment, the hydraulic gradient was maintained at 8 by using the constant head water supply tank and no additional stresses were applied to accelerate the soil discharge, such as vibration.

In analyzing the results, the hydraulic gradient, flow rate and color of the flow were measured and described. Post-test grain size distribution analysis was also conducted upon the completion of the tests.

As preferential water flow was generated across the piezometer tube, especially for the downward water flow test, the piezometer readings were not considered in the results. The flow rate was measured at regular time intervals and the color of the effluent was described rather than directly obtaining the mass of discharged soil. Similar to the study of Kenny and Lau (1985), post-test grain size distribution analysis was carried out on the tested specimens at different depths, to evaluate the effect of suffusion.

The criteria to evaluate the internal stability of the soils are summarized in table 2.1, including the ones suggested by several researchers. The features of previous suffusion tests, such as materials, relative density, filter, flow direction, hydraulic gradient and the presence of vibration, are summarized in table 2.2.

Table 2. 1 Existing criteria for suffusion

Reference	Criteria*
Istomina (1957)	$C_u \leq 10$: internally stable $10 \leq C_u \leq 20$: transitional $C_u \geq 20$: internally unstable
Kezdi (1969)	$(d_{15c}/d_{85f})_{max} \leq 4$: internally stable d_{15c} : diameter of the 15% mass passing in the coarse part d_{85f} : diameter of the 85% mass passing in the fine part
Kenny & Lau (1985)	$(H/F)_{min} \geq 1.0$: internally stable H : mass fraction between grain size D and 4D F : mass fraction at a grain size D
Burenkova (1993)	$0.76\log(d_{90}/d_{15}) + 1 < \frac{d_{90}}{d_{60}} < 1.68\log(d_{90}/d_{15}) + 1$: internally stable
Wan & Fell (2008)	$30/\log(d_{90}/d_{60}) < 80$ or $30/\log(d_{90}/d_{60}) < 80$ and $15/\log(d_{20}/d_5) > 22$: Internally stable

*C_u : Coefficient of uniformity; d_{90}, d_{60}, d_{20}, d_{15} and d_5= particle diameter at 90, 60, 20, 15 and 5% passing, respectively

Table 2. 2 Features of suffusion tests conducted by previous researchers

Reference	Materials	Relative density, (%)	Filter	Flow direction****	Hydraulic gradient	Vibration
USACE (1953)	Sand-gravel	Not mentioned	Perforated bottom plate	D	0.5-28	Vibration
Kenny and Lau (1985)	Sand-gravel	80%	Perforated bottom plate	D	5-60	Tapping
Sun (1989)	Clay-silt-sand	Not mentioned	Cap**	U	1-20	No
Burenkova (1993)	Silt-sand-gravel	Not mentioned	N/A***	D/U	<2.5	No
Skempton and Brogan (1994)	Sand-gravel	Not mentioned	Open system	U	0-1	No
Wan and Fell (2008)	Silt-sand-gravel	90, 95%(RC)*	20mm- aggregates	D/U	8	No
Fernanda and Spitia (2017)	Clay-sand	40-50, 90%	Perforated bottom plate	D	25-220	No

*(RC)= Relative compaction
**Cap= Both end of the seepage cell is closed with caps and inflow and outflow line are attached
*** N/A=Not available
****D=Downward water flow; U=Upward water flow

Chapter 3 Assessment on Internal Stability based on the Existing Criteria

3.1 Introduction

Criteria for evaluating the internal stability of soils have been suggested by several researchers, based on the laboratory suffusion test results. As shown in table 2.2, suffusion tests held by previous researchers are different in terms of the details it can lead to inconsistent evaluation results.

In this chapter, the widely used criteria of Kenny and Lau (1985) and Wan and Fell (2008) are applied to 30 grain size distributions obtained from 9 different dams and levees in Korea, in order to verify the applicability of existing criteria for evaluating the internal stability of fill dam materials.

3.2 Assessment results

Assessed grain size distributions are consisting of dams and levees (24 grain size distributions from 6 different hydraulic-earth structures) which is in operation, obtained from Korea Rural Community Corporation and embankments (six grain size distributions from three different embankments) which have gone through internal erosion dam failures obtained from the study of Kwon et al (2006).

Information about each grain size distributions including fines content, d10, d60, coefficient of uniformity is shown and summarized in figure 3.1 and table 3.1. Figure 3.2 shows the internal stability of domestic fill materials based on the method of Kenny and Lau (1985) and figure 3.3 shows the results based on the method of Wan and Fell (2008). The evaluation results are also summarized in table 3.1.

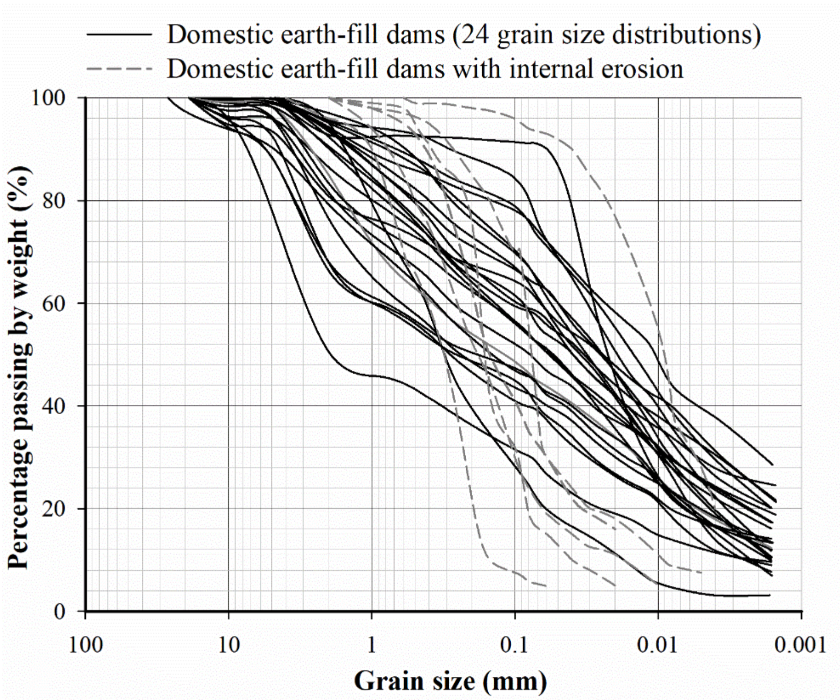

Figure 3. 1 Grain size distribution curves of domestic fill dam materials obtained from 9 different dams

Table 3. 1 Properties of fill dam materials obtained from domestic fill dams with the internal stability of the soils

Sanchuck reservoir						
Section	Percentage passing sieve no. 200 (%)	d_{10}(mm)	d_{60}(mm)	Coefficient of uniformity, (C_u)	Internal stability*	
					Kenny and Lau	Wan and Fell
BH-1 (3.0-3.8)	58.8	0.000622	0.0936	150	U	S
BH-1 (4.0-4.8)	58.2	0.000709	0.1099	155	U	S
BH-2 (4.0-4.8)	64.1	0.000699	0.0510	72	U	S
BH-2 (5.0-5.8)	49.5	0.000807	0.2722	337	U	S

Bokgu embankment						
Section	Percentage passing sieve no. 200 (%)	d_{10}(mm)	d_{60}(mm)	Coefficient of uniformity, (C_u)	Internal stability	
					Kenny and Lau	Wan and Fell
BH-1 (1.5-2.5)	39.6	0.002053	0.9186	447	U	S
BH-1 fill-up (1.5-2.5)	29.8	0.002607	3.0087	1154	U	S
BH-2 (1.5-2.5)	41.2	0.001343	0.9557	712	U	S
BH-2 fill-up (1.5-2.5)	78.3	0.000807	0.0322	40	U	S

Jiseul reservoir						
Section	Percentage passing sieve no. 200 (%)	d_{10}(mm)	d_{60}(mm)	Coefficient of uniformity, (C_u)	Internal stability	
					Kenny and Lau	Wan and Fell
BH-1 (10.0-11.0)	62.7	0.001535	0.067062	44	U	S
BH-1 (15.0-16.0)	23.2	0.017881	0.420758	24	U	S
BH-2 (11.0-12.0)	53.0	0.002473	0.160000	65	U	S
BH-2 (15.0-16.0)	65.9	0.002506	0.058387	23	S	S

Songnae reservoir						
Section	Percentage passing sieve no. 200 (%)	d_{10}(mm)	d_{60}(mm)	Coefficient of uniformity, (C_u)	Internal stability	
					Kenny and Lau	Wan and Fell
BH-1 (5.0-6.0)	61.7	0.001379	0.066175	48	S	S
BH-1 (6.0-7.0)	45.6	0.001310	0.381250	291	U	S
BH-2 (5.0-6.0)	57.2	0.001589	0.092714	58	S	S
BH-2 (6.0-7.0)	45.1	0.001166	0.817309	701	U	S

Udong reservoir						
Section	Percentage passing sieve no. 200 (%)	d_{10}(mm)	d_{60}(mm)	Coefficient of uniformity, (C_u)	Internal stability	
					Kenny and Lau	Wan and Fell
BH-1 (4.0-5.0)	45.4	0.001156	0.366667	317	U	S
BH-1 (5.0-6.0)	66.0	0.000942	0.050289	53	U	S
BH-2 (4.0-5.0)	74.5	0.000811	0.026869	33	U	S
BH-2 (5.0-6.0)	53.0	0.001009	0.149500	148	U	S

Daesong embankment						
Section	Percentage passing sieve no. 200 (%)	d_{10}(mm)	d_{60}(mm)	Coefficient of uniformity, (C_u)	Internal stability	
					Kenny and Lau	Wan and Fell
BH-1 fill-up (1.0-2.0)	42.0	0.001830	0.646739	353	U	S
BH-1 fill-up (1.0-2.0)	53.2	0.000920	0.165178	180	U	S
BH-2 (1.0-2.0)	75.3	0.000558	0.023817	43	U	S
BH-2 (2.0-3.0)	91.3	0.001195	0.028408	24	U	U

Dasan embankment						
Section	Percentage passing sieve no. 200 (%)	d_{10}(mm)	d_{60}(mm)	Coefficient of uniformity, (C_u)	Internal stability	
					Kenny and Lau	Wan and Fell
BH-1	5.2	0.150	0.433333	3	S	S
BH-2	22.5	0.015	0.255556	17	S	S
BH-3	17.5	0.040	0.176471	4	S	S
BH-4	93.8	0.002	0.012273	6	S	S

Youei embankment						
Section	Percentage passing sieve no. 200 (%)	d_{10}(mm)	d_{60}(mm)	Coefficient of uniformity, (C_u)	Internal stability	
					Kenny and Lau	Wan and Fell
BH-1	50	0.009091	0.084286	9	S	S

Daegok embankment						
Section	Percentage passing sieve no. 200 (%)	d_{10}(mm)	d_{60}(mm)	Coefficient of uniformity, (C_u)	Internal stability	
					Kenny and Lau	Wan and Fell
BH-1	32.5	0.012501	0.19	15	S	M

*S=stable; M=marginal; U=unstable

The evaluation results based on the method of Kenny and Lau (1985), shows that among the 24 grain size distribution curves obtained from 6 different dams that are still in operation, only 3 grain size distribution curves turned out to be stable. All grain size distribution curves obtained from embankments which went through an internal erosion failure turned out to be stable. It should be noted that the range of the x-axis is limited to 0.20, since the maximum range, suggested by Kenny and Lau (1985), of loose particles for widely graded soils corresponds to 0.20.

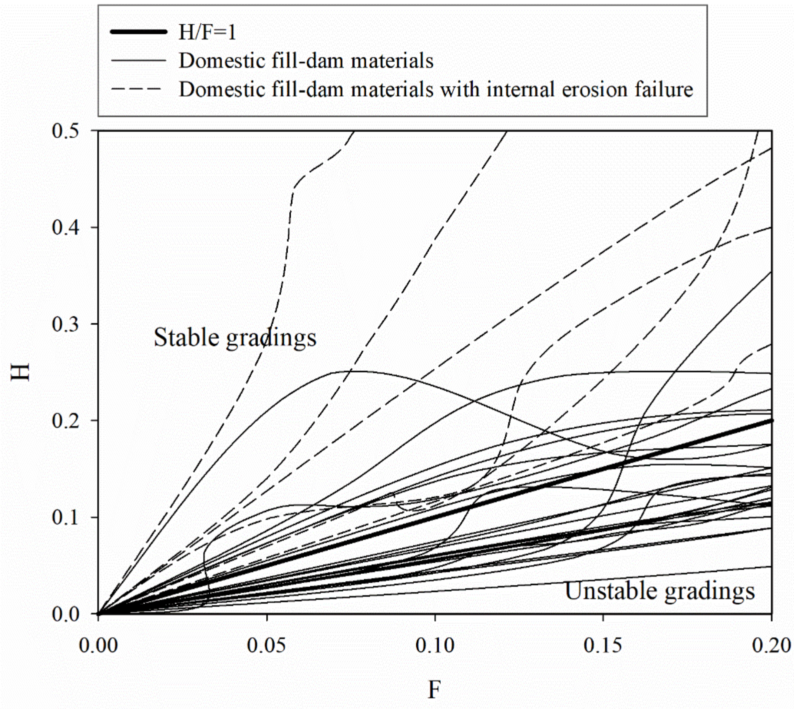

Figure 3. 2 Evaluation on internal stability of domestic fill dam materials based on the method of Kenny and Lau (1985)

The evaluation results based on the method of Wan and Fell (2008) shows that among the 24 grain size distribution curves obtained from 6 different dams still in operation, 23 grain distribution curves turned out to be stable (figure 3.3). For the embankments which went through an internal erosion failure, all of the grain size distribution curves were evaluated as internal stable or marginal.

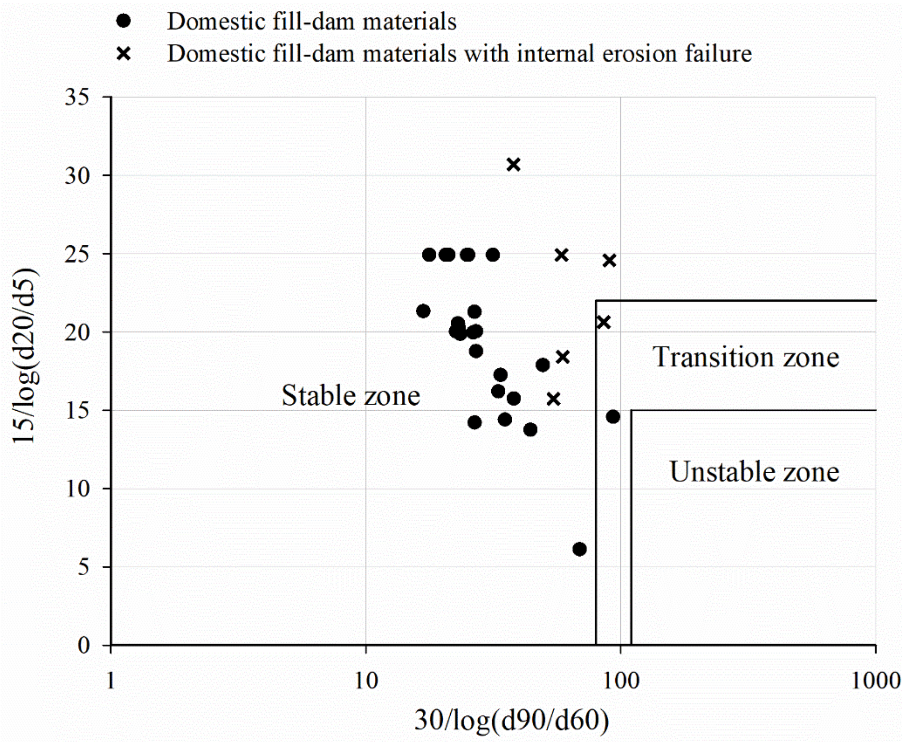

Figure 3. 3 Evaluation on internal stability of domestic fill dam materials based on the method of Wan and Fell (2008)

Just like the assessment results shown in the study of Wan and Fell (2008), Kenny and Lau (1985) method seems to show conservative and inaccurate results in terms of internal stability of domestic fill dam materials since, the dams and embankment that are still in operation turned out to be unstable. On the contrary, the embankments which went through an internal erosion failure turned out to be stable.

The method of Wan and Fell (2008), shows better predictions for the dams and embankments that are still in operation, but still inaccurate in terms of the embankments with internal erosion failure, since they are evaluated as internally stable. Hence, Wan and Fell (2008) method shows unsafe assessment results but coincides well with the current statistics of the domestic dams.

3.3 Summary and Discussion

Widely used criteria in evaluating the internal stability of the soils have been applied to grain size distribution curves obtained from domestic fill dams.

Kenny and Lau (1985) method showed conservative assessment results for the dams and embankments that are still in operation and inaccurate results for the embankments with internal erosion failure.

Wan and Fell (2008) method shows better predictions but, still shows inaccurate evaluation results for the embankments which went through internal erosion failure.

Two widely used methods show inconsistent assessment results on the internal stability of domestic fill dam materials, and it may have been affected by the different features of experimental program since, the criteria are based on the laboratory suffusion tests.

In the experimental program of Kenny and Lau (1985), tested soil specimens are consisting of sand and gravel mixtures only, which are known to be vulnerable to suffusion. Moreover, during the experiments, vibration was applied using the rubber hammer in order to accelerate the movements of the loose soil particles. This is an extreme environment, exposed to internal erosion which may unlikely occur in the field.

In the suffusion tests conducted by Wan and Fell (2008), soils with broad grain size distribution are used, but the specimens were artificially made from clay (kaolin), silt(silica), fine to medium sand (Nepean Sand), coarse sand (5 mm Blue Metal), fine gravel (10 mm Basalt and 20 mm Blue Metal), and coarse gravel (25 to 75 mm Pukaki).

And when establishing the criteria for internal stability, in order to enlarge the data-set, the suffusion test results conducted by other researchers, mostly conducted on gap-graded soil specimens, are considered. Therefore, still the criteria seem to show problems with its applicability to domestic fill dam materials.

Thus, the surest method to determine whether the soil is susceptible to suffusion is to conduct a suffusion test. In the next chapter, suffusion tests are conducted on Gwanak soils (GW soils), which has the representative grain size distribution curve of fill dam materials in Korea.

The influence factors that can affect the assessment results of the laboratory suffusion test, are evaluated by varying the properties of soils and experimental conditions.

Chapter 4 Laboratory Suffusion Tests

4.1 Introduction

The phenomenon of suffusion has been studied by several researchers, and the criteria to evaluate the internal stability of the soils are suggested based on the suffusion tests and through an analysis of the grain size distribution.

However, the details of the suffusion tests held by other researchers are different, since, there are no specific guidelines for the laboratory suffusion tests. The discrepancies in the testing procedure can give significant influence in the test results, hence the criteria for determining the internal stability of the soils, have problem with its applicability.

Therefore, in this chapter, suffusion test is conducted on Gwanak soils (GW soils), which has the representative grain size distribution of domestic fill dam materials. In order to evaluate the factors that can affect the result of the suffusion tests, test conditions are differed as shown in the experimental program summarized in table 4.1.

Table 4. 1 Summary of the laboratory suffusion experiments

Test	D_r(%)	Constriction Size (mm)	Hydraulic Gradient, (i)	Vibration
Glass beads test A	49, 77	3-7	2-3-5-9	Yes
Perforated bottom plate test		4		
Glass beads test B	49, 61, 77	2-4		
Adjusted Gwanak soil test (25%)*				
Adjusted Gwanak soil test (10%)				

* ( )= fraction of the fines content by weight passing sieve #200.

4.2 Gwanak weathered residual soils (GW soils)

Gwanak weathered residual soils (GW soils), sampled at the Mt. Gwanak area in Seoul, South Korea was used for the soil specimen. Also in order to consider the influence of fines content (finer than sieve no. 200) towards the internal stability of the soils, the GW soils with adjusted fine fraction of 25 and 10% (AG25 and AG10 soils) was used for an adjusted Gwanak soil tests (AG25 and AG10 tests).

Initial GW soil is classified as well-graded silty sand (SM) of about 40% fines content. The particle size larger than that of sieve no. 4 was eliminated.

The index properties of GW, AG25 and AG10 soils are summarized in table 4.2.

Table 4. 2 Index properties of GW, AG25 and AG10 soil

Specimen	GW soils	AG25 soils	AG10 soils
USCS		SW-SM	
Soil passing sieve #200 (%)	40	25	10
Grain diameter at 85% passing (mm)	25	27	30
Specific gravity (G_s)	2.59	2.65	2.63
Maximum dry unit weight (g/cm3)	1.87	1.86	1.84
Optimum water content (%)	12.7	12.5	11.5
Uniformity coefficient (C_u)	115	100	20

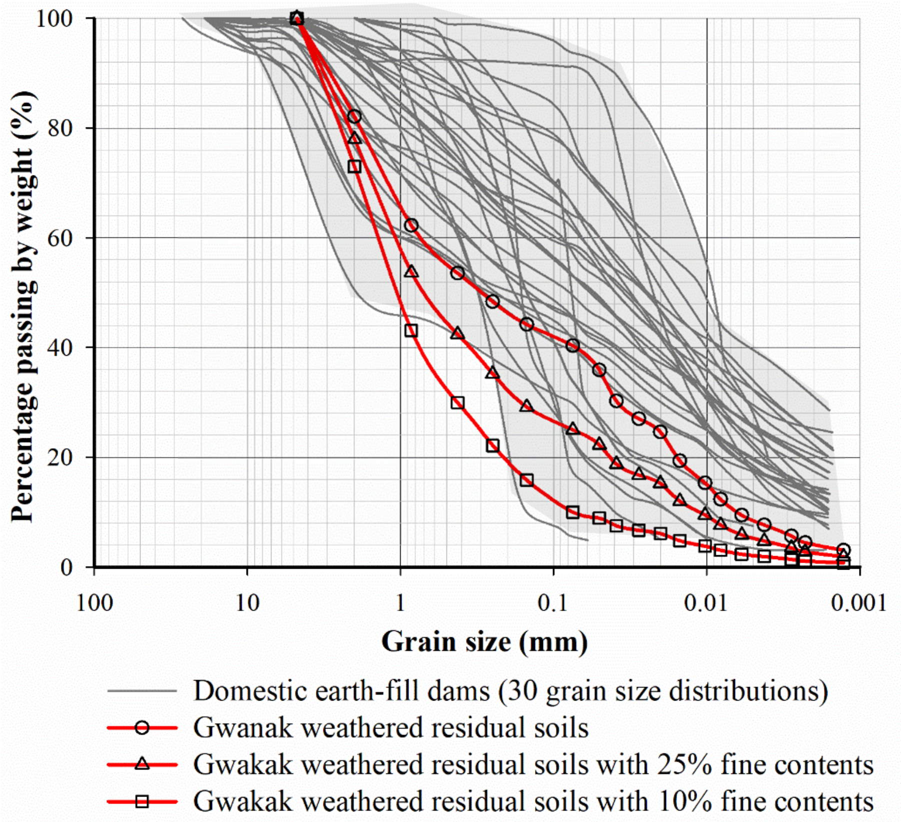

Figure 4. 1 Grain size distribution of domestic fill dam materials, GW and AG soils

It can be seen in figure 4.1 that the grain size distribution of GW soils is included in the range of grain size distribution (shaded are in figure 4.1) obtained from 9 different domestic fill dams (24 grain size distributions from 6 fill dams in operation and 6 grain size distributions from 3 fill dams which went through internal erosion failure). The grain size distribution of AG soils with 25% of fines content corresponds to the lower limit in terms of the fine fraction for the aforementioned range.

In case of the AG soils with 10% of the fines content, the grain size distribution curve of the soils does not exactly belong to the range of the grain size distribution curve of domestic fill dam materials. Although the AG10 soils is different from the materials that are actually used in domestic fill dams, the purpose of the experiment is to thoroughly evaluate the effect of fine fraction in suffusion test.

In chapter 3, the internal stability of domestic fill dam materials are assessed based on the widely used criteria of Kenny and Lau (1985) and Wan and Fell (2008). In the same vein, the internal stability of GW and AG soils are evaluated based on the laboratory suffusion tests and comparisons are made with the assessment results.

The assessment results based on the method of Kenny and Lau (1985), evaluated both the GW and AG soils as internally unstable (figure 4.2). On the contrary, the method of Wan and Fell (2008), evaluated both the soils as internally stable (figure 4.3).

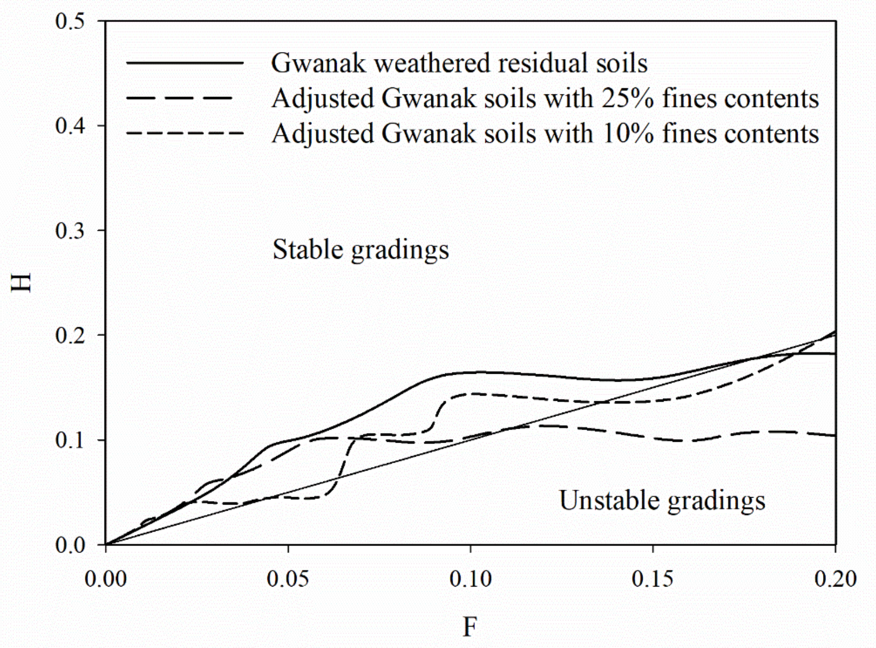

Figure 4. 2 Internal stability of the GW, AG25 and AG10 soils based on the method of Kenny and Lau (1985)

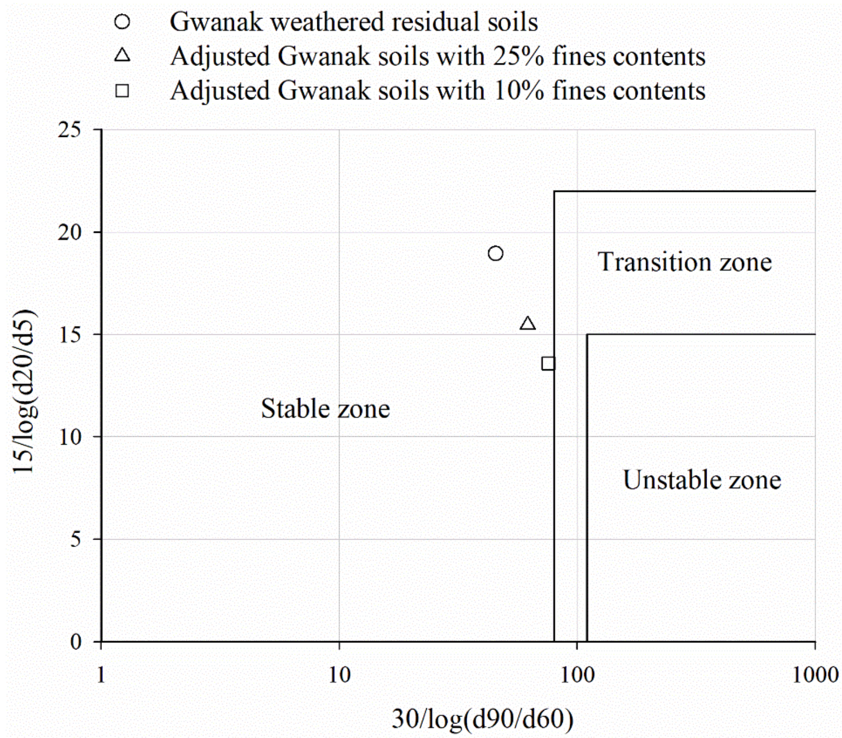

Figure 4. 3 Internal stability of the GW, AG25 and AG10 soils based on the method of Wan and Fell (2008)

The assessment results show consistent trend in internal stability than that of the grain size distribution curve obtained from domestic fill dams. Hence, conducting suffusion test on GW and AG soils can provide representative results for domestic fill dam materials. This assessment results will be compared in chapter 5, with the laboratory suffusion test results.

For the suffusion tests, the relative densities of the soil specimens were predetermined to be 49, 61 and 77%. The relative densities corresponding to the loose, intermediate and dense states were considered to evaluate the effect of the relative density on the internal stability of the soil specimens. The relative density in the dense state was determined according to the fill dam design guidelines in Korea.

4.3 Experiments

4.3.1 Apparatus

The suffusion test apparatus (figure 4.4 and 4.5) consists of an acrylic cylinder seepage cell with a 100 mm internal diameter and 250 mm height containing the soil sample to be tested. The seepage cell is placed over four horizontal beams to place the cell in the right position and to provide space for measuring the mass of discharged soil and water.

Figure 4. 4 Suffusion test apparatus

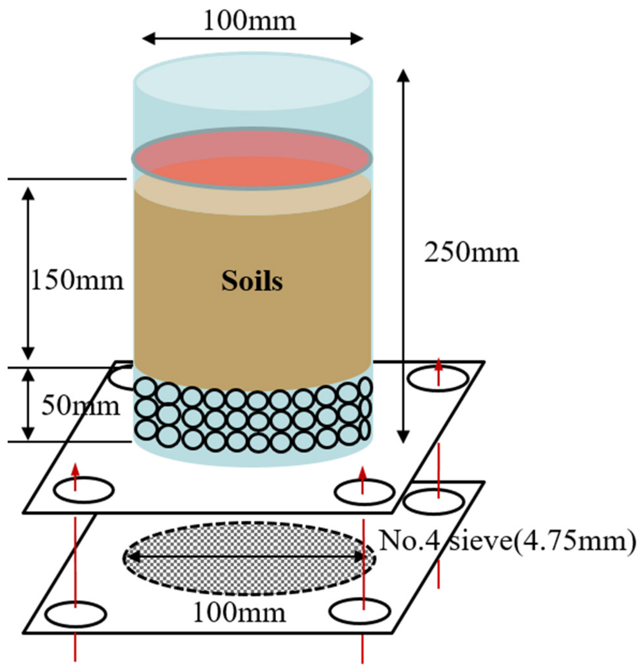

Figure 4. 5 Schematic diagram of suffusion test apparatus with glass beads

Water is supplied through the connection between the overflow constant head tank and the seepage cell. Variation in hydraulic gradient can be obtained by raising the level of the constant head tank.

For the filter, which serves as a material that provides constriction for movable fine materials, three different cases have been adopted (figure 4.6).

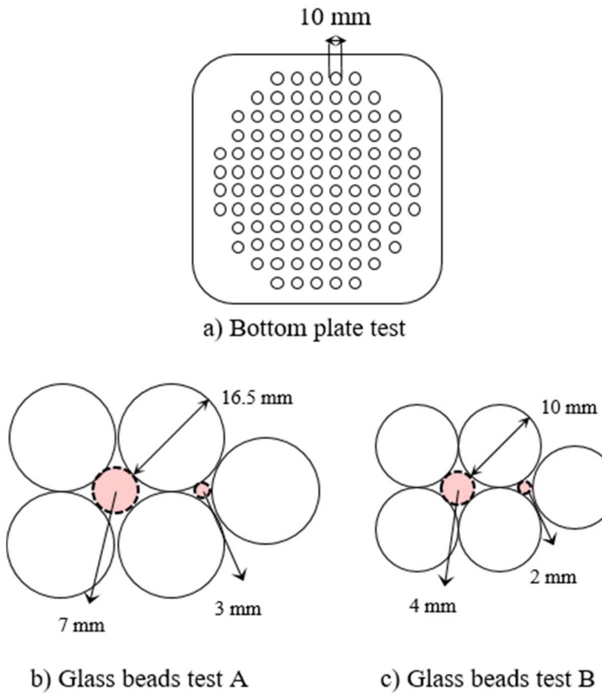

Figure 4. 6 Filter system varied in experimental program

First, a perforated acrylic bottom plate (BT test) with an equivalent hole diameter of 4 mm was installed to duplicate the constriction size formed by the filter material based on the filter criteria suggested by Terzaghi (1939). The suffusion test result of the BT test was compared to the suffusion test with filter materials (Glass beads test B) to evaluate the influence of the presence of actual filter materials.

Second, glass beads with a 16.5 mm diameter, corresponding to a 3-7 mm of constriction size based on the geometry of the loose and dense states of the soils are, used (figure 4.6). Glass beads test A (GA test) is conducted to verify the existing filter criteria proposed by Terzaghi (1939) for a proper laboratory suffusion test, since the constriction size formed by the filter materials does not satisfy the existing filter criteria.

Third, glass beads with a 10 mm diameter corresponding to a 2-4 mm constriction size are used. For the Glass beads test B (GB test), the particle size of the filter material satisfies the filter criteria, since the grain size diameter at 85% passing by weight in GW, AG25 and AG10 soils corresponds to 2.5, 3.0 and 2.7 mm respectively.

Based on the test results in chapter 5, GB test with a 10 mm diameter corresponding to a 2-4 mm constriction size is adopted for better performance of laboratory suffusion test among others (GA and BT test). Hence, further experiments, additional test for the specimen at relative density of 61%, and AG test, are conducted with the same filter system of the GB test.

4.3.2 Experimental program

The experiment program is summarized in table 4.3. Three different filters were used, a perforated bottom plate, Glass beads A and B (16.5 and 10 mm), hence having different constriction sizes.

Table 4. 3 Summary of the experimental program

<table>
<tr><th>Test•</th><th>D_r(%)</th><th>Constriction Size (mm)</th><th>Hydraulic Gradient, (i)</th><th>Vibration</th></tr>
<tr><td>GA</td><td rowspan="2">49, 77</td><td>3-7</td><td rowspan="5">2-3-5-9</td><td rowspan="5">Yes</td></tr>
<tr><td>BT</td><td>4</td></tr>
<tr><td>GB</td><td rowspan="3">49, 61, 77</td><td rowspan="3">2-4</td></tr>
<tr><td>AG25</td></tr>
<tr><td>AG10</td></tr>
</table>

* GA=Glass beads test A; BT=Perforated bottom plate test; GB=Glass beads test B; AG25 and AG10= Suffusion test on Gwanak soils with adjusted fines content of 25 and 10%.

For each experiment, the soil is tested at different relative densities (49 and 77% for Glass beads test A (GA test) and Perforated bottom plate test (BT test); 49, 61 and 77% for Glass beads test B (GB test) and Adjusted Gwanak soils test (AG25 and AG10 test). The procedure of the laboratory suffusion tests are as follows:

First, a filter is installed beneath the seepage cell (100 mmØ ×250 mm); it can be a bottom plate, glass beads with a 16.5 mm diameter (GA test), or glass beads with a 10 mm diameter (GB and AG test).

In the cases of GA and GB test, glass beads are compacted in 50 mm height, and to place the glass beads in the right position, sieve no. 4 is installed beneath the seepage cell instead of the bottom plate. Next, GW and AG soils with a 49, 61 or 77% relative density at 12.7, 12.5 (for AG25 soils) and 11.7% (for AG10 soils) moisture content is prepared.

To achieve the desired relative density, the same amount of soil is compacted in several layers using a tamping rod, and the surface of each preceding layer is scratched using a spatula.

Water is introduced downward and porous stone or glass beads are installed right above the soil specimen to distribute the water evenly across the specimens.

Lastly, the amounts of water and soil discharged are measured, and after the test, the specimen is divided into three parts and wet sieving and sieve analysis are conducted.

For all the tests, hydraulic gradients 2, 3, 5, and 9 are applied and for each hydraulic gradient, a test is conducted for 35 minutes. This process is considered, in order to evaluate the influence of different hydraulic gradient when conducting a suffusion test.

After this procedure, a test is conducted under a hydraulic gradient of 9 for 24 hours, which is a similar hydraulic gradient that were applied in the laboratory suffusion test of Wan and Fell (2008). And lastly the soil is vibrated manually for 2 hours using a rubber hammer, to evaluate the influence of vibration in suffusion test, which is a method derived from a study of Kenny and Lau (1985) and Honjo et al (1996).

In this study, in evaluating the internal stability of the soil through a seepage test, three identification methods were used.

First, the fraction of loss of soil specimen was measured by drying the discharged soil in an oven. As there is no general quantitative rule for evaluating the internal stability based on the mass loss of soil, the minimum value of 4% was adopted to determine the internal instability of the soil (Wan and Fell, 2008; Chang and Zhang 2013). From the study of Wan and Fell (2008), it turned out that the minimum value of discharged soils of internally unstable soils reached 4% of the total specimen.

Second, like the methods used in Kenny and Lau (1985) study, post-test grain size distribution analysis was conducted. Each specimen was divided into three parts (top, transition, and bottom zone), and wet sieving with mechanical sieve analysis was conducted for post-test grain size distribution analysis.

It is believed that the loss of fines from throughout the specimens, due to the suffusion process, results in the development of different grain size distribution across the specimens, hence conducting post-test grain size distribution analysis, provides the information of development and progress of suffusion process across the specimen.

In chapter 5, where the suffusion test results are provided, the grain size distribution curves of discharged soils, initial soils (GW or AG soils) and residual soils are given, since the development of minor changes in the grain size distribution of each divided layer is not visualized clearly.

Third, the hydraulic conductivity was calculated by measuring the weight of the discharged water at the designated time intervals. It has been stated by several researchers that when the permeability of a soil increased progressively or suddenly, the soil is classified as unstable. This method is adopted in the study of Sun (1989), Liu (2005) and Kaoser et al. (2006).

The results of the hydraulic conductivity are provided in the test, where a proper filter system has been used (GB, AG25 and AG10). The results of the variation in hydraulic conductivity for the BT and GA test is given in Appendix A.

Chapter 5 Suffusion Test Results

5.1 Introduction

Laboratory suffusion tests are performed on GW and AG soils. In this chapter, the result of each suffusion tests, Glass beads A (GA test), Perforated bottom plate test (BT test), Glass beads B test (GB test), Adjusted Gwanak soils test with 25 and 10% of the fines content (AG25 and AG10 test), are provided. At the end of this chapter, a summary of each suffusion test results are provided.

5.2 Glass beads test A (GA test)

Firstly, a suffusion test with the filter materials which do not satisfies the filter criteria (Terzhaghi, 1939) are conducted. Table 5.1 shows the results of the amount of soil discharged during the GA test. In the case of the soil at the loose state ($D_r = 49\%$), 11.77g of the soil was discharged, not considering the vibration.

When vibration was applied, a significant amount of soil was discharged, reaching approximately 9.17% of the initial mass of the soil. In total, 9.83% of the soil was discharged.

Table 5. 1 The results of the GA test

Hydraulic gradient (i)		2 to 5	9	9 (24h)	9 (vibration)	Total
Discharged Soil (g)	$D_r = 49\%$	3.03 (0.17%)	1.48 (0.08%)	7.26 (0.41%)	161.24 (9.17%)	173.01 (9.83%)
	$D_r = 77\%$	3.59 (0.19%)	1.44 (0.07%)	7.56 (0.40%)	195.3 (10.01%)	207.89 (10.80%)

The fine fractions of the top, transition, bottom zones reached 37.55, 40.27 and 35.06%, respectively. The difference in fine fraction across the specimens shows that the migration of fine particles develops the transition zone which had almost the same amount of fine fraction with the initial soil.

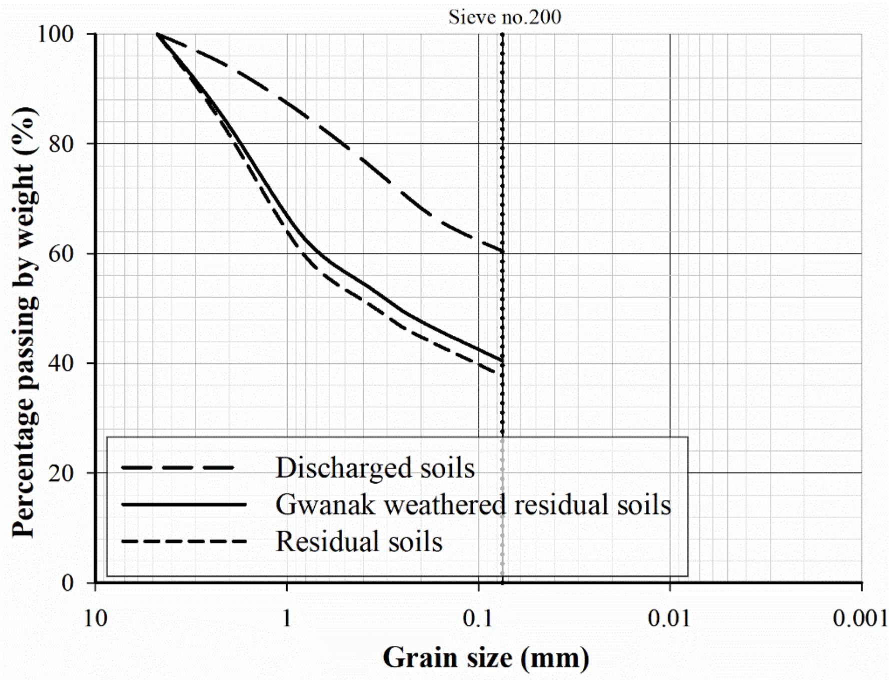

Figure 5. 1 Post-test grain size distribution of GA test at the loose state

This development is due to the migration of fine particles from the top to the transition zone, substituting for the loss of fines content towards the bottom zone. The fine fraction in the discharged, GW soils and residual soils reached 60.44, 40.44 and 37.68%, respectively, as shown in figure 5.1.

For the soil at the dense state, ($D_r = 77\%$), the amount of soil discharged (table 5.1) did not show clear difference from the tested soil at the loose state. A relatively small variation in fine fraction occurred across the specimens, reaching 39.42, 39.70 and 36.74% in regular sequence.

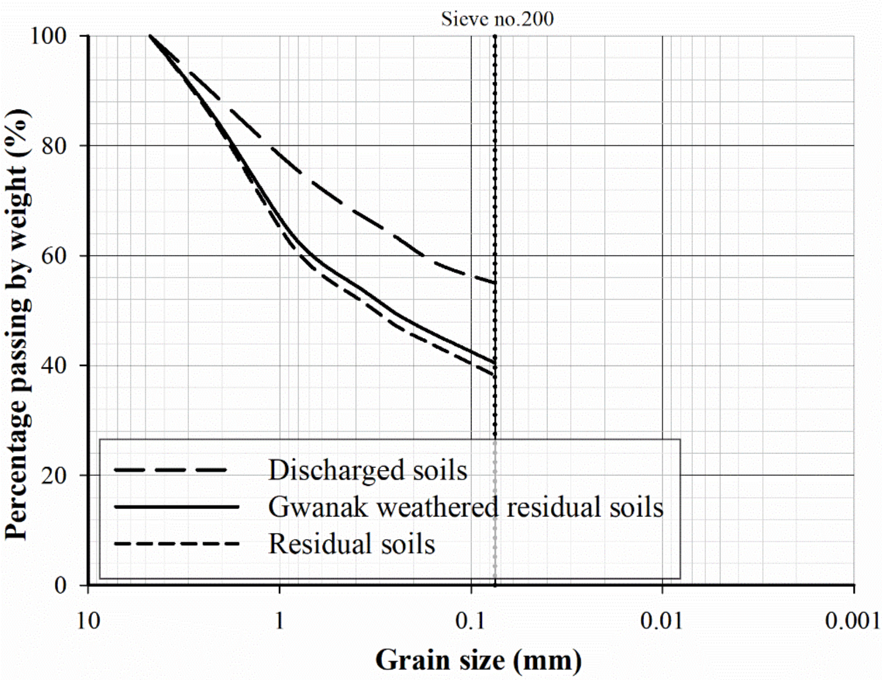

Figure 5. 2 Post-test grain size distribution of GA test at the dense state

The fine fraction reached about 55.04, 40.44 and 38.14% of the discharged, GW soils and residual soils, respectively (figure 5.2). In both tests involving soils at the loose and dense states, soils turned out to be internally unstable based on the amount of soil discharged, but unlike the other tests, both tests showed local failure in the specimens (figure 5.3), leading to the conclusion that suffusion is not the dominant failure mechanism and that filter materials do not protect the base materials properly.

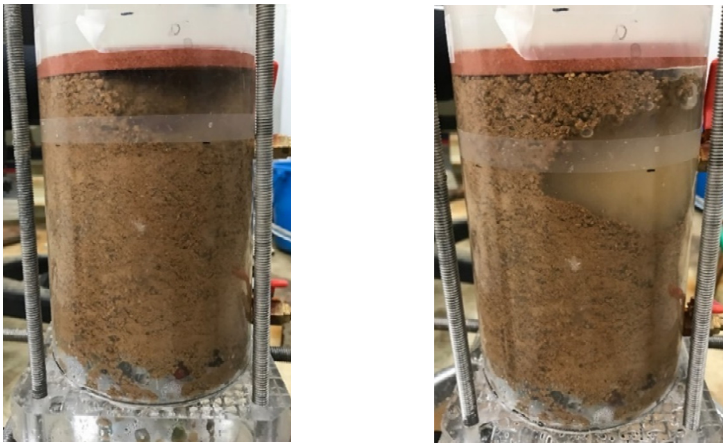

Figure 5. 3 Local failure observed in the specimen during GA test at loose (left) and dense state (right)

5.3 Perforated Bottom plate test (BT test)

The result of the BT tests is summarized in table 5.2. In the case of the soil at the loose state ($D_r = 49\%$), a significant amount of soil was discharged at the hydraulic gradient of 9, without vibration. The total fraction of discharged soil, not considering the vibration, reached 4.24% of the initial soil prepared thus, it can be considered internally unstable.

Table 5. 2 The results of the BT test

Hydraulic gradient (i)		2 to 5	9	9 (24h)	9 (vibration)	Total
Discharged Soil (g)	$D_r = 49\%$	3.92 (0.23%)	3.17 (0.19%)	64.47 (3.82%)	9.7 (0.58%)	77.34 (4.82%)
	$D_r = 77\%$	0.14* (0.01%)	0.02 (0.00%)	0.58 (0.03%)	43.52 (2.22%)	27.35 (2.26%)

* No water was discharged during the hydraulic gradient of 2

Due to the migration of the fines content across the specimen, the fine fractions of each of the parts (top, transition, and bottom zones) reached 39.61, 38.65 and 32.31%, respectively.

It could be concluded that the suffusion process took place dominantly at the bottom zone of the specimen and proceeded upwards. The post-test grain size distribution curve is shown in figure 5.4.

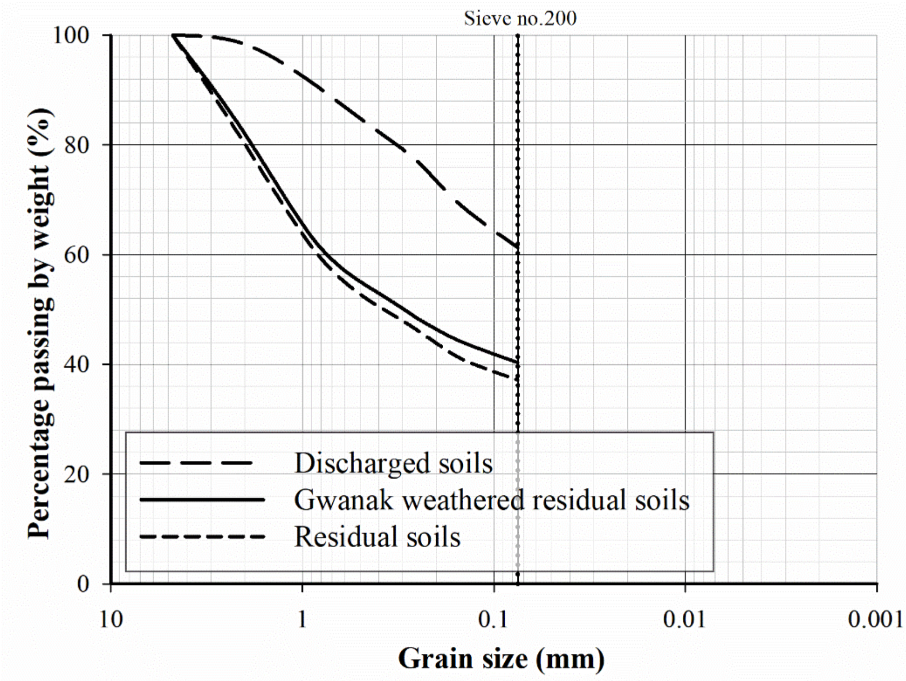

Figure 5. 4 Post-test grain size distribution of BT test at the loose state

The fine fractions of the discharged, GW soils and residual soils reached 61.32, 40.31 and 37.13 %, respectively. The increment of fine fractions in the discharged soil shows that the phenomenon of suffusion was the dominant mechanism for internal erosion.

For the soil at the dense state ($D_r = 77\%$), the amount of soil discharged did not reach 4% of the initial amount of soil, even considering the vibration.

Hence, the soil tested at the dense state could be regarded as internally stable. The fine fractions of each of the parts, (top, transition and bottom zones) reached 38.00, 38.25 and 39.38%, respectively. Increase in fines content at the bottom zone shows that the migration of fine soil particles did occur across the soil specimens, but due to low permeability, there was not enough seepage force to expel the soil out of the specimen.

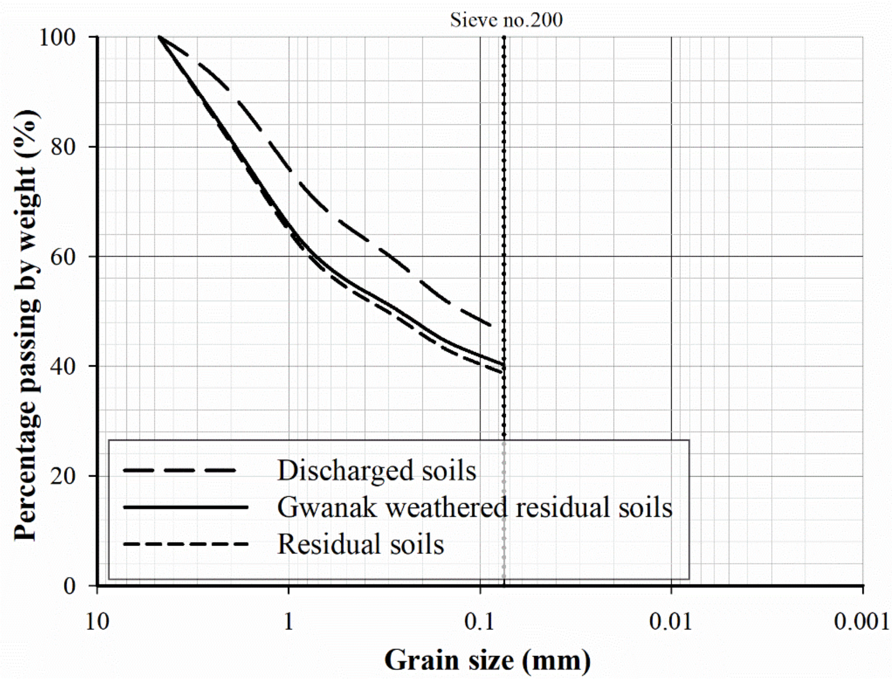

Figure 5. 5 Post-test grain size distribution of BT test at the dense state

The post-test grain size distribution curve is shown in figure 5.5. The fine fractions of the discharged, GW soils and residual soil reached 46.00, 40.23 38.64%, respectively.

It should be noted that during the test, no water was discharged under the hydraulic gradient of 2. This was due to the problem associated to the filter system since, the perforated bottom plate does not consider the actual boundaries between the base and filter materials of the dam.

5.4 Glass beads test B (GB test)

Following suffusion test is GB test with glass beads of diameter of 10mm which satisfies the abovementioned filter criteria. The amount of soil discharged during the GB test is summarized in table 5.3. For the soil at the loose state ($D_r = 49\%$), the amount of soil discharged under a low hydraulic gradient (2-5) was 0.51g. With a higher hydraulic gradient of 9, 44.45g of the initial mass of the soil, was discharged.

Table 5. 3 The results of the GB test

Hydraulic gradient (i)		**2 to 5**	**9**	**9 (24h)**	**9 (vibration)**	**Total**
Discharged Soil (g)	$D_r = 49\%$	0.51 (0.03%)	2.41 (0.41%)	44.45 (2.53%)	31.2 (1.70%)	78.57 (4.40%)
	$D_r = 61\%$	1.78 (0.10%)	0.20 (0.01%)	0.31 (0.02%)	5.22 (0.28%)	7.51 (0.41%)
	$D_r = 77\%$	3.15 (0.16%)	0.36 (0.02%)	0.14 (0.01%)	8.93 (0.45%)	12.58 (0.64%)

Unlike in the bottom plate test, small amount of water was discharged under the hydraulic gradient of 2, because glass beads are more likely to duplicate the actual filter and its void network.

Considering the amount of soils discharged under a seepage forces with relatively higher hydraulic gradient and vibration, the specimen was evaluated internally unstable.

The top and transition zones had almost the same fine fractions of 40.13 and 40.35%. For the bottom zone, it reached 37.56%. The fine fractions of the discharged, GW soils and residual soils were estimated as 56.86, 40.44 and 39.44%, respectively (figure 5.6).

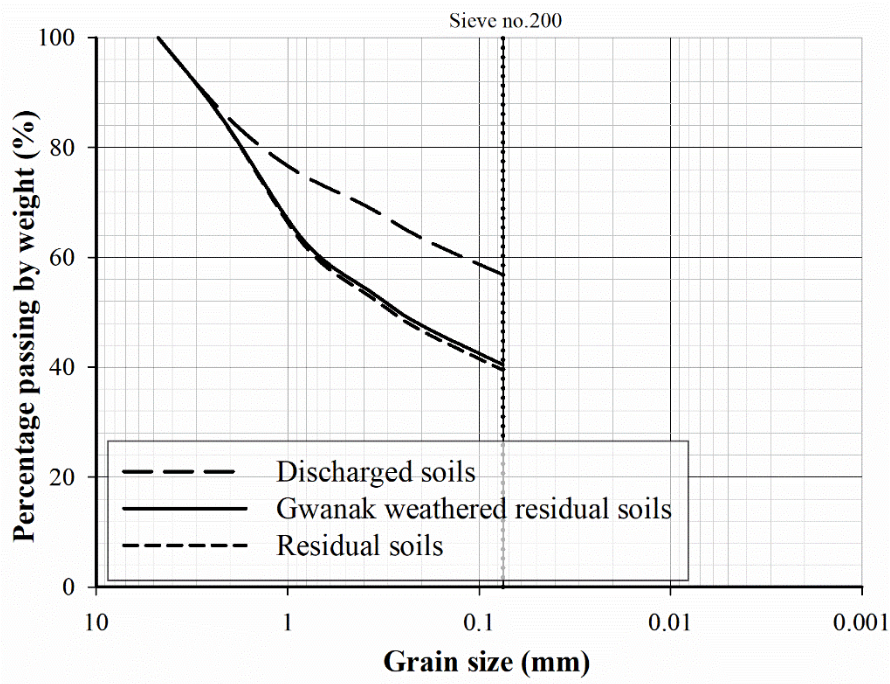

Figure 5. 6 Post-test grain size distribution of GB test at the loose state

For the GB test at relative density of 61%, the amount of soil discharged is summarized in table 5.3. Total amount of soils discharged reached only

2.29g (0.13%), not considering the vibration. Unlike the test results in the GB test with the loose state of the soils, small amount 5.22g was discharged during the vibration process. Total fraction discharged was 0.41% of the initial mass of the soil specimens, thus it is internally stable.

The fine fractions of top and transition zones were 36.70 and 36.29%. For the bottom zone, it reached 35.43%. Since, there were only small amount of soil discharged, variation in fines content across the specimen was not prominent. The fine fractions of the discharged, initial GW soils and residual soils were estimated as 78.93, 36.33 and 36.15% respectively (figure 5.7).

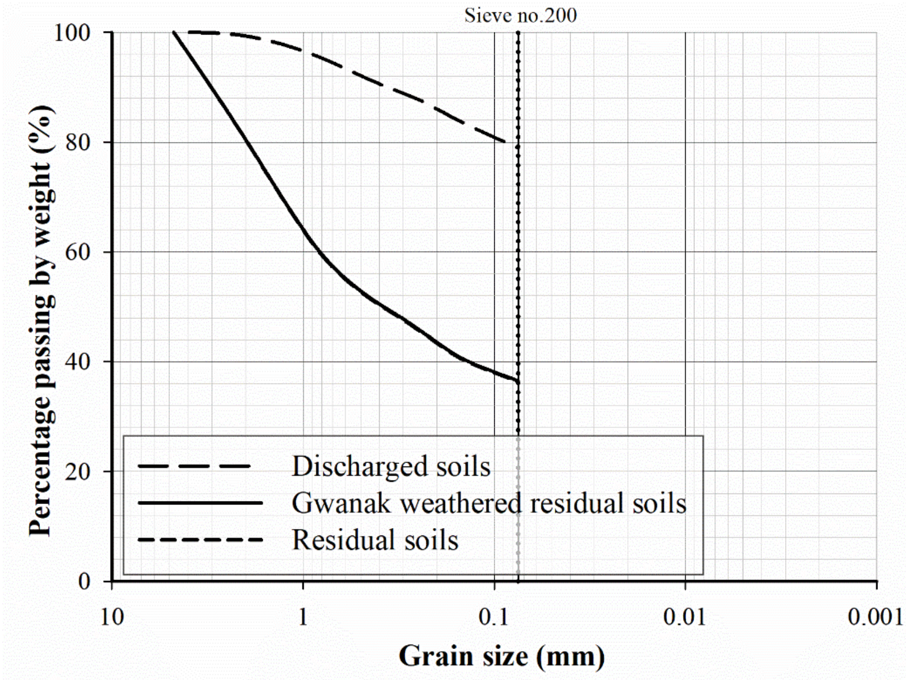

Figure 5. 7 Post-test grain size distribution of GB test at the intermediate state

The tested soil at the dense state, ($D_r = 77\%$), showed a relatively small amount of discharged soil compared to the loose state of the soils. The total amount of soil discharged was only 12.58g reaching 0.64%, thus it is regarded as internally stable.

There was no prominent variation in the fines content across the specimens, and it reached 41.47, 40.71 and 40.96% from the top to the bottom zones. As shown in figure 5.8, the fine fractions of the discharged, GW soils and residual soils were estimated as 69.20, 41.39 and 41.26%, respectively.

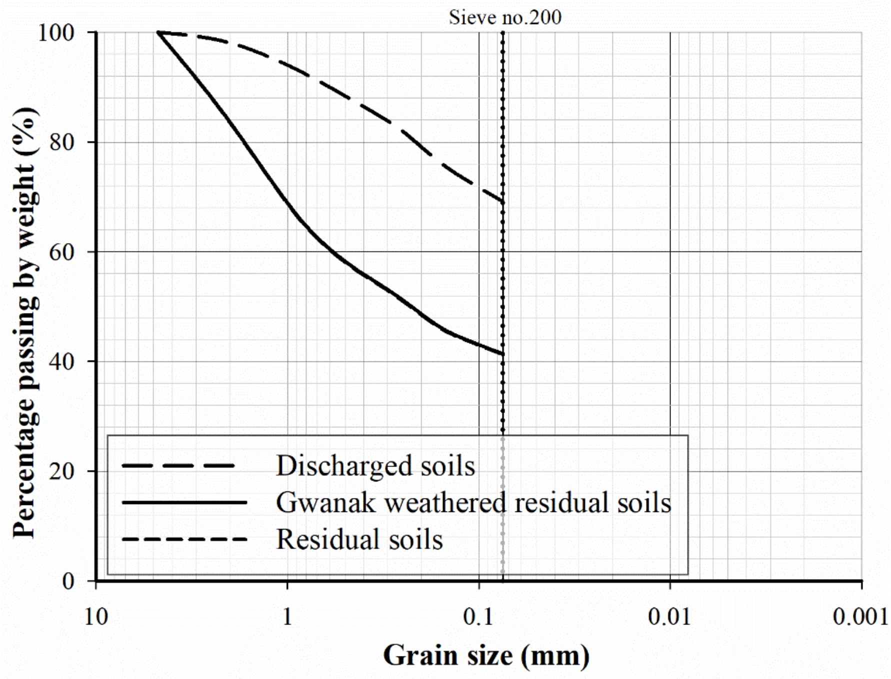

Figure 5. 8 Post-test grain size distribution of GB test at the dense state

The hydraulic conductivity of the soil in three different relative densities (49, 61, 77%), was estimated by measuring the mass of the water discharged during the experiment. The estimated hydraulic conductivity is shown in log scale in figure 5.9 and 5.10. In figure 5.9, each level of hydraulic gradient is expressed with a band separated by a dotted line, plotted at every 35 minutes of testing time for individual hydraulic gradient. The result shown in figure 5.10 was measured in regular intervals under the hydraulic gradient of 9 for 24 hours.

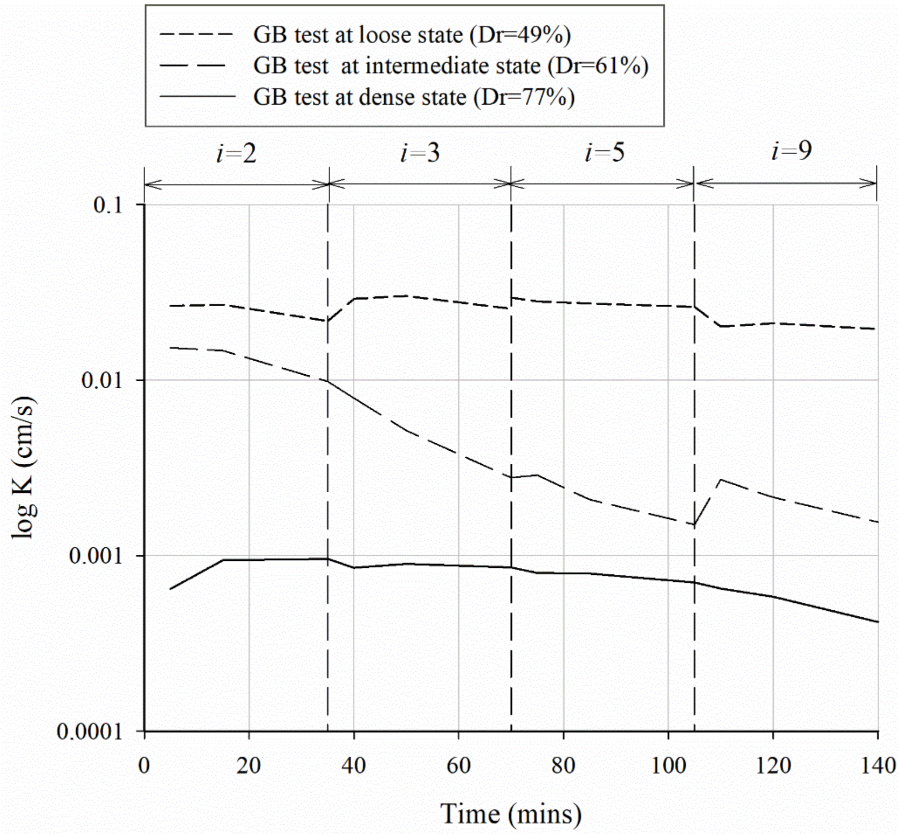

Figure 5. 9 Results of the estimated hydraulic conductivity under different hydraulic gradient for GB tests

When hydraulic gradient was increased from 2 to 9, the hydraulic conductivity of the soil at loose and dense state showed progressive reduction in its value. In the early phase of the hydraulic gradient of 2, the hydraulic conductivity increased slightly because the soil clogged at the very bottom of the glass beads were discharged when the water was initially introduced. This phenomenon was not shown in the soil specimen at the intermediate state.

For the soil at intermediate state, the hydraulic conductivity decreases significantly showing almost one order of its reduction. Taking into consideration that the amount of soils discharged, under the hydraulic gradient of 2 to 9 reached only 1.98g, it can be concluded that the significant reduction in hydraulic conductivity is resulted from the phenomenon of clogging induced by soils migration.

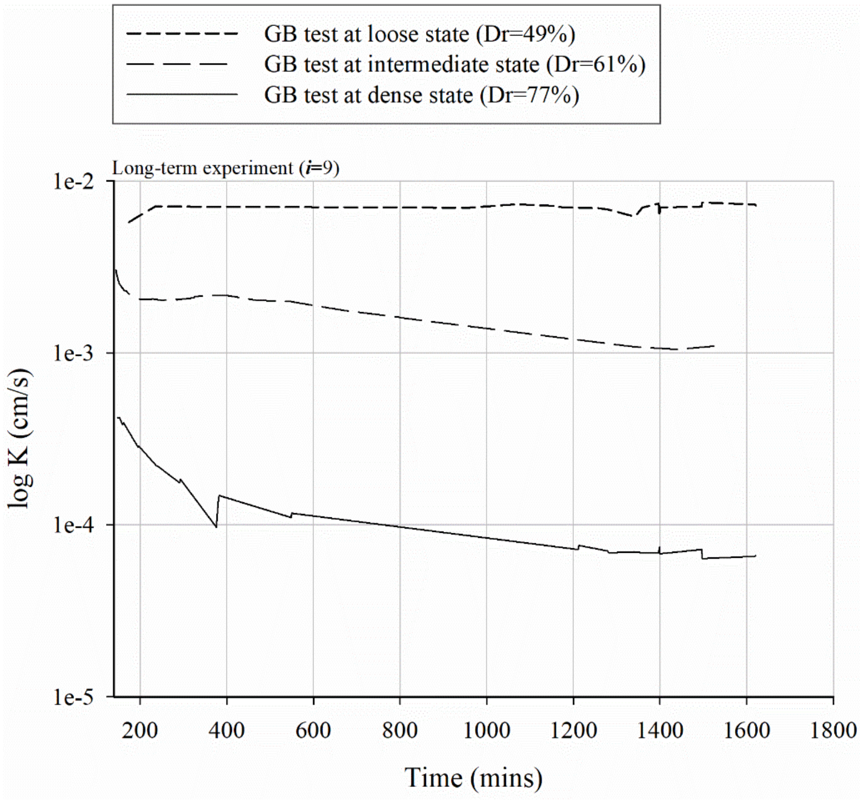

Figure 5. 10 Results of the estimated hydraulic conductivity for long-term experiment of GB tests

During 24 hours of suffusion test under the hydraulic gradient of 9, the variation in hydraulic conductivity shows different trend. As shown in figure 5.10, at the soils at loose state, the hydraulic conductivity initially increases, and it was further increased and maintained. This is due to the continuous erosion of soils, and the amount of soils discharged during 24 hours of experiment (44.45g) shows that the effect of clogging was insignificant. Thus, the soils at loose state, can be regarded as internally unstable based on the criteria related to the variation in the hydraulic conductivity.

For the soils at intermediate and dense state, the hydraulic conductivity decreased progressively due to clogging which supports the fact that the specimens are internally stable. The amount of soils discharged for 24 hours reached only 0.31(0.02%) and 0.14 (0.01%) respectively.

5.5 Adjusted Gwanak soils test

5.5.1 Adjusted Gwanak soils test (25%, AG25 test)

The amount of soil discharged during the AG25 test is summarized in table 5.4. For the soil at the loose state ($D_r = 49\%$), the amount of soil discharged under a hydraulic gradient of 2 to 9 for 140 minutes was 5.98g. With a hydraulic gradient of 9 for a long-term (24hours) experiment, 1.47g of the soil was discharged.

Table 5. 4 The results of the AG25 test

Hydraulic gradient (i)		2 to 5	9	9 (24h)	9 (vibration)	Total
Discharged Soil (g)	$D_r = 49\%$	4.00 (0.23%)	1.98 (0.11%)	1.47 (0.08%)	6.94 (0.39%)	14.39 (0.81%)
	$D_r = 61\%$	4.72 (0.25%)	3.23 (0.17%)	3.32 (0.14%)	76.33 (4.12%)	87.60 (4.73%)
	$D_r = 77\%$	3.10 (0.16%)	3.00 (0.15%)	0.09 (0.05%)	3.03 (0.15%)	9.22 (0.51%)

When vibration was applied relatively large amount of soil was discharged, reaching 6.94g. The total fraction discharged during the suffusion tests was 14.39g reaching only 0.81% of the initial soil mass, thus, even at the loose state of the soils, the soils turned out to be internally stable.

The result of the AG25 test at loose state was unexpected since, it is believed that the reduction in the initial fines content of the specimen renders the soil more susceptible to suffusion.

Migration in fine particles developed a small variation in fines content across the specimen. The fine fractions of each of the parts (top, transition, and bottom zones) reached 25.49, 26.09 and 25.20% respectively.

Taking into consideration that the initial fines content of the soil specimens corresponds to 26.16%, it is shown that the mass loss occurred in the transition zone have been compensated by the internal erosion from the top zone.

The fine fractions of the discharged, initial GW soils and residual soils were estimated as 84.99, 26.16 and 25.68% respectively (figure 5.11).

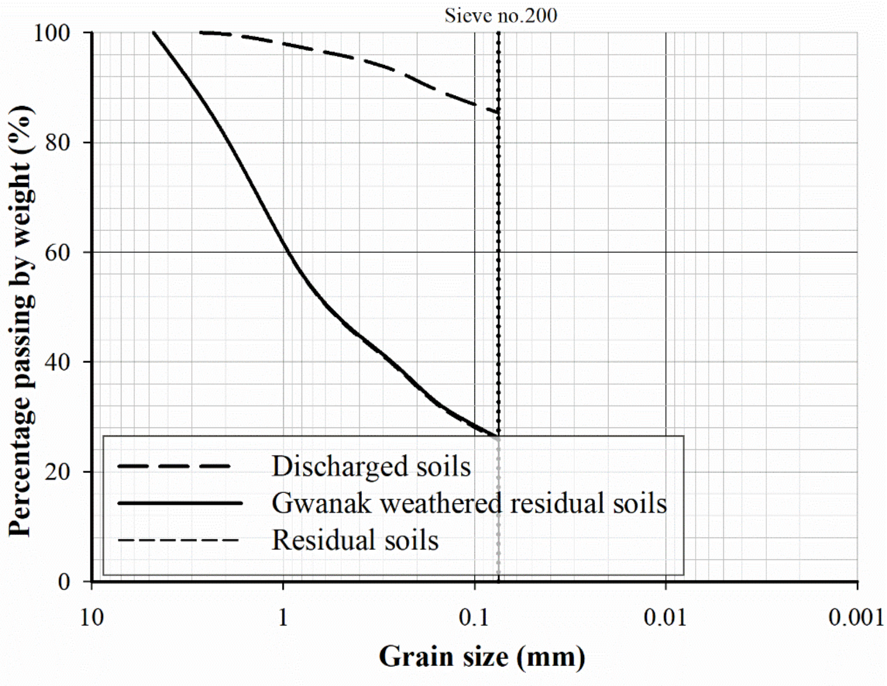

Figure 5. 11 Post-test grain size distribution of AG25 test at the loose state

For the AG25 test at relative density of 61%, the amount of soil discharged under a hydraulic gradient of 2 to 9 for 140 minutes was 7.95g, comprising 0.42% of the initial mass of the soil specimen. For the long-term experiment under the hydraulic gradient of 9, 3.32g of the initial mass of the soil was discharged. Significant amount of soils reaching 76.33g was discharged under the process of vibration. The total amount of discharged soils was 87.60g (4.73%), thus the intermediate state of AG25 soils is determined as internally unstable. The amount of soils discharged when vibration was applied shows that the soil structure at relative density of 61%, is unstable. The evaluation on the internal stability of the soils specimen will be again provided with the result based on the variation in hydraulic conductivity.

Due to the large amount of the soils discharged during the test, migration in fine particles developed a variation in fine fractions along the specimen. The fine fractions of each of the parts (top, transition, and bottom zones) reached 23.41, 21.47 and 21.42% respectively.

The fine fractions of the discharged, initial GW soils and residual soils were estimated as 84.12%, 23.01 and 22.10% respectively (figure 5.12).

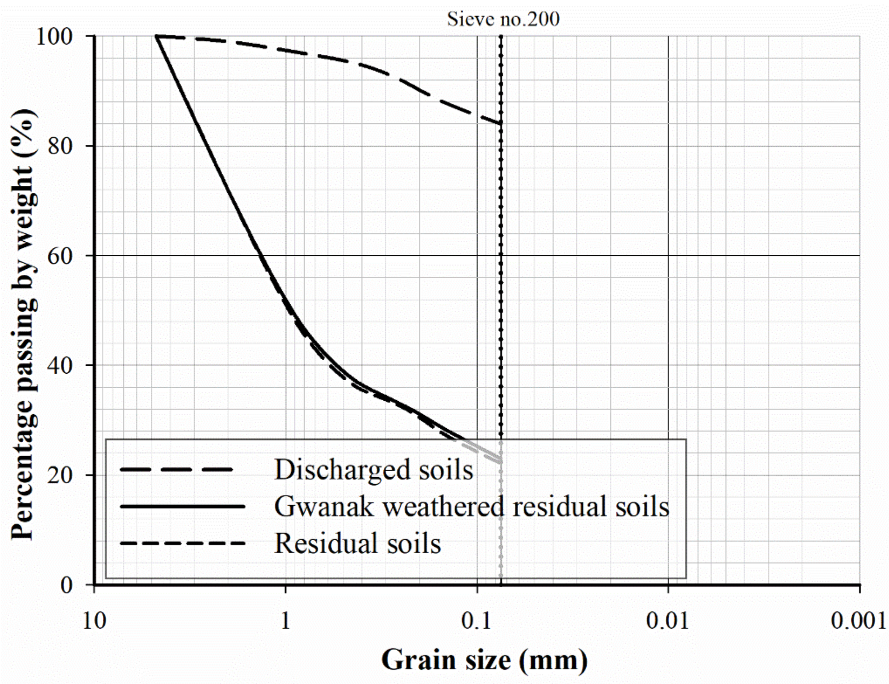

Figure 5. 12 Post-test grain size distribution of AG25 test at the intermediate state

For the soil at the dense state ($D_r = 77\%$), the amount of soil discharged under a hydraulic gradient of 2 to 9 for 140 minutes was 6.10g, which the amount of the soil discharged is similar when it is compared to the loose state of the specimen with same fines content. For the long-term experiment under the hydraulic gradient of 9, only 0.09g of the initial mass of the soil was discharged. The total amount of discharged soils reached 9.22g (0.51%) including the process of applying vibration, thus the dense state of AG25 soils is determined as internally stable.

Due to the higher relative density of the soil specimen, migration in fine particles developed a small variation in the fines content along the specimen. The fine fractions of each of the parts (top, transition, and bottom zones) reached 24.25, 23.40 and 22.78% respectively.

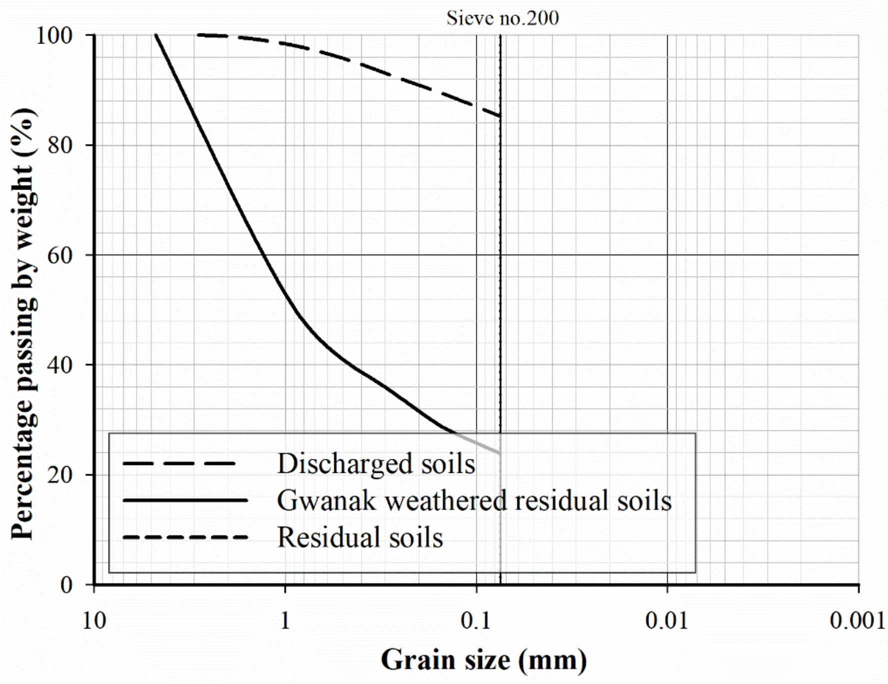

Figure 5. 13 Post-test grain size distribution of AG25 test at the dense state

The fine fractions of the discharged, initial GW soils and residual soils were estimated as 85.25, 23.90 and 23.61%, respectively (figure 5.13). It should be noted that the fine fractions of the discharged soils for all three cases of relative densities are significantly higher than other suffusion tests conducted. This will be discussed in the later chapter.

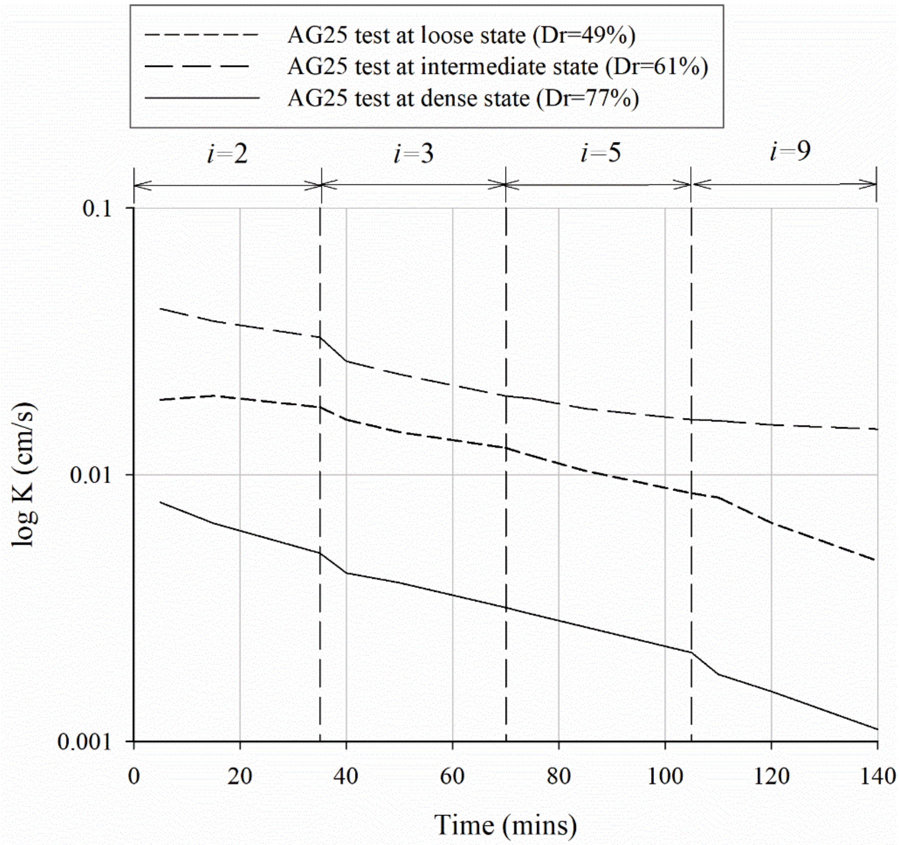

Figure 5. 14 Results of the estimated hydraulic conductivity under different hydraulic gradient for AG25 tests

When hydraulic gradient was increased from 2 to 9, the variation in hydraulic conductivity for three different relative densities of the soils showed similar trends of progressive reduction (figure 5.14).

It has been mentioned earlier that the amount of soils discharged for the soils at loose state, was unexpected and unreasonable. As it is seen in the Figure 5.14, the estimated hydraulic conductivity during the AG25 test at loose state, was lower than that of the AG 25 test at intermediate state, which can explain the small amount of soils discharged during the AG 25 test at loose state. In this study, the result of the AG 25 test at loose state is regarded as abnormal results, which needs further discussion and perhaps repeated experiment.

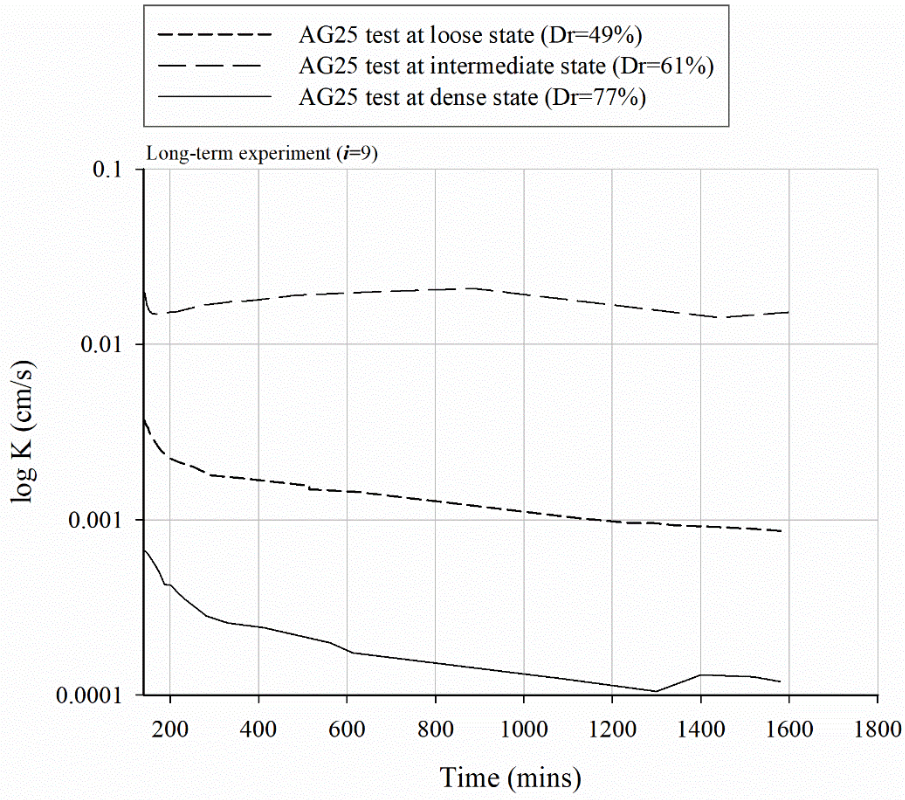

Figure 5. 15 Results of the estimated hydraulic conductivity for long-term experiment of AG25 tests

The variation in hydraulic conductivity during the long-term experiment (figure 5.15) shows that there was a significant increment in hydraulic conductivity for the soils at intermediate state, which explains the relatively large amount of soils (3.32g) discharged. Although the hydraulic conductivity started to decrease after 15 hours of the testing time, considerable variation in hydraulic conductivity during the tests support the evaluation results based on the amount of soils discharged.

The consistent reduction in hydraulic conductivity in the case of the loose and dense state of the soils corresponds well with the results of the amount of soils discharged.

5.5.2 Adjusted Gwanak soils test (10%, AG10 test)

The amount of soil discharged during the AG10 test is summarized in table 5.5. For the soil at the loose state ($D_r = 49\%$), the amount of soil discharged under a hydraulic gradient of 2 to 9 for 140 minutes was 18.19g. With a hydraulic gradient of 9 for a long-term (24hours) experiment, significant amount of soils reaching 27.55g of the initial mass of the soil was discharged. The total amount of soil discharged considering vibration reached 75.02 accounting for 4.34% of the total mass of the soil specimen, hence it is internally unstable.

Table 5. 5 The results of the AG10 test

Hydraulic gradient (i)		**2 to 5**	**9**	**9 (24h)**	**9 (vibration)**	**Total**
Discharged Soil (g)	$D_r = 49\%$	11.72 (0.68%)	6.47 (0.37%)	27.55 (1.60%)	29.28 (1.70%)	75.02 (4.34%)
	$D_r = 61\%$	7.34 (0.40%)	2.83 (0.15%)	10.03 (0.54%)	62.9 (3.41%)	83.10 (4.51%)
	$D_r = 77\%$	3.92 (0.20%)	2.34 (0.12%)	10.89 (0.56%)	49.07 (2.53%)	66.22 (3.41%)

Since considerable amount of water and soils were discharged during the experiment, variation in fines content across the specimen was prominent. The fine fractions of each of the parts (top, transition, and bottom zones) reached 7.78, 9.21, 6.18% respectively. Similar to the AG25 test at the loose state of the soils, the fine fractions of the transition zone showed that the loss of fines content in the transition zone have been compensated by the migration of fine particles from the top zone.

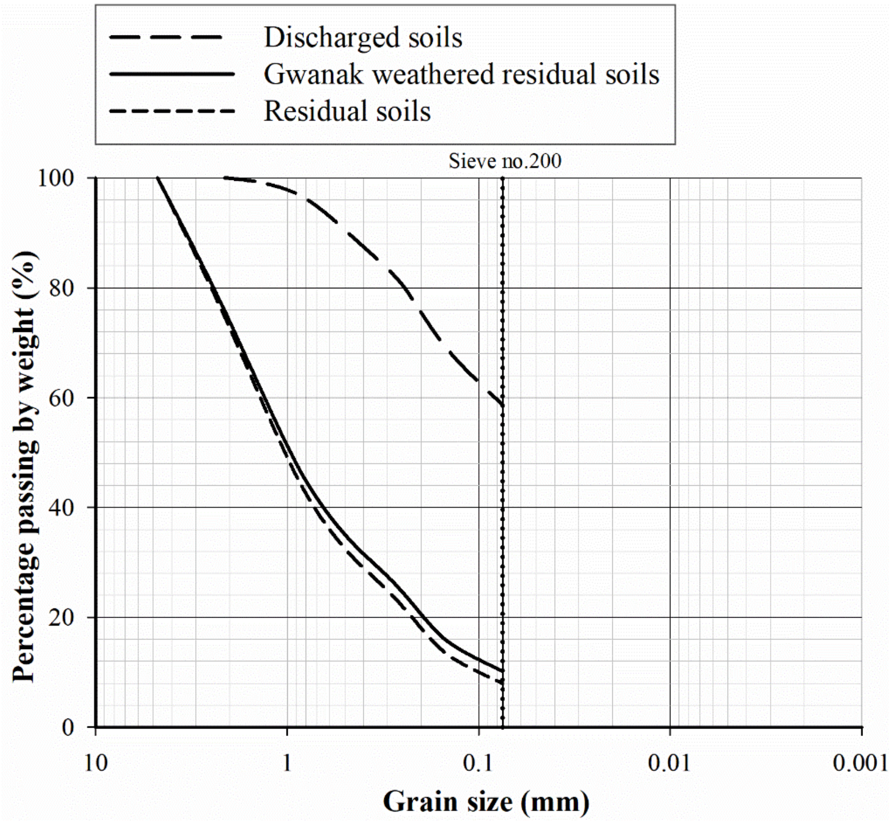

Figure 5. 16 Post-test grain size distribution of AG10 test at the loose state

The fine fractions of the discharged, initial GW soils and residual soils were estimated as 58.69, 10.19 and 7.95% respectively (figure 5.16).

The amount of soil discharged during the AG10 test with the soils at intermediate state ($D_r = 61\%$) , is summarized in table 5.5. Under a hydraulic gradient of 2 to 9 for 140 minutes, the amount of soils discharged was 10.17g. With a hydraulic gradient of 9 for a long-term (24hours) experiment, 10.03g of the initial mass of the soil was discharged. Considering the process of vibration total amount of discharged soils reached above 4% and thus, evaluated as internally unstable.

The fine fractions of each of the parts (top, transition, and bottom zones) reached 9.49, 9.71 and 6.75% respectively. The variation in fine fraction across the specimen shows that the phenomenon of suffusion took place dominantly at the bottom zone of the specimen.

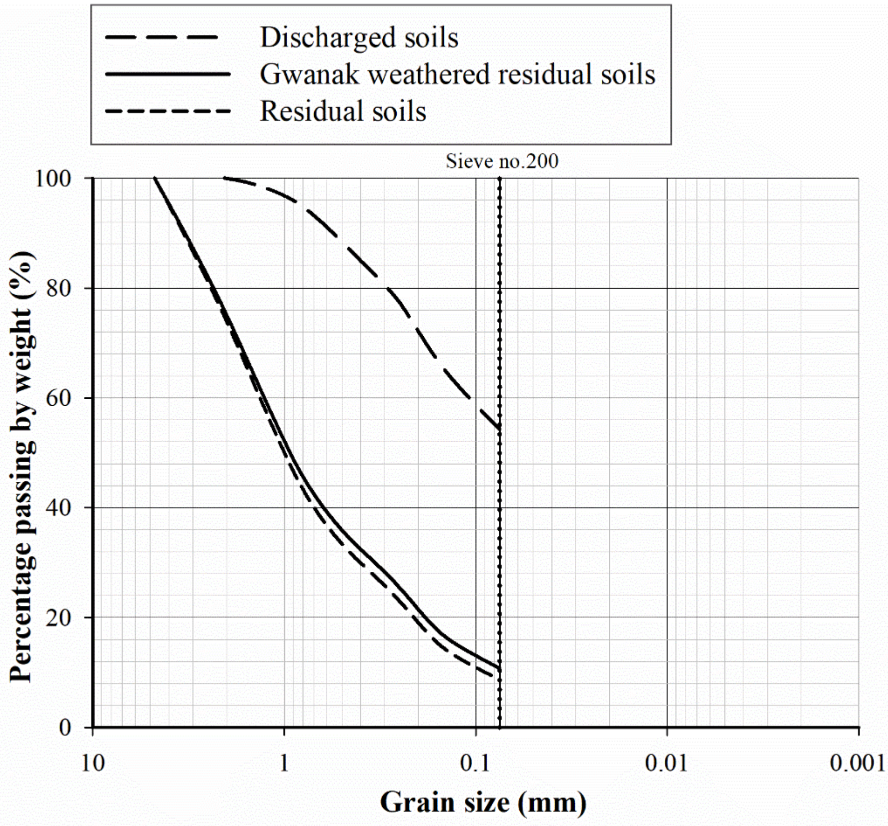

Figure 5. 17 Post-test grain size distribution of AG10 test at the intermediate state

The fine fractions of the discharged, initial GW soils and residual soils reached 54.30, 10.75 and 8.68%, respectively (figure 5.17).

For the soil at the dense state ($D_r = 77\%$), the amount of soil discharged under a hydraulic gradient of 2 to 9 for 140 minutes was 6.26g. With a hydraulic gradient of 9 for a long-term (24hours) experiment, 10.89g of the initial mass of the soil was discharged. The total amount of soil discharged considering vibration reached 66.22g and since the fraction of the discharged soils did not reach above the 4% of the initial mass of the soils specimen it is evaluated is internally stable.

The fine fractions of each of the parts (top, transition, and bottom zones) reached 10.65, 10.52 and 8.24% respectively. The variation in fine fraction of each zones, is similar to that of the AG10 test at intermediate state. The fine fractions of the discharged, initial GW soils and residual soils were estimated as 49.59, 11.17 and 9.81% respectively (figure 5.18).

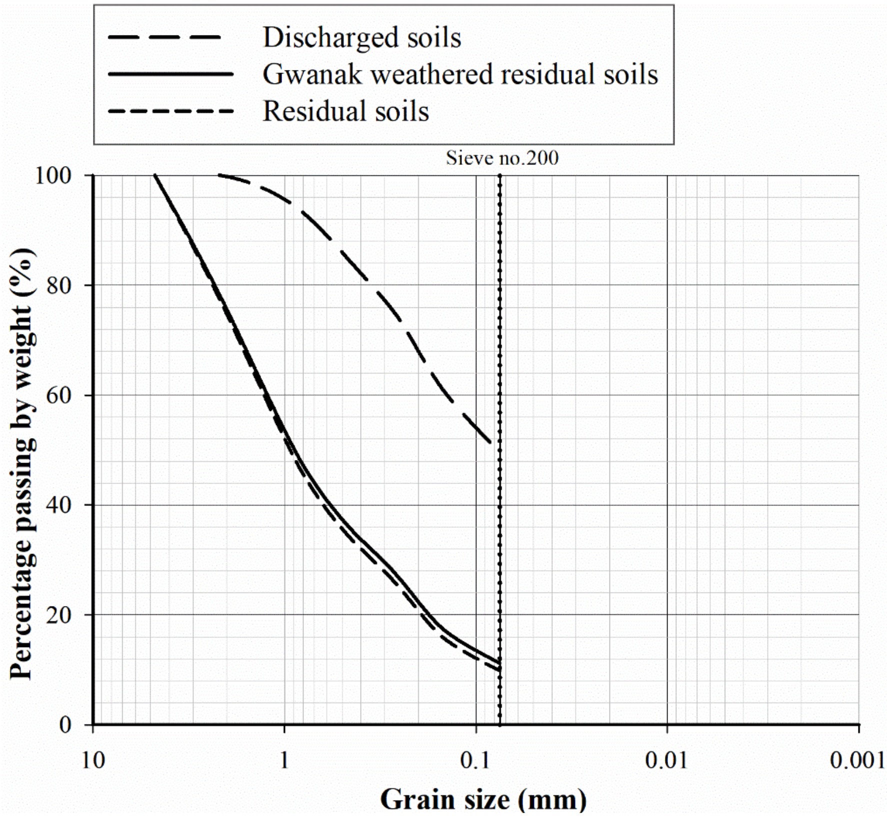

Figure 5. 18 Post-test grain size distribution of AG10 test at the dense state

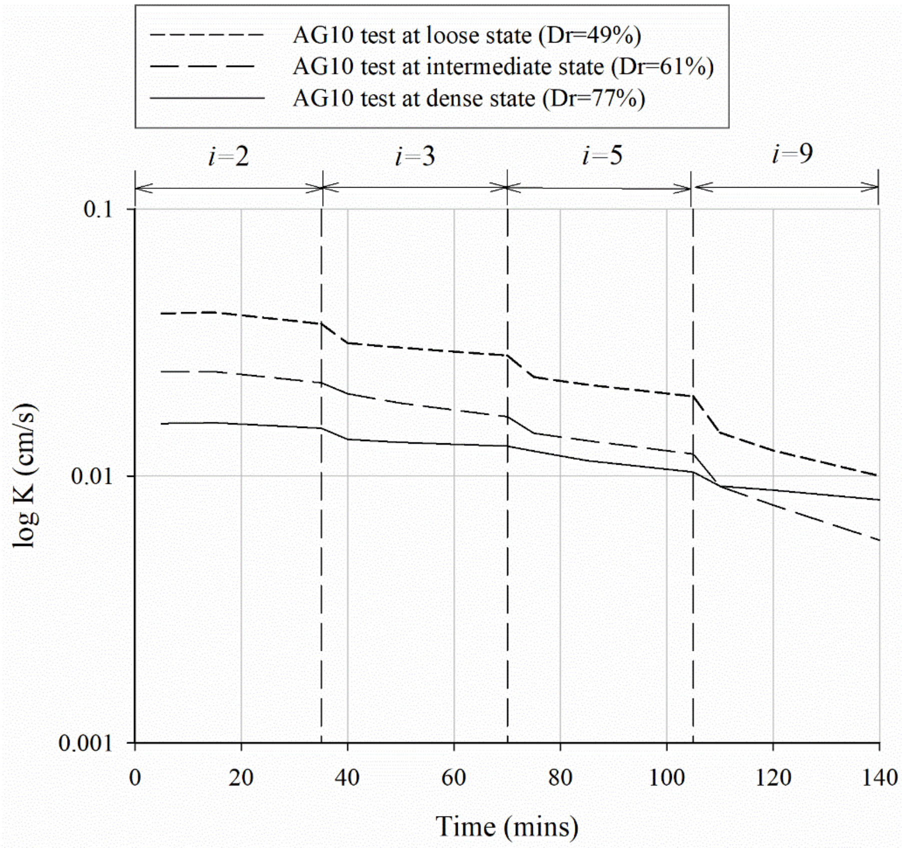

Figure 5. 19 Results of the estimated hydraulic conductivity under different hydraulic gradient for AG10 tests

The results of the estimated hydraulic gradient is shown in figure 5.19 and 5.20. During the increment of hydraulic gradient from 2 to 9, the reduction in hydraulic conductivity occurred for all three cases at different relative densities.

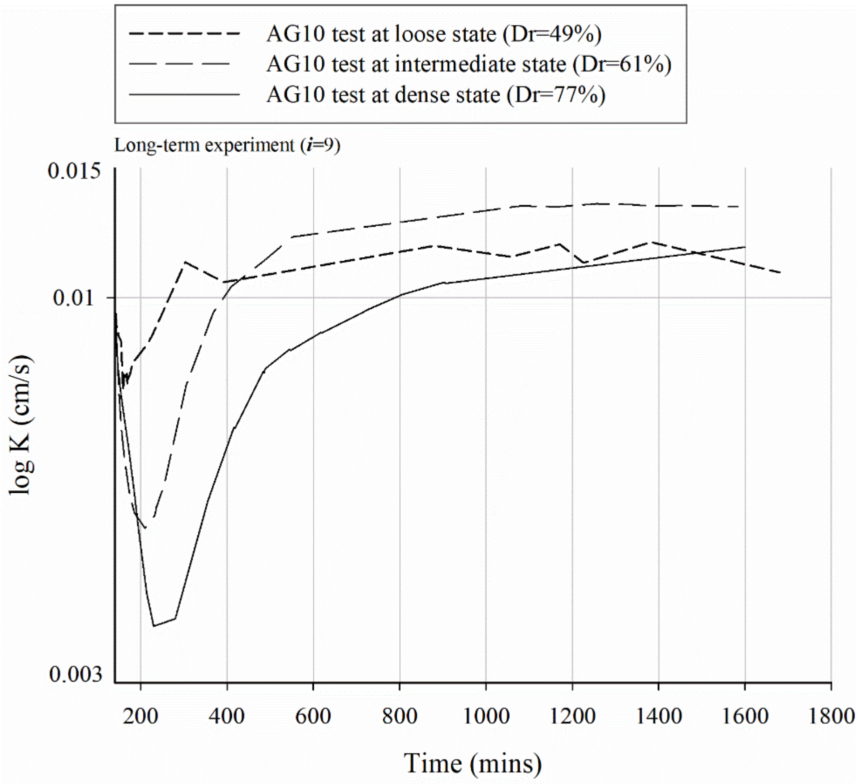

Figure 5. 20 Results of the estimated hydraulic conductivity for long-term experiment of AG10 tests

The variation in hydraulic conductivity under the hydraulic gradient of 9 at 24 hours of testing time, showed similar trend for all three different relative densities of the soils. All cases showed reduction in hydraulic conductivity in the early phase of the experiment followed by the sudden increase in its value. The time at which the transition (sudden increase) in hydraulic conductivity occurred, was pushed backwards with higher relative density.

The sudden increase in hydraulic conductivity for all three cases implies that there is a critical amount of soils discharge that can lead to the abrupt increase in hydraulic conductivity. Thus, the occurrence of the transition point in hydraulic conductivity is pushed backwards as the relative density increases since, the higher the relative density the migration of the soils is less likely to end up in the discharge of the soils.

Notwithstanding with the fact that the rate of increment in hydraulic conductivity resembles an asymptotic curve reaching to a certain value of hydraulic conductivity, it shows that AG10 soils can be regarded as internally unstable. More accurate results of evaluation regarding internal stability of the soils will be obtained with a suffusion test with an extended time scale.

In this study, a suffusion test results which showed the variation (consistent and increasing trend) in hydraulic conductivity that can be regarded as internally unstable may not always corresponds to the results based on the amount of the soils discharged.

5.6 Summary

The evaluation on internal stability of the soils based on the amount of soils discharged for each suffusion tests is summarized in table 5.6. The test which is evaluated as internally unstable, are expressed with box filled with grey color.

Table 5. 6 Summary of the laboratory suffusion test results based on the amount of soils discharged

		$D_r = 49\%$	$D_r = 61\%$	$D_r = 77\%$
Discharged soils(g)	GA test	173.01* (9.83%)	-	207.89 (10.80%)
	BT test	77.34 (4.82%)	-	27.35 (2.26%)
	GB test	78.57 (4.40%)	7.51 (0.41%)	12.58 (0.64%)
	AG25 test	14.39 (0.81%)	87.60 (4.73%)	9.22 (0.51%)
	AG10 test	75.02 (4.34%)	83.1 (4.51%)	66.22 (3.41%)

*Internally unstable results are filled with grey color in the table

Firstly, a suffusion test was conducted on GW soils with filter system that does not satisfy the filter criteria (GA test). Soils specimen at both cases of loose and dense state ($D_r = 49, 77\%$), show significant amount of soils discharged during the process of vibration. Although the fraction of discharged soils reached above 4% of the initial mass of the soils, it cannot be regarded as internally unstable, since local failure has occurred for both the cases.

Suffusion test was conducted on same soil specimen of GW soils using different filter system, perforated bottom plate (BT test). In this case, the diameter of perforated holes, which duplicates the constriction size in between the filter materials, satisfy the filter criteria. The soils at loose state showed internally unstable results based on the amount of discharged soils. For the soils at dense state, no water was discharged under the hydraulic gradient of 2, and phenomenon of suffusion was not observed, since the fine fraction of the discharged soils reached the lowest value of 46.00% when it is compared to other tests.

In order to duplicate the actual boundaries of the base and filter materials suffusion tests have been conducted on GW soils using glass beads (GB test). The soils specimens at the loose state turned out to be unstable reaching 4.40% of soils discharged. The variation in hydraulic conductivity for the soils at loose state supports that the soils is unstable, since it did not show any reduction in its value.

For the soils at the intermediate and dense state, only a small amount of soils were discharged and it is regarded as internally stable.

To evaluate the effect of fines content in the suffusion tests, adjusted GW soils with 25% of the fines content is used for the AG25 test. Only the soils at intermediate state was evaluated as internally unstable and the change in hydraulic conductivity showed different trends, compared to the other test results that are evaluated as internally unstable.

Soils at loose state are expected to be unstable, but the amount of soils didn’t reach above 4% and also the variation in hydraulic conductivity showed that the phenomenon of clogging was significant.

In the same vein, adjusted GW soils with 10% of the fines content is used for AG10 test. Amount of soils discharged for the soils at different relative densities showed that the internal stability of the soils of AG10 test is unstable than any other tests conducted in this study.

Although, the fraction of soils discharged for the soils at the dense state did not reach above 4% of the initial mass of the soils, the variation in hydraulic conductivity, showed similar trends to the soils at loose and intermediate state, thus it can also be regarded as internally unstable.

In this study, hydraulic conductivity showing progressive reduction is regarded as a trend that can be understood as internally stable due to the effect of clogging induced by soils migration. And change in hydraulic conductivity in fashion of showing sudden increase and irregular trends are regarded as internally unstable.

Although, in the study of Chang and Zhang (2013), it mentioned that the minimum loss of soils should reach above 4% in order to be internally unstable, it is based on the statistics of suffusion tests results held by the early investigators, and can differ according to the properties of the soils.

Thus, in this study, the evaluation result based on the amount of soils discharged does not always corresponds to the results based on the variation in hydraulic conductivity. The evaluation on internal stability of the soils in terms of the change in hydraulic conductivity is summarized in table 5.7.

Table 5. 7 Summary of the laboratory suffusion test results based on the variation in estimated hydraulic conductivity

State (D_r)		Loose (49%)	Intermediate (61%)	Dense (77%)
Internal stability	GB test	U	S	S
	AG25 test	S	U	S
	AG10 test	U	U	U

Chapter 6 Analysis of the test results

6.1 Introduction

In this chapter, the suffusion test results will be discussed with the assessment results based on the method of Kenny and Lau (1985) and Wan and Fell. Influential factors that are considered in the experimental program, properties of the soils (fines content), relative density, filter system, hydraulic gradient and vibration will be discussed together

6.2 Internal stability of the soils

In chapter 4, the internal stability of the GW and AG soils were evaluated based on the method of Kenny and Lau (1985) and Wan and Fell (2008). The assessment results are summarized in table 6.1. The method of Kenny and Lau (1985) evaluated all the soils with different fines content as internally unstable, and the method of Wan and Fell (2008) evaluated as internally stable. Comparison on the suffusion test and assessment results are made based on the existing criteria (table 6.1).

In the test results GA and BT test are not included, since it was concluded that the filter systems are inappropriate to conduct a suffusion test. For the suffusion test results, determination in the internal stability of the soils is made based on the amount of discharged soils (4%) and the total amount of soils are categorized and evaluated with the result including vibration and without the vibration process, since the method of vibration was only adopted in the study of Kenny and Lau (1985).

Table 6. 1 Summary of the assessment and experimental results

Soils		**Assessment results based on criteria**	
		Kenny and Lau (1985)	**Wan and Fell (2008)**
GW		U	S
AG25		U	S
AG10		U	S
Tests		**Suffusion test results**	
		With vibration	**Without vibration**
GB	$D_r = 49\%$	U	S
	$D_r = 61\%$	S	S
	$D_r = 77\%$	S	S
AG25	$D_r = 49\%$	S	S
	$D_r = 61\%$	U	S
	$D_r = 77\%$	S	S
AG10	$D_r = 49\%$	U	S
	$D_r = 61\%$	U	S
	$D_r = 77\%$	S	S

The results summarized in table 6.1 shows that when vibration is not applied, the amount of soils discharged for the suffusion tests in all cases did not reach above 4% of the initial mass of the soils. Thus, the assessment results based on the method of Wan and Fell (2008) shows robust prediction on the internal stability of the soils.

However, for the soils that showed increase or irregular variation in hydraulic conductivity in long-term experiment under the hydraulic gradient of 9, it is possible for the amount of soils discharged to reach above 4% of the initial mass of the specimen, when the time of the experiment is extended.

Thus, for the soils that are evaluated to be internally unstable, based on the variation in hydraulic conductivity, laboratory suffusion test should be conducted with an extended period of experiment time in order to evaluate the internal stability of the soils properly.

The prediction towards the internal stability of the soils was relatively poor in the case of the Kenny and Lau (1985) method. The result of the suffusion tests, in all cases with different soils (GB, AG25 and AG10), the internal stability was evaluated differently, according to the relative density. Except for the result of AG25 test at loose state of the soil specimen (table 6.1), the results showed that the soils at the lower relative density are more susceptible to vibration. Thus, it can be said that predictions on internal stability of the soils based on Kenny and Lau (1985) method showed conservative results.

Similar conservative predictions in evaluating the internal stability of the soils have been made when the method of Kenny and Lau (1985) were applied in the study of Wan and Fell (2008). The concept and the method of Kenny and Lau (1985) is easy to apply as long as with the data of the grain size distribution curves, however the relative density of the soils specimens should be considered together.

Additionally, the vibration process has been adopted in the study of suffusion by many researchers (USACE, 1953; Kenny and Lau, 1985; Honjo et al. 1996; Fannin and Moffat, 2006). However, it should be noted that none of the research have mentioned about the quantification of vibrational forces in detail. Thus, in order to adopt the process of vibration, clear relationship between the vibrational forces and the acceleration in soils migration is needed for more consistent suffusion test results.

From the suffusion test results, evaluation on the internal stability of the soils were drawn in terms of the variation in hydraulic conductivity (table 5.7). Estimated hydraulic conductivity, which shows increment and irregular trends in its value are regarded as internally unstable, since there are no general standards in determining whether the soil is susceptible to suffusion based on measured hydraulic conductivity.

Based on the test results in terms of the change in hydraulic conductivity, the suffusion test results (table 5.7), shows that the soils are more vulnerable to suffusion at lower fines content and relative density.

6.3 Influential factors

Laboratory suffusion tests are performed on GW, AG25 and AG10 soils. The internal stability of the soils specimen was evaluated based on the amount soils discharged and the variation in hydraulic conductivity. Influential factors, fines content, relative density, filter system, hydraulic gradient and the effect of vibration were evaluated together with the test results. In this chapter, the influential factors are evaluated with the laboratory suffusion test results that are based on the change in hydraulic conductivity, since the identification method of fraction of soils discharged (4%) is merely an estimation of the early suffusion test results held by several investigators and the testing time have not been clearly considered in this standards.

GW soils with different fines content ranging from 10, 25 to 40% was used as a specimen in order to evaluate the influence of fines content towards the phenomenon of suffusion.

For the BT and GA test, two different relative densities of 49 and 77% are adopted. For the GA, A25 and AG10 test a median value (61%) of aforementioned two relative densities is additionally adopted, to evaluate the effect of relative density of soils to suffusion.

Different filter system, Glass beads test A (GA test), which does not satisfy the filter criteria, perforated bottom plate (BT test), and Glass beads test B (GB test), are adopted to evaluate the influence of different filter materials.

Suffusion tests were conducted under different hydraulic gradient from 2, 3, 5 to 9, in order to assess the influence of hydraulic gradient towards the phenomenon of suffusion. After the long-term experiment (24hours) under the hydraulic gradient of 9, specimens were vibrated manually using the rubber hammer in order to evaluate the effect of vibration during the laboratory suffusion tests.

Effects of fines content

It is generally believed that the increase in fines content of the soils, reinforces the resistance against suffusion. In this study three different fines content (10, 25, 40%) were arranged to evaluate its influence on the phenomenon of suffusion.

Except for the results of the AG25 test at loose state (table 6.2), the internal stability of the soils based on the change in hydraulic conductivity shows that the more the fines content, soils specimens are less likely to be susceptible to suffusion.

Table 6. 2 Evaluation on internal stability of soils based on the change in hydraulic conductivity

State (D_r)		Loose (49%)	Intermediate (61%)	Dense (77%)
Internal stability	GB test	U	S	S
	AG25 test	S	U	S
	AG10 test	U	U	U

When GW soils were adjusted to 10% of fines content (AG10 test), the variation in hydraulic conductivity of long-term experiment under the hydraulic gradient of 9, showed clear phenomenon of suffusion.

At the early phase of the experiment (around 200 minutes), significant reduction in hydraulic conductivity induced by the migration of soil particles were dominant. Since, the initial hydraulic conductivity of the AG 10 soils was relatively higher for all three different cases of relative densities, it allowed the soil particles to migrate aggressively, causing clogging.

When fines content was discharged enough, hydraulic conductivity started to increase, and the curves showed asymptotic trend towards certain value when the experiment was held almost 24 hours. The transition point which the hydraulic conductivity was increased abruptly, was pushed backward depending on the relative density.

Abovementioned trend in hydraulic conductivity was not shown in other tests, even for the AG 25 test. This phenomenon can be understood by using the concept of intergranular void ratio. In case of the silty sand, it is assumed that up to a certain fines content, coarse materials are the main particles which transfer the contact frictional forces.

Hence, we can think that up to certain fraction of fines content, all of the fines content can be located within the voids formed by the coarser particles. In this case, the volume of the coarse particles can be expressed by the fines content (FC, percentage by weight), $(1 - \mathrm{FC}/100)$ (Kenney, 1977; Mitchell, 1993). Thus, in actual soils with global void ratio of e, the intergranular void ratio (e_s) can be expressed as $(\mathrm{e} + \mathrm{FC}/100)/(1 -$

$FC/100)$ (figure 6.1).

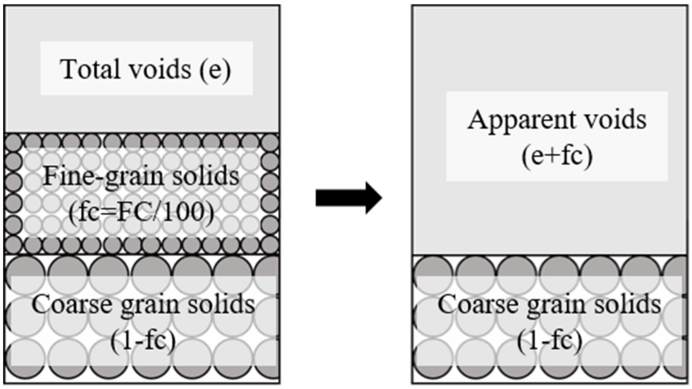

Figure 6. 1 The concept of intergranular void ratio

The intergranular void ratio can be an index of active coarser-granular frictional contact that sustain the normal and shear forces. Thus, soils specimen with higher e_s can be interpreted as a soil having lesser frictional contact between the coarser particles. When the fraction of fines content increases significantly, the finer-grained matrix becomes more compact and starts to actively participate in the force chain (Thevanayagam, 1996).

Based on the specimens used in this study (GW, AG25 and AG10 soils), as the fines content of the soils increases from 10, 25 to 40% the value of e_s increases as shown in figure 6.2.

In the study of Thevanayagam (1993), when e_s is smaller than $e_{max,HS}$ $(maximum\ void\ ratio\ of\ host\ sand\ without\ fines\ contents)$, most of the fines are expected to be confined to the intergranular void space. The $e_{max,HS}$ GW soils was 1.18, based on the results obtained from relative density test. Figure 6.2 shows that e_s of AG10 soils at three different relative densities show lower value than $e_{max,HS}$ of the GW soils. The solid line in the figure 6.2 expresses the constant $e_s = e_{max,HS}$ at different void ratio and fines content.

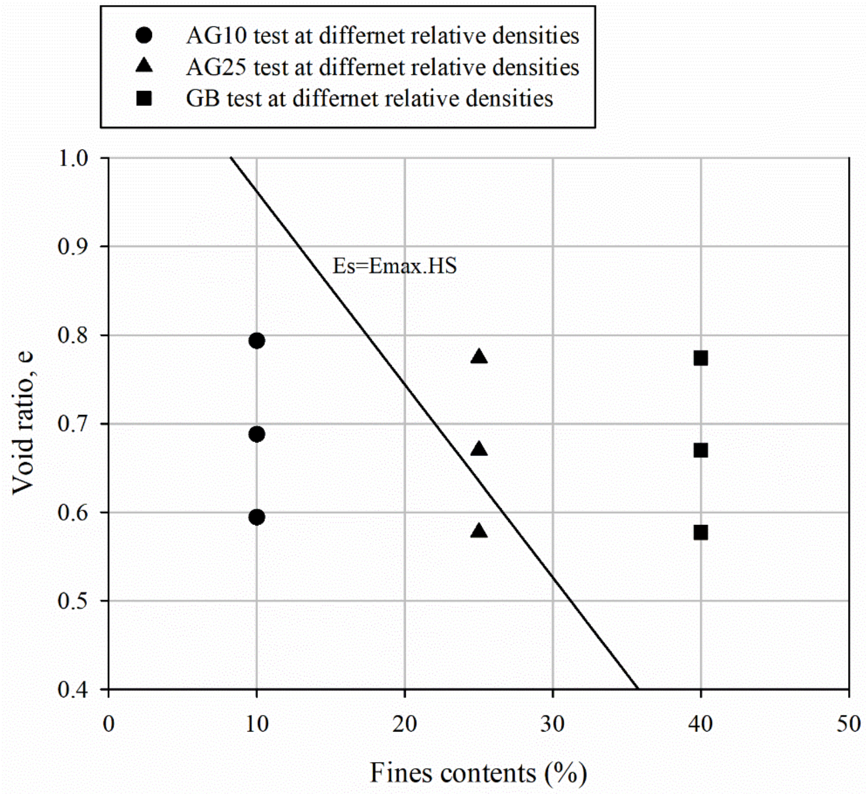

Figure 6. 2 E_s of GW, AG25 and AG10 soils at three different states

Hence, it can be understood that in the case of AG10 test at three relative densities, fine particles were likely to be located within the coarser particles, and coarser particles were the dominant grains participating in the force chain.

In the same vein, in terms of the variation in the hydraulic conductivity, fine particles were more likely to be washed away by the seepage forces, since it doesn’t hold any significant contact forces, leading to an abrupt increase in the hydraulic conductivity. And for the coarser materials, holding the contact forces, the migration was small and its influence on the change in hydraulic conductivity was insignificant.

Together with the fact that the initial hydraulic conductivity was relatively high for the AG10 test, due to the small amount of initial fines content in the specimen, significant amount of soils was discharged eventually leading to a sudden increase in hydraulic conductivity.

The result of GB test showed that the GW soils at loose state can be evaluated as internally unstable based on the amount of soils discharged and variation in hydraulic conductivity. Since the fine fraction of GW soils reached 40%, the value of e_s was significantly higher than the value of $e_{max,HS}$ (figure 6.2).

In this case, fine-grained particles participate in the force chain, and the coarse-grained particles behave like they are floating on the fine particles. Thus, when the fine particles are washed away by the seepage forces, the coarse particles might as well be discharged and the stability of the remaining coarser materials is no more guaranteed, leading to an irregular variation in hydraulic conductivity (figure 5.10).

The fine fractions of the discharged soils of the AG10 (figure 5.16, 17 and 18) and GB tests (figure 5.6) supports abovementioned phenomenon. Although the fine fractions in the soils of AG10 was significantly lower than that of GW soils, the average fraction of fines content in discharged soils reached 54.19% of the initial soil specimen close to the fine fractions in discharged soils during the GB test at loose state (56.86%).

From the suffusion test results, soil specimens with less amount of fines content are turned out to be more susceptible to suffusion. The phenomenon of suffusion is clearly detected in the AG10 test in all cases, since the fines content were mainly kept in between the coarse particles carrying marginal contact forces and was relatively easy to be washed away. For the GB test at the loose state, the soil specimen was evaluated as internally unstable, however the trends in the variation of hydraulic conductivity differs and the fine fractions in the discharged soils is smaller compared to the AG10 test results, due to higher e_s than $e_{max,HS}$. With higher e_s, discharge of the coarse particles was nearly accompanied with the discharge of the fine particles, giving irregular results in the variation of the hydraulic conductivity and yielding relatively lower fine fractions in discharged soils.

Effects of relative density

The suffusion test results based on the variation in the hydraulic conductivity is summarized in table 6.1. Results show that the instability of the soils increases with lower relative density. Except for the AG25 test at loose state, the higher the relative density, the lower the hydraulic conductivity was observed. Since, only a small amount of water flowed through the soil specimen, movable particles were not washed away, and thus the phenomenon of clogging was dominant showing higher rate of reduction in hydraulic conductivity that can be regarded as internally stable. Table 5.14 shows that for the soils at the dense state for most of the tests with proper filter system (GB, AG25 and AG10 tests), the amount of discharged soils were small.

The results summarized in table 6.1, also shows that the susceptibility of soils to suffusion differs with relative density together with the influence of the fines content. For the AG10 tests, all the specimens at different relative densities turned out to be unstable, unlike the GB test results.

It is generally believed that increase in fines content, reinforces the resistance to suffusion, hence it is possible that the soils with higher fines content are relatively more sensitive to the degree of relative density when it is compared to AG10 tests, which all the specimens turned out to be internally unstable, regardless of relative density.

Increase in clay contents provides higher plasticity of the soils, and the resistance of the soils to suffusion can be increased. However, the fine fraction of the GW soils is mainly consisting of silts and the soils shows non-plastic results based on the laboratory plasticity test. Hence, general relationship of increasing in fines content and reinforced resistance to suffusion may not be dominant phenomenon in this study.

Another explanation that can describe the sensibility of soils with higher fines content to different relative densities in terms of the suffusion test is different degree of reduction in the hydraulic conductivity when different level of relative density is applied to soils with varying fines content. The hydraulic conductivity of the soils for different tests (GB and AG10) at loose, intermediate and dense states is given in table 6.3.

Table 6. 3 Variation in hydraulic conductivity at different relative density

		GB test	AG10
Hydraulic Conductivity (cm/s)	$D_r = 49\%$	0.0265	0.0339
	$D_r = 61\%$	0.0096	0.0201
	$D_r = 77\%$	0.0006	0.0114

Hydraulic conductivity for each test is obtained during the suffusion tests, under hydraulic gradient of 2 for initial 5 minutes of testing time (first data point in the figure showing the change in hydraulic conductivity in chapter 5) to reduce the effect of suffusion in change of hydraulic conductivity.

Table 6.3 shows that the reduction in hydraulic conductivity due to higher relative density is most prominent in the case of GW soils with 40% of fines content. When fines content is reduced, the reduction in hydraulic conductivity according to the relative density is smaller.

In the research of Mostefa Belkhatir (2014), hydraulic conductivity of the sand-silt mixtures with varying fines was studied through laboratory test and results were drawn similar to this study. In their study, the hydraulic conductivity of the sand-silt mixtures decreases linearly with increase of the fines content for two different initial relative densities (figure 6.3). The results show that the sands with higher fraction of silts, yields greater reduction in permeability at two different relative densities.

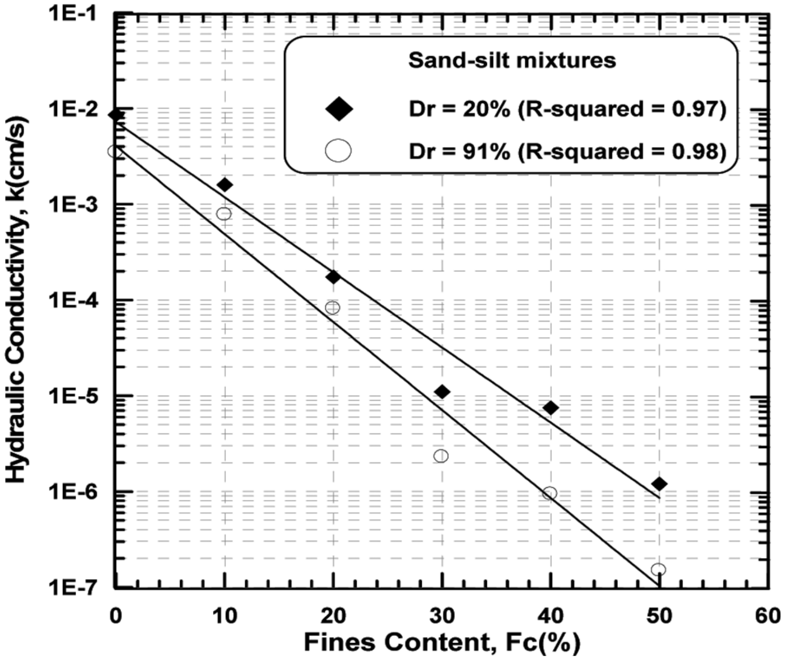

Figure 6. 3 Hydraulic conductivity of the soils with different fines content at different relative densities (Mostefa Belkhatir, 2014)

Thus, it can be concluded that for the GB tests, due to the large amount of fines content in the specimens, the initial hydraulic conductivity decreases significantly when the state reaches to the dense state and, thus the resistance of the soils towards suffusion is increased.

For the AG10 tests, the reduction in hydraulic conductivity depending on the relative density was small. Thus, although the specimens were constituted to reach the dense state, the initial hydraulic conductivity was significantly high enough to allow considerable amount of soils to be discharged.

Effects of different filter system

In this study, laboratory suffusion tests with different filter system were conducted. As shown in figure 4.6, GA test was conducted with glass beads diameter of 16.5mm, yielding 3 to 7 mm of constriction size. Since D_{85} of GW soils corresponds to 2.5mm, GA filter system does not satisfy the filter criteria.

As shown in the results (table 5.1), significant amount of soils was discharged during the experiment reaching approximately 10% of the initial soil mass in the both the soils at loose and dense state. However, during the test, local failure in the specimen was observed. This is due to the greater constriction size formed by the filter materials that does not satisfy the filter criteria. Thus in this study, it is concluded that the phenomenon of suffusion is not the dominant mechanism for the considerable amount of soils discharged in the GA test.

In order to assess the internal stability of the soils through laboratory suffusion tests, filter materials should satisfy the filter criteria, in order to clearly observe the phenomenon of suffusion and determine whether the soil is susceptible to suffusion.

When acrylic bottom plate (BT test) is used as a filter material, the analysis of the post-test grain size distribution can be done simply because it is easy to detach the plate from the seepage cell, unlike in the GA and GB tests in which the soil attached to the glass beads should be selectively washed away and collected for sieve analysis. Furthermore, in the case of the glass beads tests, the soil loss through the voids of the filter material should be considered during the compaction.

More importantly, a disadvantage of using the perforated bottom plate is that it cannot duplicate the actual boundary between the filter and base materials. As shown in the results of BT test (table 5.2 and figure A.1) at the soils at dense state, no water was discharged under the hydraulic gradient of 2 due to the lack of a void network. Since, the dense state of the soils ($D_r = 77\%$) is arranged in the experimental program based on the Dam Design Guidelines in Korea, BT test is concluded to be inappropriate to evaluate the internal stability of the domestic fill-dam materials.

Additionally, when soil specimen was compacted in the seepage cell in order to achieve the desired relative density, same amount of soils was put in the seepage cells for compaction in identical volume for several layers. Therefore, when proceeding layer was compacted using the tamping rod, the compaction energy will be transmitted to the lower layer, densifying the soils to the state which is not generally expected.

Hence, despite the inconvenience of conducting the seepage tests, a filter that can duplicate the filter materials in GB test is preferable in evaluating the internal stability of the soils.

Effects of hydraulic gradient

Hydraulic gradient is increased from 2, 3, 5 to 9 to evaluate its effect of on internal stability of the soils. Variation in hydraulic conductivity during the short-term suffusion tests (35 minutes for different hydraulic gradient, respectively) is shown in each test results.

Unexpectedly, most of the test results in terms of the change in the hydraulic conductivity, showed no clear difference in their trends when hydraulic gradient was increased.

In case of the GB test at intermediate state (figure 5.9), the hydraulic conductivity of the soils was increased abruptly under the hydraulic gradient of 9 and soon showed progressive reduction as the way the trend it was. This is due to the discharged of the soils that was not able to be discharged with relatively low seepage force under lower hydraulic gradient. When the amount of soils that can be can discharged at specific hydraulic gradient is obtained the hydraulic conductivity shows a progressive reduction, meaning that the effect of the clogging becomes dominant again.

This phenomenon is well observed when hydraulic conductivity of the soils is plotted every one minute during the experiments. Figure 6.4, shows the variation in hydraulic conductivity in different hydraulic gradient, in the case of GB test at the intermediate state (repeated experiment to estimate the hydraulic conductivity at every one minute). The abrupt increase in hydraulic conductivity is pronounced (expressed in short dashed line circle in the figure (6.4) when different hydraulic gradient was applied.

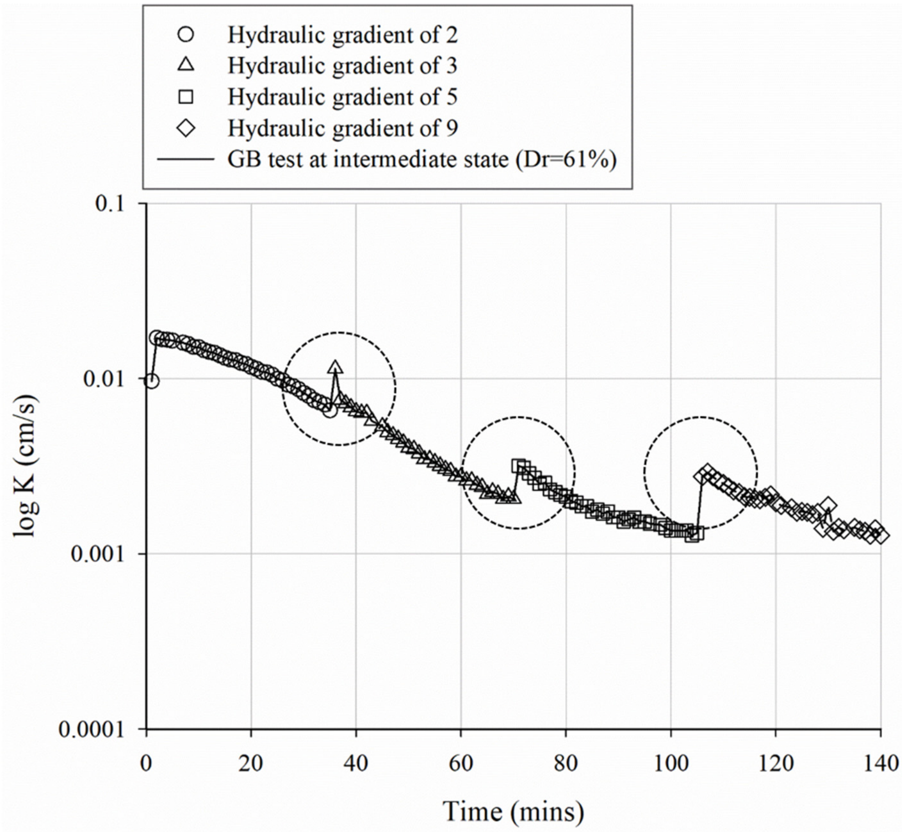

Figure 6. 4 Variation in hydraulic conductivity under the different hydraulic gradient, GB test at the intermediate state

In the study of C.Gruesbeck (1982), entrainment and deposition of fine particles in porous media was studied through laboratory tests. In here, the abrupt increase in hydraulic conductivity is described with the term 'burst'. Part of the conclusion that is drawn from this study is that the steady effluent concentration is established after an initial 'burst' of fines efflux following each flow rate change.

Thus, in this experiment, sudden increase in hydraulic conductivity is related to the soils migration that resulted in the discharged of the soils. It is authors opinion that the phenomenon of bursting can be related to the particle structure of the soils specimen, which has been expressed with the value of e_s, mentioned in the 'effect of fines content', since this phenomenon was not found in the AG10 test in which the soils are regarded to be located in the matrix of the coarser particles.

In order to evaluate the effect of different hydraulic gradient at laboratory suffusion tests, long-term experiment should be conducted, under a constant hydraulic gradient. In this test, at each hydraulic gradient, the testing time was set up for only 35 minutes, thus the clear effect of the different hydraulic gradient was not observed.

Effects of vibration

The effect of vibration is described where the comparisons are made between the assessment results based on the method of Kenny and Lau (1985) and experiment results.

The suffusion test results summarized in table 6.1 shows that the vulnerability of the soils to vibration process differs according to the relative density of the soils. Thus, when adopting the process of vibration, the density of the soils should be clarified.

As it has been mentioned earlier, the quantification in vibrational forces related to the acceleration of soils migration is needed in order to properly evaluate the effects of vibration.

Chapter 7 Conclusions

In this study, assessment on internal stability of the soils have been made based on the criteria proposed by Kenny and Lau (1985) and Wan and Fell (2008). Additionally, a series of laboratory suffusion tests are conducted in order to evaluate the internal stability of the soils, which represents the fill dam materials in Korea. Influential factors, such as the soil, filter system, relative density, hydraulic gradient and vibration are evaluated together. From the assessment and experiment results, the conclusions below were drawn.

1. The phenomenon of suffusion has been studied by several investigators, and they have proposed criteria to evaluate the vulnerability of the soils to suffusion based on the suffusion tests. However, the experiment programs are different in detail thus, the suggested criteria may not be generally applicable.

2. Using the methods proposed by Kenny and Lau (1985) and Wan and Fell (2008) the internal stability of GW soil, AG25 and AG10 soils were assessed. Kenny and Lau (1985) method showed that the soils are unstable towards suffusion whereas Wan and Fell (2008) method showed stable results.

3. The suffusion test results of GA tests showed that a suffusion test with filter materials that do not satisfy the filter criteria, is not appropriate for the suffusion test, since the phenomenon of suffusion was not clearly observed. The results of the BT test showed that the bottom plate which duplicates the constriction size of the filter materials is not suitable for suffusion tests, since suffusion tests can't be conducted for the soils at the dense state. Thus, the GB test is concluded to be more appropriate for the suffusion tests.

4. Suffusion test results of GB, AG25 and AG10 test, based on the amount of soils discharged, correspond well to the assessment results of Wan and Fell (2008), in case where the vibration is not applied. The method of Kenny and Lau (1985) showed poor prediction on the internal stability of the soils. Suffusion test results based on the change in hydraulic conductivity, showed that the soils are more susceptible to suffusion with lower fines content and relative density.

5. The effect of soil properties (fines content), can be understood based on the concept of intergranular void ratio. If the fines content are reduced, the resistance of soils to suffusion was decreased since e_s is small and movable particles are less likely to hold contact forces. With lower relative density the phenomenon of suffusion was pronounced, since finer soil particles were more likely to be eroded from the specimen with higher flow rate. In case of the soils, with small fines content, the effect of relative density was insignificant due to the small variation in hydraulic conductivity with respect

to the relative density and higher initial hydraulic conductivity. For the filter system, based on the results of the GA and BT test, filter materials that can duplicate the actual boundary of the filter and base materials should be chosen with the consideration of the filter criteria. When different hydraulic gradient was applied, hydraulic conductivity increased abruptly due to the 'burst' in soil particles. Its effect will be evaluated accurately with extended period of experiment time under consistent hydraulic gradient. The effect of the vibration was differed according to the relative density of the soils. Soils with lower relative density showed small resistance to vibration. Quantification on vibrational forces should be established in order to consider the effect of vibration in accelerating the migration of particles properly.

Appendix A

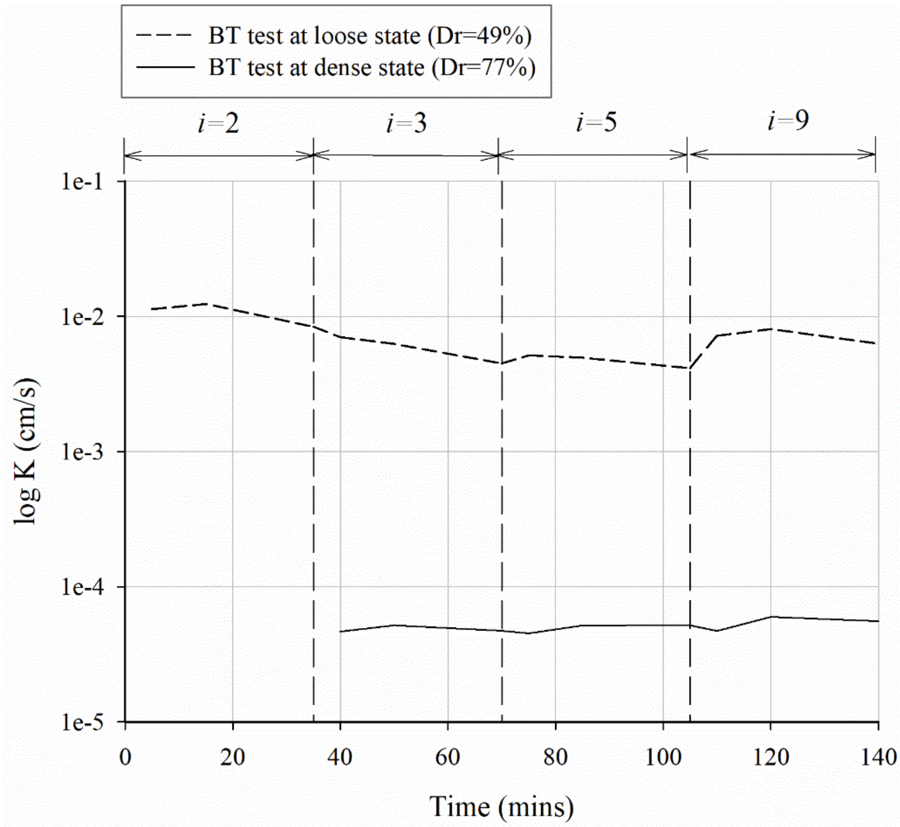

Figure A. 1 Results of the estimated hydraulic conductivity under different hydraulic gradient for BT test

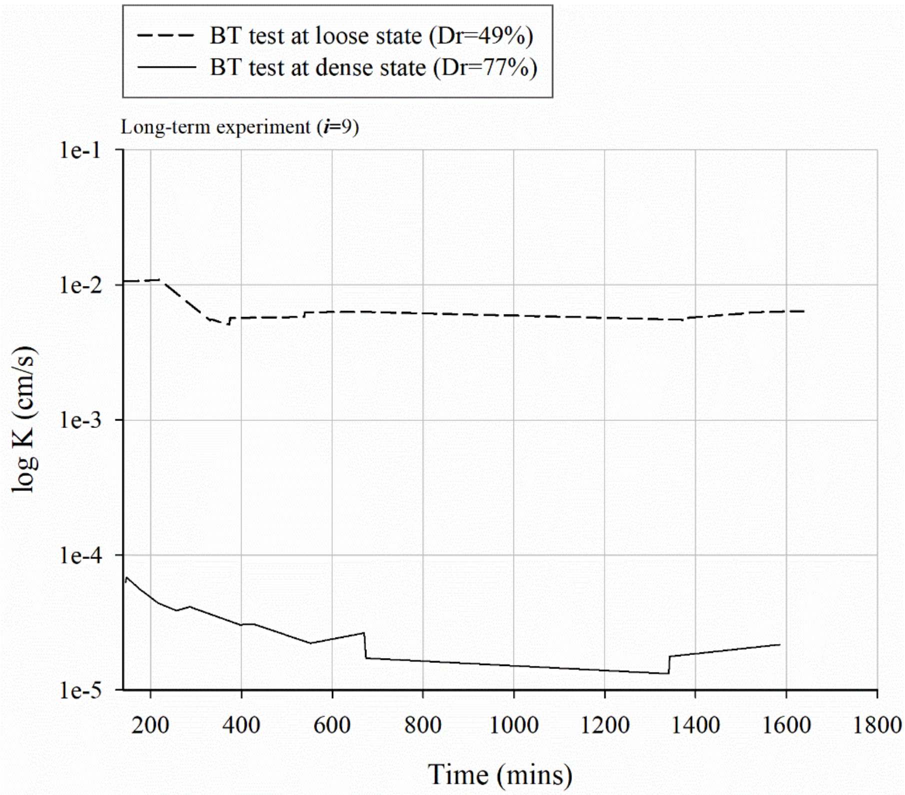

Figure A. 2 Results of the estimated hydraulic conductivity for long-term experiment of BT test

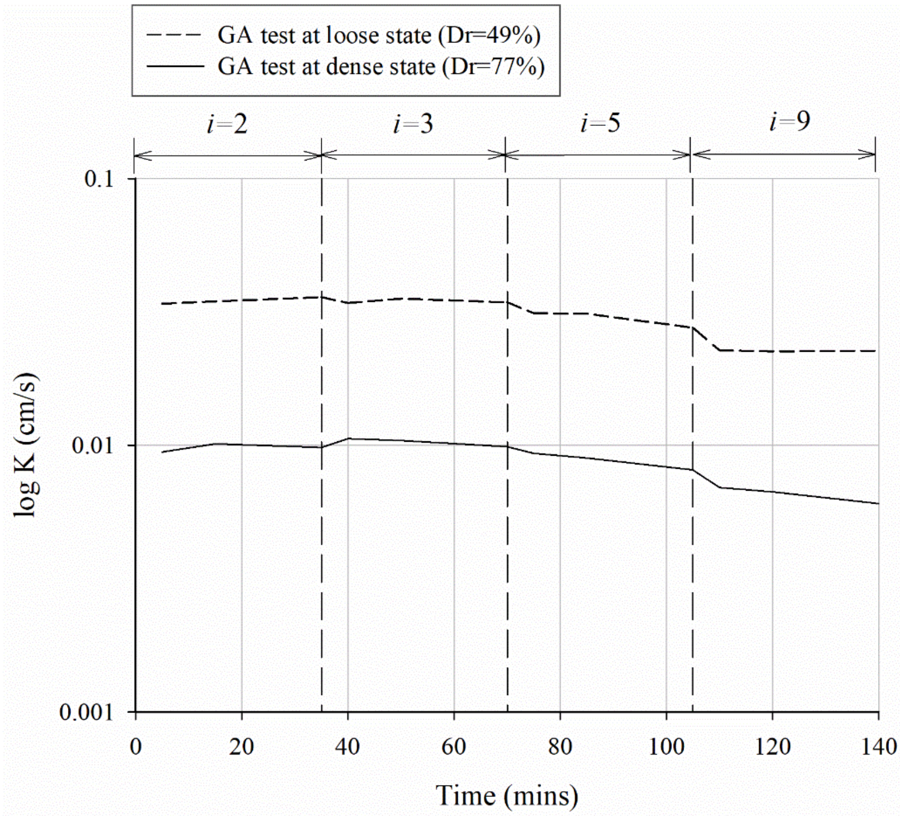

Figure A. 3 Results of the estimated hydraulic conductivity under different hydraulic gradient for GA test

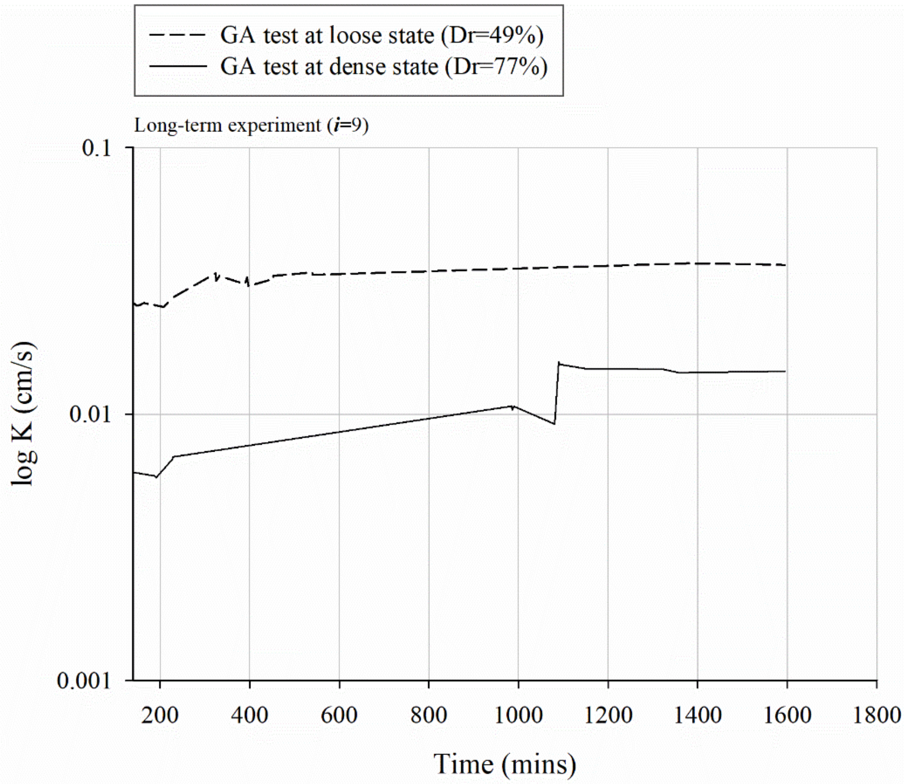

Figure A. 4 Results of the estimated hydraulic conductivity for long-term experiment of GA test

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초록

국내 댐은 대부분 필댐이며, 화강암을 모암으로 하는 풍화토를 제체 재료로 이용하고 있다. 이러한 구조물은 다양한 메커니즘에 의해 파괴로 이어질 수 있으며 그 중 내부침식은 댐 파괴의 주원인이다.

Suffusion 현상은 내부 침식 중 하나로 물의 침투에 의해서 흙의 구조를 이루는 큰 흙 입자 사이를 작은 흙 입자들이 이동하는 현상이다. 이로 인하여 흙의 투수성과 간극비가 증가되고 전단강도가 감소되어 댐에서 piping 등의 내부 침식을 유발할 수 있다.

따라서 해외에서는 suffusion에 관한 연구가 활발히 진행되고 있으며, 실내 침투 시험을 바탕으로 suffusion 기준을 설정하고 이를 적용하여 댐의 안정성을 평가하고 있다. 그러나 국내에서는 suffusion 현상 그리고 기준 설정에 대한 연구가 미비한 실정이다.

해외에서 널리 이용되는 suffusion에 대한 안정성 평가 방법은 실내 침투 시험 결과를 바탕으로 설정한 입도분포 곡선상의 기준을 대상 흙에 적용하는 것이다. 하지만, 실험 방법과 실험에 이용된 흙이 연구자마다 상이하여 기존의 기준을 이용해 국내 댐 제체 재료의 suffusion에 대한 안정성을 평가하는 것은 적합하지 않다.

실제로 suffusion에 대한 안정성 기준을 국내 댐 제체 재료에 적용해 보았을 때, 기준마다 상이한 평가 결과를 보였다. 따라서, 국내 댐 제체 재료의 suffusion에 대한 안정성을 보다 정확히 평가하기 위해서는 해당 제체 재료에 대한 실내 침투 시험이 수행되어야 한다.

본 연구에서는 국내 댐 제체 재료를 대표할 수 있는 관악산 풍화토를 이용해 실내 침투 시험을 수행하였다. 시험 결과를 바탕으로 국내 댐 제체 재료의 suffusion에 대한 안정성을 평가하였다. 또한, 실험 시 연구자마다 상이하게 고려한 흙 (세립분 함량), 상대밀도, 필터 (유출부 형상), 동수경사, 진동의 유무 등을 고려하여 suffusion 실험에 대한 영향요소를 함께 평가하였다. 결과적으로, 국내 댐 제체 재료는 세립분 함량과 상대밀도가 낮을수록 suffusion 현상에 취약한 것을 확인할 수 있었다.

주요어 : Suffusion, 내부침식, 실내 침투 시험, 필댐, 댐 파괴모드, 입도분포곡선

학 번 : 2017-22346