Effect of Fine Particles on Cohesion-less Soil

by

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2021

Abstract

Suffusion is the process in which finer soil particles moving through the spacing between larger soils particles by external forces, such as vibration or seepage force. This process which causes missing small particles in the granular soil should cause changes in the mechanical and hydraulic properties of the soil.

One of the methods to treat suffusion in granular materials is adding binding agents, such as clay, in order to save the granular materials from missing of fine particles by migration. In this experimental study, the binding agent (clay) represented in fine percentage was used to treat suffusion in an embankment filter. The results showed that the hydraulic conductivity of the soil significantly decreased with the increase in the percentage of fine particles. This can be considered as a method to treat the suffusion. In other words, the significant decrease in the hydraulic conductivity of the gap-graded soil can be considered as the elimination or reduction of the chance of occurring fine particle movement under the same hydraulic gradient.

Chapter One: Introduction

1.1 General

Earth structures, such as dams and dikes (levees), can be damaged by the presence of water through three mechanisms; sliding, overtopping, and internal erosion (**Bendahmane et al., 2008**). Subsurface erosion has been one of the most prevalent causes of catastrophic failures of levees and earthen dams. Such examples include the 1972 failure of the Buffalo Creek dam in West Virginia (**Wahler 1973**) and the 1990 collapse of an earthen dam in South Carolina (**Leonards and Deschamps 1998**).

Internal erosion appears to be one of the main causes of failures and damage to embankment dams erosion (**Foster et al., 2000; Bendahmane et al., 2008**). Foster et al. (**2000**) carried out a survey on 11.192 dams. One hundred and thirty-six dams of the total number of the surveyed dams showed dysfunctions. The dysfunctions were classified as follows; up to 5.5% was related to sliding, 48% was related to overtopping and 46% was related to internal erosion (**Foster et al. 2000**).

1.2 Internal Erosion

Internal erosion (IE) refers to any process by which soil particles are eroded from within or beneath a water-retaining structure. IE is a particularly dangerous process as it gradually degrades the integrity of a structure in a manner that is often completely undetectable. Further, 46 per cent of all historical embankment dam failures have been attributed to IE, making it one of the greatest risks associated with embankment dams, second only to overtopping related failures (**Foster et. al 2000**).

IE can be subdivided into four distinct erosion mechanisms: concentrated leak erosion, backward erosion piping, internal instability, and contact erosion (**Bonelli 2013; ICOLD 2015**).

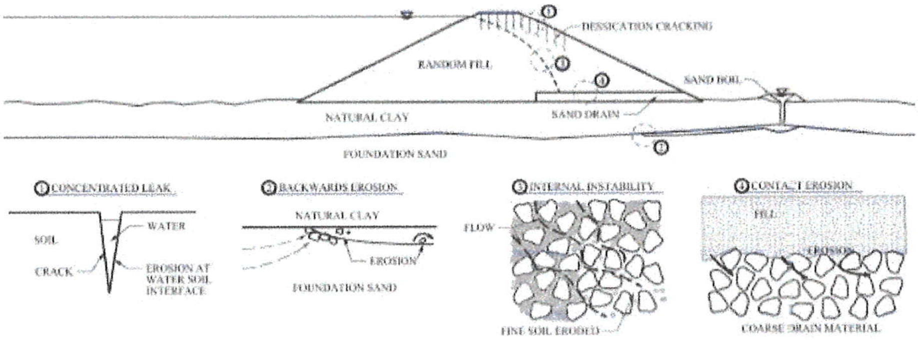


FIGURE 1.1, Illustration of the Four Types of Internal Erosion.

When internal erosion occurs, the hydraulic, permeability, and mechanical characteristics, strength, and compressibility, of the soil are altered (**Bendahmane et al., 2008**). Improvements in understanding internal erosion mechanisms are hindered by the complexity of these mechanism and the difficulties associated with their detection.

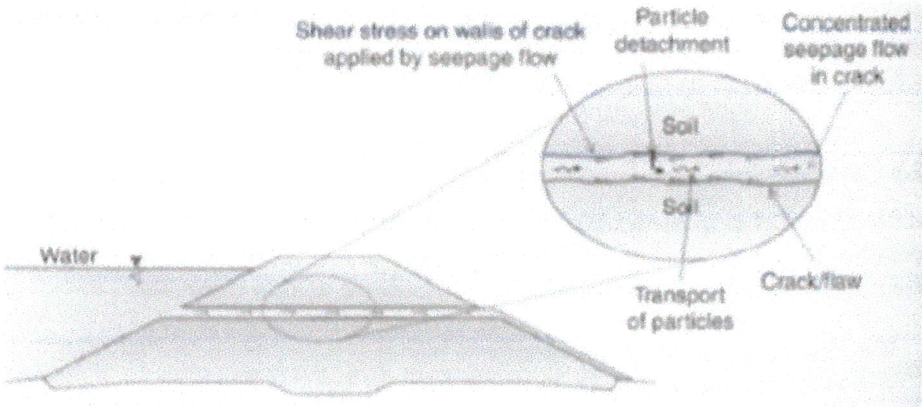


FIGURE 1.2, Internal erosion in concentrated leaks (Fell et al. 2014)

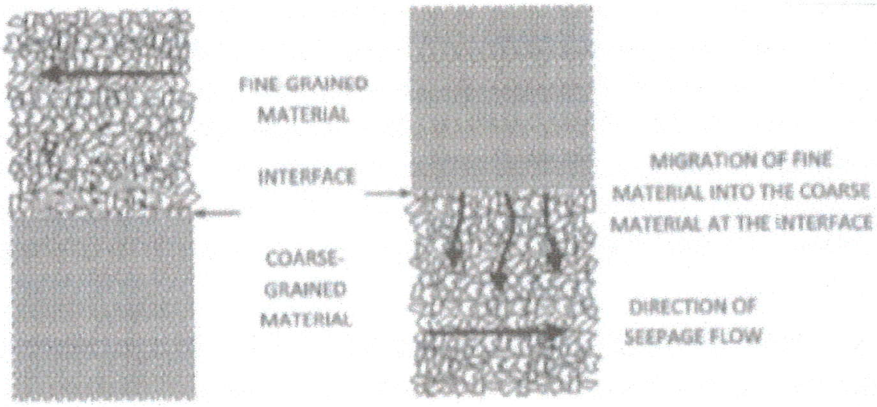


FIGURE 1.3, Diagram of contact erosion (Fell and Fry, 2013)

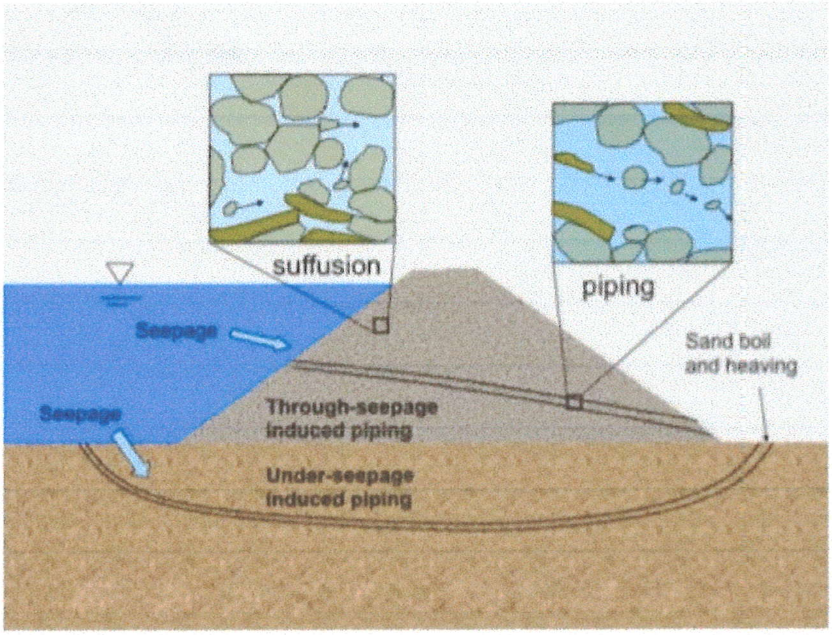


FIGURE 1.4, Sub-surface erosion in an earthen embankment. (Xiao and Shwiyhat, 2012)

1.3 Suffusion

Suffusion is the process by which finer soil particles are transported through constrictions between larger soil particles by seepage forces (**Wan and Fell, 2008**). Figure (1.5) shows the concept of suffusion. Soils susceptible to suffusion are usually described as internally unstable (**Wan and Fell, 2008**).
Internally unstable soils are usually broadly graded soils with particles from silt or clay to gravel size, whose particle size distribution curves are concave upward, or gap-graded soils (**Wan and Fell, 2008; Fell et al. 2014**). Suffusion occurring within an embankment core, see Figure (1.6), or the foundation of a dam will result in a coarser soil structure, leading to increased permeability and seepage, likely settlement of the embankment, and a higher likelihood of downstream slope instability that may fail of the dam (**Wan and Fell, 2008; Fell et al. 2014**).
Regarding the filters, in embankment dams, constructed of internally unstable materials will have a potential for erosion of the finer particles, Figure (1.5).
The concept of suffusion (**Wan and Fell, 2008**), Figure (1.6).
Suffusion occurring within an embankment core (**Fell et al. 2014**) rendering the filter coarser and less effective in protecting the core materials from erosion so the piping failure may result. According to **Skempton and Brogan (1994)**. suffusion

occurs at a hydraulic gradient of about one-third to one-fifth of Terzaghi's critical gradient method for homogeneous granular soil.

Terzaghi (1943) defined the well-known critical hydraulic gradient, i_{cr}, to cause piping failure in homogeneous granular soil as follows:

$$ic = \frac{Gs + e}{1 + e}$$

where Gs, is the density of the soil particles (or specific gravity of the soil), and e is the void ratio of the soil.

Laboratory experiments provide a potential insight into the induced processes.

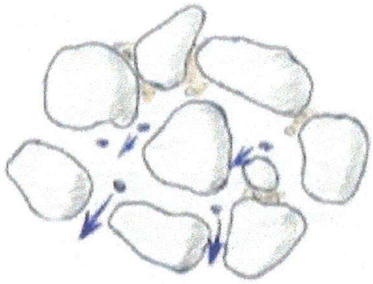


FIGURE 1.5, The concept of suffusion (Wan and Fell, 2008).

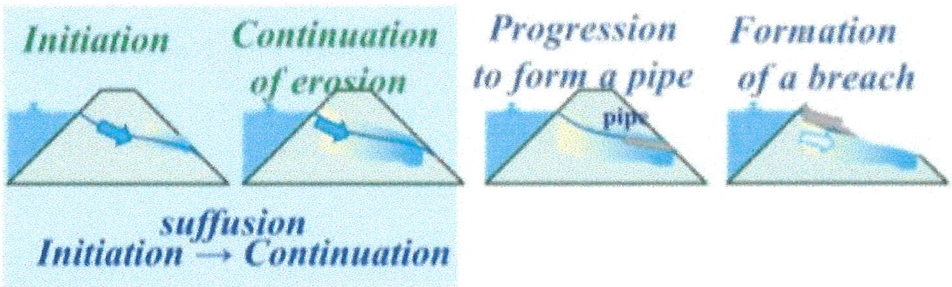


FIGURE 1.6, Suffusion occurring within an embankment core (Fell et al. 2014)

1.4 Gap graded

Soil Gap grading is a type of grading which lacks one or more than intermediary size. *By definition gap graded soils have a range of lost particles (usually fine to medium sand particles). Apparently, the hiatus in particle sizes is useful to clast-supported fabric which may respect the conditions of internal instability Fig.1.7

The size of voids build by a particular size of aggregate can hold the second or third lower size aggregates only i.e. voids created by (40) mm will be able to hold size equal to 10 mm or (4.75) mm but not (20) mm. This access is called Gap Grading.

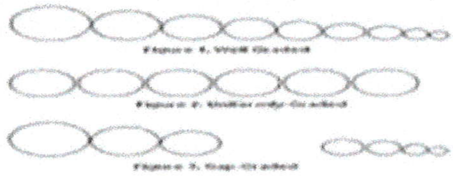


Fig. 1. Types of Soil Gradient

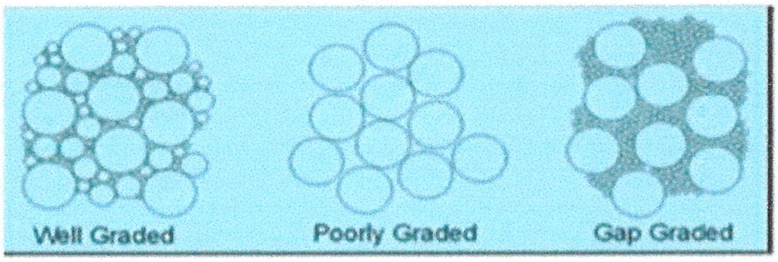


FIGURE 1.7, Types of soil gradient with voids.

1.5 Objectives of the Project

Since soils suitable to suffusion involve an easy movement of fine particles Between the coarse ones, the goal of this study is to examine the effect of silt and clay present on the seepage-induced suffusion process in cohesion less gap graded soils. The hypothesis behind the idea of this goal is that the silt and clay present, as a binder material, can reduce the mobility of fine particles among the coarse ones, which in turn may lead to eliminate or alleviate the suffusion adverse effects.

In order to achieve the goal, the objectives of this study are:

1. Firstly, to reproduce the seepage-induced suffusion with the small-scaled model in the laboratory.
2. Secondly, to identify the possibility of cement present on the elimination or alleviation of seepage-induced suffusion in cohesion less gap-graded soils.

Chapter Two: Literature Review

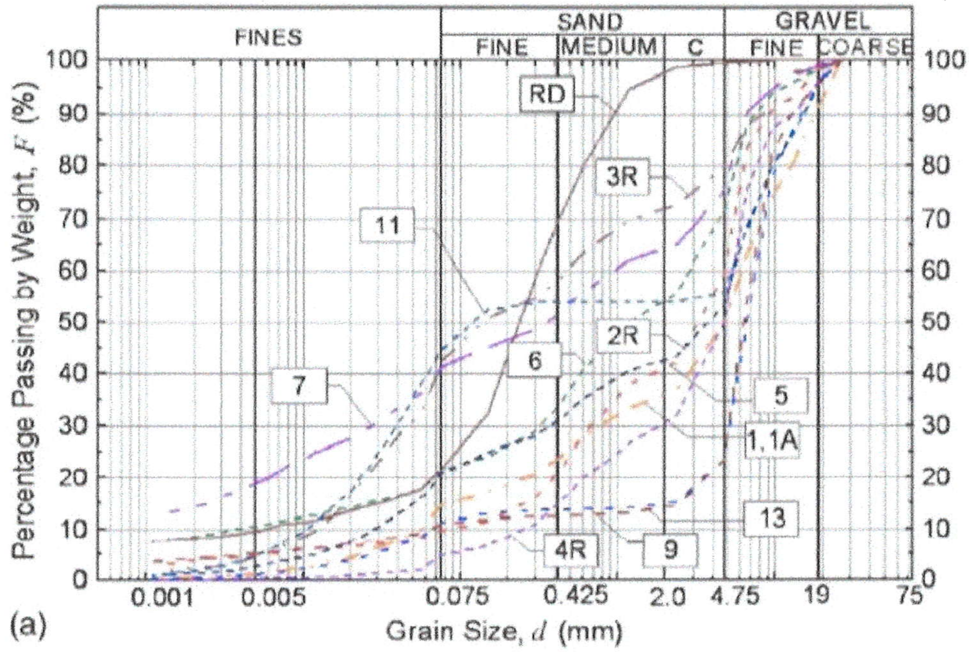
2.1 General

The phenomena of internal stability and suffusion of cohesion less soils have been studied by a number of investigators over a period of more than 50 years, commencing with the US Army Corps of Engineers in 1953. This chapter provides a brief review of the findings of those previous investigations, including terminology used to describe behaviour, geometric criteria proposed to evaluate susceptibility, and insights into the hydraulic conditions that trigger the onset of instability.

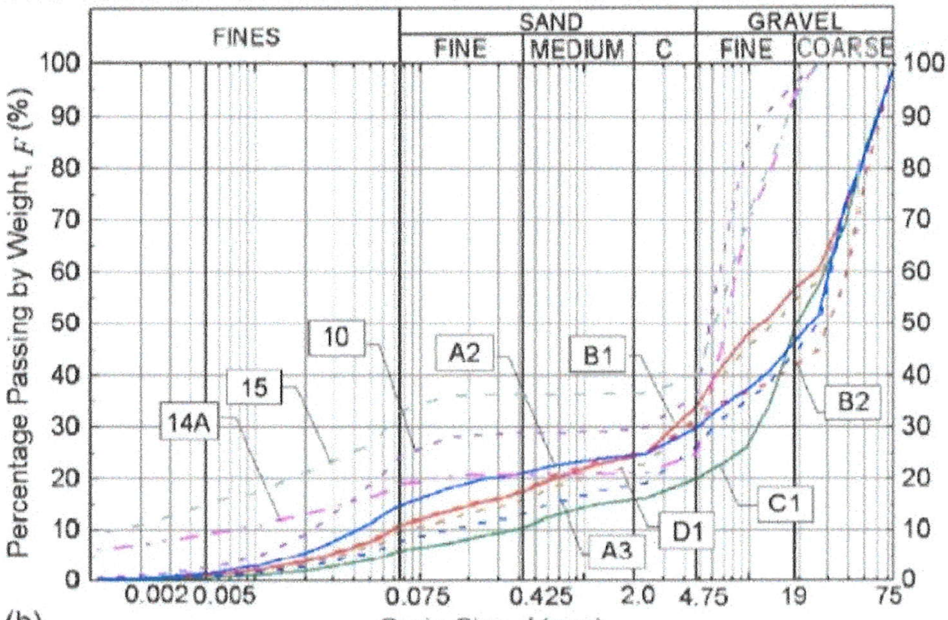
2.2 Internal Instability

Wan and Fell (2008) presented improved methods for assessing whether silt sand-gravel, or clay-silt-sand-gravel soils are internally unstable. The methods were based on laboratory tests carried out by the writers, and the results of testing by others. In the laboratory tests, twenty samples, 300-mm-thick compacted soil samples, were tested under water constant head of 2.5m. Figures (2.1a&b) show the particle size distribution curves of the 20 test samples. Six samples contain kaolin in the percentages ranging from 5 t0 22.

Other samples were non-plastic. Test samples were compacted in the seepage cell to the specified degree of compaction and water content, typically at 95 or 90% of the standard maximum dry density, and at optimum water content. This was to replicate the likely range of densities in the core of dams and gravely soils in dam foundations. The water head was corresponding to a hydraulic gradient of about 8 which is higher than would normally be expected in the core or foundation of a dam but may be experienced across filters or transition zones. The tests were maintained until no fine particles were seen washed out from the test sample and the pressures at various depths of the sample, and the rate of water flow through the sample attained steady values. The results showed that the most widely used methods to assess whether a soil is internally unstable are conservative. Mino- differences in the shape of the particle size distribution affect whether the soil is internally stable and it is recommended that for important projects laboratory tests be carried out on the soils which are tested in the marginal areas to confirm the assessments made by the methods suggested here. Soils that have less than 15% finer fraction, 20% for the alternative method, may not be adequately assessed by these methods. While it has not been proven by tests, if the slope of the finer fraction is used in lieu of the $(\frac{d20}{d5})$ ratio the alternative method should be applied.



Figures (2.1(a)), the particle size distribution curves



(b)

Figures (2.1(b)), the particle size distribution curves

Rochin et al., (2017) carried out downward seepage flow tests on three gap-graded soils and one widely-graded soil composed of sand and gravel in a cell having 50 mm diameter and heights up to 100 mm. A laser diffraction particle-size analyser was used to measure the grain size distribution of these soils (Figure 2.2). Tests were performed with demineralized water and without a deflocculating agent. These soils were selected in order to obtain internally unstable soils. Their gradations slightly differ, mainly with respect to the fine content ranging from 20% to less than 30% (see Figure 2.2). According to grain size–based criteria these soils are indeed internally unstable but close to the stability limits defined by several methods currently available and detailed hereafter. For all studied soils, the uniformity coefficient Cu is around 20. As the percentage of fine particles (smaller than 0.0633 mm) is smaller than 5%, and the gap ratio Gr is higher than 3, Chang and Zhang's (2013) method assessed widely-graded soil R and gap-graded soils A, B, and C as internally unstable. However, Gr value for soils A and B is slightly higher than 3, corresponding to the stability boundary proposed by Chang and Zhang (2013). The method proposed by Indraratna et al. (2015). combines the particle size distribution and the relative density. According to this method, all specimens are considered to be internally unstable. The results showed the significant effect of hydraulic loading history on the value of critical hydraulic gradient. Moreover, the method characterizing the erosion susceptibility based on the rate of erosion does not lead to a unique characterization of the suffusion process for different types of hydraulic loading.

The new analysis is based on energy expended by the seepage flow and the cumulative eroded dry mass. The results demonstrate that this approach is more effective to characterize suffusion susceptibility for cohesion-less soils.

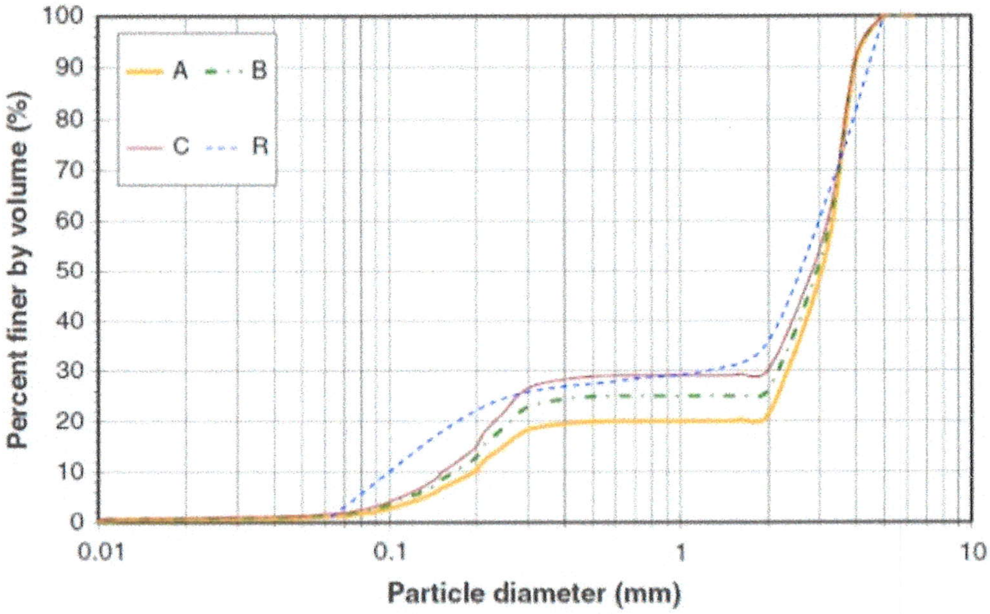


Figure (2.2), the grain size distribution

Chapter Three: Research Methodology

3.1 General

The purpose of this chapter is to recreate the initiation of the suffusion phenomenon and its continuation in an embankment, physical model tests in the small-scaled model are conducted with controlling experimental parameters, such as hydraulic boundary condition, fines content of the soil. The flow rate and piezometric heads are measured to confirm the incidence of suffusion, and to select the best experimental condition for further tests.

3.2 Material

The materials tested in this study (sand, silt and clay), were obtained from the Darband River (Pshdar).

The natural river materials, washed (wet washing) on sieve No. 200 to obtain the porous media, sands. The amount of soil passed through sieve No. 200 is 24 hours left in the oven to obtain silt and clay of the sample. And then hydrometer test used to determine the particle size distribution of clay and silt.

The washed sands were then sieved into different sizes. The fraction of materials retained between two nearest standard sieves was taken to find the particle size distribution. Table (3.1) shows the Particle Size Distribution of the gap-graded soil tested. Table (3.2) shows particle size distribution of clay and silt.

The water used in the tests was tap water having a normal turbid meter of about 0.02 nephelometric turbidity unit (NTU).

Sieves No.	3/8	4	8	16	30	60	100	150	200
Opening, mm	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.106	0.075
(% passing)	100	85.3	44.52	21.71	19.41	19.15	9.05	8.4	0

Table (3.1) Particle Size Distribution of the gap-graded soil tested

Percent finer	76.03	74.05	70.09	66.13	60.19	54.25	49.3	42.35	41.38	33.46	26.53	14.65
Particle size (D)	0.08	0.057	0.041	0.029	0.021	0.015	0.011	0.008	0.005	0.004	0.003	0.001

Table (3.2), particle size distribution of clay and silt.

3.3 Experimental Apparatus

For the purpose of the experimental works, permeability test, A special porous media bed was built. Figures (3.3) shows a photograph of the rig. The bed, porous media column, was made of a Perspex (Plexiglas) pipe, 75 mm in diameter and 100 mm in length. The Plexiglas pipe was externally threaded at both ends with two internally threaded brass caps. To support the sand inside the column, a steel screen with 75-μm openings, enhanced by a perforated steel plate, was used; this screen was placed in the lower brass cap. Hydraulic head distributions, piezometric heads, along the bed were measured by three plastic tubes, which were connected laterally to the porous media column.

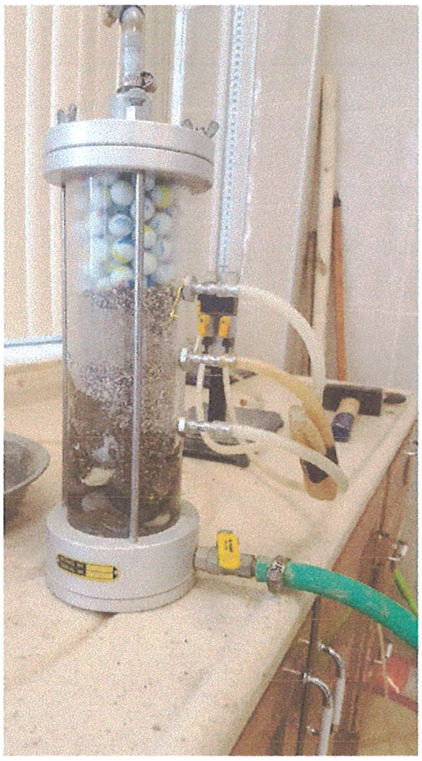


Figure (3.1), The rig - the bed and porous media column

3.4 Test Setup and Procedure

In this study, 3 tests will be carried out as shown in Table (3.3). For each test, after placing all the materials in the pipe, the porous media column will be checked for leakage. Tap water is then allowed to flow through the bed for about one hour with small discharges in order to release air bubbles in the bed, if any, and stabilize the bed grains. For the first bed, beds with zero fines content, the initial permeability (initial hydraulic conductivity - *Ki*), with tap water under minimum constant flow rate, is determined using Darcy law assuming that the flow will be laminar. The flow rate is then gradually increased until the suffusion occurs; the hydraulic gradient reaches the critical hydraulic gradient.

For the beds with non-zero fines content, beds containing fines material, the flow is gradually increased until the suffusion occurs. If the suffusion does not occur, the test will be terminated when the flow reaches the flow rate corresponding to the maximum available flow rat in the soil laboratory at the University of Sulaimani. During each test, the following measurements, with time, were taken:

1. Piezometric heads from the tubes connected to the porous media column,
2. Flow rates,
3. Effluent turbidity and
4. Temperature.

For each bed, 3 tests were attempted: one for finding the critical hydraulic gradient and the other two tests with two different fines content. Thus, the total number of experimental runs was 3.

Run Number	Bed Number	Fines Content %
R1	Bed#1	0
R2	Bed#1	5
R3	Bed#1	10

Table (3.3) Details of experimental runs

Chapter Four: Results and Discussion

4.1 General

A gap-graded cohesion less soil was prepared and tested in a transparent cell under the constant head. The seepage discharge was then increased until the suffusion process occurred.

4.2 Gap-graded soil without fines- plain soil

The prepared gap-graded cohesion less soil was tested in a transparent cell under a constant head without adding any amount of cement; plain gap-graded soil. The seepage discharge was then increased until the suffusion process occurred. The Darcy law was used to determent the hydraulic conductivity of the soil as shown below:

$$k\,(cm/s) = \frac{Q\,(cm3/s)}{(\Delta H/\Delta L) * A(cm2)}$$

where *k* is hydraulic conductivity, Q is seepage discharge, ΔH/ΔL (*i*) is a hydraulic gradient and A is soil cross-sectional area.

The results of the test are represented in Figure (4.1). From the figure, the hydraulic conductivity of the soil was increased versus seepage discharge. The reduction in the hydraulic conductivity of the soil can be attributed to the fine particle movement that may lead to clogging the pores in the soil. This phenomenon is called self-filtration and is very well known for cohesion less soils. As discharge increases, the seepage velocity inside the pores increases as well. This leads to pushing the fine particle deeper into the soil and then finally washing out them. This in turn leads to an increase in the hydraulic conductivity of the soil. From the results, see Table (4.1).

Run No.	Volume, V, cm3	Time, t, second	Discharge, *Q*, cm3/s	Hydraulic gradient, *i*	Area, A, cm2	*Hydraulic Conductivity, K*, cm/s	Velocity, *v*
1	0.045729	20.8	2.019231	2.3	44.156	0.0199	0.045729
2	0.059227	22.56	2.615248	2.79	44.156	0.0212	0.059227
3	0.111819	16	4.9375	4.06	44.156	0.0275	0.111819
4	0.173113	19.1	7.643979	5.37	44.156	0.0322	0.173113
5	0.263414	13.67	11.63131	7.26	44.156	0.0362	0.263414
6	144	11.12	12.94964	7.64	44.156	0.111	0.29327

Table (4.1) The experimental runs for the plain gap-graded soil

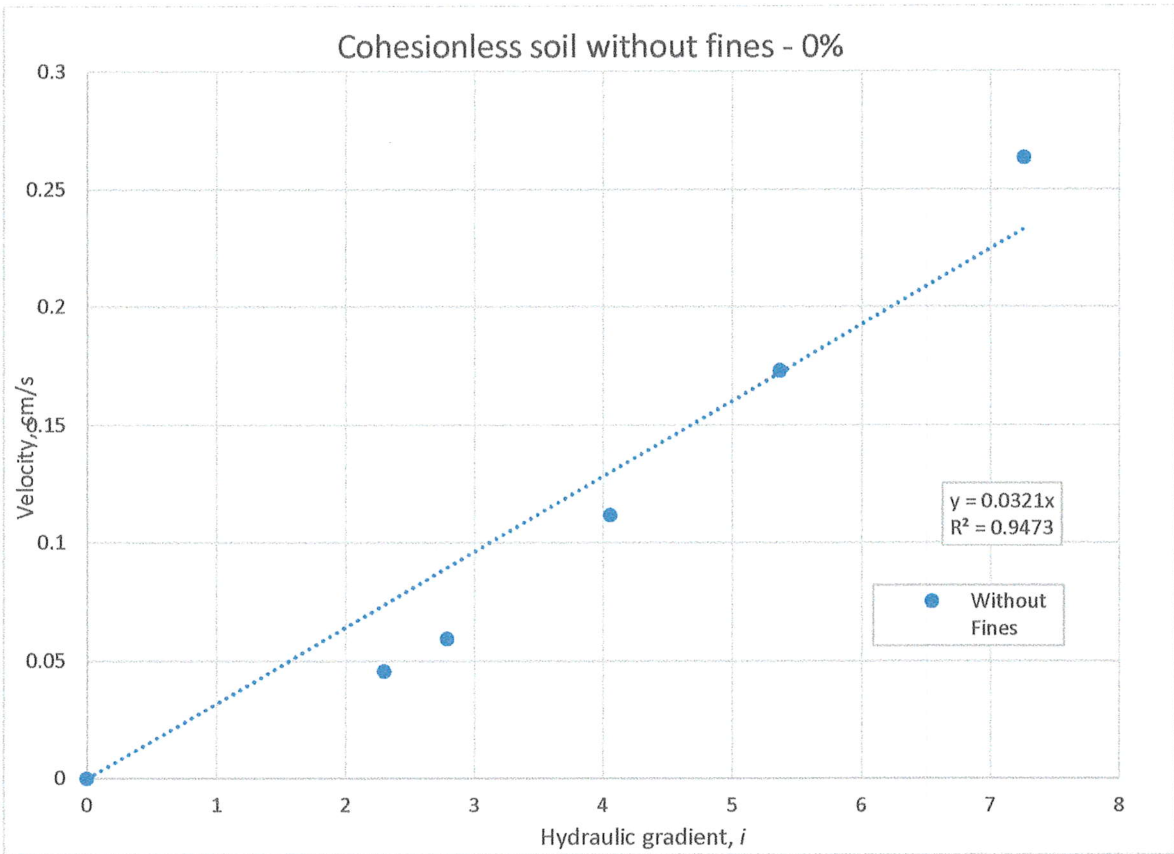


Figure (4.1) Hydraulic gradient versus velocity.

4.3 Gap-graded soil containing fines particles

Samples by mixing the plain gap-graded cohesion less soil with different percentages of clay and silt were prepared. The prepared samples were placed under constant head tests starting from very small seepage discharges.

4.3.1 Gap graded soil with 5% of clay and silt.

In order to prepare a sample containing 5% of clay and silt, one kilogram of the plain gap-graded cohesion less soil was mixed with 50 grams of clay and silt. The sample tested starting with a very small seepage discharge. The hydraulic conductivity of the soil was very small.

The gap-graded soil contains 5% of clay and silt are shown in Table (4.2).

Run No.	Volume, cm3	Time, t, second	Discharge, *Q*, cm3/s	Hydraulic gradient, *i*	Area, A, cm2	*Hydraulic Conductivity, K*, cm/s	Velocity, *v*
1	0.008373	56.8	0.369718	4.875	44.156	0.00172	0.008373
2	0.008514	58.52	0.37594	5.58	44.156	0.00152	0.008514
3	0.0087	64	0.359375	6.19	44.156	0.00132	0.0087
4	0.00887	60	0.391667	6.91	44.156	0.00128	0.00887
5	0.0091	62	0.387097	7.49	44.156	0.00117	0.0091

Table (4.2) The experimental runs for the plain gap-graded soil with 5% clay and silt.

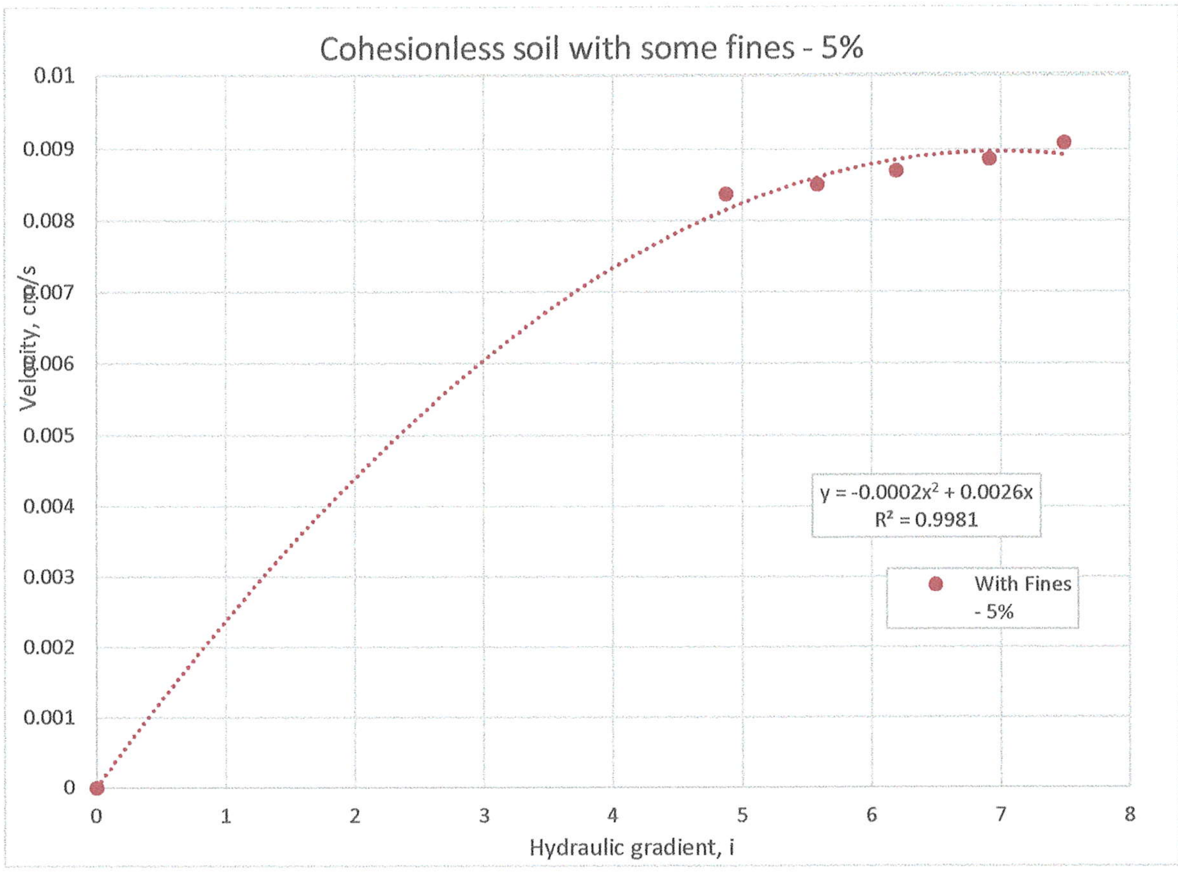


Figure (4.2) Hydraulic gradient versus velocity.

4.3.2 Gap graded soil with 2.5% of Portland cement.

In order to prepare a sample containing 10% of clay and silt, one kilogram of the plain gap-graded cohesion less soil was mixed with 100 grams of Portland cement.

The sample tested starting with a very small seepage discharge. The results of the test carried out on the gap-graded soil contain 10% of clay and silt are shown in table (4.3) and Figure (4.3). From the results, again the hydraulic conductivity of the soil was decreased versus seepage discharge.

The reduction in the hydraulic conductivity of the soil can be attributed to the fine particle movement that may lead to clogging the pores in the soil. This phenomenon is called self-filtration and is very well known for cohesion less soils. As discharge increases, the seepage velocity inside the pores increases as well. This leads to pushing the fine particle deeper into the soil and then finally washing out them. This in turn leads to an increase in the hydraulic conductivity of the soil. From the results, see Table (4.3).

Run No.	Volume, V, cm3	Time, t, second	Discharge, *Q*, cm3/s	Hydraulic gradient, *i*	Area, A, cm2	*Hydraulic Conductivity, K*, cm/s	Velocity, *v*
1	7	57	0.122807	4.89	44.156	0.00172	0.002781
2	7.333333	58.52	0.125313	5.59	44.156	0.00152	0.002838
3	7.666667	64	0.119792	6.2	44.156	0.00132	0.002713
4	7.833333	60	0.130556	7.5	44.156	0.00128	0.002957
5	8	62	0.129032	7.5	44.156	0.00117	0.002922

Table (4.3) The experimental runs for the plain gap-graded soil with 5% clay and silt.

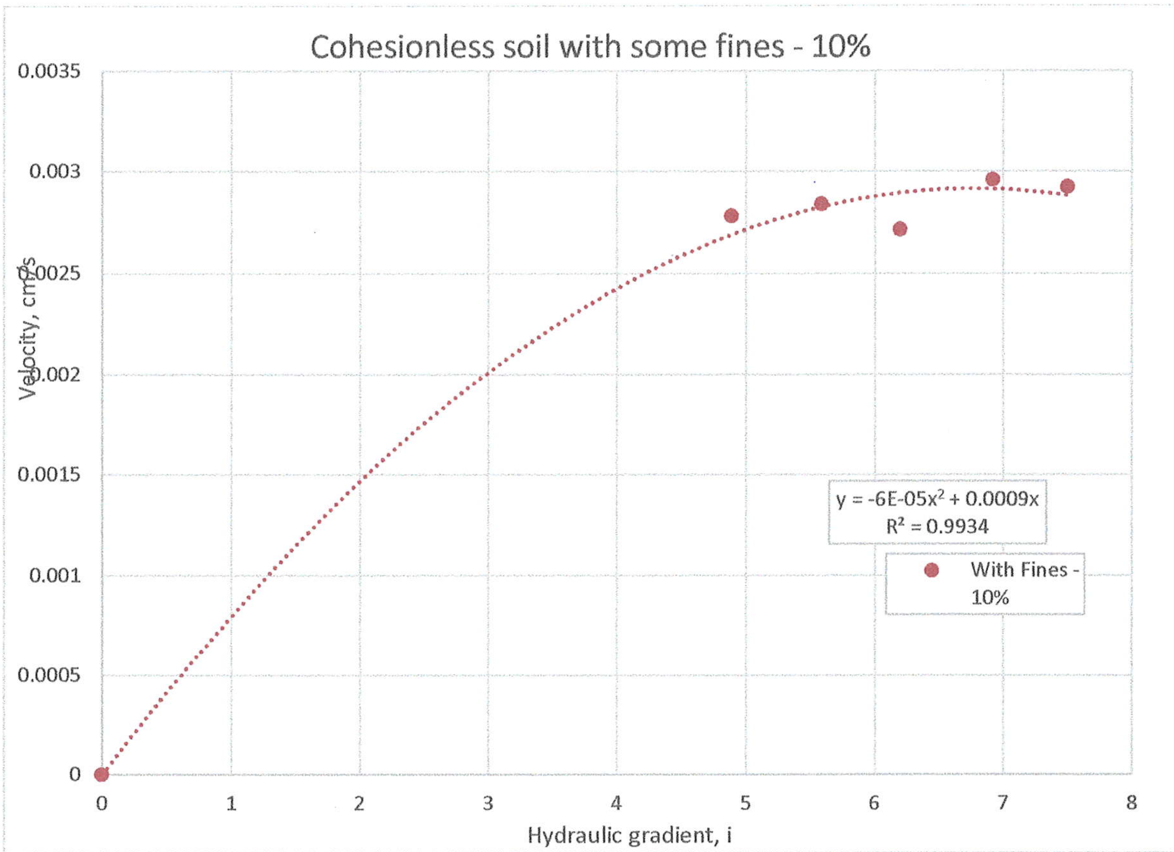


Figure (4.3) Hydraulic gradient versus velocity.

Chapter Five: Conclusions

5.1 Conclusions

The process which causes losing fine particles in a granular soil that can cause changes in the mechanical and hydraulic properties of the soil is called suffusion. One of the methods to treat suffusion in granular materials is adding binding agents, such as clay, to protect the granular materials from losing fine particles. In this experimental study, the binding agent (clay) represented in fine percentage was used to treat suffusion in cohesion-less gap-graded soil.

Through laboratory work and analysis of the results for the soils investigated, the hydraulic conductivity of the soil significantly decreased with the increase in the percentage of fine particles. This can be considered as a method to treat the suffusion. In other words, the significant decrease in the hydraulic conductivity of the gap-graded soil can be considered as the elimination or reduction of the chance of occurring fine particle movement under the same hydraulic gradient.

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