International Journal of Material Science & Engineering– IJMSE
Volume 2 : Issue 2 [ISSN : 2374-149X]
Publication Date : 30 October, 2015

Soil Sensibility Characterization of Granular Soils Due to Suffusion

[Abdul Rochim, Didier Marot, Luc Sibille]

***Abstract*—This paper studies the characterization of soil sensibility due to suffusion process by carrying out a series of one-dimensional downward seepage flow tests realized with an erodimeter. Tests were performed under controlled hydraulic gradients in sandy gravel soils. We propose the analysis based on energy induced by the seepage flow to characterize the hydraulic loading and the cumulative eroded dry mass to characterize the soil response. With this approach, the effect of hydraulic loading histories and initial fines contents to soil sensibility are presented. It is found that for given soils, erosion coefficients are different if tests are performed under different hydraulic loading histories. For given initial fines fraction contents, the sensibility may be grouped in the same classification. The lower fines content soils tend to require larger flow energy to the development of erosion. These results demonstrate that this approach is effective to characterize suffusion sensibility for granular soils.**

***Keywords*—Erodimeter, sandy gravel, suffusion, water seepage energy**

I. Introduction

Many hydraulic structures were built, such as dams and levees to protect people and property against flooding or to make canals and dams for electricity generation or creation of water reserves. These man-made structures can fail due to several factors such as sub-standard construction materials, poor quality control during construction, internal erosion or overtopping. Hydraulic structures made of soil may be in contact with variable interstitial flow that can generate the detachment and the transport of some constituent particles of the structure or its foundations during the cycle of seasons. This problem is called internal erosion. Foster et al. [1] among 11.192 surveyed dams, 136 experienced failure with 48% due to overtopping, 46% due to internal erosion (piping), and 5.5% due to sliding. Fell et al. [2] also indicated that overtopping and internal erosion are the two main causes of earthen embankment failure. Fell and Fry [3] classified internal erosion as: suffusion, piping, backward erosion, and contact erosion.

Abdul Rochim
Institut GeM - University of Nantes – ECN - CNRS
France

Didier Marot
Institut GeM - University of Nantes –ECN - CNRS
France

Luc Sibille
University of Grenoble Alpes, CNRS, 3SR, F-38000, Grenoble
France

Suffusion mechanisms referring to detachment and migration of certain grains through a coarser soil matrix due to seepage flow can generate a change in particle size distribution, porosity of the material and its hydraulic conductivity. In entire suffusion process, the detachment of finer particle from its parent material by seepage flow will be migrated through its constriction. The phenomenon of suffusion on sand-gravel soils has been studied by a number of investigators, including Kenney and Lau [4], Burenkova [5], Skempton and Brogan [6], Sterpi [7], Moffat and Fannin [8], Wan and Fell [9], Sail et al. [10], Chang and Zhang [11], Ke and Takahashi [12], Luo et al. [13]. However, the study on characterization of soil sensibility due to suffusion is far to be completed. This study aims to propose an approach to characterize suffusion sensibility due to suffusion.

II. Suffusion

A. *Controlling Parameters of Likelihood of Suffusion*

The term “internal stability” is defined as the ability of a granular material to prevent loss of its own small particles due to disturbing agents such as seepage and vibration (Kenney and Lau [4]). There is not a general rule to judge the instability of soils based on the testing results. Three identification methods are summarized according to: the fraction of mass loss, the evolution of permeability, and the change in gradation curve.

The onset of suffusion is governed by geometrical condition, mechanical condition, and hydraulic condition. According to Wan and Fell [9] the criteria to have suffusion occurred are 1) the size of fine fraction is smaller than the size of void or constriction, 2) the volume of fine particles within the soil is less than enough the volume of void formed by the coarse soil fraction, and 3) hydraulic gradient is large enough to detach and transport fine particles.

With respect to geometrical condition, for development of suffusion, the size of fine fraction should be smaller than the size of void or constriction, moreover the volume of fine particles should be less than the volume of void formed by the coarse particles. This can result in criteria on the shape of the grading curves. According to Lafleur et al. [14], and Wan and Fell [9] soils with a steep slope on coarse fraction and flat slope on the finer fraction were likely to be internally unstable, as shown in the particle size distribution 3 and 4 in Fig. 1. For such curves, Skempton and Brogan [6] and Ke and Takahashi [12] defined a term for them as bimodal structure or binary mixture, to represent a soil possessing a skeleton mode of coarse particles that support the transfer of stresses (grain supported soils).

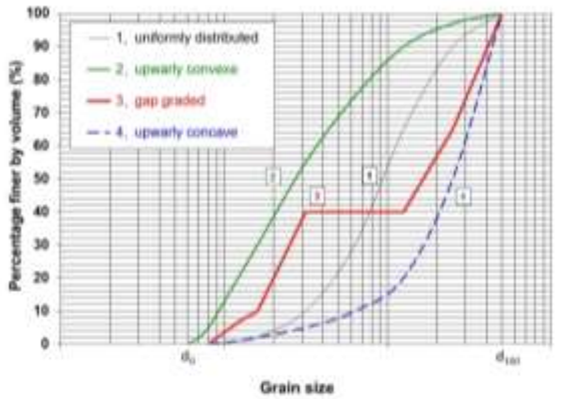

Figure 1. Classification of the particle size distribution of soils (Lafleur et al. [14])

However, in case of suffusion, both curves 1 and 2 are not susceptible to erosion. With a large range of particle sizes, curve 1 is internally stable, and soils having particle size distribution curve 2 are defined as matrix supported soils since the coarser fraction floats within the fine matrix.

With regard to fine contents within a soil, Thevanayagam and Mohan [15] defined "intergranular void ratio, e_s" by assuming that the volume of fines is a part of the voids between the coarser particles. With this approach, the soil behavior can be divided into three cases by comparing the maximum void ratio of coarse particles and intergranular void ratio. Geometric condition of a soil may control the likelihood of suffusion. Geometric criteria can be divided into (i) gradation-based internal stability criteria: Kezdi [16], Kenney and Lau [4], Wan and Fell [9], Li and Fannin [17] proposed quantitative geometric criteria of internal stability based on the soil gradation. Alternatively constriction-based criteria have also been defined by Indraratna et al. [18] for instance.

The study of hydraulic conditions, as external triggers, is required to investigate the onset of suffusion even the soil is "unstable" according to the geometric condition. The hydraulic loading applied on a soil is often described by hydraulic gradient, pore velocity or hydraulic shear stress. Several investigators such as Skempton and Brogan [6] and Li [19] have developed the concept of critical hydraulic gradient of Terzaghi [20], even if this concept was initial introduced to describe the hydraulic heave. Skempton and Brogan [6] presented tests under upward seepage on gap-graded soil, highly unstable sandy gravel. The results indicated that the critical hydraulic gradient of suffusion initiation can be much lower than the theoretical values by Terzaghi [20]. This can be explained that the overburden load is taken predominantly by the coarse fraction, leaving the finer fraction under relatively small stress. The critical hydraulic gradient required to initiate suffusion, i_{cr}, by Skempton and Brogan [6] is expressed in Equation (1).

$$i_{cr} = (1-\alpha)\left(\frac{\gamma'}{\gamma_w}\right) \qquad (1)$$

where α is stress reduction factor in the finer fraction that less than 0.1 for sandy gravel and its value needed to be determined by internal erosion tests; γ' is submerged unit mass of the soil specimen; and γ_w is the unit weight of water.

From Skempton and Brogan's [6] concept of stress reduction and with the objective to eliminate scale effect, Li [19] expressed the critical hydraulic gradient for upward seepage flow, i_{cr}, as a function of normalized vertical effective stress as shown in Equation (2).

$$i_{cr} = \alpha\left(\frac{\sigma'_{to}}{\gamma_w g \Delta_z} + \frac{\gamma'}{\gamma_w}\right) = \alpha\left(\frac{\sigma'_{vmo}}{\gamma_w g \Delta_z} + 0.5\,\frac{\gamma'}{\gamma_w}\right) \qquad (2)$$

where σ'_{t0} is vertical effective stress on top of specimen at hydraulic gradient i = 0, Δ_Z soil specimen thickness, g gravity, σ'_{vm0} mean vertical effective stress in the middle of soil layer.

It can be indicated that soil specimen thickness relates to the seepage path in the case of a vertical seepage flow. Thus the value of critical hydraulic gradient seems to decline with the seepage path.

Regarding hydraulic shear stress, Reddi et al. [21] proposed hydraulic shear stress for a vertical flow that is presented in Equation (3).

$$\tau = \left(\frac{\Delta h\, \gamma_w}{\Delta z}\right)\sqrt{\frac{2k\mu}{\gamma_w n}} \qquad (3)$$

where Δh is the hydraulic head drop, ΔZ the altitude change for a one dimensional flow between an inlet section A and an outlet section B, k the hydraulic conductivity, μ the dynamic viscosity, and n the porosity.

Recently Marot et al. [22] proposed a new method to quantity the hydraulic loading based on the energy dissipated by the fluid seepage attributed to the hydraulic loading and the soil response respectively. This approach is based on the assumptions: 1) the system is considered as adiabatic, 2) the temperature and 3) the internal energy with time are assumed to be constant for the volume, and the flow is in steady state condition. In the case of the suffusion process, due to relatively low value of the Reynolds number, it is assumed that intrafluid energy dissipation is neglected and energy is mainly dissipated in fluid-solid interface (Marot et al. [23])

In consequence, the time derivative of mechanical work related to the water seepage called as "erosion power" can be expressed by Equation (4). The energy dissipation, $E_{erosion}$ is the temporal integration of the instantaneous erosion power ($W_{erosion}$) for the test duration.

$$\frac{dW_{erosion}}{d_t} = \gamma_w\, \Delta z\, Q + Q\, \Delta P \qquad (4)$$

where $\Delta P = P_A - P_B$, the pressure drop; Q the fluid flow rate, $\Delta z > 0$ if the flow is in downward direction, $\Delta z < 0$ if the flow is upward and the temporal derivative of erosion work is equal to $Q\, \Delta P$ if the flow is horizontal.

B. *Soil Sensibility*

Sensibility or erodibility is the erosion resistance of soil subjected to water flow. Erodibility can be estimated with respect to the hydraulic shear stress assumed to be representative of the hydraulic loading. Then, erodibility coefficient indicates the erosion rate for a unit excess of shear stress. Hanson [24], Wan and Fell [25] proposed the Equation (5) to describe soil sensibility using shear stress term called erosion function.

$$E = k_d(\tau - \tau_c) \tag{5}$$

where E is the soil erosion rate; k_d the erodibility coefficient; τ the hydraulic shear stress at the soil-water interface; and τ_c the critical shear stress at onset of erosion.

Concerning erosion sensibility classification, different methods were proposed in the case of interface erosion. Hanson and Simon [26] proposed the classification of soil susceptibility to interface erosion based on the values of erosion coefficient k_d and hydraulic shear stress measured using Jet Erosion Test (JET). The classification is divided into five classes from highly resistant to highly erodible. Using Hole Erosion Test (HET), Wan and Fell [25] proposed a method assuming a linier expression between the rate of erosion and the hydraulic shear stress. The gradient of this correlation was named erosion rate coefficient k_d. According the value of the erosion rate index, $I_{kd} = -\log(k_d)$ Wan and Fell [25] proposed six categories varying from extremely slow to extremely rapid as presented in Table I.

We stress that (5) has been developed only for piping and contact erosion. However one can try to apply it to suffusion case. For that one can use the expression of the hydraulic shear stress (3).

TABLE I. CLASSIFICATION OF INTERFACE EROSION BY WAN AND FELL [25]

Group number	Erosion rate index (I_{kd})	Category of erosion
1	< 2	Extremely rapid
2	2 - 3	Very rapid
3	3 - 4	Moderately rapid
4	4 - 5	Moderately slow
5	5 - 6	Very slow
6	> 6	Extremely slow

The value of erosion rate per unit of surface area much depends on the definition of surface area. Considering the surface of pores is more representative than surface of the cross section of the sample for suffusion process, the erosion rate of soils per unit pore defined by Reddi et al. [21] as presented in Equation (6) – (10) was used.

$$\dot{m}(t) = \frac{m(t)}{N_p S_p t} \tag{6}$$

where m is eroded dry mass, N_p number of average pore, S_p the average pore area, and t duration.

$$N_p = \frac{S\,n}{\pi r_p^2} \tag{7}$$

$$S_p = 2\,\pi\,r_p\,\Delta z \tag{8}$$

where S is the cross section of the specimen, r_p radius of average pore, L length of the specimen.

$$r_p = \sqrt{\frac{8K}{n}} \tag{9}$$

$$K = k\,\frac{\mu}{\gamma_w} \tag{10}$$

where K is intrinsic permeability.

Always in the cases of piping and interface erosions, Marot et al. [22] proposed to characterize erosion sensibility with respect to the energy dissipated by the water seepage ($E_{erosion}$), through the erosion resistance index, I_α for surface erosion in the Equation (11).

$$I_\alpha = -log_{10}(\alpha) = -log_{10}\left(\frac{dry\ eroded\ mass}{E_{erosion}}\right) \tag{11}$$

Hanson and Simon [26], Wan & Fell [25] (with respect to shear stress), and Marot et al. [22] (with respect to flow energy) presented classifications of soil sensibility for piping and contact erosion, however up to now, there is no classification for suffusion sensibility.

III. Downward Seepage Test

A. *Tested Specimens*

To investigate soil sensibility, downward seepage tests were conducted on sandy gravel soils. The binary mixtures in this study consists of gravel and sandy soil from Sabliere Palvadeau.

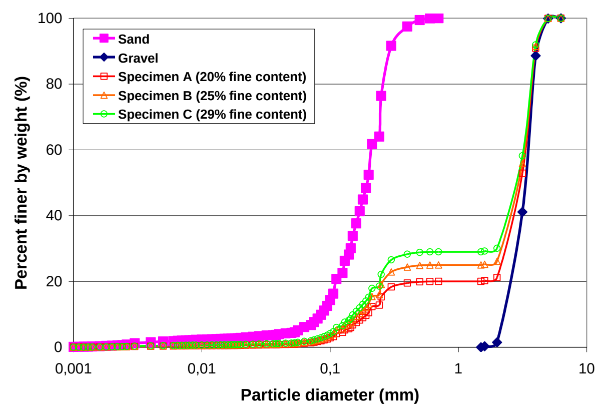

Figure 2. The particle size distribution of tested gradations

International Journal of Material Science & Engineering– IJMSE
Volume 2 : Issue 2 [ISSN : 2374-149X]
Publication Date : 30 October, 2015

TABLE II. PROPERTIES OF THE GRADATIONS

Properties	**Specimen Gradation**		
	A	B	C
Maximum void ratio, e_{max}	0.504	0.410	0.335
Minimum void ratio, e_{min}	0.298	0.217	0.152
Coefficient of uniformity, C_u	17.06	19.52	21.07
Coefficient of curvature, C_c	8.380	8.546	8.002
$(H/F)_{min}$	0.038	0.035	0.033
$(d15_c/d85_f)_{max}$	8.594	8.594	8.594

With a larger particle size, gravel works as the coarse particle, while sand soil as erodible fine particles. The coarse particle is classified as an angular to sub-angular material. The possible maximum value for fine mass ratio, assessed by the formula proposed by Ke and Takahashi [12] to fill voids form by the coarse skeleton, is 35%. Here fine contents of 20%, 25% and 29% will be used. The particle size distribution, the parameters of the soil are shown in Fig. 2, and Table II.

TABLE III. ASSESSMENT OF SOIL INSTABILITY BY CURRENT METHODS

Methods	**Gradations**		
	A	B	C
Kezdi [16]	Unstable	Unstable	Unstable
Kenney & Lau [4]	Unstable	Unstable	Unstable
Li & Fannin [17]	Unstable	Unstable	Unstable

Several methods are used: Kezdi [16], Kenney and Lau [4], and Li and Fannin [17] to ensure the specimens are geometrically susceptible to suffusion as presented in Table III. Based on these methods, all the specimens are considered as unstable. A series of 8 specimens is subjected to multi-stage hydraulic gradients, as presented in the Table IV. The name of the specimen, for instance B-90a, the first letter "*B*" refers to the gradation, "*90*" for 90% of maximum γ *dry* and "*a*" for hydraulic loading history.

TABLE IV. PROPERTIES OF THE TESTED SPECIMENS

Tested Specimen	**γ dry (g/cm^3)**	**Multi-stage global hydraulic gradient**	**Duration/ stage (min)**
A-90a	1.739	0.1-0.2-0.3-0.4-0.5-0.65-0.8-1-1.25, …	10
A-90b	1.739	1-2-3-4-5-6, …	10
B-90a	1.739	0.1-0.2-0.3-0.4-0.5-0.65-0.8-1-1.25, …	10
B-90b	1.739	1-2-3-4-5-6, …	10
B-97a	1.874	0.1-0.2-0.3-0.4-0.5-0.65-0.8-1-1.25, …	10
B-97b	1.874	1-2-3-4-5-6, …	10
C-97a	1.874	0.1-0.2-0.3-0.4-0.5-0.65-0.8-1-1.25, …	10
C-97b	1.874	1-2-3-4-5-6, …	10

B. *Erodimeter*

A specific testing apparatus as shown in Fig. 3 was used to characterize the erodibility of soils. It comprises an erosion cell, a water supply system, a soil collection system, and a water collection system. The testing device comprises a modified cell to saturate the sample in upward direction, and to force fluid through the sample in downward direction. A water tank as a supply of demineralized water is provided as inlet into the soil specimen. The funnel-shaped draining system is connected to effluent tank by a glass pipe. The effluent tank is equipped with an overflow outlet in order to control the downstream hydraulic head and a rotating sampling system containing 8 beakers for the sampling of eroded particles. Overflow water is continuously weighed by mass balance in order to determine injected flow rate.

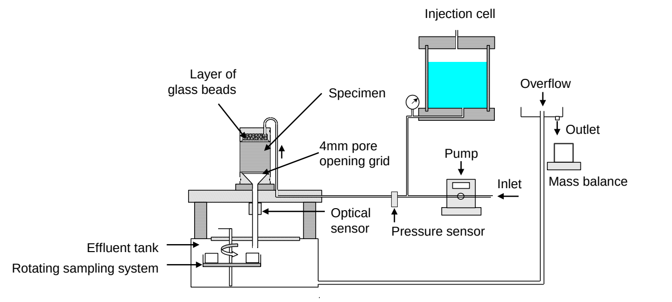

Figure 3. Schematic diagram of the erodimeter

A series of tests was conducted in two steps: specimen preparation and downward seepage test. The specimen preparation phase was divided into two steps; production of the specimen, and saturation. The sand grains and gravel were first mixed with a moisture content of 7.8%. The specimens were prepared using a single layer semi-static compaction technique. The mixture was placed in a mould of 50 mm diameter and 50 mm height and subsequently compressed under the action of two pistons until the initial fixed dry density was reached. In the erosion cell device, the specimen was placed on a 4 mm pore opening grid and wrapped with a layer of membrane, then closed with metal mold. This pore opening allowed the migration of all particles of sand and clay. The saturation phase began with injection of carbon dioxide for duration of 5 minutes to improve dissolution of gases into water, and afterward continued by injecting demineralized water. The whole saturation phase required approximately 24 hours. Finally, the specimen was subjected to a hydraulic flow in a downward direction using demineralized water.

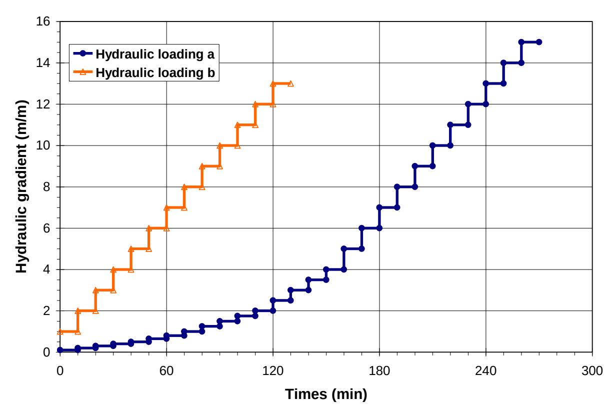

Figure 4. Applied multi-stage hydraulic gradients

A series of 8 tests (Table IV) with two different hydraulic loadings was performed as plotted in Fig. 4. The first hydraulic loading consisted of increasing the hydraulic head by steps of 0.1 until 2, then by steps of 0.5 between 2 and 4 and by steps of 1 beyond; whereas steps were directly equal to 1 for the second kind of hydraulic loading. For each step the hydraulic gradient was kept constant during 10 minutes.

IV. Results and Discussion

A. *Hydraulic Conductivity and Erosion Rate*

The change of hydraulic conductivity provides information of soil response to hydraulic loading. The variation of hydraulic conductivity can be a criterion of identification of suffusion. In this study, two kinds of hydraulic loading history, as shown in Fig. 4, were used to erode the tested specimens. The specimens A, B, C were subjected to two different multi-stage hydraulic gradients to investigate the effect of hydraulic loading history. The hydraulic gradient "*a*" was commenced with very low hydraulic gradient 0.1 and increased by low increment of hydraulic gradient as presented in Table IV. With such low multi-stage hydraulic gradients, the determination of the onset of suffusion can be possible. As for the erosion rate, the computation of which used Reddi's method : (6) to (10).

As in Fig. 5 there is a general trend of declined hydraulic conductivity before it increases progressively and reaches constant values from the arrow signs. We assume this decrease of the hydraulic conductivity is related to some fine particles detached under the water seepage action but not transported until the outlet of the sample, but filtered within the soil itself.

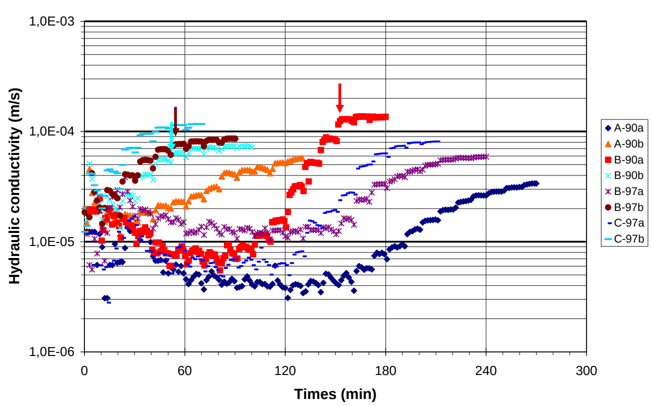

Figure 5. Variation of hydraulic conductivity

This filtration thus makes a clogging and decreases the hydraulic conductivity. Hydraulic conductivity increases only latter, for much larger hydraulic gradients possibly blowing the clogging. For instance, for the test B-90a the hydraulic conductivity gradually decreases during the first 70 min while the mass erosion rate (displayed in Fig. 6) is relatively low and itself decreases.

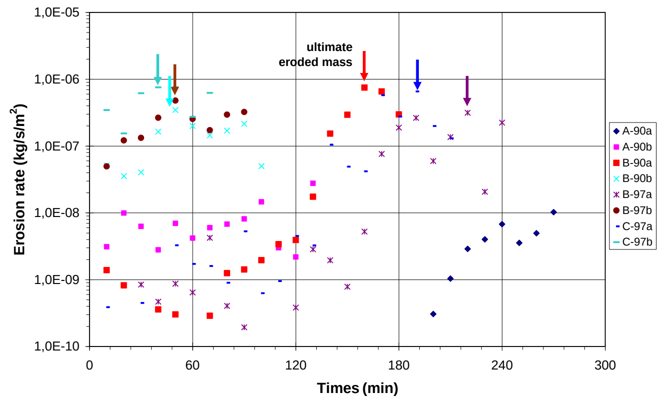

Figure 6. Variation of erosion rate during elapsed time

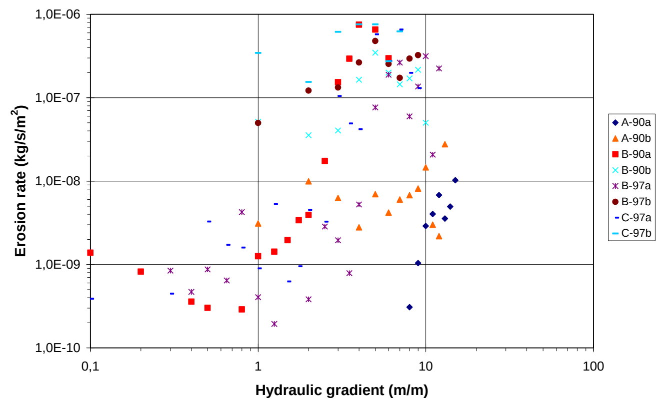

Figure 7. Variation of erosion rate to hydraulic gradient

An important increase of the erosion rate occurs in a second phase from 80 min, simultaneously with the increase of the hydraulic conductivity, confirming the assumption of a clogging firstly limiting the water flow and secondly blown by the seepage itself. Finally from 130 min hydraulic conductivity tends to stabilize while an ultimate (maximum) erosion rate represented by an arrow in Fig. 6 is reached.

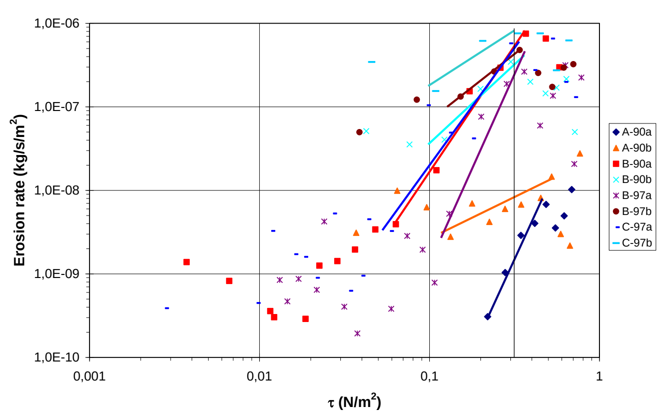

Figure 8. Variation of erosion rate to shear stress

This last phase can be explained by the fact that after reaching significant eroded mass, the soil becomes more permeable than before due to larger volume of void. There may still be concentration of fine fraction in one part of soil but not in another part. The latter condition may create preferential flow path for seeping water. It is pointed by the arrows in Fig. 5 and Fig. 6 and corresponds to hydraulic gradient called failure hydraulic gradient.

The variation of erosion rate to hydraulic gradient and erosion rate to hydraulic shear stress, computed according to (3) are presented in Fig. 7 and Fig. 8. It is shown in both diagrams, erosion rate does not always increase when hydraulic gradient or shear stress increases. This is due to filtration that makes a clogging and thus decreases the erosion rate even if the hydraulic gradient or shear stress increases.

TABLE V. ASSESSMENT OF SOIL SENSIBILITY CLASSIFICATION

Specimen	k_d (g/N.s)	τ_c (Pa)	I_{kd}	Methods	
				Hanson and Simon [26]	Wan and Fell [25]
A-90a	2,0E-05	0,219	4,699	moderately resistant	moderately slow
A-90b	2,0E-05	0,133	4,699	moderately resistant	moderately slow
B-90a	2,4E-03	0,063	2,620	moderately resistant	very rapid
B-90b	1,5E-03	0,043	2,824	moderately resistant	very rapid
B-97a	1,1E-03	0,131	2,959	moderately resistant	very rapid
B-97b	1,4E-03	0,084	2,854	moderately resistant	very rapid
C-97a	2,3E-03	0,059	2,638	moderately resistant	very rapid
C-97b	1,9E-03	0,046	2,721	moderately resistant	very rapid

In the point of view of erosion sensibility, the specimens are assessed with recent methods of the classification of piping or contact erosion proposed by Hanson and Simon [26] and Wan and Fell [25] with the results as shown in the Table V. The value of "erosion rate coefficient, k_d" is defined by linear correlation between erosion rate and critical hydraulic shear stress with initiation (critical) hydraulic shear stress is determined by the starting point of the inflection of hydraulic conductivity or velocity as shown in Fig. 9.

B. *The Onset of Suffusion*

Determination of the onset of suffusion can be identified by several methods. In this study the onset of suffusion is determined by the change of the hydraulic conductivity and the fraction of mass loss.

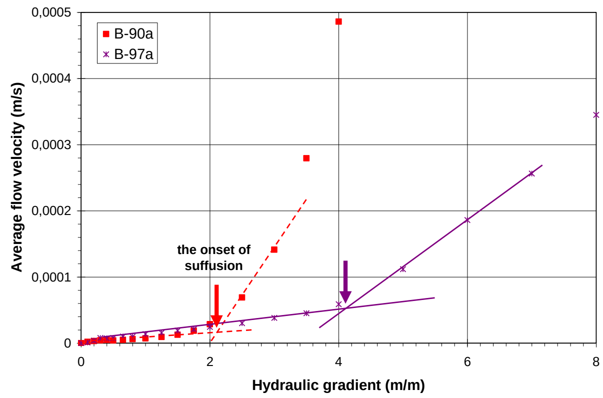

Figure 9. Hydraulic gradient to average flow velocity (specimens B-90a and B-97a)

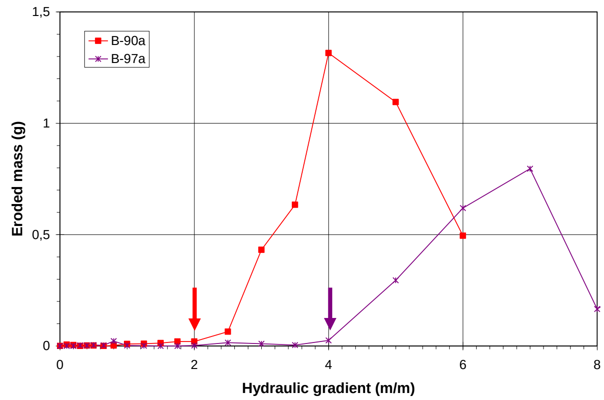

Figure 10. Hydraulic gradient to temporal eroded mass (specimens B-90a and B-97a)

The diagram of relationship between the hydraulic gradient and the average flow velocity (representing hydraulic conductivity) of two specimens B-90a and B-97a is shown in Fig. 9. The sign of "arrow" points out a critical hydraulic gradient as at this hydraulic gradient suffusion starts to occur. The linier relationship between the hydraulic gradient and the average flow velocity before the sign of arrow indicates no erosion or only a few eroded mass as presented in Fig. 10. During this stage, the detachment and transport of fine fraction only filtrate somewhere within the soil and clogging may occur thus decreases the hydraulic conductivity. After reaching critical hydraulic gradient, the energy induced by hydraulic gradient can push the clogging and wash out the fine fraction, leading to larger porosity, and thus increases hydraulic conductivity. This can be then presented by the inflection of the curve slope.

C. *The Effect of Hydraulic Loading*

In order to investigate the hydraulic loading history to erosion and to classify the soil sensibility, we propose an energy-based approach.

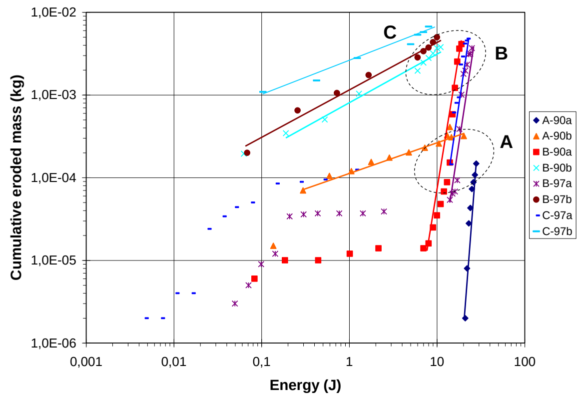

Figure 11. Cumulative eroded dry mass to cumulative expanded energy

The energy-based approach is provided by energy induced by the act of hydraulic flow to characterize the hydraulic loading and the cumulative eroded dry mass to characterize the soil response. The ratio of the cumulative eroded dry mass to the cumulative expended energy was used to compare the soil sensibility of tested soils. The plot of cumulative eroded dry mass against energy is presented in Fig. 11. It is shown in Fig. 11 and Table VI the erosion coefficient α for given soils are different for two different hydraulic loading histories.

TABLE VI. EROSION RESISTANT INDEX BY METHOD OF MAROT ET AL. [22]

Specimen	α	I_α	Category of erosion
A-90a	9,14E-06	5,039	very resistant
A-90b	1,71E-05	4,768	resistant
B-90a	1,17E-03	2,930	moderately erodible
B-90b	2,01E-03	2,697	moderately erodible
B-97a	7,49E-04	3,125	moderately resistant
B-97b	1,66E-03	2,779	moderately erodible
C-97a	1,98E-03	2,703	moderately erodible
C-97b	2,68E-03	2,571	moderately erodible

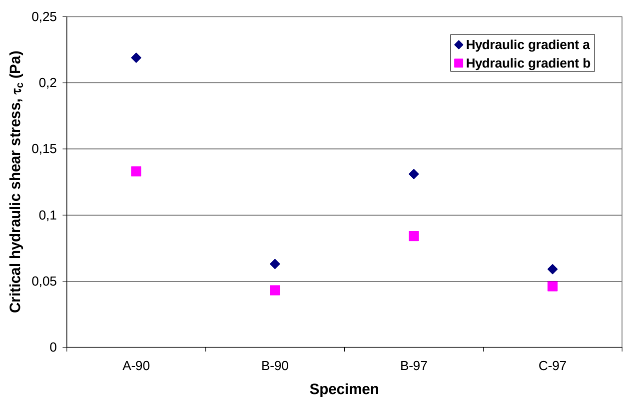

Figure 12. Relation between critical hydraulic shear stress and hydraulic loading history for all the specimens

As presented in Table VI, all the erosion coefficients α for hydraulic loading *b* are larger than those of hydraulic loading a that means all the soils imposed by the hydraulic gradient b are more erodible than those imposed by the hydraulic gradient *a*. It can be noticed in Fig. 12 the critical hydraulic shear stress for all the specimens imposed by hydraulic gradients *b* commence earlier than those imposed by hydraulic gradient *a*. It could be explained when large multi-stage hydraulic gradient *b* were imposed to the specimens by progressively increasing the hydraulic gradient, this may not allow enough time the fine fraction to filtrate and clog the filter. Thus at given gradient these binary mixtures that may commonly be stable may become unstable if the same gradient injected rapidly. This result is in accordance with the test results of Tomlinson [27]. For a given soil, two different rates of hydraulic gradient increase were imposed: 1) normal rate of increase of 2 cm increments every 10 min and 2) rate of increase of 23 cm in 1 min. A very rapid rate of increase of 23 cm in 1 min resulted lower critical hydraulic gradient, equals to one third of the value of normal rate. Therefore for given soil the sensibility can be different under different hydraulic loading histories.

D. *The Effect of Fine Content*

To study the effect of fine content to erosion and to classify the soil sensibility, the energy-based approach was used. As depicted in Fig. 11, the results indicate that for a given percentage of fines, the sensibility can be classified in the same group.

It is indicated that the lower fine content soils (specimen A) tend to require larger energy to the onset and development of erosion. It can be explained the reason of less fine content more resistant to suffusion is since the small amount of fines within the void of coarser particle leads to the specimen more porous. Thus when fluid imposed to the specimen, the detachment of fine particles may be only transported and filtrated sideways to the coarse particle contacts. This result is in accordance with the test results of Ke and Takahashi [12]. Given three different fine particle contents : 16.7%, 20%, and 25%, Ke and Takahashi [12] showed the less percentage of fine content (16.7%) required larger critical hydraulic gradients to the onset of internal erosion for relative density 0.2 and 0.6. These results demonstrate that this approach is effective to characterize suffusion sensibility for the binary mixtures of cohesionless soils.

E. *Proposal of Suffusion Sensibility Classification*

Erosion sensibility classifications were proposed by different methods in the case of interface erosion. Thus the study on characterization of suffusion sensibility and its classification are far to be completed. Based on the test results on a series of tested specimens, the authors propose the classification of suffusion sensibility. The classification is divided into six classes from very resistant to very erodible as presented in Fig. 13.

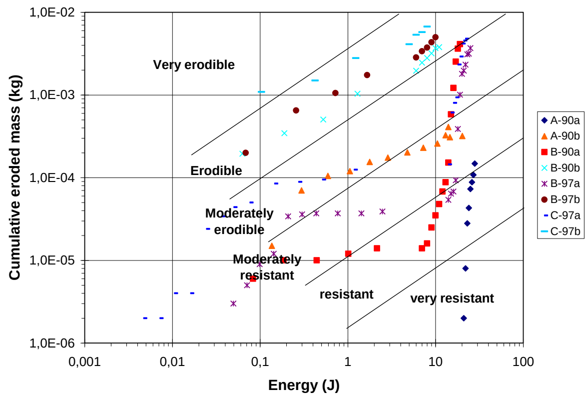

Figure 13. Classification of suffusion sensibility

V. Conclusion

In this study, the effect of fine content and history of hydraulic loading on the characterization of suffusion sensibility of granular soil was investigated through a series of tests using erodimeter. In the authors' perspective, the method of increased hydraulic gradient is efficient. The injection of larger hydraulic gradient can detach a clogging that may provide information of soil sensibility in a short time. It can be noticed that for given soil, the onset of suffusion may be different for different hydraulic loadings that effects to the soil sensibility classification. An energy-based approach to determine erosion coefficient and classification of soil sensibility seems effective. For given soils, it results different erosion coefficient for different hydraulic loading histories. The gradient of erosion coefficient of all the specimens for hydraulic gradients with increment 0.1 shows more resistant than ones with increment 1. For all the specimens, the critical hydraulic shear stress imposed by hydraulic gradients *b* start earlier than those imposed by hydraulic gradient *a*. This result thus shows how hydraulic loading is an important parameter for characterization of suffusion. With respect to fine content, for given fine content, they may be classified in the same group of soil sensibility. The less fine content soils required larger energy to the onset of suffusion. The proposal of suffusion sensibility classification is still far from perfection thus further interpretation and study should be carried out.

Acknowledgment

The authors thank The Indonesian Directorate General of Higher Education (**DIKTI**), Sultan Agung Islamic University Indonesia, GeM Institute - University of Nantes-ECN-CNRS for providing financial support.

References

[1] M. Foster, R. Fell, M. Spannagle, The statistics of embankment dam failures and accidents, *Canadian Geotechnical Journal* **37**(5) (2000), 1000-1024.

[2] R. Fell, et al., Time for development of internal erosion and piping in embankment dams, *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* **129**(4) (2003): 307-314.

[3] R. Fell, J. J. Fry, The state of the art of assesing the likelihood of internal erosion of embankment dams, water retaining structures and their foundations, *Internal Erosion of Dams and their Foundations*, Taylor & Francis Publisher, New York, 2007.

[4] T.C. Kenney, D. Lau, Internal stability of granular filters, *Canadian Geotechnical Journal* **23** **(**1985), 420-423.

[5] V.V. Burenkova, Assessment of suffusion in non-cohesive and graded soils, *Proc. 1st Conf Geo-Filters, Kralsuhe, Germany* (1993), 357-360.

[6] A.W. Skempton, J.M. Brogan, Experiments on Piping in Sandy Gravels, *Geotechnique* **44**(3) (1994), 449–460.

[7] D. Sterpi, Effects of the Erosion and Transport of Fine Particles due to Seepage Flow. *International Journal of Geomechanics, ASCE, September* (2003), 111-122.

[8] R. Moffat, R.J. Fannin. A large permeameter for study of internal stability in cohesionless soils, *Geotechnical Testing Journal* **29**(4) (2006), 1-7.

[9] C.F. Wan, R. Fell, Assessing the Potential of Internal Instability and Suffusion in Embankment Dams and Their Foundations, *Journal of Geotechnical and Geoenvironmental Engineering ASCE* **134**(3) (2008), 401-407.

[10] Y. Sail, D. Marot, L. Sibille, A. Alexis, Suffusion test on cohesionless granular matter – Experimental study, *EJECE* Vol. **15**(5) (2011), 799-817.

[11] D.S. Chang, L.M. Zhang, A Stress-controlled Erosion Apparatus for Studying Internal Erosion in Soils. *Geotechnical Testing Journal* **34**(6) (2011), 1-11.

[12] L. Ke, A. Takahashi, Strength reduction of cohesionless soil due to internal erosion induced by one-dimensional upward seepage flow, *Soils and Foundations* **52**(4) (2012), 698-711.

[13] Y. Luo, L. Qiao, X. Liu, M. Zhan, J. Sheng, Hydro-mechanical experiments on suffusion under long-term large hydraulic heads, *Nat Hazards* **65** (2013), 1361–1377.

[14] J. Lafleur, J. Mlynarek and A.L. Rollin, Filtration of broadly graded cohesionless soils. *Journal of Geotechnical Engineering* **115**(12) (1989), 1747-1768.

[15] S. Thevanayagam, S. Mohan. Intergranular state variables and stress-strain behavior of silty sands. *Geotechnique* **50**(1) (2000), 1-23.

[16] A. Kezdi, *Soil physics selected topics*, Elsevier Scientific Publishing Company, Amsterdam, 1979.

[17] M. Li, J. Fannin, Comparison of two criteria for internal stability of granular soil, *Canadian Geotechnical Journal* **45** (2008), 1303-1309.

[18] B. Indraratna, V.T. Trong, C. Rujikiatkamjorn, Assessing the potential of internal erosion and suffusion of granular soils, *Journal of Geotechnical and Geoenvironmental Engineering* **133** (2011) 550-554.

[19] M. Li. Seepage induced failure of widely graded cohesion-less soils. *Ph.D Thesis, Department of Civil Engineering, The University of British Columbia, Vancouver, BC.* 2008.

[20] K. Terzaghi. Soil mechanics: a new chapter in engineering science. *Journal of the Institution of Civil Engineers*, **12**(7) (1939), 106–141.

[21] L.N. Reddi, I. Lee, M.V.S. Bonala. Comparison of internal and surface erosion using flow pump test on a sand-kaolinite mixture, *Geotechnical Testing Journal*, **23**(1) (2000), 116-122.

[22] D. Marot, P.L. Regazzoni, T. Wahl. Energy based method for providing soil surface erodibility rankings, *Journal of Geotechnical and Geoenvironmental Engineering (ASCE)* **137**(12) (2011), 1290-1294.

[23] D. Marot, V. Le, J. Garnier, L. Thorel, P. Audrain. Study of scale effect in an internal erosion mechanism: centrifuge model and energy analysis. *European Journal of Environmental and Civil Engineering* 16 (2012), 1-19.

[24] G.J. Hanson. Channel erosion study of two compacted soils. *Transactions of the ASAE*, **32**(2) (1989), 485-490.

[25] C.F. Wan, R. Fell. Investigation of rate of erosion of soils in embankment dams. *Journal of Geotechnical and Geoenvironmental Engineering (ASCE)* **130**(4) (2004), 373-380.

[26] G.J. Hanson, A. Simon. Erodibility of cohesive streambeds in the loess area of the midwestern U.S.A. *Hydrological Processes*, **15**(1) (2001), 23-38.

[27] S.S. Tomlinson, Y.P. Vaid. Seepage forces and confining pressure effects on piping erosion, *Canadian Geotechnical Journal*, **37** (2000), 1-13.