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The Effect of Fine Content and History of Hydraulic Loading on the Characterization of Suffusion Sensibility of Cohesionless Soil

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Abstract. Suffusion involves a selective erosion of fine particles in a soil by the water seepage in the matrix formed by coarser particles. This phenomenon can induce a change in particle size distribution, porosity and hydraulic conductivity of the material. With the objective to characterize the soil sensibility and propose suffusion sensibility classification, a series of one-dimensional downward seepage flow tests was realized with an erodimeter. Tests were performed under controlled hydraulic gradients in binary mixtures of sandy gravel soils. Two controlling parameters were used: 1) fine content and 2) hydraulic loading history. An analysis based on energy induced by the seepage flow is proposed to characterize the hydraulic loading and the cumulative eroded dry mass to characterize the soil response. The results show that for a given soil different hydraulic loading histories result in different soil sensibilities. Soils with the lowest fine contents tend to require larger flow energy for the development of erosion. These results demonstrate that this approach is effective to characterize suffusion sensibility for cohesionless soils.

Keywords. Cohesionless soils, erodimeter, suffusion, water seepage power

1. Introduction

During the cycle of seasons, hydraulic structures made of soil may be in contact with variable interstitial flows, possibly generating the detachment and the transport of some constituent particles of the structure or their foundations. Different categories can be distinguished in this problem generally is called internal erosion: concentrated leak erosion, suffusion, contact erosion and backward erosion [1]. Suffusion corresponds to selective erosion of fine particles by seepage flow leaving behind the matrix of coarser particles. However, only soil sensibility classifications for interface erosion were proposed so far [2, 3, 4], and classification of soils with respect to suffusion sensibility is still missing.

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2. Literature Review

Suffusion is a complex matter as it depends on geometric, mechanical and hydraulic condition. The size of fine fraction should be smaller than the size of constrictions, in addition 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 [5, 6]. Hydraulic conditions should be studied to investigate the onset of suffusion even if the transport of particles is geometrically possible. The hydraulic loading applied on a soil is often described by the hydraulic gradient, the pore velocity or hydraulic shear stress. Recently a new method has been proposed in [4] to describe the hydraulic loading from the energy dissipated by the fluid seepage.

The stream power related to water seepage, and called here “erosion power”, $P_{erosion}$ can be expressed by:

$$P_{erosion} = \gamma_w \Delta z Q + Q \Delta P \quad (1)$$

where γ_w is the unit weight of water, $\Delta P = P_A - P_B$, the pressure drop; $\Delta z = Z_A - Z_B$, the altitude change for a one dimensional flow between an inlet section A and an outlet B; and Q the fluid flow rate. The erosion energy, $P_{erosion}$, is defined as the time integration over the test duration of $P_{erosion}$.

When the erodibility, or erosion sensibility, is estimated with respect to the hydraulic shear stress (assumed to be representative of the hydraulic loading), an erodibility coefficient indicates the erosion rate for a unit excess of shear stress through an erosion function [7, 3]:

$$\dot{m} = k_d(\tau - \tau_c) \quad (2)$$

where \dot{m} 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.

It is worth stressing that Equation 2 has been developed only for interface erosion. However in case of suffusion, the expression of the hydraulic shear stress within a soil defined in [8] can be used. For a vertical downward flow the shear stress is given by:

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

where Δh is the hydraulic head drop, k the hydraulic conductivity, μ the viscosity, and n the porosity.

3. Downward Seepage Test

3.1. Tested Gradations and Specimens

Three grain size distributions corresponding to sandy gravel soils were tested (Figure 1). Properties of gradations are summarized in Table 1. The grain size distributions are assessed Table 1 with respect to several gradation-based criteria [6, 9, 10, 11]. The definitions of H/F and d_{15}/d_{85} are given in [9] and [10] respectively.

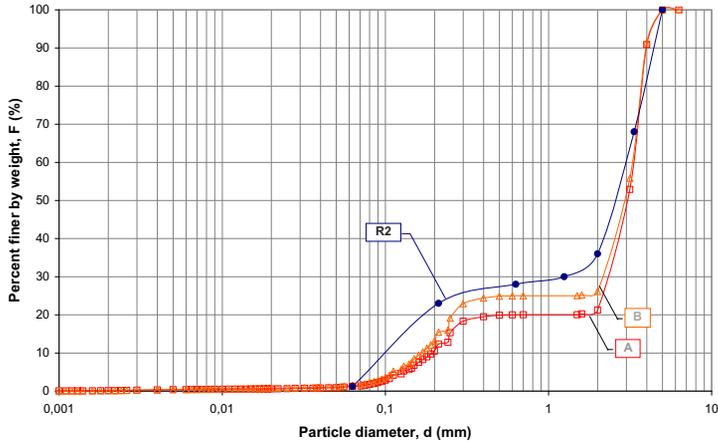


Figure 1. The particle size distribution of tested specimens

Table 1. Tested gradations properties and assessment of soil internal stability by recent criteria

Tested gradation	Cu	Gr	P (%)	(H/F)min	d (H/F=min) (mm)	d15/d85	Assessment method			
							[9]	[10]	[11]	[6]
A	17.06	2.14	1.227	0.038	0.400	8.761	U	U	U	U
B	19.52	2.14	1.533	0.035	0.400	8.741	U	U	U	S
R2	24.46	WG	1.200	0.165	0.212	9.653	U	U	U	S

Cu: uniformity coefficient; Gr: gap ratio (see [12]); P: percentage of particle smaller than 0.063 mm

U: internally unstable gradation, S: internally stable gradation

[6, 9, 10, 11] are gradation criteria: Wan and Fell, Kezdi, Kenney and Lau, Li and Fannin respectively

3.2. Erodimeter

An erodimeter as shown in Figure 2 was used to characterize the soil sensibility. It consists of an erosion cell, a demineralised water supply system, a soil collection system, and a water collection system. The sample is saturated by flushing water in the upward direction, and erosion test is then performed by injecting through the sample in the downward direction from the injection tank. 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 catching eroded particles. Overflow water is continuously weighed to determine flow rate.

A series of tests was conducted in two steps: specimen preparation (production of the specimen, and saturation) and downward seepage test. The sand grains and gravel are then first mixed with a fixed moisture content. The specimens are then prepared using a single layer semi-static compaction technique. The mixture is 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 is reached. In the erosion cell device, the specimen is placed on a 4 mm pore opening grid and wrapped within membrane. This pore opening allowed the migration of all particles of sand. For the saturation phase carbon dioxide is first injected in the specimen for duration of 5 minutes, before

injecting demineralised water. The whole saturation phase required approximately one night. Finally, the specimen is subjected to a hydraulic flow in a downward direction using demineralized water.

A series of nine tests with two different hydraulic loadings was performed: multi-stage (*a* and *b*) and a single-stage (*c*) hydraulic gradients. The first (*a*) hydraulic loading consisted of increasing the hydraulic head by steps from 0.1 to 2, then by steps of 0.5 between 2 and 4 and by steps of 1 beyond; whereas steps were equal to 1 for the second kind of hydraulic loading (*b*). For each step the hydraulic gradient was kept constant during 10 minutes. However *c* corresponds to a single-stage hydraulic gradient equal to 4 m/m.

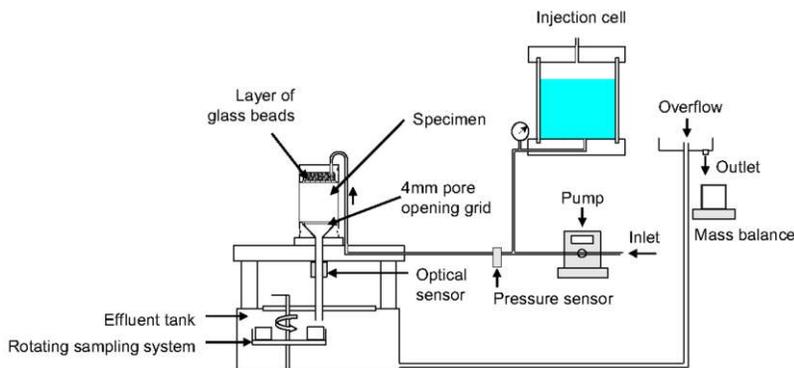


Figure 2. Schematic diagram of the erodimeter

4. Results and Discussion

4.1. Erosion rate and Hydraulic conductivity

Erosion rate and hydraulic conductivity can be interpreted as a soil response to hydraulic loadings. Figure 3 shows the evolution of hydraulic conductivity of tested specimen during test and Figure 4 depicts the variation of erosion rate versus hydraulic shear stress. The arrow signs in both figures highlight the time when hydraulic conductivity reaches constant and significant eroded mass is captured. The evolution of hydraulic conductivity present a typical trend: a decrease is firstly observed before it progressively increases and finally reaches a constant value from the arrow sign as shown in Figure 3. We assume this decrease of the hydraulic conductivity is attributed to some detached particles that were transported under the imposed water seepage and then filtered further within the soil itself. This filtration leads to partial clogging corresponding the first decreasing of the hydraulic conductivity. Hydraulic conductivity increases only latter, for much larger hydraulic gradients able to detach again these filtrated particles.

From the variation of hydraulic conductivity of specimens subjected to a multi-stage hydraulic gradients (*A-90a*, *A-90b*, *B-90a*, *B-97a*, *B-97b*, *R2-90a*, *R2-90b*) three predominant processes can be identified: filtration, process of erosion and finally steady state (represented by constant value of hydraulic conductivity). However such successive phases do not seem to occur when a single stage hydraulic gradient equal to 4. Considering test *B-90a*, by increasing progressively the applied hydraulic gradient

from 1.3 to 4 the hydraulic conductivity increases by a factor of 20. Whereas in the case of test *B-90c*, performed with a single-stage hydraulic gradient, even by applying hydraulic gradient of 4, the hydraulic conductivity continuously decreases. Thus for the need to the classification of suffusion sensibility, the method by increasing hydraulic gradients is preferred.

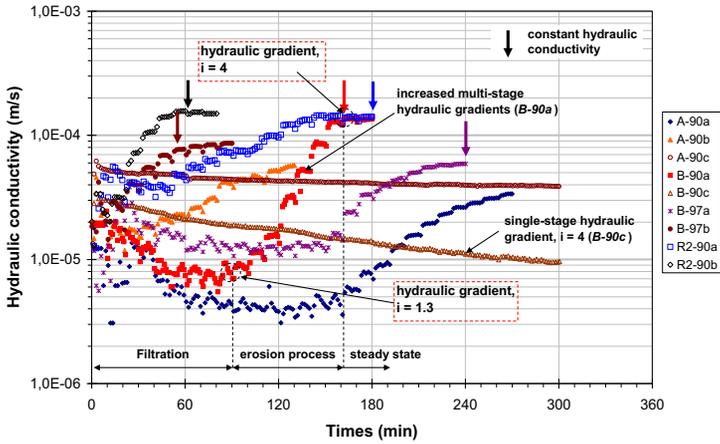


Figure 3. Time series of hydraulic conductivity

4.2. Soil sensibility

In conformity with methods proposed for interface erosion classification, a first approach to define a suffusion sensibility classification can consist to investigate the variation of the erosion rate with the hydraulic shear stress. It is worth stressing that the erosion function proposed by [3] and [7] has been developed only for interface erosion.

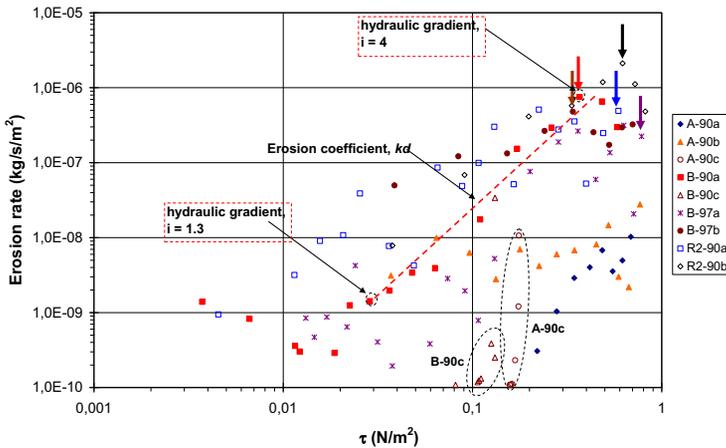


Figure 4. Erosion rate versus hydraulic shear stress

The hydraulic shear stress within the soil is computed from Equation 3 and the erosion rate coefficient k_d is assumed to be representative of the erosion sensibility. In the necessity to evaluate the classification of suffusion sensibility of tested specimens a first approach proposed by [3] for interface erosion can be used. This approach is based on the determination of k_d coefficient. In order to apply such approach for suffusion process, the value of k_d is defined from linear approximation of the plot of the erosion rate with respect to the critical hydraulic shear stress. The critical hydraulic shear stress is determined at the point where the hydraulic conductivity presents a minimum or where the hydraulic conductivity starts to inflect. For instance, for specimen *B-90a* this point corresponds to a hydraulic gradient equal to 1.3 as shown in Figure 3 and 4. The difficulty to determine k_d coefficient is encountered for a single-stage hydraulic gradient (*A-90c* and *B-90c*) as shown in Figure 4. Thus these specimens are not taken into account for proposition of suffusion sensibility classification.

The approach based on the erosion energy, as introduced in Section 2, and corresponding to the energy expanded by the water to seep through the soil, is now considered. Figure 5 shows the relationship between cumulative expanded energy and cumulative eroded mass. The arrow signs indicate the point from which the hydraulic conductivity is stabilized.

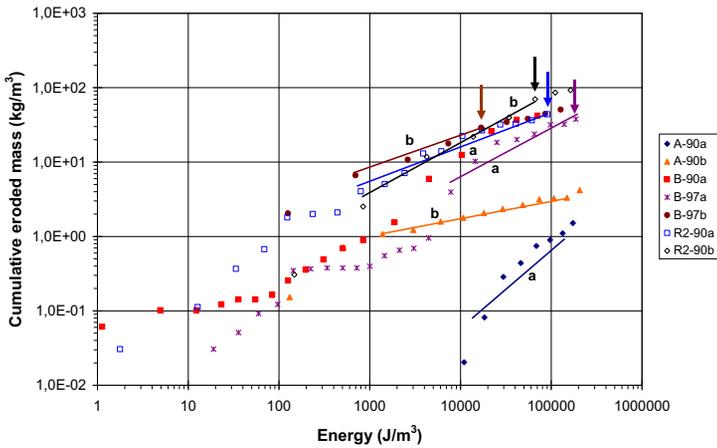


Figure 5. Cumulative eroded dry mass in terms of the cumulative energy expanded by the water to seep through the soil.

4.3. Classification of suffusion sensibility

The proposed classification is built from the approach based on the erosion energy (Figure 5). This classification is divided into five classes from resistant to highly erodible as presented in Figure 6. The points highlighted by arrows correspond to the end of development of suffusion (i.e. time from which hydraulic conductivity is stabilized) in order to classify the soil sensibility. It is worth noting that the points before and after the arrows do not represent the soil sensibility. The eroded mass in the beginning may be attributed to loss mass during saturation phase and during filtration process. The after-arrow points also do not represent the soil sensibility since they

correspond to the steady state. If the series of final points is taken into account, the soil sensibility becomes less erodible.

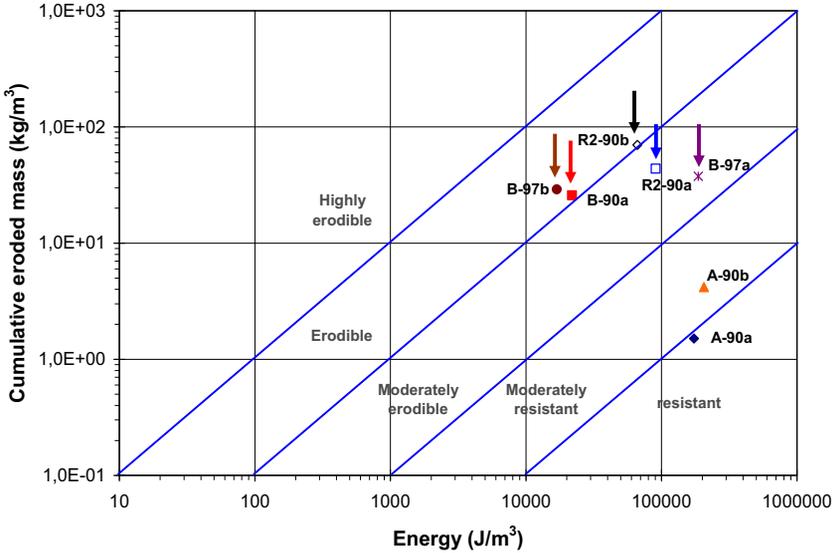


Figure 6. Classification of suffusion sensibility based on the energy expended by the water seepage in the soil

4.4. Effect of hydraulic loading history and fine contents

Figure 5 shows that soils *A*, *B* and *R2* imposed to hydraulic gradient *a* are less erodible than those imposed to hydraulic gradient *b*. It can be also shown in Figure 6, given *B-90* and *R2-97* different hydraulic loading histories give different classifications. Thus hydraulic loading history can be an important parameter to soil sensibility. With respect to fine content, it seems that a specimen with a low fine content soil, specimens *A* tends to require a larger energy for the onset of erosion than a specimen with the same initial density but a higher fine content, specimens *B*. Indeed, since the same initial global density is obtained for specimens *A* and *B*, but with a larger content of coarse particles *A*, density proper to the coarse fraction should be higher in *A* than in *B*. Therefore constriction sizes of the coarse skeleton may be smaller for specimen *A*, limiting the possibility of erosion of the fine fraction. This result is in good agreement with the test results presented in [13]. Given three different fine contents: 16.7%, 20%, and 25%, it is demonstrated that the samples with the lowest fine content (16.7%) required a larger critical hydraulic gradients for the onset of internal erosion for relative density of 0.2 and 0.6 respectively. These results show that the energy-based approach should be effective to distinguish suffusion sensibility for cohesionless soils.

5. Conclusion

In this study, the effect of history of hydraulic loading and fine content on the characterization of suffusion sensibility of cohesionless soil was investigated through a series of tests using erodimeter. When a soil is susceptible to erosion, the soil

sensibility has to be characterized by imposing seepage flow in suffusion tests. The test should be performed by progressively increasing the applied hydraulic gradient and it should be carried on until the hydraulic conductivity reaches a steady state. With the objective to characterize independently the hydraulic loading and the induced erosion, the cumulative eroded dry mass and the cumulative energy expanded by the seepage flow, $E_{erosion}$ are computed. Finally with the aim to classify suffusion sensibility, the first time hydraulic conductivity reaches constant value can be determined as the time to suffusion sensibility classification of a soil on the diagram of the cumulative eroded dry mass versus the cumulative expanded energy. For given soils, it demonstrates different soil sensibility classification for different hydraulic loading history and fine content. The gradient of erosion coefficient for hydraulic gradients with increment 1 (hydraulic gradient b) shows more erodible than ones with increment 0.1 (hydraulic gradient a). This result shows how hydraulic loading is an important parameter for characterization of suffusion.

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