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Systematic methodology for characterization of suffusion sensibility

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ABSTRACT: The complex phenomenon of suffusion corresponds to the process of detachment and then transport of the finest particles within the soil porous network. Suffusion may cause changes in porosity and can also lead to important modifications in the hydraulic and mechanical characteristics of the soil. With the aim to evaluate the likelihood of suffusion initiation, several criteria based on the study of grain size distribution have been proposed in the literature. The most successful criteria are identified for each type of grain size distribution in order to estimate the susceptibility of suffusion. For the characterization of soil suffusion sensibility, two specific devices were designed and tests were performed on cohesionless granular matter and on clayey sand with different fine particle contents. We propose to characterize the hydraulic loading from the energy dissipated by the seepage flow and to characterize the soil response by the cumulative eroded dry mass. We define the erosion resistance index as the ratio of eroded dry mass to energy dissipated by the seepage flow. For the tested soils, this erosion resistance index leads to a similar erodibility classification for different hydraulic loading histories. These results demonstrate that this approach is efficient to characterize suffusion development for cohesionless granular matter and clayey sand.

1 INTRODUCTION

The complex phenomenon of suffusion corresponds to the process of detachment and then transport of the finest particles within the porous network. However a fraction of the detached particles can re-settle or be filtered at the bulk of the porous network. This process can then locally induce a clogging. The processes of detachment, transport and filtration of fine particles are thus inseparable.

Suffusion is the result of a seepage flow in the pores of a soil. Consequently, its initiation and its development depend on one hand, of the parameters that influence the characteristics of the fluid and solid phases and on the other hand, of the interstitial geometry, i.e. of the exchange interface between the two phases. Garner & Fannin (2010) describe the main initiation conditions for suffusion with the aid of a diagram comprising three components: material susceptibility, critical hydraulic load and the critical stress condition. In the same manner, Fell & Fry (2013) describe three criteria which have to be satisfied for suffusion to occur: geometric criterion, stress criterion and hydraulic criterion.

Suffusion may cause changes in porosity and can also lead to important modifications in the hydraulic and mechanical characteristics of the soil. Thus the hydraulic loading and its evolution, and the soil response to this solicitation are completely coupled. Moreover modifications of the porous medium can be the catalyst for significant instabilities at the scale of hydraulic embankments. Thus the suffusion sensibility of embankment soils needs to be characterized to ensure the safety assessment of these structures.

2 A PHYSICS-BASED UNDERSTANDING

With the objective to take into account all predominant parameters which influence suffusion, i.e. the interaction between water and soil, it is worth noting that this process is conditioned by the evolving and interdependent characteristics of the fluid phase as well as the solid phase. Therefore, its study is a complex matter as the phenomenon of suffusion depends on the geometry of the porous medium and also on the physicochemical characteristics of medium and interstitial fluid.

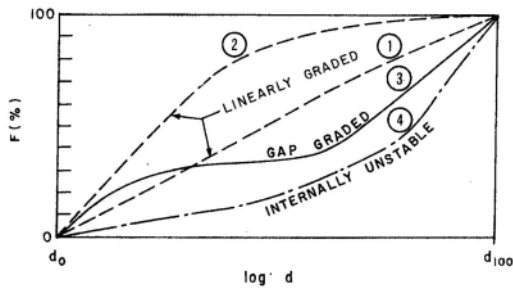


Figure 1. Classification of the grain size distribution of soils (Lafleur et al. 1989).

2.1 Influence of the geometry of the porous medium

The detachment of fine particles and their subsequent transport throughout the porous network of the soil requires that the constriction sizes are sufficiently large. This constriction size is conditioned by the granular distribution, but depends also on the grain shape and the density of the granular packing.

Three main gradation curves can be distinguished (Lafleur et al. 1989): linear distribution (curves 1 and 2 in Figure 1), discontinuous distribution (curve 3) and finally, upwardly concave distribution (curve 4).

In the case of the curve 2 the coarser fraction is a minority (<40%) and ‘floats’ within the fine fraction. In the case of the discontinuous distribution, a series of intermediary-size grains is missing. The concave distribution consists of a poorly graded coarser fraction associated to a highly graded fine fraction. In this type of soil, the volume between the grains of the coarser fraction is higher than the volume of fine particles, thus enabling the fine particles to migrate. The soils whose grain-size distribution curve corresponds to curves 1 or 2 are stable to suffusion (Lafleur et al. 1989). The soils that are likely to suffer from suffusion are, according to Fell & Fry (2007) ‘internally unstable’, i.e. their grain-size distribution curve is either discontinuous (curve 3) or upwardly concave (curve 4).

In 1981, Kovacs proposed to calculate the diameter of the average pore by using a shape coefficient whose values ranging between 6 for the spherical particles and from 7 to 9 for the more angular particles. By using a triaxial erodimeter, Marot et al. (2012a) determined the suffusion sensitivity of three mixtures of kaolin-aggregates (mixtures with 10% of kaolin). Results clearly demonstrate that suffusion process depends on the grain angularity of coarse fraction. With a same grain size distribution, angularity of coarse fraction grains contributes to increase the suffusion resistance. Thus shape of grains which has an influence on pore diameter size and appears as a key parameter of seepage flow in porous media.

For the same granular distribution, the modification of the effective stress can induce grain rearrangements. Several tests performed in oedometric conditions on instable soils show that a rise in the effective stress causes an increase of the soils’ resistance to

suffusion (Moffat & Fannin 2006). In the same manner, when tests were carried out under isotropic confinement (Bendahmane et al. 2008), the increase in the confinement pressure allowed for a decrease in the suffusion rate.

Suffusion can be described as the result of the process of surface erosion, the surface being here the surface of the pores, together with the fate of detached particles (Reddi et al. 2000, Bonelli & Marot, 2011). Furthermore, the distinction between internal suffusion and external suffusion (Kovacs, 1981) demonstrates the need to take into account the conditions for the evacuation of the detached particles in relation to the soil volume. This problematic is at the center of the study of filter efficiency, whether they are made of a geotextile material or of a layer of draining soil. For cohesionless soils, Lafleur (1999) identifies the ideal diameter d_i of the opening of the filter, by starting from the uniformity coefficient and from the aspect of the grain size distribution curve. Depending on the real opening O_F of the pores of a filter, several phenomena can be observed: suffusion, if $O_F \gg d_i$, clogging if $O_F \ll d_i$ and self-filtration if $O_F \approx d_i$. Even when filters that allow the migration of all the fine particles are being used, the size of the opening of the filter’s pores constitutes a parameter that can modify significantly the initiation and the development of suffusion. When testing suffusion on clayey sands, replacing a filter with a 4 mm opening by another filter of a 0.08 mm opening has enabled the critical hydraulic gradient to rise by 6 for the initiation of clay suffusion (Marot et al. 2009).

2.2 Influence of physicochemical characteristics of the medium and the interstitial fluid

The physicochemical characteristics of the fluid and solid phases are also crucial, particularly in the case of cohesive soils. According to Arulanandan & Perry (1983) the size of eroded aggregates is a function of either the state of flocculation or of de-flocculation. The state of flocculation or de-flocculation depends particularly on the chemical composition of the interstitial fluid, as well as on the quantity and nature of the clay. Reddi et al. (2000) have carried out a series of suffusion tests on clayey sand, injecting fluids that had different concentrations of sodium chlorate. The rate of erosion by suffusion decreases when the concentration in sodium chlorate increases. There are two distinct processes that can be responsible for this decrease in the quantity of eroded particles: the decrease of the detachment of particles and the increase in the filtration of detached particles. This reduction of the suffusion could be attributed, as is the case of surface erosion (Arulanandan & Perry, 1983), to the influence of sodium chlorate on the flocculation of the soil. If the rate of sodium absorption is high, the forces of physicochemical interaction decrease, which in turn causes a de-flocculation of the clay and a decrease in the resistance of clay particle detachment.

Clay particles are made of flakes, which are in turn made of atoms that are arranged in tetrahedral or octahedral meshes. By studying these different packing of atoms and flakes, one can classify the different types of clay into eight categories. Among these, we should mention in particular the kaolinite group, the smectite group (mainly comprising of montmorillonite) and the illite group. Their structure and their differing chemical composition give them different particle sizes and a different sensitivity to water.

For the same type of clay, several tests performed in clayey sands have shown that suffusion decreases with the increase of the clay percentage (Bendahmane et al. 2008). Arulanandan & Perry (1983) show that the nature of the clay influences the indicator of dielectric dispersion. This indicator is obtained by measuring the electric properties of the soil and of the interstitial fluid. By taking into consideration the concentration of the interstitial fluid and the rate of sodium absorption, the dielectric dispersion indicator enables us to characterize the initiation of the detachment of clay particles. Thus, as any other type of erosion, suffusion, which depends on the conditions of detachment of particles or aggregates of particles, appears to depend on the nature of the clay and for a given type of clay, on the clay percentage.

2.3 *Experimental procedure to detect the onset of suffusion*

One of the main difficulties of interpretation of those tests is related to the detection of suffusion initiation. Three approaches to characterize initiation were published in literature.

Skempton & Brogan (1994) proposed to relate the onset of suffusion with an increase of hydraulic conductivity.

Perzmaier (2007) observed that the use of local hydraulic gradient improves the precision of onset of instability detection and Moffat et al. (2011) defined the occurrence of suffusion by the decrease with time in local hydraulic gradient. However different studies (Moffat & Fannin 2006; Li 2008; Sail et al. 2011) show that when the average hydraulic gradient and the local hydraulic gradient in a part of a cohesionless sample are constant, at the same moment in another part of the same sample, the local hydraulic gradient can vary by several orders of magnitude. Thus, the detection of initiation of soil particle detachment based on the variation of local hydraulic gradient may depend on sample length and on distance between two pressure transducers or piezometers.

The third approach to detect onset of suffusion is based on the effluent turbidity (Reddi et al., 2000; Wan and Fell, 2008; Bendahmane et al., 2008; Marot et al. 2009; 2011a, 2012b, Nguyen et al. 2012). However, suffusion initiation with such approach will effectively detected only if detached particles a carried until the outlet of the soil sample.

An upward flow test makes it easy the observation of fine particles detachment but the accuracy of erosion

rate measurement is low because of the detached particles sedimentation process at the upper sample's end. In a downward flow test, the visual detection of fine particles detachment is not easy to perform with accuracy. The use of a turbidimeter allows measuring the effluent turbidity. Unfortunately this type of device requires an upward flow or horizontal flow which may generate a process of fines sedimentation between sample exit and turbidimeter. This, in turn, creates a bias in the measurements.

For all tests quoted above, the sample can be weighed in order to determine the erosion rate. However, the quantity of eroded particles can be very low. Thus the measurement by weighing or by visual observation is not accurate enough to detect the initiation of suffusion. During downward flow tests, Li (2008) and Sail et al. (2011) quantified the rate of erosion by collecting the eroded particles in several collection troughs.

Marot et al. (2011a) proposed a multichannel optical sensor which is able to measure the erosion rate of clay particles or cohesionless fine particles continuously and with a flow in downward direction. This sensor is composed of four Light Emitting Diodes and four associated Light Dependent Resistors allowing the measurement of fluid transparency. Given the small device dimensions, it can be placed close to the particles exit from specimen. The optical sensor is able to measure instantaneously a large range of clay or silt concentrations in the effluent, without a significant influence of flow rate. The presence of sand grains in fluid flow can also be detected.

3 DETERMINATION OF SUFFUSION SUSCEPTIBILITY

3.1 *Comparison of grain size distribution criteria*

Several criteria based on the study of grain size distribution have been proposed in literature by Kézdi (1979), Kenney & Lau (1985), Lafleur et al. (1989), Burenkova (1993) among others.

In the aim of applying the filter criterion to the case of suffusion, Kézdi (1979) proposed the distinction between the coarser fraction and the fine fraction in a point chosen randomly in the distribution of the grains. He considers that the coarser fraction will act as a filter for the fine fraction. The sieve size for which 15% of the weighed coarser fraction is finer (called D'_{15}) characterizes the size of the constrictions of this fraction and the sieve size for which 85% of the weighed fine fraction is finer (d'_{85}) is used to characterize the size of the particles in this fraction. Kézdi thus advances the assumption that the soil will be stable to suffusion if the ratio D'_{15}/d'_{85} is well below 4 for every random division point throughout the grain size distribution.

One of the most currently used criteria is the one proposed by Kenney & Lau (1985). This criterion was established on results of tests that were carried out on samples composed of sand and gravel. It consists in

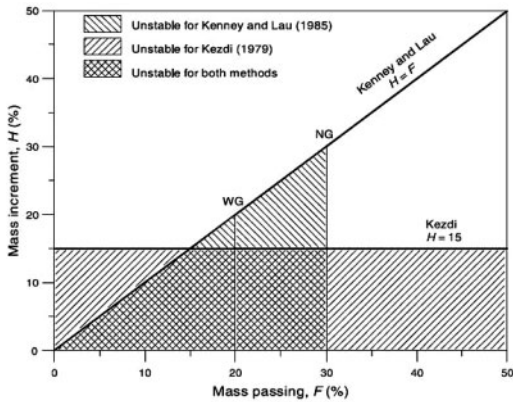


Figure 2. Comparison between Kézdi's criteria and Kenney and Lau's criteria (Li & Fannin, 2008).

determining, for each size of the particle d , the mass percentage F of the grains, having a size that is lower than d as well as the mass percentage H of the grains having a size between d and $4d$ ($H = F_{4d} - F_d$). These researchers consider that the grains smaller than d can detach themselves if the soil does not have enough grains within the interval between d and $4d$. They represent the values of H versus the values of F (the obtained curve is called shape curve). Within the interval $0 < F < X$, they propose that the soil be deemed unstable if its shape curve is situated completely or partially under the line represented by $H = 1.3 F$ (the equation once modified in 1986 becomes $H = 1.0 F$). In the case of soils whose coefficient of uniformity $C_u = d_{60}/d_{10} = 3$ (where d_{60} and d_{10} are the sieve size for which 60% and 10% respectively of the weighed soil is finer), X is chosen to be equal to 0.3 and if $C_u > 3$, then $X = 0.2$.

According to Li & Fannin (2008) the risk evaluation for suffusion made with Kézdi's criterion and Kenney & Lau's criterion can be reformulated by: within an interval that corresponds to 4 grain diameters, the slope is lower than 15% in the case of Kézdi's criterion and lower than $F\%$ in the case of the criteria proposed by Kenney and Lau. The authors draw the following conclusions: the two criteria converge for $F = 15\%$ (see Figure 2).

In the case of gap graded soils, Kézdi's criterion seems to be more suitable for distinguishing the stable soils from the unstable ones. For the soils with continuous grain-size distribution, the best results are obtained with the help of the Kenney and Lau criterion. Kézdi's criterion is more conservative for $F < 15\%$ and conversely, Kenney and Lau's criterion is more conservative for $F > 15\%$.

Wan & Fell (2008) have carried out 20 suffusion tests on mixtures of clay-silt-sand-gravel and silt-sand-gravel mixtures. Three criteria were used for predicting the initiation of suffusion: the Sherard criterion, the Kenney & Lau criterion and finally, Burenkova's criterion. They concluded that the used methods based on particle size distribution are conservative and they

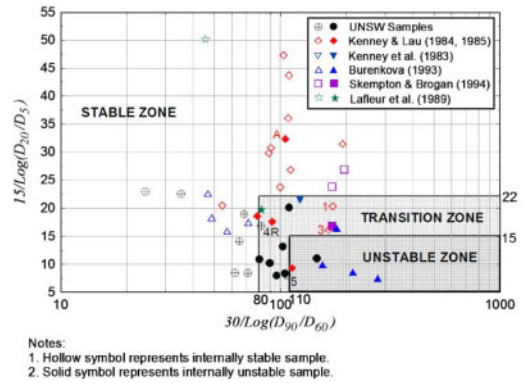


Figure 3. Wan & Fell (2008)'s method for determining the stability for suffusion.

proposed a method for assessing internal instability of broadly graded silt-sand-gravel soils. This method is based on two ratios: d_{90}/d_{60} and d_{20}/d_5 (where d_{90} , d_{60} , d_{20} and d_5 are the sieve size for which 90%, 60%, 20% and 5% respectively of the weighed soil is finer). Figure 3 shows $15/\log(d_{20}/d_5)$ versus $30/\log(d_{90}/d_{60})$. Wan & Fell (2008) discern an area where the soils are stable to suffusion, an area where they are unstable and finally a transition area.

According to Wan & Fell, this method seems to be not applicable for gap graded soils and soils with a percentage of finer fraction lower than 15%.

3.2 Identification of the most successful criteria

With the aim of evaluating the soil susceptibility to suffusion process, three grain size distribution criteria can be used.

In the case of gap graded soils, Kézdi's criterion seems to be the less conservative.

For widely graded soils, the fine fraction is identified within the granular distribution by the minimum value of Kenney & Lau ratio H/F . If the percentage of fine particles is lower than 15%, the evaluation of susceptibility can be determined by Kenney & Lau criterion. For a higher percentage of fine particles, the susceptibility is evaluated by Wan & Fell criterion.

4 CHARACTERIZATION OF SUFFUSION SENSIBILITY

4.1 Introduction

It is worth stressing that grain size distribution criteria don't take into account several important parameters such as: the mineralogy of the material, the shape of the grains, the effective stress and the viscosity of the fluid. Furthermore, most of the tests were performed on cohesionless materials and did not concern cohesive soils. Finally, even if the transport of particles is geometrically feasible, the action of the hydraulic flow must be sufficient for detaching the soil particles. Thus Kovacs (1981) recognized that even if the

geometrical conditions allow particle movements, the hydraulic conditions have to be studied.

4.2 Hydraulic criteria

The hydraulic loading on the grains is often described by three distinct approaches: the hydraulic gradient, the hydraulic shear stress and the pore velocity. The critical values of these three quantities can then be used to characterize the suffusion initiation.

By carrying out tests on the mixtures of sand and gravel with an upward flow, Skempton & Brogan (1994) concluded that the value of the critical gradient of the suffusion initiation, named i_{cr} , can be approximately a third or a fifth of the value of the critical heave gradient i_c (with $i_c = \rho' / \rho_w$, ρ' : submerged unit mass of the soil specimen and ρ_w : unit mass of water). Authors explain that the deviation between the values of the critical gradient is caused by the fact that the major part of the effective stress is supported by the granular skeleton made of gravel. They propose to express the critical suffusion gradient of the sand i_{cr} by:

$$i_{cr} = (1 - \alpha) \left(\frac{\rho'}{\rho_w} \right) \quad (1)$$

with α a reduction factor for the effective stress (Skempton & Brogan suggested an order of magnitude less than 0.1 for sandy gravel and its value needed to be determined by internal erosion tests).

Li (2008) performed suffusion tests on cohesionless soils with a large permeameter (inner diameter: 279 mm) and a small permeameter (inner diameter: 102 mm). Li (2008) evaluated the suffusion initiation thanks to a temporal variation of local hydraulic gradient. He observed that the critical hydraulic gradient can be seven times higher with the small permeameter than with the large one for a same type of tested specimen and a same mean vertical effective stress. The difference was attributed to scale effects. From Skempton & Brogan (1994)'s concept of stress reduction and with the objective to eliminate this effect, Li (2008) expressed the critical hydraulic gradient for upward seepage flow, i_{cr} , as a function of normalized vertical effective stress as:

$$i_{cr} = \alpha \left(\frac{\sigma'_{i0}}{\rho_w g \Delta z} + \frac{\rho'}{\rho_w} \right) = \alpha \left(\frac{\sigma'_{vm0}}{\rho_w g \Delta z} + 0.5 \frac{\rho'}{\rho_w} \right) \quad (2)$$

where, σ'_{i0} : vertical effective stress on the top of specimen at hydraulic gradient $i = 0$, Δz : thickness of soil specimen, g : gravity, σ'_{vm0} : mean vertical effective stress in the middle of soil layer ($\sigma'_{vm0} = \sigma'_{i0} + 0.5 \rho' g \Delta z$). It can be noted that the thickness of soil specimen corresponds to the seepage path in the case of a vertical seepage flow. Thus the value of critical hydraulic gradient seems to decrease with the seepage path.

Marot et al. (2012a) performed suffusion tests on clayey sand and the obtained results show that for an increase of tested specimen length by a factor 2, the value of critical hydraulic gradient can be multiplied by a factor of 0.6 and rate of erosion can double. With the aim to evaluate the likelihood of suffusion initiation on the field by a hydraulic gradient approach, it is worth noting that this decrease of critical hydraulic gradient with the size of tested sample completely contrasts with risk management.

The filtration of some detached particles can induce a clogging process within the soil accompanied with the decrease of the hydraulic conductivity (Reddi et al. 2000, Bendahmane et al. 2008; Marot et al. 2009, 2011a, Nguyen et al. 2012). Therefore, variations of both seepage velocity and hydraulic gradient (or pressure gradient) have to be taken into account to evaluate the hydraulic loading.

Reddi et al. (2000) proposed to represent the porous medium by a system of parallel capillary tubes each of a constant radius r . Assuming that hydraulic loading can be represented by a shear stress, the hydraulic shear stress for a horizontal flow between upstream section A and downstream section B of the system can be expressed by:

$$\tau = \left(\frac{\Delta P}{\Delta L} \right) \frac{r}{2} \quad (3)$$

where $\Delta P = P_A - P_B$ is the pressure drop between sections A and B, ΔL is the distance between sections A and B and $r = d_0/2$ with d_0 the average pore diameter in coarse fraction defined by Kovacs (1981).

This concept of hydraulic shear stress can be reformulated in the case of a vertical flow by the equation:

$$\tau = \left(\frac{\Delta h \gamma_w}{\Delta z} \right) \frac{r}{2} \quad (4)$$

where h is the hydraulic head. It is worth stressing that such approach leads to the same expression of hydraulic shear stress as expression proposed by Wörman & Olafsdottir (1992).

In the case of cohesive soils, Reddi et al. (2000) proposed to estimate the constant radius r by:

$$r = \sqrt{\frac{8K}{n}} \quad (5)$$

where n is the porosity, K is the intrinsic permeability determined by:

$$K = k \frac{\eta}{\gamma_w} \quad (6)$$

where k is the hydraulic conductivity, η is the dynamic viscosity and γ_w is the unit weight of water. Thus by this approach, the hydraulic shear stress along a horizontal capillary tubes system can be expressed by:

$$\tau = \left(\frac{\Delta P}{\Delta L} \right) \frac{r}{2} = \left(\frac{\Delta P}{\Delta L} \right) \sqrt{\frac{2K}{n}} \quad (7)$$

It is worth noting that in Equation 7, pressure gradient and permeability are both considered.

From results of interface erosion tests, Marot et al. (2011b) proposed a new analysis based on the energy expended by seepage flow which is a function of flow rate and pressure gradient. Four assumptions were used: the fluid temperature is assumed constant, the system is considered as adiabatic and only a steady state is considered. Moreover in the case of the suffusion process, the value of the Reynolds number is relatively low. Accordingly, Marot et al. (2012b) assumed that the dissipation of energy is mainly transformed into suffusion and finally, the power dissipated by suffusion process, P_{flow} is expressed by:

$$P_{flow} = (\gamma_w \Delta z + \Delta P) Q \quad (8)$$

where $\Delta z = z_A - z_B$, z_A and z_B are coordinates of section A and B respectively, Q is fluid flow rate.

$\Delta z > 0$ if the flow is in downward direction, $\Delta z < 0$ if the flow is upward and the erosion power is equal to $Q\Delta P$ if the flow is horizontal.

The expended energy E_{flow} is the temporal integration of the instantaneous power dissipated by the water seepage for the test duration.

4.3 Suffusion sensibility classification

Concerning erosion sensibility classification, three methods were proposed in the case of interface erosion. The method proposed by Hanson and Simon (2001) and the one proposed by Wan and Fell (2004) assumed a linear expression of the rate of erosion as a function of hydraulic shear stress:

$$m = k_d (\tau - \tau_c) \quad (9)$$

where k_d is the erosion rate coefficient, τ is the hydraulic shear stress and τ_c is the critical shear stress.

According to values of both k_d coefficient and critical shear stress, Hanson & Simon (2001) proposed five categories of soil erodibility between very resistant to very erodible. Wan & Fell (2004) proposed six categories varying from extremely slow to extremely rapid and based on the value of the erosion rate index I_{kd} determined by:

$$I_{kd} = -\log(k_d) \quad (10)$$

The third method (Marot et al., 2011b) was based on an erosion resistance index as:

$$I_\alpha = -\log_{10} \left(\frac{\text{Eroded dry mass}}{E_{flow}} \right) \quad (11)$$

Depending on the values of I_α index, six categories of soil erodibility were proposed from highly erodible to highly resistant.

However, these classifications concern only cases of interface erosion and suffusion erodibility classification is not yet well established.

5 DISCUSSION

5.1 Specific devices

Two complementary devices were developed with the aim to characterize the suffusion sensibility of coarse soils and also fine soils.

5.1.1 Erodimeter for coarse soils

The experimental device dedicated to coarse soils is named oedopermeameter. It is configured to perform tests on cylindrical specimens (280 mm in diameter and height up to 600 mm), saturated and consolidated under oedometric conditions. Specimens are then subjected to a downward flow with a constant hydraulic gradient increased by steps.

The device and its equipments are illustrated in Figure 4. It comprises a rigid wall cell made of Plexiglas in order to observe specimen during testing time. This cell is equipped with fourteen pressure ports, all connected to a single pressure sensor via a multiplex unit (components are detailed in Alexis et al. 2004). Such system avoids measurement deviation between different pressure sensors. The device includes also an axial loading system which is composed of a pneumatic cylinder and a piston (itself composed of two perforated plates with a layer of gravel in between as represented in Figure 4, in order to diffuse the injected fluid uniformly at the top of the specimen). This axial loading system allows the measurement of the axial effective stress on the top of the specimen thanks to a load sensor. The specimen settlement is measured by a linear variable differential transducer (LVDT). The specimen is supported by a lower wire mesh itself fixed on a coarse and rigid mesh screen. The collecting system, downstream of the cell, includes an effluent tank with an overflow outlet (to control the downstream hydraulic head) and is equipped with a rotating sampling system containing 8 beakers for the sampling of eroded particles carried with the effluent. The detail of each component is reported in Sail et al. (2011).

5.1.2 Erodimeter for fine soils

A triaxial erodimeter was designed to apply downward seepage flow on intact fine soil sample or on reconstituted fine soil specimen (50 mm in diameter and height

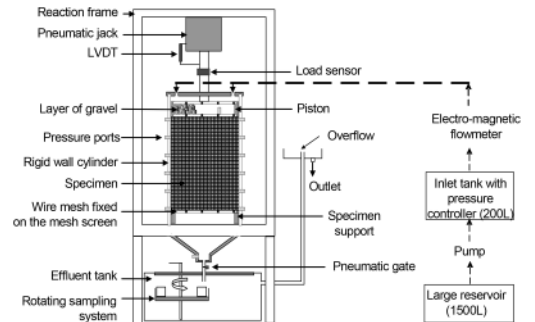


Figure 4. Schematic diagram of the oedopermeameter.

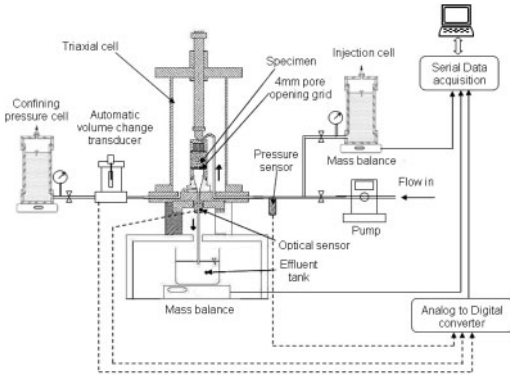


Figure 5. Schematic diagram of the triaxial erodimeter.

up to 100 mm) (see Figure 5). A detailed description of the device was reported by Bendahmane et al. (2008) and a brief summary is provided hereafter.

The testing device comprises a modified triaxial cell which was designed to saturate the sample in upward direction, to consolidate it under isotropic confinement and finally to force fluid through the sample in downward direction. The system to generate seepage flow under constant hydraulic gradient comprises a pressure sensor and an injection cell connected to air/water interface cylinder. Injection cell is continuously weighed in order to determine injected flow rate. The system to generate seepage flow in flow-rate-controlled conditions comprises a gear pump connected to a pressure sensor.

The sample is supported by a lower mesh screen of 4 mm opening size. The funnel-shaped draining system is connected to effluent tank by a glass pipe. Effluent tank is placed on a mass balance in order to continuously measure the effluent mass.

In the case of clay suffusion, the detection of suffusion is not accurate enough by weighing measurement or by visual observation. Thus a multichannel optical sensor was placed at the end of the draining pipe (Marot et al. 2011a). Thanks to a previous calibration, the optical sensor allows measuring the clay concentration, within the fluid which is expressed by the ratio of clay mass particles to water mass within the fluid. Moreover the comparison of the voltages of each optical sensor LED makes possible the detection of sand grains in the effluent.

A confining pressure cell connected to an air/water interface cylinder is used to generate isotropic confinement. Sample volume change is measured by automatic volume change transducer connected between confining pressure cell and the inlet of triaxial cell.

5.2 Soils properties and test procedure

5.2.1 Coarse materials

Tested coarse materials are two mixtures of glass beads. Glass beads have been chosen to avoid the influence of cohesion and grain angularity on the erosion

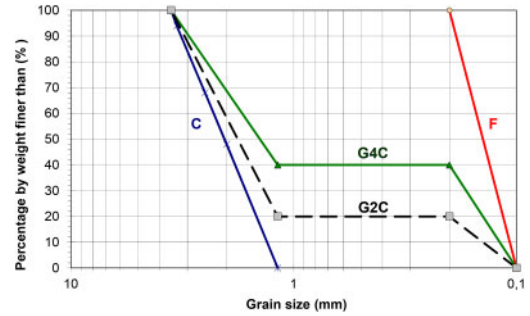


Figure 6. Grain size distribution of tested coarse materials.

process (Marot et al. 2012a), and also to perform comparisons with previously published results obtained by Moffat & Fannin (2006) with bead assemblies.

The two glass bead mixtures, G4C (as named by Moffat & Fannin 2006) and G2C, are composed of a coarse fraction C and a fine fraction F. Their grain size distributions are plotted in Figure 6, together with the grain size distribution of the coarse C and fine F fractions.

For both gap graded mixtures, the ratio D'_{15}/d'_{85} exceeds the ratio of 4 advocated by Kézdi (1979) in distinction between stable and unstable gradations. Thus these materials can be defined as unstable according to Kézdi's criterion.

Each specimen is created by a technique of slurry deposition used by Moffat & Fannin (2006). The specimen is reconstituted on a lower wire mesh with a 1.25 mm pore opening size (see Figure 4) in order to allow the migration of fine particles only. The water level in the cell is initially set at 2 cm above wire mesh (i.e. the specimen support). Glass beads are then placed in several successive slurry-mixed layers (by ensuring a vanishing drop height to prevent mixture segregation), each one covered by the same 2 cm thin film of standing water, with the aim to maintain saturation of the material. The specimen is finally consolidated under a 25 kPa axial loading with drainage from the top and the bottom of the specimen. The average value of specimen saturated unit weight is 20.6 kN/m³.

5.2.2 Clayey sand

The tested fine material is a mixture of 75% Fontainebleau sand (percentage by weight) and 25% Kaolinite Proclay. A laser diffraction particle-size analyzer was used to measure the grain size distribution of sand, clay and mixture (see Figure 7). These measurements were performed with demineralised water and without deflocculation agent.

By using the method proposed by Wan & Fell (2008) for assessing the potential of suffusion, tested clayey sand would be placed in transition zone ($15/\text{Log}(D_{20}/D_5) = 16$ and $30/\text{Log}(D_{90}/D_{60}) = 137$; Figure 3).

The specimens are prepared using a single layer semi-static compaction technique with a 50 mm diameter and 50 mm high mould. The obtained value of

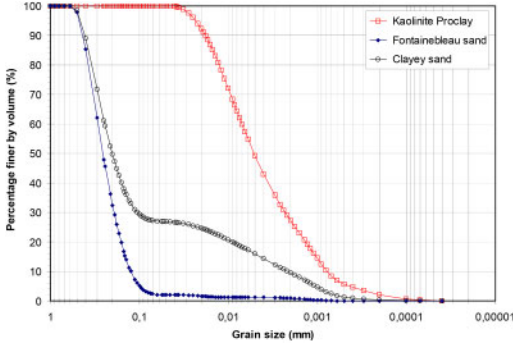


Figure 7. Grain size distribution of tested clayey sand.

Table 1. Main characteristics of tests on coarse materials.

Test	% fine	Initial specimen length (mm)	Multi-stage global hydraulic gradient
G4C-1	40	246	1-2-3
G4C-2	40	449	1-2-3-4-4.5
G4C-3	40	442	1-2-3-4-4.5
G4C-4	40	246	0.1-0.2-0.4-0.8-1-2-3
G2C-1	20	244	0.1-0.2-0.4
G2C-2	20	244	0.1-0.2-0.3

dry unit weight is 16 kN/m^3 . Specimen is placed in cell and a 15 kPa isotropic confinement pressure is applied. Carbon dioxide is injected followed by the saturation phase which requires approximately 24 h. Specimens were subjected to a seepage flow in downward direction with deaerated and demineralised water.

5.3 Comparison of suffusion sensibility classifications

5.3.1 Suffusion sensibility of coarse materials

Six tests were performed in different conditions characterized by four parameters (see Table 1): the initial fine particle content, the initial specimen length, the stage amplitude of global hydraulic gradient (defined as the ratio of the difference between upstream and downstream hydraulic heads to initial total specimen length). The duration of each stage of applied hydraulic gradient for all tests was one hour.

With the aim to consider the erosion rate normalized with respect to the erosion area, as in hydraulic shear stress concept expressed by Equation 4, the erosion rate is expressed here per unit pore area by:

$$m_p(t) = \frac{\Delta m_{eroded}(t)}{N_p S_p \Delta t} \quad (12)$$

where $\Delta m_{eroded}(t)$ is the dry mass of eroded particles collected during duration Δt of eroded particle sampling (about 6 min), S_p is the pore area with

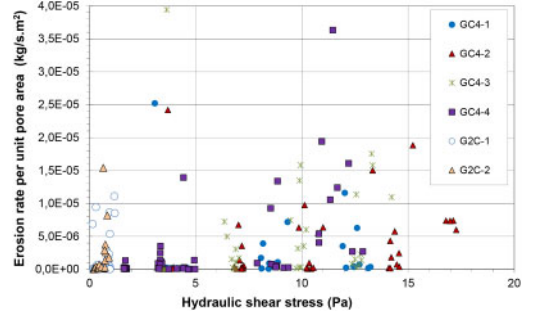


Figure 8. Erosion rate per unit pore area versus hydraulic shear stress (mixtures of glass beads).

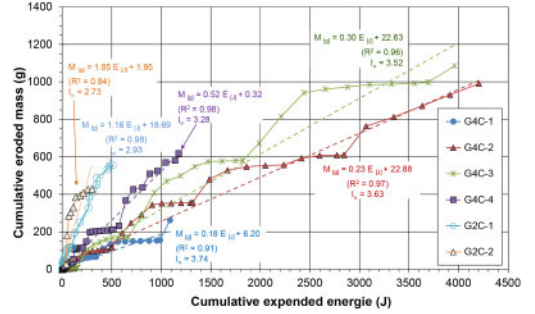


Figure 9. Cumulative eroded mass versus cumulative expended energy (mixtures of glass beads).

$S_p = \pi d_0 \Delta z$; and N_p is the number of average pore calculated by:

$$N_p = \frac{4 S n}{\pi d_0^2} \quad (13)$$

where S is the specimen cross section and n the specimen porosity.

As shown in Figure 8, no clear relation appears between erosion rate per unit pore area and hydraulic shear stress, because for a given value of hydraulic shear stress, different values of erosion rate were measured.

With the objective to take into account the history of the hydraulic loading on one hand, and the evolution of the corresponding specimen answer on the other hand, the cumulative eroded mass is plotted versus the cumulative expended energy in Figure 9.

A linear approximation can be established for each test and the erosion resistance index is deduced from the slope of linear approximations thanks to Eq. 11. The values of I_a are from 2.73 to 2.93 for G2C mixture and from 3.28 to 3.74 for G4C mixture. Thus the maximum relative error for erodibility characterization of these granular assemblies is limited to 12%.

5.3.2 Suffusion sensibility of clayey sand

Four tests were performed under either flow-rate-controlled or hydraulic-gradient-controlled conditions. Table 2 summarizes the main characteristics of performed tests.

Table 2. Main characteristics of tests on clayey sand.

Test	Applied constant flow rate (ml/min)	Applied constant hydraulic gradient (-)	Time of initiation of sand erosion (min)
KPF-1	1.24	—	65.96
KPF-2	1.47	—	69.29
KPF-3	1.62	—	58.62
KPF-4	—	18	20.06

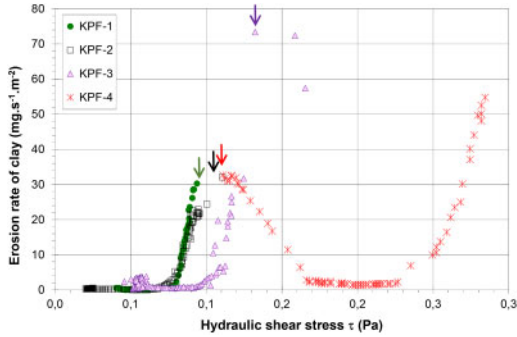


Figure 10. Erosion rate of clay versus hydraulic shear stress. Arrows show time detection of sand grains in effluent.

Under a high hydraulic gradient or under flow-rate-controlled conditions, initial clay suffusion leads eventually to both sand and clay erosion which induces a great decrease of specimen volume. This clay erosion accompanied with sand departure can be first observed at the specimen bottom and progresses upwards. In consequence, it can be named backward erosion.

For such type of soil, the hydraulic shear stress is computed by Equation 7 and the erosion rate is expressed per unit specimen cross section.

Figure 10 shows the erosion rate of clay versus hydraulic shear stress for all performed tests and the detection of sand grains in effluent with the optical sensor is indicated by arrows.

As shown by the curve plotted for test KPF-4, under hydraulic-gradient-controlled conditions, the hydraulic shear stress decreases during clay suffusion (the maximum value of hydraulic shear stress is obtained at the beginning of this test), whereas it increases under flow-rate-controlled conditions (the maximum value is obtained at the end of these tests).

When sand grains appear in effluent, concentration of clay cannot be computed. Then the eroded mass of clay particles and sand grains is determined by continuous weighing. Figure 11 shows the values of erosion rate of clay and sand versus the hydraulic shear stress.

As in the case of coarse materials, for clayey sand no clear relation appears between hydraulic shear stress and erosion clay and sand.

The cumulative eroded mass is plotted versus the cumulative expended energy for clay suffusion process

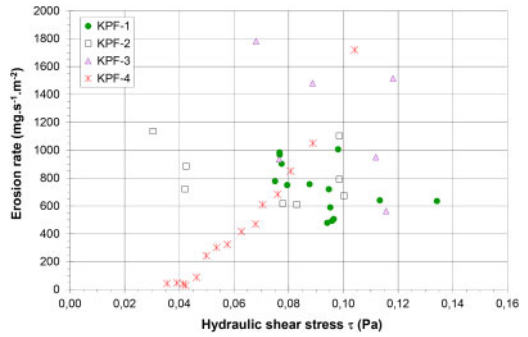


Figure 11. Erosion rate of clay and sand versus hydraulic shear stress.

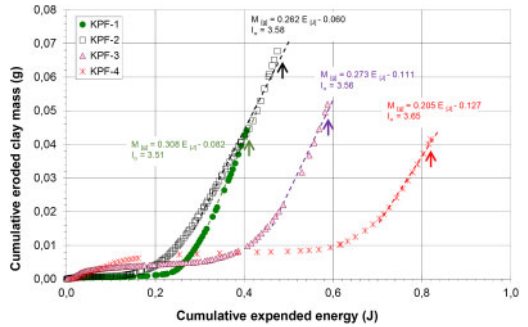


Figure 12. Cumulative eroded mass versus cumulative expended energy (suffusion of clay). Arrows show time detection of sand grains in effluent.

in Figure 12 and for sand and clay backward erosion process in Figure 13.

For clay suffusion process, a linear approximation can be established for each test and the corresponding values of erosion resistance index are from 3.51 to 3.65. Thus the maximum relative error for characterization of clay suffusion is limited to 4%.

For clay and sand backward erosion, the values of I_α are from 1.93 to 2.30 (maximum relative error for characterization of backward erosion: 19%).

According to the erosion resistance index, the obtained classification of erosion processes was identical for hydraulic-gradient-controlled tests and for flow-rate-controlled tests. These results demonstrate that this approach is efficient to characterize clay suffusion development and also the induced clayey sand erosion.

6 IMPLICATIONS FOR ENGINEERING PRACTICE

According to the aforementioned results, a systematic method can be proposed. Two successive steps can be distinguished: the evaluation of the susceptibility and the erodibility classification.

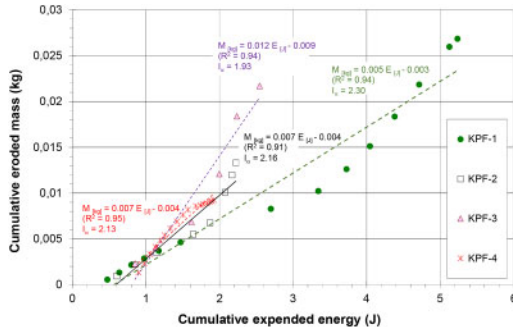


Figure 13. Cumulative eroded mass versus cumulative expended energy (backward erosion of clay and sand).

According to the type of grain size distribution, the most successful criterion can be chosen between criteria from Kézdi, Kenney & Lau or Wan & Fell.

When the evaluation of the susceptibility leads to potential instability, the erodibility characterisation needs suffusion tests, which should be performed with water from the site.

The size of the opening of the downstream filter's pores should be chosen in conformity with the real boundary conditions of soil in field. Thus the pore opening size of the filter in laboratory should match the pore opening of the granular filter or the geotextile in the considered earth structure. If there is no filter in the earth structure, soil from this structure should be tested with a downstream grid that allows the migration of all particles.

With the objective to characterize independently the hydraulic loading and the induced erosion, the energy dissipated the water seepage, E_{flow} can be computed by temporal integration of the erosion power (Equation 8) and the cumulative eroded dry mass is measured. Finally the erosion sensibility classification can be evaluated by the erosion resistance index I_α computed by Equation 11.

7 CONCLUSIONS

With the objective to evaluate the likelihood of suffusion initiation, several criteria based on the study of grain size distribution have been proposed in literature. The confrontation of the estimations obtained with the help of these grain-size distribution criteria, permits to identify three grain size distribution criteria that can be used in order to define the soil susceptibility to suffusion. However the confrontation has emphasized the limits of these criteria and the necessity to associate the analysis of the grain size distribution to the characterization of soil erodibility.

The characterization of soil sensibility to suffusion requires suffusion tests and the interpretation of such tests is based on the evaluation of the generated load by the fluid flow. This evaluation is mainly carried out by expressing the critical value of the hydraulic gradient, the shearing stress or the pore velocity. However,

different experimental campaigns have pointed out the presence of a scaling effect that perturbs the hydraulic approach based on the expression of a global hydraulic gradient. Moreover suffusion and filtration are two coupled processes that are governed by the geometry of the porous network, the physicochemical interactions between the solid phase and the fluid phase, as well as by the hydrodynamic conditions. In consequence, variations of both seepage velocity and hydraulic gradient (or pressure gradient) have to be taken into account to evaluate the hydraulic loading.

Methods characterizing the erosion sensibility which are based on rate of erosion cannot allow obtaining a unique characterization of suffusion process for different histories of hydraulic loading. Thus, such approaches do not allow the estimation of the development of suffusion.

The energetic approach which consists in determining the energy dissipated by the fluid flow is efficient to characterize suffusion development in coarse materials and in clayey sand. Characterization of the development of clayey sand backward erosion is also addressed by this method.

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