Influence of fine particles on internal erosion of sandy Soils

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Internal erosion has long been a major problem associated with earth structures and its field investigation has been limited because of its complexity. Laboratory experiments provide a potential insight into the processes involved. Gap graded soils are usually susceptible to suffusion because in these soils the volume of fines is less than the volume of voids between the coarse particles. However, it was known that soils containing more than 30% fines are stable against erosion. Some suffusion experiments were performed on a laboratory column packed with different sand-fines mixtures and subjected to controlled flow conditions. The initiation and the rate of soil suffusion were investigated and compared; the permeability variation along the soil column was controlled and the amount of remained fines in the sample was measured. Only a thick downstream part of the sample was affected by erosion. Attempts are also made to assess the influence of the clay content and the type of fine particles. The results show quite great resistance of illite against erosion. Silty Sand mixtures are the most suitable to suffusion as well as sand-kaolin mixtures. A mathematical model is used for simulating the soil suffusion curves obtained with a short soil sample. Comparison of model and experimental results indicate a quite good agreement.

Key words
Erosion, suffusion, grading, soil, clay, model, flow.

I INTRODUCTION

Detachment and mobilization of fine particles are important considerations both in soil erosion and in transport and fate of colloidal contaminants. The phenomenon of induced fines migration is of concern of both scientific and industrial fields. It finds application in flow in porous media when severe formation damage occurs, in the migration of wastes, in the ineffective regeneration of filter beds, and in the failure of earthen dams and dykes. Internal erosion involves detachment of fine particles whose subsequent mobilization and transport is related to the clogging occurrence. When flowing through porous medium, the particles are brought in contact with retention sites; they stop there or are carried away by the stream. During the flow of the suspension through a porous medium, particle transport and capture result from several forces and mechanisms, depending on particle size. [Khilar et al., 1985] used a capillary model for clay particle dispersion (detachment) in porous media to study piping and plugging mechanisms in earthen structures. They do not distinguish between size distributions of particles in suspension, and assume that particle trapping does not occur until the concentration of clay particles in suspension reaches a certain threshold value. The release occurs below a critical salt concentration and above a critical flow velocity. Natural clay in a dispersive state has been known as one of the fundamental factors that contribute to piping in earth dam and erosion of compacted soil of landfill clay liner. The process of internal erosion is usually described by the initiation, continuation and progression phases. The identification of pipe development and the likely failure of earth embankment lie in the understanding of initiation mechanism of internal erosion. Suffusion is the process where the fine particles of the soil wash out or erode through the voids formed by coarser particles. In order to assess the stability of the broadly-graded soils, [Sherard, 1979] suggested splitting the gradation curve at the 1.0 mm particle size and analysing it as two separate gradations. [Kenney et al., 1985] have carried out further investigations on pore size distribution of granular filters using either a theoretical or experimental approach. Many studies regarding the design of filters have been done and currently [Sherard and Dunnigan’s, 1989] results are widely used. [Lefebvre et al., 1986] investigated the influence of the natural structure of the undisturbed clay samples on the rate of erosion. They showed that the undisturbed
structured clay showed much higher erosion resistance than the de-structured remoulded clay samples. Internal erosion involves the dispersion of clay particles, and before dispersion, eroded particles are significantly larger than the primary particles of the soil. This indicates that erosion occurs as aggregates of materials [Locke et al., 2000]. [Wan and Fell, 2004a] used slot erosion and hole erosion tests to investigate the erosion resistance of the core material of fill dams. Both tests essentially adopted similar concepts, except that the slot erosion test possessed a longer flow channel. 14 different core materials were tested and an ‘erosion rate index’ was introduced to classify and grade the erosion resistance observed. [Wan and Fell, 2004a, b] defined the variation of erosion rate assuming the erosion curves (i.e. erosion rate vs. shear stress) were linear with constant slopes. The erosion characteristics are described by the erosion rate index, which measures the rate of erosion, and the critical shear stress, which represents the minimum shear stress when erosion starts. Coarse-grained, noncohesive soils erode more rapidly and have lower critical shear stresses than fine-grained soils. [Briaud et al., 2001] also defined the variation of erosion rate linearly, but used an initial tangent slope for determination of the critical shear stress. While solute transport in porous media is intensively studied, there are relatively few studies which include modeling of particles adsorbed to the mobile solid phase. [Khilar et al., 1985] assigned a critical shear stress to the porous matrix, representing the force with which fines are bound to the solid matrix by cementing agents or electrostatic. The present study is devoted to the investigation of the influence of fines content on the initiation and development of suffusion in soil mixtures and to use a mathematical model to simulate laboratory suffusion tests.

II SUFFUSION TESTS

The experimental set up (figure 1) involves a vertical Plexiglas cylinder of 40 mm internal diameter and 120 mm length. The specimen rests on a lower mesh screen (80 μm opening size), supported by a perforated base plate, and a large size opening mesh (1.2 mm) is used in the upper face. The specimen was made by mixing silica sand (Hostun HN34) and fine particles (kaolin, illite, silt) in various proportions and, after two-day curing, deposited in the cylinder (three layers) and compacted (double compaction) at the target density of 1.6. The moulding water content at which the mixtures were prepared to achieve the fixed density was close to 10%. The fabric is believed best controlled than a natural compacted fill. Suffusion tests were performed using upward flow through the sample and head-controlled using a supply of taped water at about 20°C or a pressured tank if necessary (high water heads). After the soil was saturated (during one day), flow was initiated at a low hydraulic gradient, and increased in stages until the specimen exhibits internal erosion. Many hydraulic loads were applied successively in the same sample beyond erosion starts. At the outlet, particles that wash from the specimen are directed to a turbid meter whose readings were correlated previously to fines concentrations in water. Differential pressure transducer mounted between the upstream and downstream of the soil sample allows the measure of the difference of water head, and hence the average hydraulic gradient along the specimen. Periodic measurement of volumetric discharge rate determines the corresponding hydraulic conductivity. Upon completion of testing, one specimen was extracted from the cylinder for grain size analysis. Outlet samples are collected in order to analyse the particle size distribution.

Figure 1: Drawing schema and a picture of the experimental set up
### III RESULTS AND DISCUSSION

#### III.1 Effect of fines on soil mixture suffusion

Experiments with mixtures of sand and 10% of fines were performed using kaolin, illite and silt. Illite is known to be less dispersive than kaolin and the average size of silt particles is close to 200 μm. Figure 2 below shows the typical concentration-time curves obtained for two mixtures with four steps of water head level (0.7 m; 1.2 m; 1.6 m and 3.5 m), and the cumulative mass curves deduced using flow rate measurements. Silt shows early suitability to suffusion while illite offers a resistance against suffusion. The cumulative curves indicate that silt mixture suffers internal erosion more than kaolin and illite which exhibit durably a quite similar behaviour.

![Figure 2: Suffusion curves and cumulative eroded mass of fine particles](image)

The influence of the amount of fines contained in the mixtures is illustrated on figure 3. If comparing the behaviour of kaolin and illite, one can observe that there is no evidence that the augmentation of fines content can lead to the increase of resistance against erosion. Increasing of kaolin level in the mixture leads to increasing suffusion, but illite level had a significant inverse effect on the soil suffusion. The augmentation of illite content allows the mixture to get greater cohesion and more attachment of fine particles to the sand matrix. In opposite, kaolin being more dispersive, offers more removal potential from sand matrix.

![Figure 3: Influence of fines content (illite, kaolin) on the soil suffusion](image)

#### III.2 Influence of hydraulic gradient on erosion rate of soil mixtures and hydraulic conductivity

The erodibility of a soil is widely described in term of the rate of erosion, when the soil is subjected to hydraulic shear stress. There is an approximate linear relationship between the rate erosion and the applied hydraulic shear stress:

\[ \dot{\epsilon} = C_e (\tau - \tau_c), \]

where:

- \( \dot{\epsilon} \): rate of erosion per unit surface area (kg/s/m²)
- \( C_e \): proportionality constant (s/m), defined as coefficient of erosion rate of soil: \( I = -\log C_e \), with
- \( I \): erosion rate index
\( \tau \): applied hydraulic shear stress (Pa)
\( \tau_c \): critical shear stress (Pa)

Wan and Fell (2004) suggested guidelines based on the erosion rate index value to estimate the suitability of soil to erosion. Table 1 summarizes the deduced classification obtained for the mixtures tested. Suffusion of sand-silt mixture is classified as extremely rapid, while the two other mixtures involve very slow erosion.

We discuss the influence of suffusion of the mixtures under a given hydraulic gradient, on the final value of the permeability \( k \). The permeability of mixtures decreases with increasing hydraulic gradient. The influence of internal erosion of sand-bentonite mixtures on the variation of permeability was previously highlighted by [Koaser et al., 2006] and a power correlation between erodibility and hydraulic conductivity was suggested.

The relation between erosion rate and hydraulic gradient shows a non-linear trend over a certain value of the gradient. The extrapolation of related curves to lower values can lead to critical gradients (minimum values when erosion starts). The slope of the linear part of these curves \( (i<8) \) represents the erosion characteristic of the mixture. One can deduce that this erodibility parameter makes sand-kaolin mixture the most erodible sample, while sand-illite mixture is the least erodible one. Decrease of permeability for sand mixtures made of silt and kaolin indicate the occurrence of clogging in a part of the sample. This reduction is more important for kaolin and illite over the test duration. This result explains the achievement of suffusion process which involves particle detachment, their subsequent transport in the soil matrix and likely clogging.

![Figure 4: Effect of hydraulic gradient on erosion rate and hydraulic conductivity](image)

**Table 1: Erosion rate index values and Fell guidelines**

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Erosion rate index</th>
<th>Erosion speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand NE34+10% Kaolinite</td>
<td>3.2</td>
<td>Very slow</td>
</tr>
<tr>
<td>sand NE34+10% Illite</td>
<td>4.4</td>
<td>Very slow</td>
</tr>
<tr>
<td>sand NE34+10% Silt</td>
<td>1.8</td>
<td>Extremely rapid</td>
</tr>
</tbody>
</table>

### III.3 Suffusion morphology in the soil

Internal erosion involves the migration of the finest soil particles through the soil matrix and the loss of soil particles washed out by the water flow. But erosion takes place only if particles detached from soil matrix are transported by the flow out of the soil. Because of filtration, some particles removed from the soil matrix are immediately trapped and do not travel longer. Internal erosion is then the result of a coupled process of particle removal (surface erosion) and the subsequent fate of eroded particles in the pores. It is significantly influenced by the processes subsequent to particle detachment, like redeposition of the particles on pore walls and clogging of pores. Three processes are presumed to occur simultaneously during particle transport: Detachment of clay particles from the parent soil matrix, Transport of particles in pore water by convective-dispersive processes; Depositon of clay particles which may be trapped in some pores owing to local changes in pore flow velocities or variations in pore geometry. The removal of particles from the soil matrix into pore water suspension causes an increase in pore space, which in turn increases the permeability of the medium. If the soil sample is subjected to a constant external pressure gradient, then the flow velocity (both Darcian and seepage) increases, which in turn causes more particles to be removed. One may be led to believe that this process would continue indefinitely and wash out the sample entirely. However, the soil...
matrix is held together rigidly and the applied stresses cannot remove more than a fraction of available particles. A test performed with a mixture containing 20% of silt was analysed after suffusion in order to investigate the part of sample from which particles were removed. Figure 5 below shows the variation of fines content along the sample from initial value (20%). We can conclude that most particles washed out from the sample are provided by the downstream third part and the whole volume is not concerned by erosion process. This suggests that longer test with higher pressure may lead to regressive erosion, but such test were conducted until a pressure close to 200 kPa and the sample collapse (fluidisation) before reaching complete suffusion of fine particles. This result allows assuming that internal erosion is not dependent on sample length and only a localised area is of concern with the process.

![Figure 5: Distribution of fines content along the sample after erosion test](image)

**IV MODELISATION**

A physical model developed by Govindaraju et al. (1995) was used for simulating the movement of clay particles in laboratory soil columns. The physical mechanism of detachment of particles from the soil matrix, their subsequent transport in the pore water, and possible entrapment or clogging was included in the model. In this model, the equation governing the conservation of clay particles in the porous medium in one dimension may be expressed as:

\[
\frac{\partial (\eta c)}{\partial t} + \frac{\partial (cq)}{\partial x} - \frac{\partial}{\partial x} \left( \eta D \frac{\partial c}{\partial x} \right) = R(c),
\]

where \( c(x,t) \) is the concentration of clay particles, \( D \) is the dispersion coefficient, \( \eta(x,t) \) is the soil porosity and \( q(x,t) \) is the flow rate given by Darcy equation:

\[
q(x,t) = \frac{k(x,t)}{\mu} A \Delta P, \tag{3}
\]

with \( k \) the absolute permeability of the porous medium, and \( \mu \) the dynamic viscosity of the fluid (water). \( A \) and \( L \) are respectively the cross section and the sample length. \( \Delta P = \rho gh \), is the pressure drop across the soil sample. Where \( \rho \) is the density of water, \( g \) the gravitational acceleration and \( h \) the head water acting on the sample. The second member \( R(c) \) in equation (1) represents the detachment rate of clay particles; it is proportional to the difference between the transport capacity of the flow and the actual particle suspension load in the flow. The clay particles removal is expressed as:

\[
R(c) = \sigma \left( T_c / \rho_s - cq \right), \tag{4}
\]

The constant of proportionality \( \sigma \) is a measure of the detachability of the clay particles. It expresses the ease with which particles (of density \( \rho_s \)) may be detached from the soil matrix, and is a measure of the intersurface forces binding the particles to the soil. The flow transport capacity \( T_c \) is proportional to the effective shear stress applied by the flow on pore surface [Khilar et al., 1985]:

\[
T_c = \alpha (\tau_w - \tau_{cp}), \tag{5}
\]
where $\alpha$ is the proportionality constant, $\tau_w$ is the total applied shear stress and $\tau_{cr}$ the critical shear stress. The applied shear stress is expressed as the sum of a velocity component and an acceleration component:

$$\tau_w = a q + b \frac{dP}{dt},$$

where $a$ and $b$ are proportionality constants and $p$ is the pressure across the soil sample. The change of porosity was related to change of permeability through the Kozeny-Carman equation as:

$$k = \frac{1}{C_s S_s^2 m^2 T^2} \frac{\eta^3}{(1-\eta)^2},$$

where $C_s$ is shape factor ($\approx 2.5$), $T$ is the tortuosity ($\approx \sqrt{2}$) and $S_s$ is the specific surface (per unit volume of soil solids). Equation (7) yields to the following expression related to initial permeability $k_i$:

$$k = k_i \left( \frac{\eta}{\eta_i} \right)^3 \left( 1 - \eta_i \right)^2,$$

where $\eta_i$ is the initial porosity of the soil and $\eta$ is the actual porosity expressed as a function of the concentration [Moghadasi et al., 2004]:

$$\eta = \eta_i \left( 1 - \frac{C_s - C}{\rho_s - C} \right),$$

Because of the small size of the tested sample (3 cm long), the dispersion of clay particles was neglected and the equation (2) is expressed as:

$$\frac{\partial (\eta c)}{\partial t} = \sigma \left( \frac{\alpha}{\rho_s} \left( a q + b \frac{dP}{dt} - \tau_{cr} \right) - c q \right)$$

An increase in soil detachability $\sigma$, a parameter which expresses the ease with which particles are removed from parent soil matrix, caused greater removal to a point. In order to simulate soil suffusion using the previous model, appropriate test was performed using a short sample (3 cm long) of coarse sand mixed with a weak proportion (2% and 4%) of silt. This accommodation lets fines to be removed easier from the matrix, leading to substantial suffusion. Figure 6 shows the adjustment obtained for a test performed on a mixture (coarse sand and 2% silt) subjected to a single step of water head. Time dependent concentration and cumulative mass curves from measurement and modelling present similar variation over the test time. The quite good adjustment obtained indicates the ability of used model which integrate the two phases of erosion process.

Figure 6: Numerical adjustment of measured suffusion curve and cumulative mass (single hydraulic load)
The second suffusion test simulated was performed with finer sand mixed with 4% of silt and subjected progressively to two steps of hydraulic load. Results for cumulative particle removal and time dependent concentration are presented on figure 7. Both the experimental and theoretical curves show the initial steep rise in concentration resulting from the imposed hydraulic gradient rate. As time progresses and the second hydraulic gradient imposed, the theory predicts small concentrations and underpredicts the experimental concentrations. The theoretical predictions are in good agreement for $t < 50$ s, but gradually deviates from observations with increasing time. The theory underestimates particle removal at large times. The primary reason for this discrepancy may be the high value of soil detachability predicted.

![Figure 7: Adjustment obtained for a test with two successive hydraulic loads](image)

**V CONCLUSIONS**

This paper dealt with the results of an experimental investigation of the suffusion of sandy soils reconstituted in laboratory and the use of numerical model to simulate particle removal under external hydraulic load. Flow tests on sand/fines mixture were conducted with the purpose of comparing the suitability to suffusion of each mixture. This study shows that either the type or content of fines affect initiation and rate of suffusion. The potential for instability is governed by the matrix porosity and the proportion of fines. Silt mixtures are more suitable to suffusion than kaolinite mixtures which in turn are more suitable to suffusion than illite mixtures. But the fines content acts inversely: more illite fines make the mixture more resistant against erosion while greater kaolinite content leads the mixture suffering larger suffusion. This result can be related to the greater dispersion of kaolinite. The permeability of mixtures decreases with increasing hydraulic gradient and rate erosion. The analysis of the sample after suffusion test provides interesting result about the sample volume affected by erosion. Washed particles from the sample are provided by the downstream third part and the whole volume is not concerned by erosion process. This result allows assuming that internal erosion is not dependent on sample length and only a localised area is of concern with the process. Some processes leading to particle retention and clogging must be taken into account in the modelization of suffusion.

Comparison of theoretical model and experimental results indicated a quite good agreement for a single hydraulic load. The results obtained for more than a single load indicate that the model proposed have to be performed for future wide application in particle transport and suffusion at the laboratory scale.

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VII REFERENCES AND CITATIONS


