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On the boundary conditions of suffusion tests and its relation to dam safety assessment

Sur les conditions aux limites des essais de suffusion et sa relation avec l'évaluation de la sécurité des barrages

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ABSTRACT: The characterization, detection and healing of internal erosion by suffusion in embankment dams is a common but unsolved safety issue affecting, particularly, dams built with a glacial till core. Despite the large amount of data related to suffusion experimental tests, the variability of testing conditions such as: type of soil, stress conditions, hydraulic loading, experimental scale and duration, limits the generalization of conclusions on the likelihood of suffusion in a specific type of soil. This contribution summarizes, compares and discuss the influences of various testing and boundaries conditions on the interpretation of results and its possible application to dam safety assessment. The data used in this contribution were compiled from the literature.

RÉSUMÉ : La caractérisation, la détection et la guérison de l'érosion interne par suffusion dans les barrages en remblai est un problème de sécurité courant mais non résolu affectant, en particulier, les barrages construits avec un noyau de till glaciaire. Malgré la grande quantité de données liées aux essais expérimentaux de suffusion, la variabilité des conditions d'essai telles que : type de sol, conditions de contraintes, charge hydraulique, échelle et durée expérimentales, limite la généralisation des conclusions sur la probabilité de suffusion dans un type spécifique de sol. Cette contribution résume, compare et discute les influences de divers tests et conditions limites sur l'interprétation des résultats et son application possible à l'évaluation de la sécurité des barrages. Les données utilisées dans cette contribution ont été compilées à partir de la littérature.

KEYWORDS: suffusion test, hydraulic gradient, glacial till soil, dam safety, embankment dams.

1 INTRODUCTION

Suffusion is an internal erosion mechanism that occurs within a matrix of soil when the seepage-stresses are high enough to transport the loose fine-grained particles through the constrictions defined by the coarser particles forming the matrix of soil. This phenomenon occurs typically in gap graded or coarse widely graded soils such as glacial till soils used often as core soil in embankment dams located in areas once glaciated. Even though suffusion is a common issue in glacial till dam cores, its initiation, development and healing is yet poorly understood. This condition and the increased need from the industry sector for a comprehensive dam safety assessment have derivate in the necessity of a major number of studies on suffusion.

Suffusion tests, also named hydraulic test (Kenney & Lau 1985), seepage flow test (Li & Fannin 2008) and seepage-induced internal instability test (Slangen & Fannin 2019), are generally performed in seepage-based apparatus, which consistent of rigid wall permeameters adapted from the device used in permeability tests (e.g. ASTM D2434 2006). Up to date, several researchers have been performed aiming to recognize the physical conditions that trigger suffusion (Kenney & Lau 1985, 1986, Burenkova 1993, Skempton & Brogan 1994, Foster & Fell 2001, Wan & Fell 2004, Moffat & Fannin 2006, Hunter et al. 2012, Douglas et al. 2016, Rönnqvist 2015, Rochim et al. 2017, among others). As result of those researches, today it is understood that the initiation of suffusion depends on three major factors: i) particle size distribution of the soil, ii) stress conditions within the soil matrix and iii) applied hydraulic load; whilst its continuation depends on the filter. Moreover, the development of methods allowing to predict the soil's susceptibility to suffusion based on geometrical analysis of its particle size distribution have been accomplished. However, despite the large amount of data related to suffusion experimental tests, the variability of testing conditions such as: type of soil, stress conditions, hydraulic loading, experimental scale and testing duration, limits the generalization of conclusions on the likelihood of suffusion in a specific type of soil.

Herein the authors summarizes, compares and discuss the testing and boundaries conditions of different studies on suffusion, this aiming to give a general perspective of the potential influences of the experimental conditions on the interpretation of results and understanding of the suffusion process. The data used in this contribution were compiled from literature.

1.1 *Suffusion tests*

Suffusion tests have developed as an extension of permeability tests, thus are performed in a seepage apparatus and have the Darcy's law as main principle. In both suffusion and permeability tests a cylindrical soil specimen with known initial particle size distribution (PSD) and density is expose to water seepage collected and measured over time to calculate the hydraulic conductivity (k). However, in suffusion tests the fine-grained particles of the tested soil could experience a re-arrangement or washout from the soil matrix during the test, consequently affecting the hydraulic conductivity over time. Furthermore, suffusion tests differs from the permeability tests on the boundary and testing conditions applied.

The boundary and testing conditions in suffusion tests are in close relation to the real state in the dam site. The real state in the dam site is mainly defined by the geotechnical properties of the core soil, the PSD of the filter, the hydraulic head in the reservoir and the stress conditions.

Regarding the geotechnical properties of the soil, the main property to be determined prior to initiate the test is the soil classification in terms of susceptibility to suffusion. Therefore, the PSD and the plasticity index must be determined. The maximum density and optimum water content are also important characteristic to know about the material. However, these parameters might vary in the test depending on the in-situ conditions to be represented. Thus, the maximum density and the water content are considered as boundary conditions of the test along with the initial consolidation state, and degree of saturation of the specimens.

The PSD of the filter also represents a boundary condition for the test, whiles the hydraulic and stress conditions are variables to change during the test and therefore categorized as testing conditions.

The following sections include a brief description of the soil classification in terms of susceptibility to suffusion, followed by the main features of a suffusion test device and the boundary and testing conditions to consider in suffusion tests.

2 SOIL CLASSIFICATION IN TERMS OF SUFFUSION

Soils susceptible to suffusion, known as internally unstable, are either coarsely graded with a flat tail of fines or gap-graded with a low percent of fine particles (ICOLD 2015). In addition, according to Rönnqvist (2015) glacial tills with fine content < ≈15–20 % (at $d_{max} \approx 30$ mm), sand content < ≈20%, and gravel fraction > ≈60% appear to be susceptible to suffusion.

Four of the empirical methods widely used to evaluate the potential of internal instability of granular soils are: i) Kezdi (1979), ii) Kenney & Lau (1985, 1986), iii) the modified Burenkova (1993) method by Wan & Fell (2004), and iv) the alternative Wan & Fell (2008) method. These methods are based on the shape of the particle size distribution curve and suffusion tests performed to evaluate the behaviour of the soil under seepage stresses. Each of these tests define boundary values to classify the soil as either internally stable or internally unstable.

3 TESTING DEVICE

Suffusion test devices consist on a cylindrical permeameters with typically the following components: a) permeameter cell, b) hydraulic control system, c) optional stress control system, d) seepage and eroded soil collection system and e) instrumentation. Each component is described in the following sub-sections.

3.1 *Permeameter cell*

The permeameter cell can be either a rigid-wall (Fig. 1) or flexible-wall. Rigid-wall permeameters can be made of aluminum, stainless steel or plastic (e.g. Kenney & Lau 1985, Burenkova 1993, Skempton & Brogan 1994, Foster & Fell 2001, Hunter et al. 2012, Indraratna et al. 2015). The advantage of plastic permeameters relies on the possibility to observe the potential changes within the soil matrix during the test, which proved to be very useful when interpreting the response of the test specimen. Nevertheless, rigid-wall permeameters have two main disadvantage: a) preferential seepage paths at the interface between the wall of the permeameter and the soil, and b) the impossibility to measure volumetric changes.

Flexible-wall permeameters reduce the potential effects of preferential seepage paths and allows testing specimens under triaxial loads. The general configuration of flexible-wall permeameters is an adaptation from the device used in the measurement of hydraulic conductivity of saturated porous material using flexible-wall permeameter (ASTM D5084-16 2016). A novel feature of the device is the doble-walled triaxial cell introduced by Slagen & Fannin (2017), which allows the measurement of volume change during multistage seepage flow. An additional advantage of flexible-wall permeameters is the inclusion of a backpressure system to facilitate saturation and provides a means for determining hydraulic conductivity at a controlled level of effective stress. Hydraulic conductivity varies with varying void ratio, which changes when the effective stress changes. Nevertheless, the drawback of this type of permeameters is the limitation in the maximum particle size that can be used in the test. Therefore, flexible-wall permeameters are mostly used in small-scale specimens.

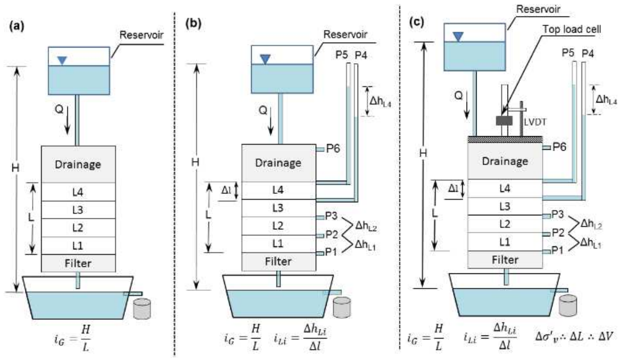

Figure 1. Rigid wall permeameter: (a) basic setup, (b) includes piezometers and (c) includes piezometers and axial load.

3.2 *Hydraulic control system*

The inflow to the permeameter cell is controlled either by a head control system (e.g. Rönnqvist 2015 and Douglas et al. 2016) or by a flow control system (Ke & Takahashi 2014). The head control system refers to the difference in water level between the inflow and outflow tank. The inflow and outflow tanks are often at atmospheric pressure with a constant hydraulic head insured by an overflow outlet. Nevertheless, some testing devices, particularly those including a stress control system, have a pressurized constant head inflow tank. Some devices include a peristatic pump to recirculate the water collected at the outflow tank back to the inflow tank. In addition, several devices include a filter and de-air water system to in order to remove the suspended solids and minimize the air content into water and into the specimen.

The hydraulic gradient is controlled by changing the vertical position of the inlet tank. Nonetheless, Silva et al. (2018) changed the hydraulic gradient by changing the vertical position of the outflow tank. The hydraulic gradient can be keep constant (e.g. Wan 2006 and Rönnqvist 2015) or increased stepwise throughout the test (e.g. Moffat et al. 2011, Douglas et al. 2016 and Rochim et al 2017). The seepage flow direction can be upward or downward. The inflow water is uniformly distributed at the top/bottom of the specimen by mean of: a) a layer of natural gravel soil, b) a layer of glass beads, c) a perforated plate made of PVC or wire mesh and d) paper filter in case of small scale specimens with downward seepage.

3.3 *Stress control system*

The stress control system allows control of effective stress within the specimen by the application of loads. Four type of loading conditions are identify from the experimental studies in literature: a) no load (e.g. Hunter et al. 2012 and Rönnqvist 2015), b) uniaxial vertical load (e.g. Sail et al. 2011 and Moffat et al. 2011), c) triaxial load (e.g. Ke & Takahashi 2014 and Slangen & Fannin 2019) and d) vibration load (e.g. Kenney & Lau 1985).

The uniaxial and triaxial loads can be either constant or variable. The advantage of this type of loading is that allows consolidate the specimen to the stage representing the stress conditions in situ. Moreover, in triaxial cells the stress conditions can be isotropic or anisotropic. In uniaxial stress control systems the axial force is applied at the top of the specimen through a loading rod placed above the top plate covering the specimen. In some experimental devices, the loading rod is substitute by the pressure generated by the weight of aggregates or a water column.

3.4 *Seepage and eroded soil collection system*

The configuration of the seepage and eroded soil collection system depends on the flow direction. In tests with downward direction the collection system includes a subsidence funnel that allows to collect both the outflow seepage and the eroded particles into an outlet pipe that goes to the outflow tank (e.g. Bendahmane et al. 2008). Some devices do not include the outlet pipe, and others do not include the subsidence funnel. In this last cases, the outflow seepage go directly to the outflow tank whiles the eroded soil particles are caught by a filter/sieve with opening size 0.075mm placed at the top of the outflow tank.

The seepage and eroded soil collection system can include one or two outflow tanks. In case of one tank, the estimation of outflow seepage is done by measuring the weight of the tank during the test; therefore, the tank is placed on a digital weight scale. In case of two outflow tanks, the first tank collects both the eroded soil and the seepage from the specimen. This water tank has a constant hydraulic head thanks to the overflow outlet that fills the second outflow tank. The second outflow tank is placed on a digital weight scale and the measurements of its weight are used to calculate the variations of hydraulic conductivity.

The seepage and eroded soil collection system of an upward seepage test is based on an overflow concept in which the specimen is covered with a water column and the permeameter cell is placed inside a reservoir where the overflow seepage from the water column is collected. An alternative is to have an overflow outlet in the permeameter cell that allows collecting the overflow seepage in a tank. In this type of tests the eroded fine particles can be catch at the bottom of the reservoir or by placing a filter/sieve at the top of the reservoir.

3.5 *Instrumentation*

The instrumentation included in the testing device depends on the type of stress control system, the type of seepage - eroded soil collection system and the scope of the test. The most common instruments used are:

a) Flow rate: digital weight scale in the outflow and/or outlet tank, flowmeters, weight manually the seepage in the outflow tank;

b) Pore water pressure: total pressure transducer transducers, differential water pressure transducers, manometers, standpipes;

c) Water temperature: thermometer;

d) Soil mass loss: digital weight scale, turbidimeter, optical aids such photo sensor;

e) Axial displacement: linear variable differential transducer - LVDT placed at the top loading plate);

f) Radial deformation: photographic method;

g) Density changes: gammadensitometric system.

4 BOUNDARY CONDITIONS

The continuation of internal erosion by suffusion depends on the ability of the filter to capture particles eroded from the core soil (Sherard 1979). Therefore, the system core-filter defines the safety conditions of the dam. Likewise, experimental studies show that the type of filter used in suffusion tests influence significantly the results in terms of variation of hydraulic conductivity and mass loss. Consequently, the type of filter to use in the test is an essential boundary condition to analyze the test results and identify the onset of suffusion of the soil tested.

The initial degree of compaction, consolidation state and degree of saturation of the tested soil are boundary conditions playing and important role on the test results. The following sub-sections describe briefly each of these boundary conditions mentioned.

4.1 *Filter*

Similar to the design of filter in dams, the filter used in suffusion tests must fulfil the permeability criterion $D_{15F} > 4D_{15b}$ (ICOLD 2015). The particle capture ability of the filter is controlled by the finer particles, for which D_{15F} is a measure. The D_{15F} or each condition can be defined taking as reference the erosion boundaries proposed by Foster & Fell (2001), e.g.: i) no erosion, ii) excessive erosion and iii) continuing erosion..

The filter used in laboratory can consists on: a) layer of natural soil, b) layer of glass beads, c) wire mesh or d) steel plate with holes. The layer of natural soil (Fig. 2a) can be made of gravel or a soil with the PSD of the filter in the dam. The layer of gravel typically allows the excessive or continuing erosion of the tested soil, whiles the filter made of finer soil particles usually results clogged by the particles eroded from the tested soil inducing then the a system core-filter with no erosion. This last condition difficult to identify the hydraulic gradient at which suffusion initiates and the rate of mass eroded. Filters consisting of layers of glass beads generates testing conditions similar to that of the layer of gravel soil. The disadvantage of these two type of filters is the segregation of the tested soil during compaction.

Filters consisting of wire mesh or steel plate (Fig. 2b) are characterized by its equivalent opening size (EOS), which defines the maximum particle size that can be washout from the soil tested. This type of filters allows a more consistent compaction (no or reduced segregation), the easy capture of the material eroded from the specimen during testing and a clear view of the bottom of the specimen facilitating to identify potential flow concentration (Douglas et al. 2016).

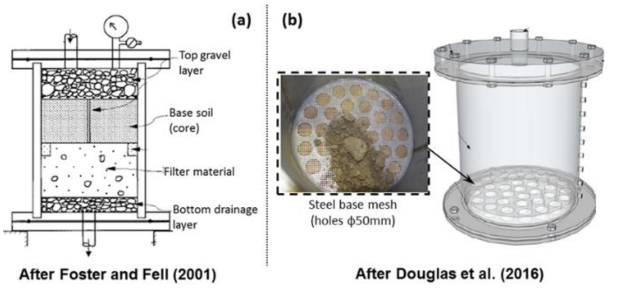

Figure 2. Suffusion test set-up: (a) closed system with soil filter, and (b) open system with wire mesh filter.

4.2 *Initial degree of compaction*

The degree of compaction defines the density of the soil and thus the initial void ratio. The initial void ratio is related to the size of the constrictions in the pore network. Indraratna et al. (2007) pointed out that a particle size distribution is considered internally unstable when the size of the constrictions in the pore network is larger than the size of the loose particles forming the primary soil matrix, giving these particles the possibility of being moved. Consequently, it is expected that the higher the density of the soil the (higher degree of compaction), the lowest the risk of suffusion. Nevertheless, Wan (2006) observed that the 90% versus 95% degree of compaction did not significantly influence the initiation of suffusion. Complementary, Rönnqvist (2015) concluded that the degree of compaction appears to have little effect on the resistance to erosion of till soils with pronounced instability.

The water content for compaction on the other hand has shown to influence the initial pore pressure within the matrix of soil and thus the likelihood of internal erosion. Chapuis et al. (1989) found that wet till specimen heavily compacted may generate high pore pressure and a local internal erosion, whilst the compaction of dry till may produce micro-fissures that contribute to the initiation of internal erosion.

4.3 *Consolidation*

The consolidation of specimens is conducted by increasing the confining stress gradually to the proposed value representing the in-situ conditions. Specimens can be consolidated just in experimental devices including a stress control system. The magnitude of each load increment should be controlled in order to avoid a potential for internal instability as result of transient hydraulic gradients during the consolidation stage (Moffat & Fannin 2006). The consolidation allows the dissipation of excess pore water pressure due to the reduction of the void ratio.

4.4 *Initial saturation state*

The hydraulic conductivity of unsaturated specimens varies significantly over time compared to saturated specimens (Lafleur 1984). Therefore, guaranty full saturation prior and during suffusion tests is important in order to avoid affecting the measurements of outflow seepage and thus the calculated hydraulic conductivity.

Chapuis (2004) highlighted that, in rigid-wall permeameter, the saturation of the specimen may be increased up to 100% by either: i) applying a high vacuum followed by circulation of de-aired water in initially dry specimen, or ii) applying a back pressure increased in steps in initially wet specimen.

Upward saturation is recommended over downward saturation in order to avoid entrapped air. Aiming to decrease the time needed for saturation, some tests include the use of de-aired water and the upward injection of CO_2 prior upward saturation. The CO_2 replaces the air and improving the dissolution of gases into water. The applied hydraulic gradient for saturation must be low enough to prevent the occurrence of the heave phenomenon.

5 TESTING CONDITIONS

The testing conditions to be defined prior the initiation of test are: i) hydraulic conditions and ii) stress conditions. The factors defining the hydraulic conditions include: direction of seepage flow, the hydraulic gradient to be applied *(i)*, the rate of increase of hydraulic gradient *(Δi),* time interval to increase hydraulic gradient (Δ*t*), duration of the test. The factors defining stress conditions are based on the type of load applied (no load, axial load, triaxial load) and the interval to increase the load. A brief description of the mentioned factors is described below.

5.1 *Hydraulic conditions*

5.1.1 *Direction of seepage flow*

Downward flows represents the most adverse conditions since the seeping or drag force on the particles acts in the same direction as gravity (Lafleur 1984). In upward flow suffusion tests the hydraulic gradient to apply must be lower than the zero effective stress gradient (critical hydraulic gradient to initiate heave).

5.1.2 *Hydraulic gradient to be applied*

The hydraulic gradient can be constant or increased stepwise during the test. Tests at constant hydraulic gradient are used to evaluate the internal stability of a soil; whilst tests with hydraulic gradient increased stepwise are used to know the hydraulic gradient triggering suffusion in a soil (Douglas et al. 2016). Nevertheless, several studies on suffusion have been performed with constant hydraulic gradient (Wan 2006 and Rönnqvist 2015).

5.1.3 *Rate of increase of hydraulic gradient*

Rochim et al. (2017) showed that the type of hydraulic loading and the duration of each load stage can substantially modify the value of the critical hydraulic gradient. Moffat & Fannin (2011) and Moffat et al. (2011) applied, for both downward and upward suffusion test, a multistage hydraulic gradient with $\Delta i = 1$, starting from $i = 1$. Douglas et al. (2016) also increased the hydraulic gradient by steps of $\Delta i = 1$ in their tests, reaching gradients up to 10 in some specimens. Wan (2006) and Rönnqvist (2015), for example, performed their tests with a constant hydraulic gradient.

5.1.4 *Duration of the test*

The duration of the experiments depends on both material and test conditions. Douglas et al. (2016) observed that, in the laboratory, erosion by suffusion occurred rapidly, usually in minutes and occasionally in hours. Rönnqvist (2015) found that the higher the amount of gravel fraction the shorter the test time. Suffusion tests finished when the seepage rate and hydraulic conductivity becomes steady, and particles are no longer flushed out (Kenney & Lau 1985). Therefore, tests should be performed during a time long enough to reach such steady-state conditions.

5.2 *Stress conditions*

Suffusion tests can be carry out with and without external loads controlling the stress condition within the specimen. Moffat (2006) observed that the onset of internal instability is triggered either by an increase in hydraulic gradient or by a decrease in effective stress. Moffat (2006) also observed that the critical hydraulic gradient increase with the increase of the initial vertical stress. In addition, Chang & Zhang (2011) highlighted that, as the applied stress ratio increases, the primary structure formed by the coarse particles becomes more unstable; thus, the erosion rate is much larger in specimens tested with large stress ratio than with isotropic stress.

6 STEPS OF SUFFUSION TESTS

The experimental procedure in suffusion tests is summarized in the following steps: a) specimen reconstitution, b) saturation, c) consolidation, d) hydraulic test, e) stress test and f) post-test sieve and mass loss calculation.

The reconstitution of the specimens includes mixing different soil fractions aiming to obtain the target PSD and placing the soil inside the permeameter cell. In some experiments, the soil tested has a natural PSD. The methods for dispose the soil inside the permeameter cell: a) moist tamping by hand, hammer or following the proctor or standard compaction method; b) slurry technique, c) pluviation technique and d) statical compaction. The last two techniques a suitable for experimental devices based on triaxial apparatus.

The saturation and consolidation steps were discussed in the sub-sections 2.3.3 and 2.3.4 of this paper. A description of the hydraulic test step and the factors involved in it is presented in the section 2.4 along with a description of the stress conditions in the stress step.

The post-test sieve step consists on digging up the specimen layer by layer and sieve each layer in order to compare the final PSD with the initial condition. This comparison allows estimating the amount of soil particles eroded from the specimen in each layer and thus identify the special erosion distribution. Chang & Zhang (2011) found that the fine fraction of the soil in the top layer is nearly 6.0 % less than that in the bottom layer; Moffat & Fannin (2006) and Douglas et al. (2016) found similar trend.

In addition, measuring the eroded mass collected in the eroded soil collection system allows to estimation the rate of erosion over time and classified the erosion as low, medium or high erosion. This classification is often used to compare the soils likelihood to be eroded in relation to the boundary and testing conditions.

6.1 *Onset of suffusion*

Skempton & Brogan (1994) proposed to relate the initiation of suffusion with a sudden increase of seepage, thus with an increase of hydraulic conductivity. The sudden increase of seepage is followed by a tendency to be steady while the erosion rate decreases. However, the filtration of some detached particles can induce a clogging process within the soil; condition that might decrease the hydraulic conductivity locally (Bendahmane et al. 2008 and Zhong et al. 2018). Therefore, for a better precision in the results, recommended is to measure the local hydraulic gradients along the specimen, which give a better insight of where the onset of instability occurs (Moffat & Fannin 2011).

Piezometers located along the test sample allow identifying local increase in hydraulic conductivity due to particle migration from a particular layer. Rönnqvist (2015) found that, in general, the unstable specimens exhibit local gradients significantly higher than the global gradient applied over the whole specimen.

The initiation of internal instability can be established on the basics of three conditions, depending on the type of test device. The three conditions are: i) observation of outflow turbidity; ii) sudden changes of the seepage rate through the specimen; and iii) sudden changes of the hydraulic pressure head at various depths of the specimen (Wan & Fell 2008). Changes in the seepage rate lead to changes in hydraulic conductivity, which can be explained as the result of the changes of void ratio generated by the detachment, filtration or washout of the eroded particles.

7 CONCLUSIONS

The safety assessment of dams is an essential requirement to the dam owners and its important have become even more notorious in the recent years. Dam safety assessments include the evaluation of the core soil to be susceptible to internal erosion. This evaluation is mostly requires an experimental investigation of the soil. Nevertheless, knowledge about the testing device, boundary and conditions is yet limited. Moreover, since the testing program, testing conditions and testing aim of the experimental studies performed by different research vary amount them, it is difficult to compare results and/or extend conclusions to a different similar type of soil.

This paper highlighted all the aspects to be considered in suffusion tests, including the main characteristic of the test device, the boundary conditions and testing conditions. The boundary conditions are those geotechnical parameters of the tested soil defined before to start the test; these parameters include: the initial density and water content, the initial consolidation state, and the degree of saturation. The type of filter to be used is also a boundary condition since it is also defined before starting the test. The testing conditions refers to those conditions that can be modified during the test, it is: the hydraulic and the stress conditions. The hydraulic conditions can be modify by changing the direction of the seepage flow, the hydraulic gradient, the duration of each hydraulic gradient stage and the total duration of the test. Similar modifications can be done to the stress conditions. Finally, the paper describes the aspects to look after in order to identify the occurrence of internal erosion by suffusion and the hydraulic gradient at which it occurs.

Based on all the aspects described in this paper, it is concluded that the experimental study of suffusion tests is susceptible to several variables that include not just the different type of soil, filter, hydraulic gradients and stress applied, but also variables more difficult to control such air burble, full saturation, and segregation. Controlling successfully these last factors is very challenging and require advance experimental devices. However, it is important to keep in mind that most of the current empirical methods used to evaluate / predict soil's susceptibility to suffusion were done in testing devices relative simple and yet provided repeatable results and proved to be optimum for the development of soil classification methods.

Nevertheless, the authors want to highlight the importance of develop a database of the experimental studies on suffusion as well as a guideline for the performance of suffusion tests. These two in order to support the dam owners and research working on dam safety assessment of internal erosion by suffusion.

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