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Internal erosion of cohesive soils: laboratory parametric study

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Abstract: Internal erosion by piping is one of the main causes responsible of accidents and failures of earth structures such as embankment dams and dykes. This phenomenon occurs when concentrated leak develop in pre-existing defects in the earth fill such cracks and micro fissures, discontinuities, hydraulic fracture, channels, roots and burrows. It involves the removal of soil particles from the subsurface of these defaults to an exit point, leading to the formation and the evolution of a continuous "pipe" between the upstream and the downstream side.

A new experimental device has been developed to carry out hole erosion tests in laboratory in order to better understand the mechanism of internal erosion process of soil. A series of hole erosion tests were carried out under constant flow rate in order to quantify the critical shear stress (τ_c) and the coefficient of piping erosion (k_{er}) of soils. Parametric studies were conducted on Kaolinite and Hostun sand/Kaolinite mixture. The key parameters investigated in this study were effects of moisture content, compaction energy and percentage of fines. The experimental results show that these parameters play a key role on the erosion characteristics (τ_c and k_{er}). A numerical piping model has been developed from equations of diphasic flow with diffusion and the equation of jump with erosion to interpret the hole erosion tests.

Key words

Internal erosion, piping, experimental study, cohesive soils, critical shear stress, rate of erosion, hydraulic works.

I INTRODUCTION

Internal erosion is a complex phenomenon which causes major problems to levees, dikes and embankment dam stability. Several examples of failures of embankment dams have been reported in the literature (Fry *et al.*, 1997; Foster *et al.*, 2000) and most of them are related to this phenomenon.

Internal erosion due to defects (cracks and micro fissures, hydraulic fracture, roots and burrows) in the embankment dams may lead to their failure. Concentrated leakage appears in these defects and seepage forces initiate the detachment of soil particles and carry them away from the surface of the cracks, leading to their enlargement and the formation of a continuous tunnel between the upstream and downstream sides. This type of process is called concentrated leak erosion.

Over the years, considerable research has been conducted worldwide to study the erodibility of cohesive soil. Initially, most experimental methods involved qualitative tests such the Crumb test (Emerson, 1964, 1967) and Pinhole test (Sherard *et al.*, 1976), which focused on identifying the dispersivity of materials rather than on quantifying the shear stress required to initiate the erosion process. However, in recent decades significant progress has been made in assessing internal erosion quantitatively by developing different improved methods like the rotating cylinder test (Arulanandan *et al.*, 1975; Chapuis and gatién, 1986), the flume test (Arulanandan *et al.*, 1980), the drill hole test (Lefebvre *et al.*, 1985; Rohan *et al.*, 1986), the erosion function apparatus EFA (Briaud *et al.*, 2001), the triaxial erosion test (Sanchez *et al.*, 1983; Bendahmane *et al.*, 2006), the flow pump test (Reddi *et al.*, 2000) and the jet erosion test (Hanson *et al.*, 1991, 2004).

More recently, the Hole Erosion Test (HET) was developed by Wan and Fell (2002, 2004a, b), Benahmed (2009), Benahmed and Bonelli (2007, 2012), Benahmed *et al.* (2012) to measure the erosion properties of soils. This type of experiment, which is described herein, allows simulating of the erosion phenomenon in open cracks.

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Evaluating the erodibility of soil, both in terms of erosion threshold and erosion rate is critical when evaluating the safety of a water retaining structure (Bonelli and Benahmed, 2011). The nature and state of soils determine their vulnerability to erosion and govern their rate of erosion. However, the relationship between the erosion parameters and the geotechnical and physico-chemical properties of soils still remains in the research stage and is not yet fully understood.

An overview of the research work on the erodibility of soils is presented in Fell and Fry (2007).

The present study concerns erosion in concentrated leaks and should not be confused with backward erosion piping in cohesionless soils whose mechanics are completely different. We put a particular emphasis on the effect of some important physical parameters such as density, water content, and fines content on soil erosion characteristics.

II THEORIE

The two main variables of interest in characterizing the erodibility of soil are the critical shear stress (τ_c) above which the detachment of particles occurs and the coefficient of erosion (k_{er}) which allows to quantify the failure time.

The classical threshold law is often expressed as:

$$\dot{m} = \begin{cases} 0 & \text{if } |\tau_b| \leq \tau_c \\ k_{er} (|\tau_b| - \tau_c) & \text{if } |\tau_b| > \tau_c \end{cases} \quad (1)$$

Where \dot{m} is the eroded mass rate in kg/m/sec, τ_b is the shear stress in Pa, τ_c is the critical shear stress in Pa, k_{er} is the erosion kinetics coefficient in sec/m.

To interpret the hole erosion tests, and hence, to determine the two parameters of the previous equation, a numerical piping model which is not presented here, has been developed from equations of diphasic flow with diffusion and the equation of jump with erosion by Bonelli *et al.* (2006, 2007), Brivois *et al.* (2007), Bonelli and Brivois (2008). This model can be appropriate to different situations: boundary layer flows, pipe flows with erosion, and has been validated upon an extensive experimental data of hole erosion tests obtained on referential and natural soils.

III EXPERIMENTS

III.1 Description of the erosion test apparatus

A new device to carry out erosion tests on soil on laboratory has been developed. It is similar to the hole erosion test apparatus designed by Wan and Fell (2002, 2004) but slightly modified in term of metrology, and type of hydraulic stress (controlled flow rather than pressure). Figure 1 shows a photograph of the experimental setup.

The cylindrical cell, divided into three parts, was made of Perspex in order to visualize the sample and detect the initiation of the erosion process. The inlet diameter is about 80mm. The central part is designed to receive either reconstituted or intact soil samples. Two pressure gauges are mounted on both extremities of the cell, upstream and downstream, to measure the inflow and outflow pressures, and thus, to evaluate the hydraulic gradient applied to the soil sample.

The upstream side of the device is connected to the incoming water and pressure regulator. The flow rate is controlled by an outflow vane and measured by the flowmeter on the downstream side of the device. A turbidity meter for analysing the outflow water and quantify the mass of soil transported during the flow is installed downstream of the cell. A honeycomb is installed inside the cell at its upstream side to homogenise the flow.

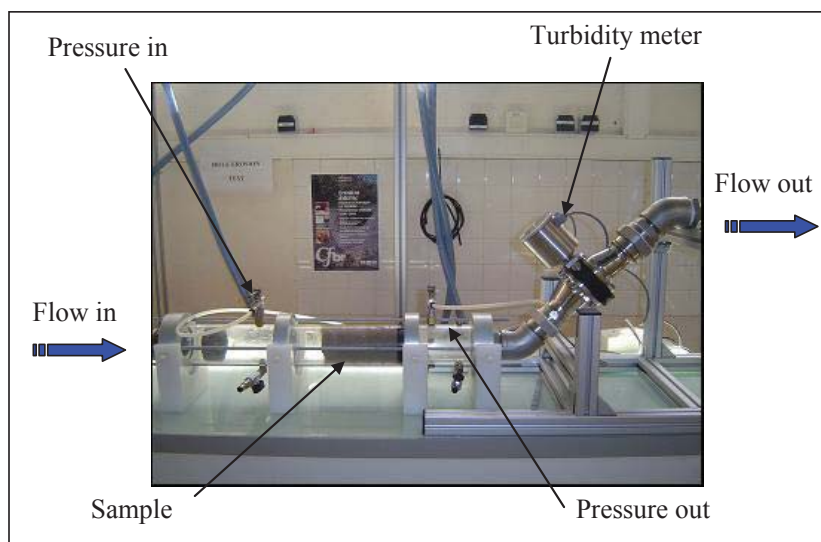


Figure 1: Photography of the Hole Erosion Test Apparatus.

III.2 Materials used

As we were interested in the physical mechanism of the internal erosion of soils, Kaolinite was chosen in the experimental program for its low electrochemical activity. This material is considered as a reference material whose properties are well documented and known. The sand used is Hostun sand which consists of uniform, fine sand with sub angular to angular grains. The engineering properties of these soils are outlined in Tables 1 and 2.

Material	Clay < 2 μ m (%)	Silt > 2 μ m (%)	Liquid Limit	Plastic Limit	Plastic. Index	W _{OPN} (%)	$\gamma_{d\text{OPN}}$ (%)
Proclay Kaolinite	70	25	57	33	24	21	15.8

Table 1: Properties of used clay.

Material	D ₅₀	Cu	e _{min}	e _{max}	ρ_s (g/cm ³)	$\rho_{d\text{min}}$ (g/cm ³)	$\rho_{d\text{max}}$ (g/cm ³)
Hostun Sand HN31	0.35	1.57	0.656	1	2.65	1.33	1.60

Table 2: Properties of used sand.

III.3 Specimen preparation and test procedure.

To reconstitute the samples, tap water was gradually added to a predetermined amount of dried Kaolinite powder to obtain the desired water content values, below, equal and above Optimum Moisture Content (OMC), as determined from standard Proctor Testing. The soil was mixed carefully, transferred in watertight plastic bags and then kept in humid storage for 48 to 72 hours to ensure uniform moisture content and homogeneity of the matrix. Mixtures were compacted manually using a proctor hammer on 5 layers directly inside the test cell. The height of each layer was predetermined beforehand to achieve the wanted dry density.

A hole of 6 mm in diameter was drilled through the longitudinal axis of the compacted specimen by using a drill rod. The aim was to induce erosion only in the preformed hole in order to simulate the surface erosion phenomenon in pre-existing defaults (cracks or micro fissures). Especial care was taken to drill the hole, in order to minimise disturbance of the surrounding area of the cavity. However, the procedure overcomes the

initial disturbance because the critical stress is determined at the end of the test when this smeared zone is eroded.

After closing the cell, the inlet and outlet chamber were filled with tap water simultaneously and carefully letting the air to be expelled completely from the hole and the cell. Water was circulated through the hole at a given flow rate Q kept constant, and the pressure gradient was measured by the pressure gauges. If the value of Q was large enough to induce erosion, then the initial diameter of the hole was enlarged, leading to a decrease in velocity, so in shear stress which is causing erosion. If not, the flow rate was increased until the erosion occurred. At constant flow, this erosion had to stop after a certain time. The value of the flow rate was maintained long enough for turbidity to decrease to a low value (<5 NTU), and for the differential pressure to become constant. The effluent from the sample was then characterised through its turbidity in term of Nephelometric Turbidity Units (NTU). The data are acquired by Profibus data acquisition system.

IV TYPICAL TESTS RESULTS

The test conditions are given in Table 3. Different levels of water content and dry density were used by referring to the optimum values obtained at standard Proctor test. The mixtures were prepared with different mass fraction of clay. Tap water was used as an eroding fluid and all the tests were conducted on compacted samples under controlled flow.

Nature of soil	Tests	Massique fraction (%)		Compacted water content (%)	Compacted dry density (t/m^3)
		Clay	Sand		
Proclay Kaolinite	KP100-1	100	-	15	1.50
	KP100-2	100	-	18	1.51
	KP100-3	100	-	24	1.52
	KP100-4	100	-	21	1.42
	KP100-5	100	-	21	1.52
	KP100-6	100	-	21	1.57
Proclay Kaolinite + Hostun sand HN31	KP90 SH10	90	10	21	1.59
	KP70 SH30	70	30	21	1.62
	KP50 SH50	50	50	21	1.60
	KP30 SH70	30	70	21	1.66

Table 3: Tests conditions.

IV.1 Typical result of hole erosion test

A typical experimental result of a hole erosion test carried out on kaolinite sample is shown in Figure 2. The experimental data are expressed in terms of pressure gradient and turbidity versus time. At the beginning of the test, a flow rate of about 0.05 m^3/h was applied. At this stage, no turbidity was measured and the pressure gradient remained constant. When the flow rate, hence the shear stress, was increased to 0.550 m^3/h , the erosion process occurred suddenly and rapidly, and high turbidity was measured. The soil particles were detached and driven out of the hole. Therefore, the initial diameter of the hole increased, leading to a gradual decrease of the pressure gradient, as observed on the pressure curve. After nearly one hour, the pressure gradient started to stabilise and remained fairly constant until the end of the test. No more erosion was observed.

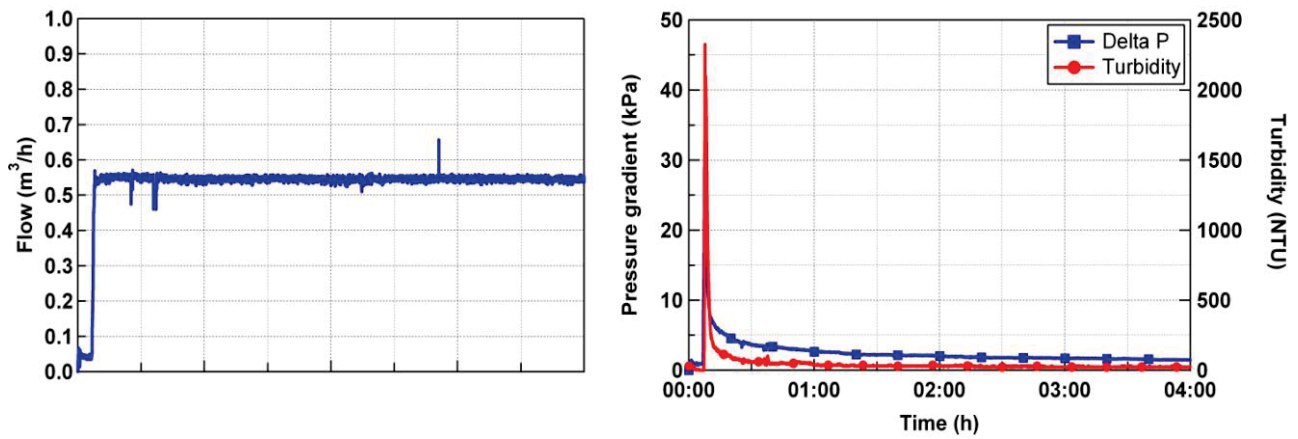


Figure 2: Evolution of the turbidity and the pressure gradient during hole erosion test on kaolinite sample.

A longitudinal cut was made on the eroded kaolinite sample at the end of the erosion test. Clear enlargement of the initial hole after the erosion process could be seen (Figure 3).

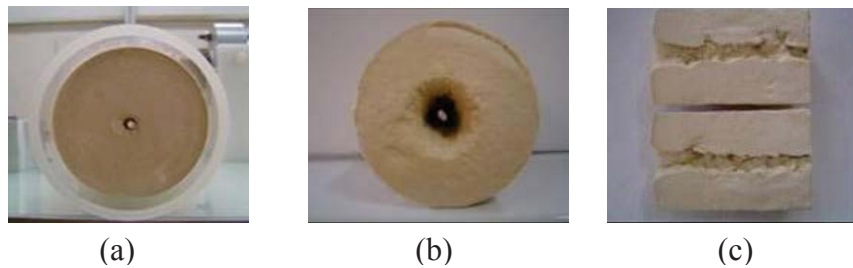


Figure 3: Example of enlargement of initial hole by erosion on kaolinite sample: (a) sample before test, (b) sample after test, (c) longitudinal cut of the sample after test.

IV.2 Effect of dry density

In order to investigate the effect of dry density on erosion parameters, three hole erosion tests were carried out on Proclay kaolinite. The samples were reconstituted at compaction energies of about 90%, 95% and 100% respectively of Standard Proctor Maximum Dry Density (SMDD), corresponding to dry densities varying from 1.42 t/m³ to 1.57 t/m³. The moulding moisture content was essentially the optimum moisture content W_{opt} determined by the Standard Proctor test, and equal to 21%.

Figure 4 shows that, in accordance with conventional experimental observations, the increase of dry density of soil have the effect to increase the critical erosion stress. More the soil is dense, the better it resists to the erosion phenomena. Regarding the erosion coefficient, it does not appear to be strongly affected by density changes and its value of the order of 4. 10⁻³ s/m is fairly constant for the three densities tested.

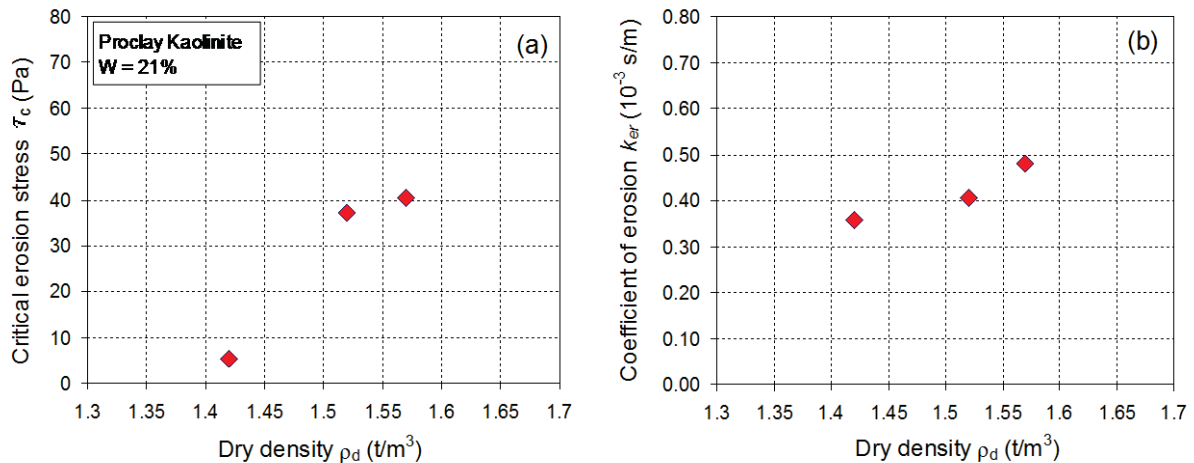


Figure 4: Influence of the density on the erosion parameters of Proclay kaolinite

IV.3 Effect of water content

The effect of water content on erosion parameters was investigated by performing similar hole erosion tests on three reconstituted samples of Proclay kaolinite. The effort of compaction was about 95% of optimum Proctor energy, corresponding to a dry density of about 1.5 t/m^3 . The moisture contents were W_{opt} , $W_{opt} + 3\%$, and $W_{opt} - 3\%$, respectively.

According to Figure 5, the test results show clearly the dependency of the critical shear stress on the moisture content. Resistance to erosion increases by increasing the moisture content and the erosion coefficient in this case is very sensitive to variations of water content. Thus the erosion coefficient decreases as water content increases. Therefore, the increase of water content leads to an improvement of soil resistance against erosion. This result is in agreement to what is usually reported in literature (Wan and Fell, 2002, 2004; Lim, 2006).

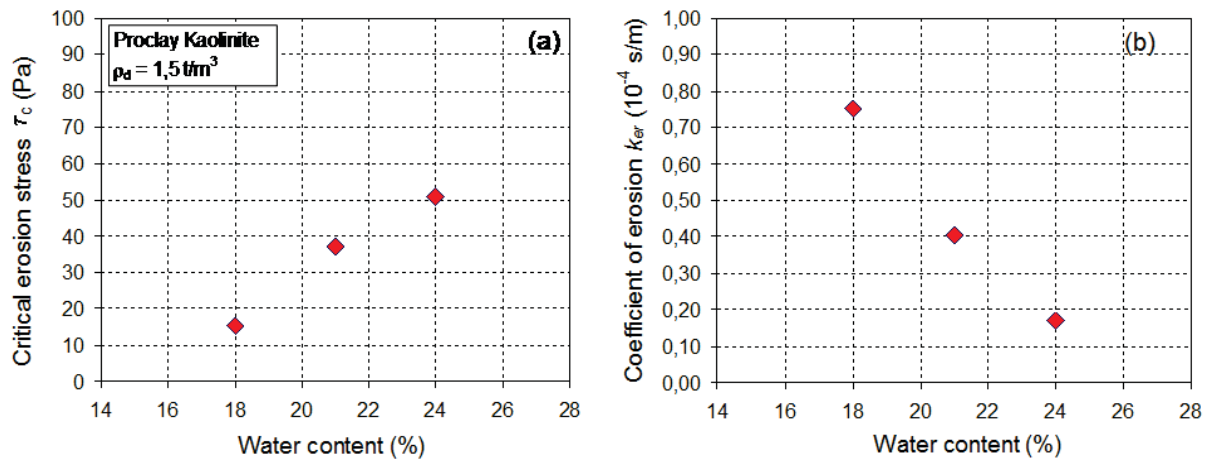


Figure 5: Influence of the water content on the erosion parameters of Proclay Kaolinite.

IV.4 Effect of clay content

A series of samples consisting of a mixture of kaolinite Proclay and Hostun sand HN31 were tested to evaluate the effect of the clay content on the erosion characteristics. Different percentages of clay varying from 30 to 90% were used. The samples were compacted to a standard Proctor energy, with a constant moisture content equal to 21% for all of them.

Figure 6 clearly shows the preponderant influence of the clay fraction on the critical shear stress of erosion. This parameter increases significantly with increasing of percentage of clay present in the mixture and its value passes from 6.3 Pa for a clay percentage of 30% to 407 Pa for a soil containing 90% of clay. Hence, clayey soil is far less vulnerable to erosion than sandy soil. This trend is in agreement with the results reported by Lim (2006), Pham (2008).

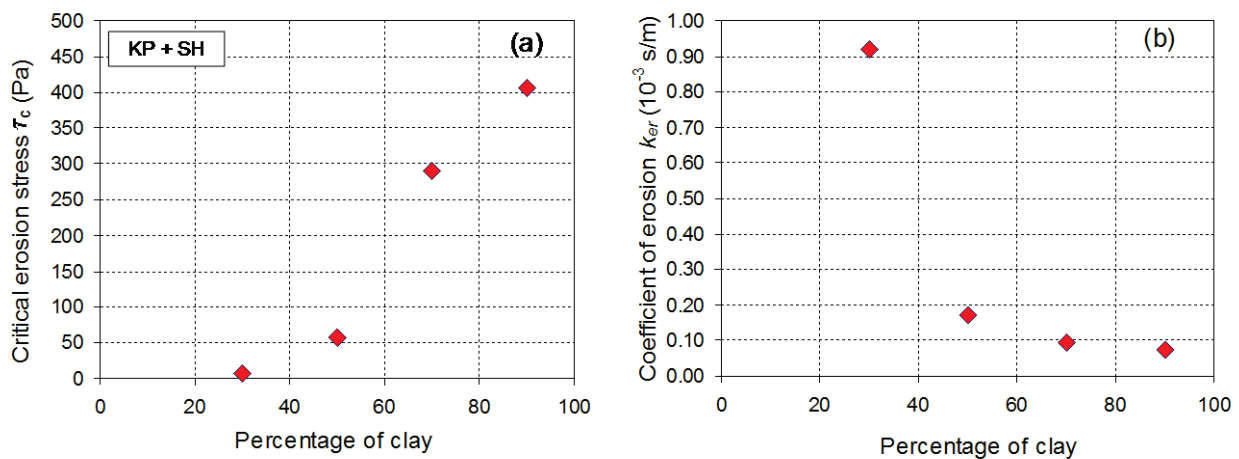


Figure 6: (a) Critical erosion stress; (b) Coefficient of erosion versus the percentage of clay for the soil mixture Hostun sand / Proclay kaolinite

It is also noteworthy that the clay contents for the percentages of 50, 70 and 90% produce an effect on the coefficient of erosion which decreases slightly as the percentage of fines increases. However, for the case of the sample with 30% of clay, it is interesting to note that the coefficient of erosion varies quite significantly. This suggests that below a certain percentage of clay close to critical clay content (25% in this case), the soil behaves like a sandy clay with low cohesion, which lead to lower resistance to erosion process. The clay particles take up the space between the sand particles without contributing to soil strength.

V CONCLUSION

The hole erosion test (HET) is a widely recognized laboratory procedure for evaluating the erodibility of cohesive soils that might be susceptible to internal erosion, and quantifying the rate of concentrated leak erosion.

The purpose of this paper was to present the hole erosion device developed and to investigate the effects of some parameters on critical shear stress and the erosion coefficient of cohesive soils through hole erosion tests. A reference cohesive soil such kaolinite and granular soil such Hostun sand were used for there well known proprieties.

This study focused on significant factors, namely dry density, moisture content, and clay content. The experimental results obtained provide evidence of the dependency of the critical shear stress on these factors. However, for one type of soil, they also reveal that the erosion coefficient may not be affected by dry density. In addition, the results suggest that is very important to take into account the clay content when evaluating soil erodibility.

For design of earth fill structures or carry out risk analysis on internal erosion, it is desirable to consider and to take into account how the moisture content, the dry density and the percentage of clay content affect the resistance of soil against internal erosion.

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