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Soil surface erosion: influence of soil properties on the erosion resistance

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Résumé:

L'érosion de conduit se produit lorsqu'il y a départ de particules de sol le long d'un chemin d'écoulement préférentiel existant dans un ouvrage hydraulique. Pour évaluer la vulnérabilité des sols vis-à-vis de ce phénomène, et plus généralement à l'érosion de surface, plusieurs dispositifs expérimentaux de laboratoire existent, parmi lesquels le Hole Erosion Test. Nous étudions ici l'impact de plusieurs paramètres constitutifs du sol sur sa résistance à l'érosion, à l'aide d'une campagne expérimentale réalisée sur des sols de teneur en argile, forme des grains grossiers et taux de compactage variables. En accord avec des résultats antérieurs, il est montré que la présence d'argile confère une meilleure résistance à l'érosion ; de même, plus l'échantillon est dense, plus il est résistant. Concernant la forme des grains, les essais réalisés montrent deux résultats : d'une part, et contre intuitivement, les échantillons avec des particules sub-arrondies à arrondies présentent une meilleure résistance vis-à-vis de l'initiation de l'érosion, cependant, une fois l'érosion enclenchée, ces échantillons s'érodent plus rapidement que ceux ayant des particules de forme sub-angulaire à angulaire.

Abstract:

One type of internal erosion, identified as concentrated leak erosion, consists in loss of particles of soil along a preferential flow paths existing in hydraulic earthen work. To assess the vulnerability of soils to this phenomenon, and more generally to surface erosion, several experimental devices exist, among them the Hole Erosion Test. We investigate here the effect of several parameters depending on the nature of soil considered, on erosion characteristics. A comprehensive campaign was conducted on soil, varying clay content, coarse grain shape and degree of compaction. In agreement with previous results, it is shown that presence of clay allows a better resistance to erosion; in the same way, the denser the sample, the more resistant it is. Concerning the grains shape, the experiments show two results: samples *with sub-rounded to rounded particles exhibit a better resistance concerning the critical shear stress, (i.e. the shear stress needed to initiate erosion), but when erosion begins, these samples are eroded faster than those with sub-angular to angular particles.*

Mots clefs: Internal erosion, parametric study, hole erosion test, cohesive soils, erosion characteristics.

1 Introduction

The erosion of hydraulic earthworks by piping, among different kinds of so-called internal erosion, is widely considered as one of the main mechanism causing failures and accidents of embankment dams as described in *Foster et al. 2000* [1]. This topic has been broadly investigated in last decades and, owing that different soils show different erodibility, previous researches have attempted to investigate the effect of several parameters related to soil properties on the resistance of soil to surface erosion. However, data on this are not abundant, making difficult to draw reliable relationships between erosion characteristics and soil properties.

Assessing the resistance of soil to internal erosion lie in investigating its erodibility, which is quantified in terms of erosion rate and critical shear stress. The erodibility parameters are expressed by the following equation:

$$\dot{m} = k_{er}\,(\tau - \tau_c)$$

Where $\dot{m}$ is the mass rate of erosion in kg/m/s, k_{er} is the erosion kinetics coefficient in s/m, τ is the applied shear stress to soil surface in Pa, and τ_c is the critical shear stress for initiation of erosion in Pa.

The present study focuses specifically on materials consisting of a mixture of coarse grains and fine particles, to investigate the effect of nature and state of soil on (i) the initiation conditions of erosion process, (ii) the erosion kinetics under stationary or near-stationary conditions. To this end, HET (Hole Erosion Test) device is used to determine the erosion parameters, τ_c and k_{er} . A particular emphasis was put in studying the influence of different material properties on the process, such as coarse particles shape, compaction degree, and fines content on the erodibility of the tested soils.

2 HET apparatus and studied materials

Nowadays, Hole Erosion Test (HET) device is being used increasingly for studying the resistance of cohesive soils to surface erosion, in a configuration reminiscent, on a smaller scale, to *concentrated leak erosion*, one specific type of internal erosion. During this test, erosion takes place along the wall of a pipe, which was initially drilled with a cylindrical shape through the soil sample length. This pipe is assumed to remain cylindrical during the test with radial expansion [2]. The apparatus used in the present study is shown in **Figure1**. It is composed by three chambers: upstream chamber, downstream chamber, and central chamber, which holds the soil sample. Flowmeter is installed at the inlet of the water flow to record the flowrate and pressure transducers are mounted on both sides of the soil sample to measure the differential pressure for calculating the hydraulic gradient. The flow rate is controlled by an outflow micrometric vane at the upstream side. Eroded mass is estimated using a turbidity meter at the downstream side, after specific calibration.

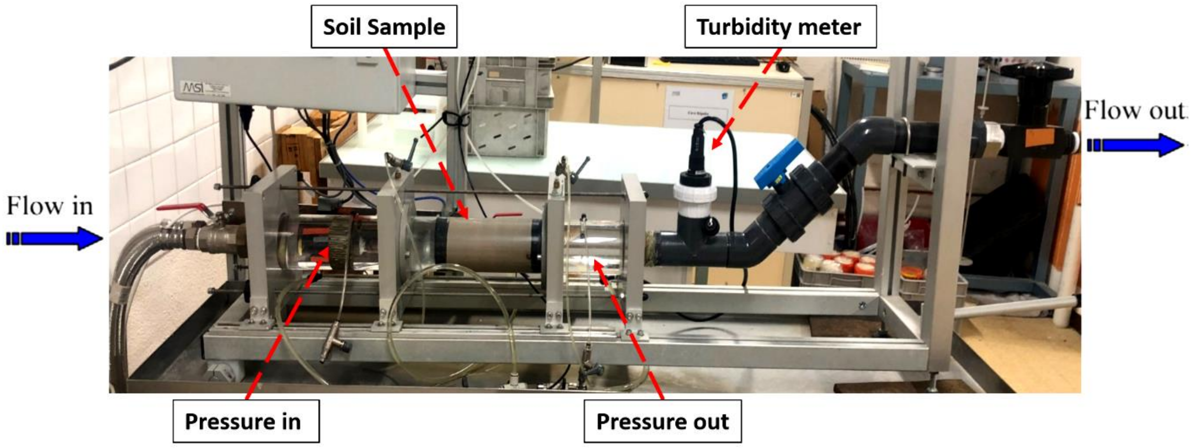

Figure 1 : Photograph of the hole erosion test apparatus.

The materials selected for the present study consist on fine clay, namely Armoricaine kaolinite (KA) from Quessoy (France), and three different coarse materials: siliceous Hostun sand (HN0.4/0.8), siliceous Loire sand (TEN0.55), and glass beads (GB0.4/0.8) made of soda lime glass. Grain size distribution curves of these materials are plotted in **Figure 2**. The coarse granular soils as well as glass beads show a rather uniform grain size distribution and very similar mean grain size D_{50}. Furthermore, glass beads present a roundness ratio ≥ 0.95 (i.e. ratio width/length) and a polished (uncoated) surface whereas Loire sand is composed of sub-rounded elongated particles with substantially smooth surface, and Hostun sand is a sub-angular granular material characterized by a considerably rough surface. The Armoricaine kaolinite has a plasticity index of 25.2, particle density of 2.6 g/cm^3, and contains 33% of particles less than 2 μm.

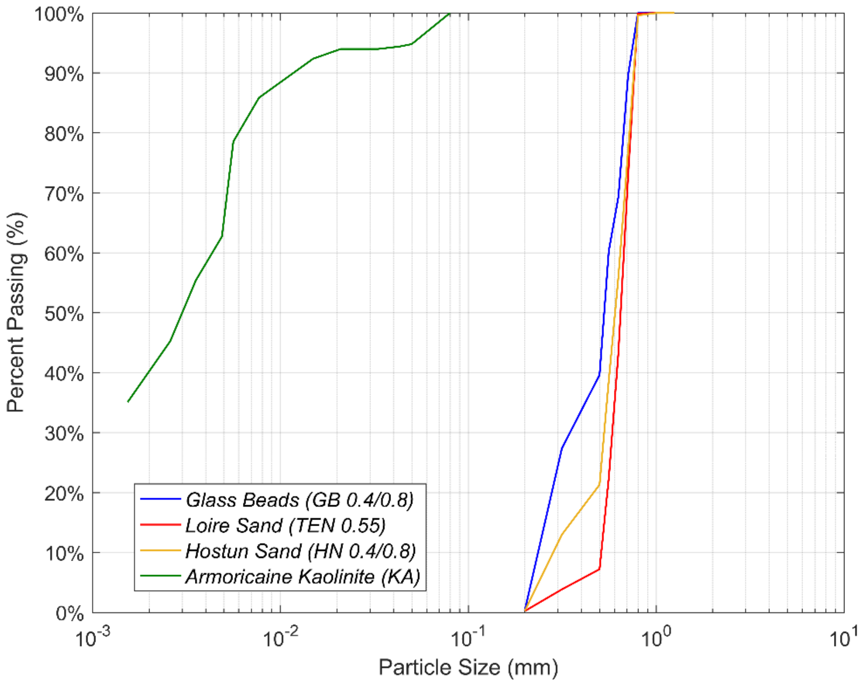

Figure 2 : Particle Size Distribution curves for the tested materials.

3 Experimental program and protocol

The influence of particle shape is investigated throughout 15 compacted soil samples (five samples per mixture) of 150 mm height each. All samples are composed, in mass, of 50% of fine cohesive material (KA) and 50% of coarse material (HN, TEN, or GB). Considering the influence of fines mass fraction on the resistance of soil to erosion, 7 soil samples are tested with different fine contents, namely 20%, 30%, 40%, 50%, 70%, 90%, and 100%. Due to the effect of sample preparation on the structure of sand-clay mixtures [3], one mixing procedure of the different components is chosen: firstly, dried granular material is mixed with fine material, then water is sprayed over the mixture with an amount corresponding to the optimum water content determined by Proctor test. After 72 hours of storage in hermetic bags for moisture content homogenisation, samples are compacted dynamically in 5 layers to the desired bulk density. As regards both particle shape and density effects, the soil of each mixture is compacted at 5 different degrees of about 88%, 92%, 95%, 98%, and 100% of Standard Proctor maximum dry density, corresponding to dry densities varying from 1.51 t/m^3 to 1.72 t/m^3. Furthermore, as far as the effect of fine percentage is concerned, all soil samples are identically compacted at 95% of maximum dry density. Each hole erosion test is performed immediately after sample compaction. Soil sample compaction and testing procedure are described in more detail in [4].

In order to determine erosion law's parameters, namely τ_c and K_{er}, we followed two of the main methods of interpretations currently used in the literature [5]–[7]. The application of these methods requires some input data such as soil density, water content, the evolution over time of the outlet turbidity, the total pressure drop, the average flowrate, and the final diameter of the eroded hole. One should point out that the latter is the most critical one, which is determined *post-mortem* at the end of the test.

4 Experimental results

Results are obtained for the variation of the erosion parameters, critical shear stress τ_c and erosion coefficient K_{er}, with respect to the coarse grain shape, compaction degree, and the fines mass fraction of the soil sample. These parameters are determined considering three regression models, which use different input data of the experimentations. Each point represents a weighted average of the three values determined throughout these methods of interpretation, the weight of each being based on the corresponding R^2 value. Error bars indicate the standard deviation for each determined critical shear stress and erosion coefficient by means of the three interpretation models.

4.1 Influence of coarse grain shape

The experimental results obtained for the 15 tests focusing on the effect of coarse grain shape on the resistance of soil to surface erosion are presented in **Table 1** and plotted in **Figure 3**. As can be observed, the mixture with rounded particles (KA50GB50) shows the highest critical shear stress τ_c, whereas the mixture with angular particles (KA50HN50) presents the lowest one. The difference in behavior of these two types of materials become more pronounced as far as the compaction degree increases. Moreover, for compaction degrees less than 95%, the critical shear stresses of KA50TEN50 are quite close from those of KA50HN50, while for compaction degrees above 95%, there is a substantial divergence between the two mixtures to such an extent that, at 100% compaction degree, KA50TEN50 reaches the KA50GB50 value.

Sample n°	Test ID	$W(\%)$	Compaction degree (%)	ρ_d (t/m^3)	τ_c (Pa)	K_{er} (s/m)
Mixture n°1 : 50% Armoricaine Kaolinite (KA) + 50% Glass Beads (GB0.4/0.8)						
1	KA50GB50-88%PROCTOR-15.6%	15.6	88	1.51	14	11.3
2	KA50GB50-92%PROCTOR-15.6%	15.6	92	1.58	17	7.3
3	KA50GB50-95%PROCTOR-15.6%	15.6	95	1.63	22	2.2
4	KA50GB50-98%PROCTOR-15.6%	15.6	98	1.68	29	2.8
5	KA50GB50-100%PROCTOR-15.6%	15.6	100	1.72	34	2.4
Mixture n°2 : 50% Armoricaine Kaolinite (KA) + 50% Loire sand (TEN0.5)						
6	KA50TEN50-88%PROCTOR-16.6%	16.6	88	1.51	8	4.5
7	KA50TEN50-92%PROCTOR-16.6%	16.6	92	1.58	9	2.3
8	KA50TEN50-95%PROCTOR-16.6%	16.6	95	1.63	13	2.9
9	KA50TEN50-98%PROCTOR-16.6%	16.6	98	1.68	27	0.9
10	KA50TEN50-100%PROCTOR-16.6%	16.6	100	1.72	35	1.1
Mixture n°3 : 50% Armoricaine Kaolinite (KA) + 50% Hostun sand (HN0.4/0.8)						
11	KA50HN50-88%PROCTOR-15.6%	15.6	88	1.50	7	5.5
12	KA50HN50-92%PROCTOR-15.6%	15.6	92	1.57	7	3.1
13	KA50HN50-95%PROCTOR-15.6%	15.6	95	1.62	9	2.3
14	KA50HN50-98%PROCTOR-15.6%	15.6	98	1.67	17	1.2
15	KA50HN50-100%PROCTOR-15.6%	15.6	100	1.71	19	1.4

Table 1 : Erosion parameters of soil samples obtained from HET tests.

Concerning the erosion coefficient K_{er}, and considering global tendencies, the rounded particles mixture displays also the highest values compared to the two other mixtures, and, similarly to τ_c , sub-angular mixture show the lowest erosion coefficient. Besides, as far as the degree of compaction increases, the erosion coefficient of the three mixtures tends to converge. Accordingly, contrary to τ_c, the variation of K_{er} for the different mixtures demonstrates that the presence of glass beads seems to lead to the highest soil's erodibility, once erosion is initiated.

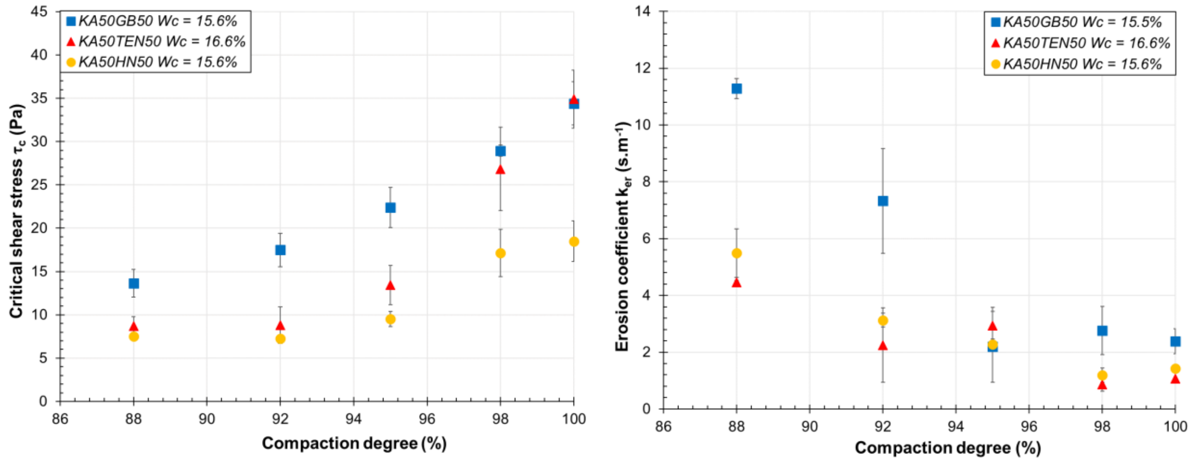

Figure 3 : Effect of coarse particles shape on the erosion parameters, critical shear stress τ_c and erosion coefficient K_{er} for three types of mixtures.

4.2 Influence of compaction degree

The effect of compaction state on the resistance to erosion of the tested samples can also be discussed based on the results presented in **Figure 3**. In the whole range of compaction degrees and especially above 92%, the mixtures made of glass beads and Loire sand, namely KA50GB50 and KA50TEN50 respectively, reveal a significant increase of the critical shear stress τ_c with the degree of compaction, particularly for Loire sand mixture which varies from 8 Pa to 35 Pa at maximum density. For the other mixture (KA50HN50), the increase of τ_c remains much more limited below 95% and then becomes more marked beyond. The dependence of the erosion coefficient K_{er} on the compaction degree is also shown on **Figure 3**. Similarly, to τ_c, there is a change in behavior around 95%, where the value of K_{er} decreases as the compaction degree increases, with the coefficient obtained for the glass beads mixture being systematically much higher than the one of the two other mixtures. Above 95% compaction degree, there is almost a plateau, or even a very slight decrease of k_{er}, with values fairly comparable for the three mixtures.

Considering the two parameters τ_c and K_{er}, this analysis leads to the conclusion that an increase in soil's density leads to a higher resistance to surface erosion. Nevertheless, there is a quantitative discrepancy when considering the shape of the coarse grains: regardless of their nature, the mixtures with sands show very similar values (except for τ_c at the highest compaction degrees) while the glass beads mixture has significantly higher erosion parameters, both the critical stress and the erosion coefficient.

4.3 Influence of fines mass fraction

The experimental results related to the effect of fines fraction on the erosion parameters of samples prepared with mixtures of Armoricaine kaolinite and Hostun sand are given in **Table 2** and **Figure 4.**

Sample n°	Test ID	% Clay	W (%)	Compaction degree (%)	ρd (t/m^3)	τ_c (Pa)	K_{er} (s/m)
1	KA20HN80-95%PROCTOR-11.9%	20	11.9	95	1.82	3	26.5
2	KA30HN70-95%PROCTOR-12.5%	30	12.5	95	1.80	7	9.7
3	KA40HN60-95%PROCTOR-14%	40	14	95	1.73	10	8.4
4	KA50HN50-95%PROCTOR-15.6%	50	15.6	95	1.62	9	2.3
5	KA70HN30-95%PROCTOR-22.6%	70	22.6	95	1.47	13	0.7
6	KA90HN10-95%PROCTOR-28.2%	90	28.2	95	1.32	13	0.6
7	KA100HN0-95%PROCTOR-32%	100	32	95	1.23	15	0.6

Table 2 : Erosion parameters of soil samples from HET tests.

From the variation of both the critical shear stress τ_c and the erosion coefficient K_{er} with respect to the percentage of fine material in the sand soil mixture, it can be seen that, for fines content ≤ 40-50%, there is a significant increase of the critical shear stress τ_c, whereas the erosion coefficient K_{er} shows a steep decrease. For mixtures composed of more than 50% of fines, the erosion coefficient remains very small, on a kind of plateau about 1 $s.m^{-1}$ with a minimum value of 0.74 at 70% of fines content. In the same time, τ_c keeps increasing, but less sharply, until reaching almost 15 Pa at 100% of fines where the soil sample is essentially constituted of pure Armoricaine kaolinite. Overall, the trend is therefore towards a more resistant material as the fine fraction is increased. However, as highlighted here and clearly observed in Figure 4, one should point out that there are two distinct regimes of the erosion parameters evolution with a demarcation point around 50% of fines content.

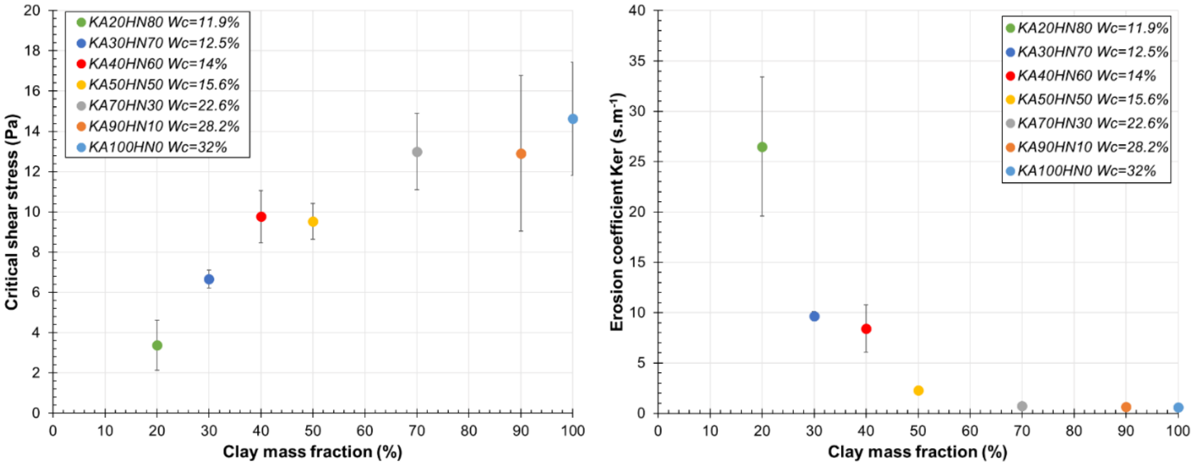

Figure 4 : Effect of clay mass fraction on the erosion characteristics, critical shear stress τ_c and erosion coefficient K_{er}, for 7 various KA-HN mixtures.

5 Discussion & Conclusions

Based on HET test, the present study investigated the impact of the coarse particles shape, the soil's compaction degree, as well as the fines content on the resistance to surface erosion of samples constituted by mixtures of fines and coarse grains. The main outcomes are as follow:

1. The increase in soil's density leads, generally, to a decrease in soil's erodibility, which is in agreement with previous results [4], [8]. The response to the increase of soil's density seems to depend on the shape of coarse material. Indeed, it appears that the more rounded the coarse particles in the mixture the sharper the response for the erosion coefficient K_{er}.
2. Concerning particles shape, the experimental results point out two counterintuitive conclusions since, on the one hand, the highest τ_c value is found for the more rounded coarse particles. This is in contradiction with the findings of *Choo et al. 2020*, who pointed out that the increase in particles angularity leads to an increase of resistance to erosion [8]. However, Choo's study concerned purely coarse material erosion and cannot be strictly compared to our study on cohesive soils. This fact might probably be attributed to the manner that the coarse particles were coated by fines. On the other hand, it was showed that K_{er} is higher for rounded particles mixtures, which defines a more erodible soil in comparison to angular particles mixtures. Considering a non-cohesive soil, *Guo et al. 2018* [9] gave a possible explanation to this observation as they demonstrated numerically that the ellipsoidal particles show more resistance to erosion in comparison to spherical particles due to the lack of rotation resistance for spheres.
3. The increase in fines content results in less erodible soils, which is fully consistent with previous studies [10]–[13]. A change in behavior is observed around 40-50% of fines content, in line with a previous study by *Panagiotopoulos et al. 1997* [13] which revealed that the increase in mud content results in two different regimes of increase for the threshold shear stress, with 30% mud content being the frontier between the two regimes.

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