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I. INTRODUCTION

Since the last catastrophic floods appeared in the southeast of France, the state, land planning agencies and urban planners worry about the susceptibility of dikes and road embankments to floods [5]. The internal phenomenon of piping is often estimated in projects and expertises using finite elements software through the evolution of the calculated gradient. The theoretical values of critical head gradient, used as reference in France, results from relatively old research of the Thirties. To revalue the relevance of this criterion very much used in practice, it is necessary to study the initiation of erosion within soil material.

The research program presented in this paper is interested in the process of erosion of the argillaceous matrix of structured soil using various types of tests:

- surface erosion tests with the LPC mobile water jets test apparatus developed by reference [7]. The characteristic of this test is to be able to characterize the surface erosion of soil under a gauged water flow. It can be carried out on site. This apparatus is similar to the jet erosion test developed by reference [6].

- dispersity tests with the pinhole test: it acts of a rather qualitative test which makes it possible to evaluate the dispersiveness of a soil subjected to a given hydraulic gradient [1,2].

- internal erosion test with Hole Erosion Test (HET). This test, which is the most recently developed, is carried out for a given hydraulic gradient and gives the variation of the rate of erosion versus time. This apparatus allows to follow the evolution of the geometry of the cavity in which water circulates [14]. A parametric study has been initiated by French Public Works Laboratory (Laboratoire Central des Ponts et Chaussées, Paris, France) with this new experimental device to provide more values of internal erosion characteristics.

The complementarity of these techniques to estimate stability of soil to internal erosion, makes it possible to dissociate the mechanisms due to dispersion, with the shear stress to the soil-fluid interface due to water flow. The triaxial erosion test, which is an alternative, was not elected. It is a more sophisticated version of the last cited apparatus where confinement allows the exploration of another dimension of the problem. However the absence of hole totally or partially traversing the sample makes the analysis more difficult as suffusion is superimposed to erosion [3,10,13].

A work of interpretation of the results of these experiments is presented. A first approach of an application to well documented pathologies was carried out.

The capacity to carry out the modelling of internal erosion is one of the finalities of this study. This is an important repercussion towards the practice necessary to the engineers to evaluate a priori the stability of geotechnical works on which they carried out leak detection surveys [4].

II. EXPERIMENTAL DEVICE

A. *Description*

The device consists in a modified Hole Erosion Test apparatus [14]. The main body is composed of three cells with an internal diameter of 72 mm: a first cell filled with glass beads or gravel, a second cell in which the soil sample is compacted and a third cell including measuring devices. A Hengstler turbine flow rate sensor placed between the fluid supply tank and the apparatus measures the flow rate. As during the test, we measure the pressure upstream and downstream using Honeywell miniature pressure transducers (0-100 kPa), we can calculate the gradient. We propose to make the exact measurement of eroded material quantity by the monitoring of turbidity (ATI turbidimeter) caused by fine particles suspended in the water downstream the eroded zone (fig. 1). All the transducers are connected to a HBM spider 8 datalogger. Measurements are displayed and recorded by a software developed under Labview from National Instruments.

The control of the water head is obtained by the use of an air compressor regulator connected to the fluid supply tank.

Figure 1. Photograph of the experimental device

Figure 2. Detail of the three cells

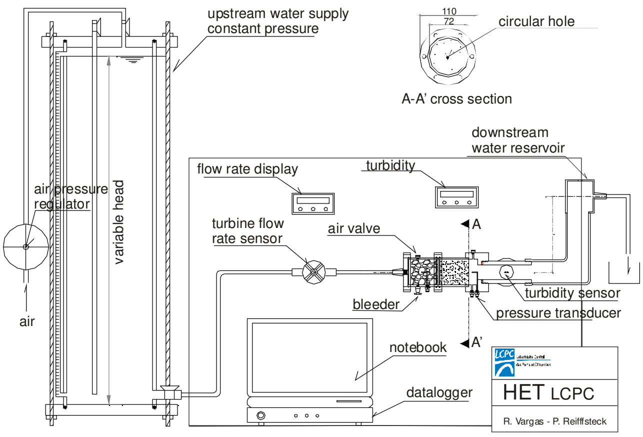

Figure 3. Schema of the experimental device

B. *Materials used*

To achieve our parametric study we have planned to test mixtures of textbook soils (kaolin, silt, sand), which would correspond as much as possible to a class of classical textural classification of original and altered grounds. We made this choice because the aim of the study is to connect under conventional test conditions in laboratory or on site, the erodibility of a soil to the classification of the GTR design guide (i.e. Guide for Road Earthworks) familiar for French public works actors in dyke and embankment construction [9].

When the characteristics of each mixture are determined, the proportion of each component is calculated using a graphical method [13]. The entry parameters observed are particularly the porosity, expressed in term of texture, and void ratio, as well as the water sensibility of the fine fraction evaluated via the physicochemical characterization of the soil and the fluid.

C. *Preparation of sample*

The preparation of soil sample is divided into three steps:

- First step, the soil is placed in a drying oven during 24 hours then it is weighted in order to determine the water quantity necessary to obtain the desired water content. We gradually introduce water into the soil during mixing. Then we soak the samples during 24 hours, after having covered it with a plastic film to avoid evaporation.

- Second step, we take a mass of soil which when it has been compressed to the height of the test-cell, will give the projected dry density. The dry density required corresponds to 95% of the Proctor optimum density. The compression is realized in four layers using a hydraulic jack.

- Third step, a vertical drilling machine is used to create a hole of 4 mm of diameter along the longitudinal axis of the soil sample to simulate a concentrated leak.

D. *Test procedure*

After having connected the pipes, we open gently the water flow in order to avoid soil sample movement. At this stage, the air valves must stay open. While water goes up in the cell, we pour the water in the tank downstream in order to balance the pressure, still to avoid a displacement of the sample. When the cell is filled, we close the air valves after having checked that there does not remain any air bubbles. We use the air pressure regulator to maintain the water head at the desired height. The test begins at the same time we start the specific software to monitor the different measuring devices. In the test, time, flow rate, upstream pressure, downstream pressure, turbidity are measured automatically every 30 seconds. We conventionally realized the test in three hours with the initial gradient and initial flow rate chosen after few trial tests.

III. TEST AND ANALYSIS

We have already tested 35 soils with mobile water jet and pinhole tests [11] but the delay for the design and validation process of our apparatus only allow us to test 16 samples of 4 different textures up to now. We present here the results of three tests made with two different textures. Table 1 summarizes the soils used and their classification.

TABLE I .

Different texture tested

Type	Desired mix design (%)			W_l (%)	Wp (%)	I_P	Wopn (%)	γ_{opn} (t/m^3)
	clay	silt	sand					
1.1	25	5	70	18,1	14	4,1	11	2
1.3	35	25	40	25,6	16,7	8,9	13,81	1,927

A. *Test for texture 1.1*

This texture corresponds to clayey sand. In this test, the initial gradient is equal to one, and the initial flow rate to about 700 ml/min. During the test, the diameter of the hole increases as a result the flow rate rises and the gradient decreases (fig. 4 and fig. 5). In the 50 initial minutes, the flow rate increases sharply, the gradient decreases dramatically, the cumulated turbidity rise considerably (until 4000 ppm) and then it grows moderately (at the end of test, the turbidity is only about 5000 ppm) (fig. 6). Thus, the erosion goes up significantly in the initial time and then it improves slightly before having the tendency stabilized.

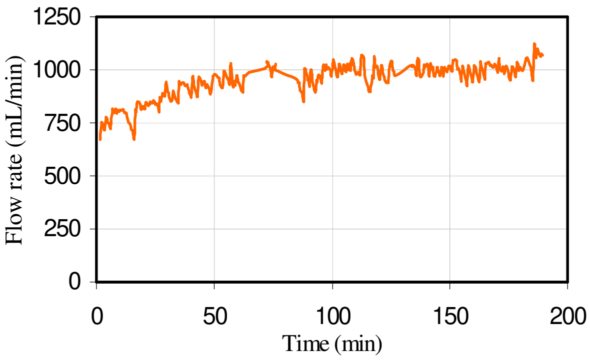

Figure 4. Flow rate vs. time for sample 1.1.3

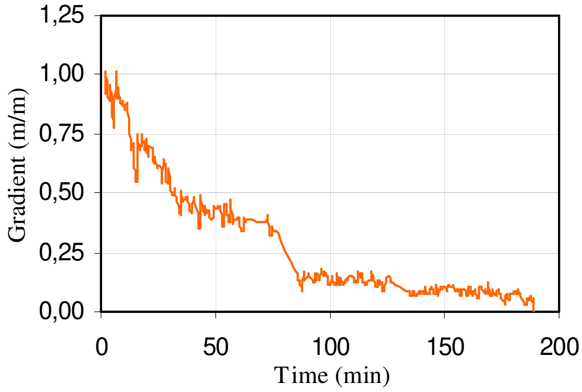

Figure 5. Gradient vs. time for sample 1.1.3

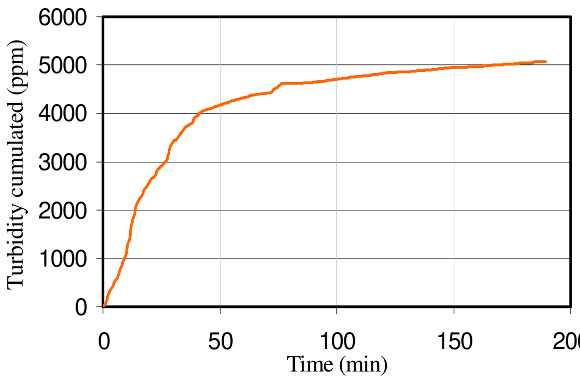

Figure 6. Cumulated turbidity vs. time for sample 1.1.3

B *Influence of compaction*

For the sample 1.1.3 described above, the most compacted layer was placed downstream. For the sample 1.1.6, we changed the orientation so that the least compacted layer was downstream.

It can be seen that for the sample 1.1.6 the flow rate increases slightly (fig. 7), the gradient decreases moderately (fig. 8) and the cumulated turbidity grows not much in the 50 initial minutes (only 800 ppm) (fig. 9). It is noticeable that the sample is more difficult to erode because the most compacted layer, limiting the erosion, is placed in upstream position so it needs more time to increase the diameter of the hole. At the end of test the flow rate goes up not much (about only 800 mL/min), the gradient is still high (about 0,8 m/m) and the cumulated turbidity is slightly more than 3000 ppm. It is spot on that the compaction plays a very important role in the erosion of soil.

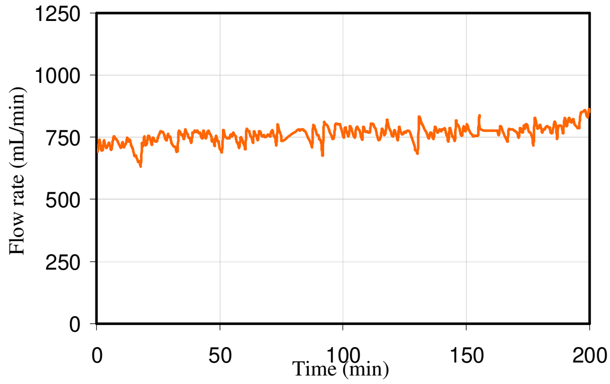

Figure 7. Flow rate vs. time for sample 1.1.6

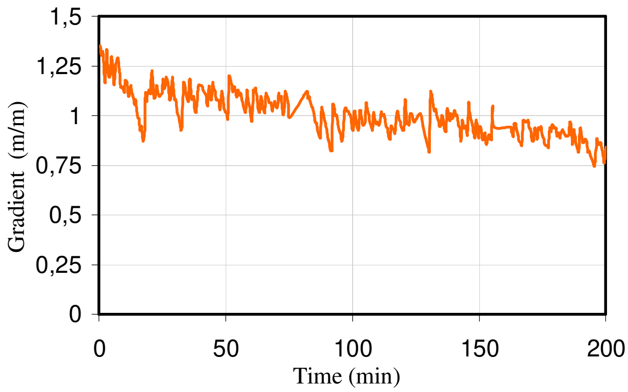

Figure 8. Gradient vs. time for sample 1.1.6

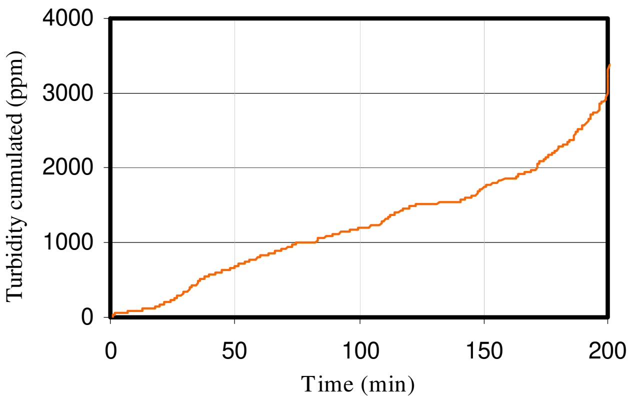

Figure 9. Cumulated turbidity vs. time for sample 1.1.6

It implies also that in this particular case, the apparition of erosion takes more time: almost 2 hours, than in the first test presented. The choice of the conventional test duration has to be revised. Some trial tests have been done using duration of 6 hours and gave interesting results. We decide for some texture to use this duration preferentially.

C. *Test for texture 1.3*

This texture corresponds to sandy clay. Although we start the test with a high gradient (s=5) (for the sample 1.1.3 and 1.1.6 we start with s is around 1), the cumulated turbidity increases very moderately (after 50 initial minutes, the turbidity is only 360 ppm and at the end of test it is 650 ppm) (figure 11). We can observe eight times less erosion than for texture 1.1. Soil with a high fraction of clay is less eroded than a soil with a small clay fraction.

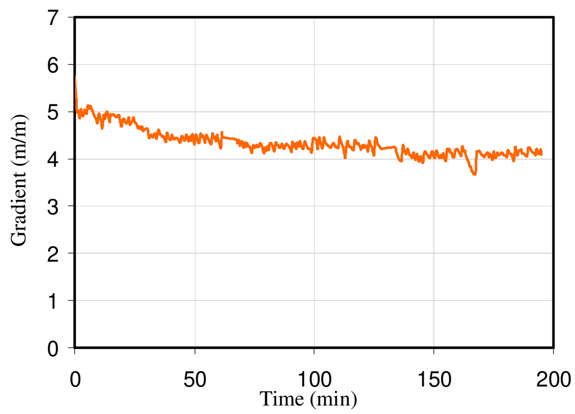

Figure 10. Gradient vs. time for sample 1.3.1

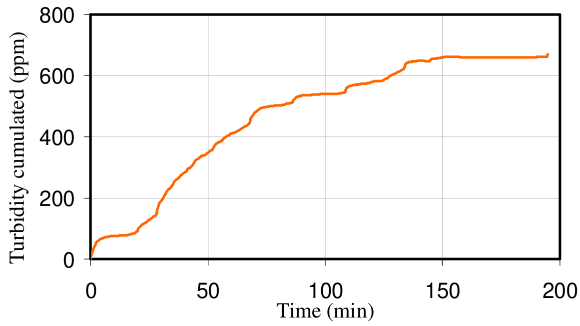

Figure 11. Cumulated turbidity vs. time for sample 1.3.1

D. *Synthesis of test results*

All the results of performed tests underline very different magnitude of erosion rate (cumulated turbidity), the turbidity vary from hundred ppm (sample 1.3.1) to thousand ppm (sample 1.1.3 and 1.1.6).

The comparison of the erosion rate index I_{HET} defined by [14] made in table II indicates that the texture 1.1 erode very rapidly and that the texture 1.3 erode moderately rapidly. These results are in very good accordance with the mobile water jet apparatus results [11]. For this test, the results are separated in three classes proposed by previous studies: solid loads higher than 150g and from 150g to 50g are respectively classified as soils with low and moderate resistance to erosion. Lower values of solid load are obtained for soil having a good resistance to erosion.

TABLE II.
Comparison of results

Type	Desired mix design (%)			E_{10}	E_{67}	Dispersivity	I_{HET}
	clay	silt	sand				
1.1	25	5	70	58.5	141.5	D	2.48
1.3	35	25	40	48	70	SD	3.30

The dispersivity obtained with the pinhole test show a similar trend.

The compaction is an important parameter to influence the erosion rate. With the same sample, if we change the position of the more compacted layer at downstream to upstream, we have an erosion rate about two times lower.

The time factor is another remarkable parameter. For the sandy soil type (sample 1.1.3), major erosion occurs in the 100 initial minutes and then erosion rate is relatively low. For the clayey soil type, after 200 minutes the erosion rate is very small. It is obvious that it takes much more time to erode a clayey soil compared to a sandy soil. Therefore the test procedure and more particularly the test duration must be adapted

The fine grain faction appears as a strong influence for soil erodibility. The performed tests tend to underline that for 30% of fine samples the erosion rate is about seven times higher than for 70% of fine although the gradient is five times less.

IV. Modelling

The application to a well-documented case study and pathology was carried out using the finite element software CESAR-LCPC. We were interested to understand the behaviour of a dyke build along the Loire river in the middle age and improved at the end of the XIXth century. The dyke made with alluvium sand and silt has an average height of 5 m, a with of 10 m at the crest and around 30 m at the toe (figure 12). We consider three cases:

- a single-layered fill subjected to an increasing hydraulic load and respecting the critical head gradient suggested by Lane and observed in the HET.
- a multi-layer embankment comporting a contrast of permeability subjected to a hydraulic load. In this model, the Lane gradient criterion is maintained but it is necessary to take into account other important criteria, like the flow rate and the flow, which determines the direction of erosion.
- a multi-layer fill identical to the previous one and subjected to an overflow. The criterion relates to the rate of flow and the shear stress due to flow (critical tractive speed).

During the calculation, the zone of the mesh where the critical head gradient is reached vanishes and the stability of the structure is checked. So at each step, a geometry of the erosion process is obtained, a velocity field can be observed and a factor of safety analysed. For these three different structures of embankment, the water head, the width at the crest and the slope have been varied. Finally in this parametric study, more than 130 cases have been calculated to produce abacus. This study showed us the capacity to obtain realistic mechanisms of rupture with a simple modelling and a standard calculation procedure of the finite element method while waiting to be able to implement a piping model fitted on the experiments presented before. For example, reference [8] developed a piping model for levees resting on clayey foundations within the framework of a Darcy's law-based critical head model.

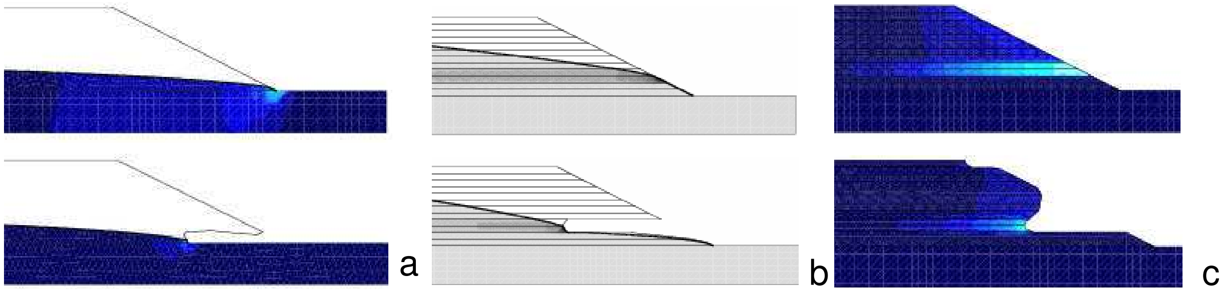

Figure 12. Result of modeling showing flow field on (a) a single-layered fill (b) a multi-layer fill subjected to an increasing hydraulic load and (c) a multi-layer fill subjected to an overflow

IV. CONCLUSIONS

The first results obtain with our modified hole erosion test are rich and promising. In the near future, tests on a large panel of soil texture are needed to build a database.

This research focuses on the influence of the soil texture on the erosion characteristics of soils. This first set of tests doesn't take into account the clay mineralogy of the fine fraction of the soil, which has been point out to be a major factor of influence [1,13]. This will be done in the second part of the program.

This comparative study of testing techniques is supplemented by a multi-scale analysis including the analysis of the susceptibility of the various types of colloids composing the matrix of the ground (silt, kaolinite, illite or smectite) to be dispersed in a fluid charged with cations with various valences.

The modelling of internal erosion gives realistic results and need to be improved by the use of empirical laws fitted on experimental results.

These different goals are in the objectives of a four years national research program founded in France by the French Ministry of Research, Science and Technology and manage by the French energy company EDF. This research program is called ERINOH. A lot of the French authors listed in the references involve in this program.

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