Dikes reinforced by deep mixing techniques - Long term properties

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ABSTRACT: The deep Soil-Mixing technique consists in mixing a hydraulic binder into the soil mechanically in order to improve its properties. As far as dikes are concerned, two methods are available. The dry method which is one of these, consists in making a 1 m pre-trenched zone where cement powder is spread and the mixing tool mixes the soil and the cement with water down to a depth of 9 m from the top of the dyke. For the study of erodibility with laboratory tests, a hole erosion test apparatus is used in order to characterize the internal erosion of soils. Samples created in the laboratory as well as cored samples have been tested to get some ranges of soil-mixed responses.

1 INTRODUCTION

Deep soil mixing is a reinforcement technique that consists in mixing in situ soil with cement to achieve a panel with the following geometry : 60 cm width and 8 m deep. The dry method is used in the described case with the following procedure : a pre-trenched zone of 1m width and 1m deep is dug and cement powder is spread in this 1m deep trenched zone (Figure 1 (a)). Then, the trenchmix machine is positioned at the top of the pretrenched zone and the production can begin (Figure 1 (b)). Finally showing, the end of the reinforcement works (Figure 1 (c)).

This new technique represents a good alternative to the usual techniques used for hydraulic and erodibility purposes.

Nevertheless, the long-term behaviour of this treated material still represents an issue.

Hydraulic tests are used to validate the limit imposed by the project. Mechanical tests can help in justifying the homogeneity of the treated material. Erosion tests could be considered as gathering the two issues ; mechanical and hydraulic.

In this paper, the focus is given on the erosion tests.

Laboratory erosion tests are a convenient way to understand how various factors affect the complicated process of soil erosion. It is easy in the laboratory to collect runoff water in a measuring tank and to measure the quantity of eroded soil. Many apparatus able to produce an artificial erosion of a soil surface have been thus developed in the past decades (Aru-lanandan et al. 1980, Bendahmane et al. 2006, Sanchez et al. 1983, Wan and Fell 2002, 2004).

In this study the Hole Erosion Test (HET) developed at IFSTTAR is used to compare results on soils prepared with various ground textures.

2 HOLE EROSION TEST (HET)

The relationship at the solid-fluid interface with a tangential flow, called "erosion law", correlates the two following physical quantities (Fig. 2a):
- the shear stress τ, between the flowing liquid and the soil (SI unit: Pa); and
- the erosion rate $\dot{\varepsilon}$, that represents the mass of soil eroded per unit area and time (SI unit: kg•m^{-2}•s^{-1}).

The empirical erosion low is generally given in the form (Briaud et al. 2001; Wan and Fell 2004; Bonelli and Brivois 2008):

$$\dot{\varepsilon} = k_{er}(\tau - \tau_c), \qquad (1)$$

where k$_{er}$ (SI unit: s•m^{-1}) is called the erosion coefficient and τ_c (SI unit: Pa) is the critical shear stress. However no basic argument other than experiences justifies such a law. As a result, the suggested interpretation method is not based on any specific empirical relationship between the erosion rate ($\dot{\varepsilon}$) and the shear stress τ.
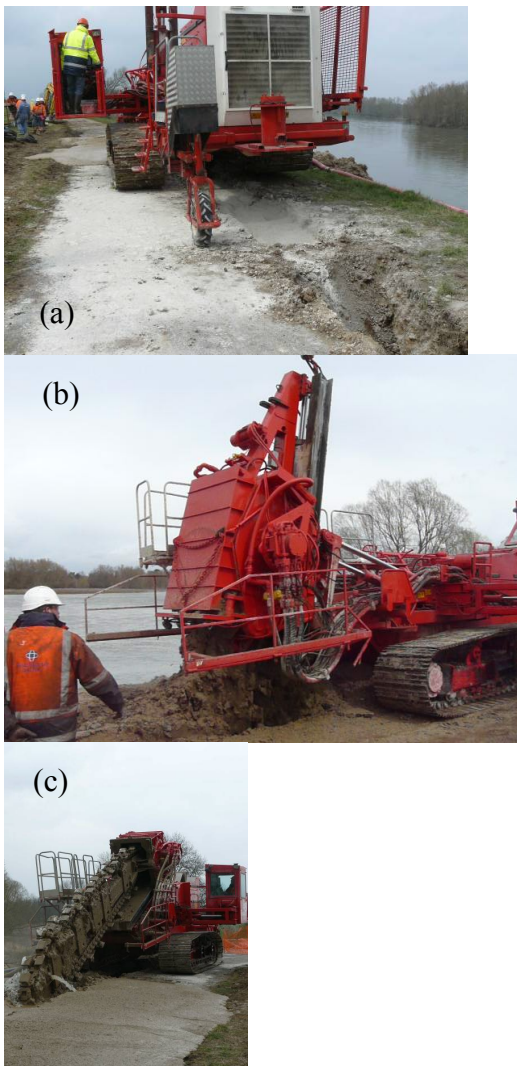
Figure 1. Dry method for soil mixing reinforcement (a) pre-trenched zone and cement powder, (b) production and (c) end of mixing.

In order to quantitatively characterize the piping erosion, the Hole Erosion Test recently developed by Wan and Fell (2002,2004) was a great understanding step forward.

IFSTTAR developed its own HET device (Pham 2008, Reiffsteck et al. 2006). Similar to the one developed by Wan and Fell, it presents a number of improvements designed to make it easier to use and more comprehensive for measuring parameters of erosion.

2.1 Apparatus

The HET device has three parts: an upstream water tank, an eroding unit where the sample is located (Fig. 2) and a downstream water exit.
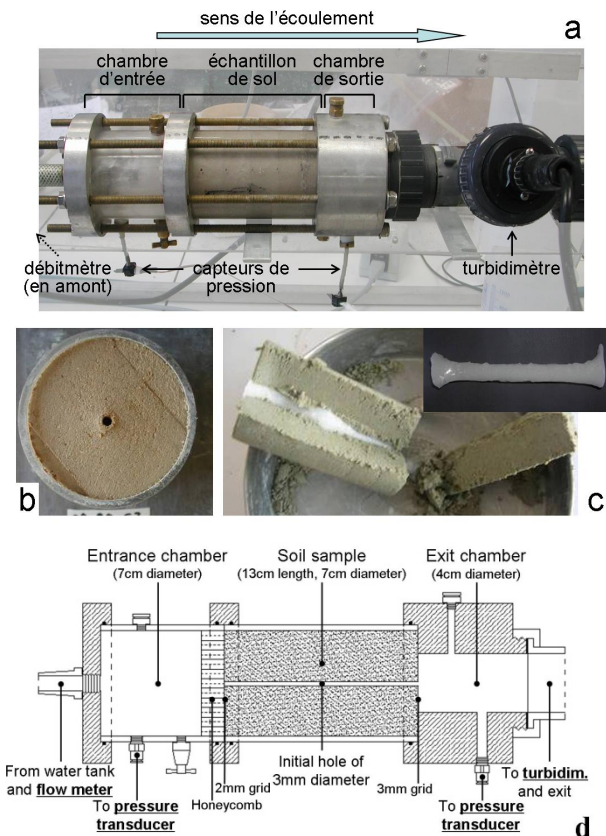

Figure 2. Hole erosion test set-up. (a) Image of eroding unit. (b) Sample before test with 3mm diameter hole. (c) Cut sample after test with molded wax. (d) Drawing of eroding unit. Sensors are indicated in bold and underlined characters.

The upstream tank is a PVC cylinder of 80 litres volume. It can be pressurized by air and recharged with water during the test. A turbine flow meter is placed in the vicinity of the eroding unit.

The column of water downstream is constant at 20cm.

The eroding unit is depicted ion Figures 2(a-d). It includes three parts: The first part is the entrance chamber of water. In addition to a miniature pressure transducer, this part includes a honeycomb in order to reduce swirl in entry hole as well as a grid of 2 mm x 2 mm. The second part consists of the soil sample itself with a central hole of 3mm in diameter. The Plexiglas transparent mould allows checking to ensure that no unexpected erosion occurs between the sample and the mould. The third part is the exit chamber. This section includes a second miniature pressure transducer. A turbidimeter is placed right after this section in order to measure the turbidity of the fluid out of the specimen.

2.2 Procedure

Soil samples are prepared in a cylindrical Plexiglas mold. The dimensions of the mould are 7 cm in diameter and 13 cm in length (volume: 500 cm^3). The soil is prepared in advance at a given water content. Water content and final density are generally defined

using a standard Proctor test (ASTM, 2005b) for comparison with practical conditions in embankments. The initial hole of 3 mm diameter in the middle of the sample is finally achieved with a vertical drill (Fig. 2b).

After bringing water in all the system and especially in the sample, the air pressure in the upstream water reservoir is raised gradually until the desired pressure drop at the sample is reached. As erosion occurs, the sample hole grows during the test and the water flow increases. This increasing flow induces a head loss in the upstream hydraulic system, which then increases the pressure in the water reservoir whilst the pressure drop ΔP at the sample boundaries is maintained constant. When the total head loss of the hydraulic system is too large, increasing pressure in the reservoir is no longer sufficient to maintain a constant pressure drop in the sample. This happens when the diameter of the hole is nearly the same as the pipes diameter supplying the circuit. The pressure in the tank is slowly reduced and then reduced to zero.

The sample of eroded soil is then taken out of the device and molten wax is poured into the eroded hole. The sample is cut out and the "candle" is carefully extracted (Fig. 2c). This "candle" represents the shape of the hole of the sample after erosion. The volume allows the calculation the final average radius of the eroded hole.

During the entire test, from the increase of head charge to the decrease, the data collected by flow meter (flow rate Q), pressure transducers (pressure drop ΔP) and turbidimeter (turbidity T) are stored on a computer using a datalogger. The frequency of acquisition is generally 1Hz. These measurements and data on the initial and final radii allow erosion curves to be calculated [interpretation method detailed in (Pham, 2008; Pham et al., 2010)] i.e. the relationship between the two following physical quantities:

- the shear stress τ, that the flowing liquid applies on the interface (SI unit: Pa); and
- the erosion rate $\dot{\varepsilon}$, that represents the mass of soil eroded per unit area and time (SI unit: kg.m^{-2}.s^{-1}).

3 TESTED MATERIALS

Long-term investigation of the built structures has been carried out; from boreholes and laboratory tests to in situ tests.

As far as laboratory tests are concerned, erosion tests using HET have been considered as key laboratory tests to analyse long-term response of soil mixing material.

Different reconstituted textures of soil were tested in order to cover a wide variety of situations

Table 1. Tested textures: components and physical characteristics.

Paramètre	Densité	%<80µm	VBS	w$_L$	w$_P$	IP	Classe GTR
Unité	(kg/m^3)	(%)	(g/100g de sol sec)	(%)	(%)	(%)	
Kaolinite Armoricaine	1200	100	0,84	55,31	42,50	12,81	A1
Sigloy	1600	62	2,41	32	15	17	A2
Maison Vieille	1600	48	1,26	33	14	19	A1

Five soil-cement mixes were achieved to test the erodability of treated materials (Table 2):

- The two natural soils from site (Val Orléans) with a cement content of 140 kg/m^3.
- Kaolinite armoricaine with cement contents of 70 and 140 kg/m^3. The kaolinite armoricaine, with characteristics described in Table 1. It represents a laboratory material that allows cement contents that could produce erodability of a treated soil to be determined.

Table 2. Synthesis of the results of erosion tests.

| Tests	Height (mm)	Density (kg/m^3)	P max (mbar)	T max (ppm)	flow (l/min)	D$_i$ (mm)	D$_f$ (mm)	eroded mass (g)	τ$_C$ (Pa)	erosion rate (s/m)
MV C140	140	1740	150	600	20	6	14,6	34	entre 150 et 250 ?	?
S C140	140	1740	150	4500	20	6	13,6	28	env 150	about 0,0025
KAO C70	140	1340	<150		20	3	20	57		
KAO C140 1	140	1340	650	600	8,1	4	5,3	1,8	>500	-
KAO C140 2	140	1340	580	200	13,6	5	6,7	2,8	>500	-

For the three first tests, the eroded mass was observed validating the erosion potential of the treated soils whereas for the soil-cement mixes at 140kg/m^3, no noticeable erosion was observed.

The test carried out on the Sigloy soil show the response of an eroded treated soil. Measurements and interpretations are given on Figure 3 and Figure 4. On Figure 3, measurements are (a) erosion rate vs stress, (b) water flow., (c) turbidity. On Figure 4 (a) variation of pressure, (b) stress and (c) erosion rate with time

The interpretation of the erosion curve with equation 1 can be done and erodability parameters; critical stress, erosion coefficient are given in Table 2.

The threshold shear stress reaches high values up to 150-200 Pa with high erosion coefficients. It means that once the erosion starts, it increases very quickly which is not a typical response.
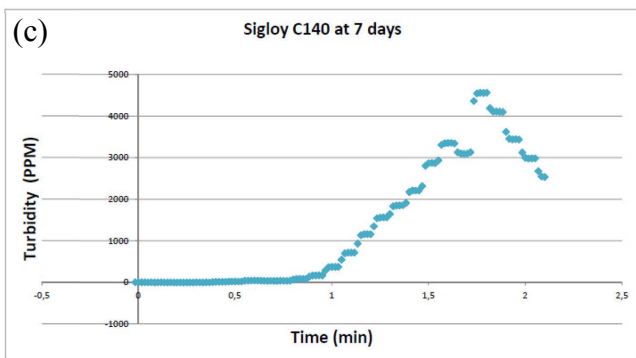
On the second natural soil at the Maison Vieille site, the test is more difficult to interpret (Figure 5 and Figure 6). The treated soil withstands erosion but the erosion parameters are difficult to determine. Only a range of these parameters can be estimated (Table 2).
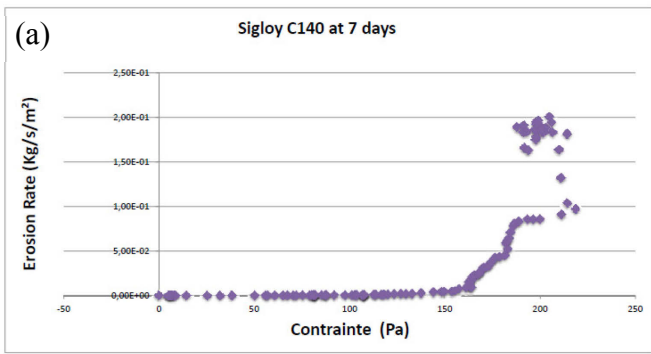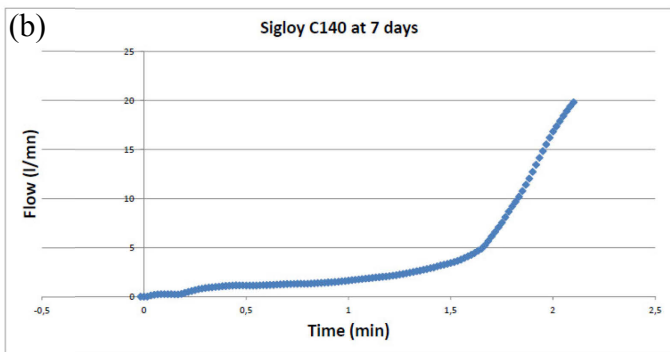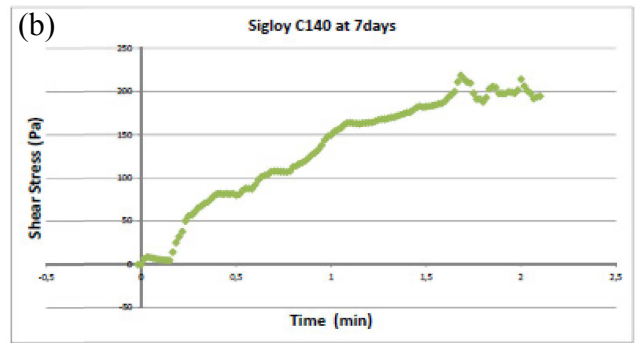
Figure 3. Hole erosion test set-up: (a) erosion rate vs stress, (b) flow vs time, (c) turbidity vs time.
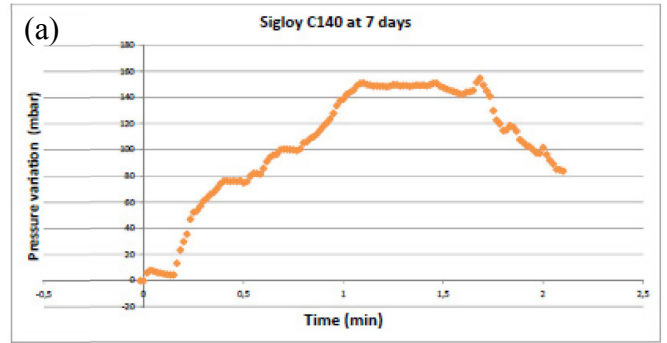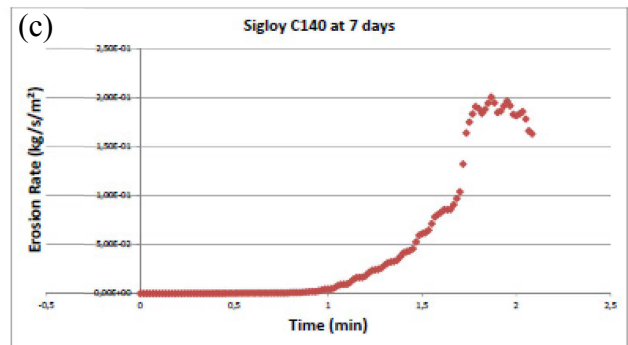
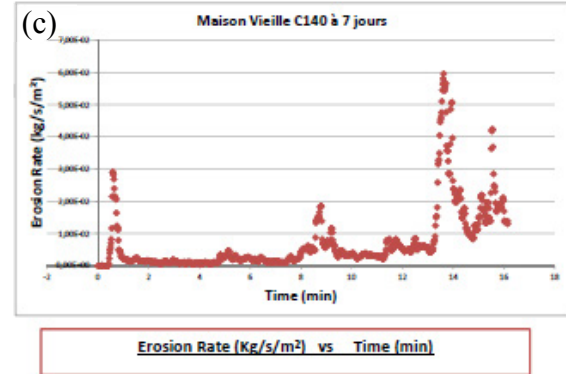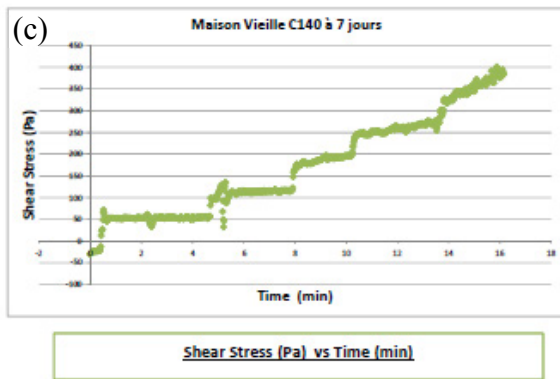Figure 4. Hole erosion test set-up. (a) variation of pressure, (b) shear stress vs time, (c) erosion rate vs time.
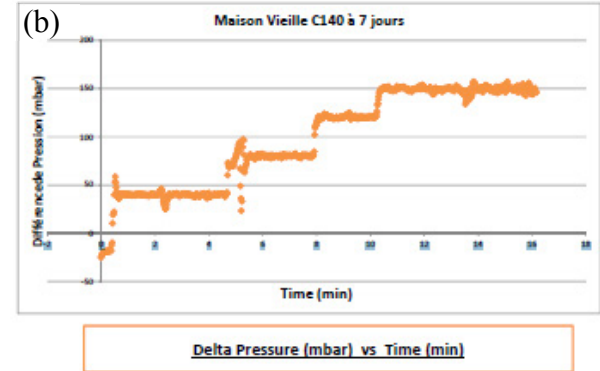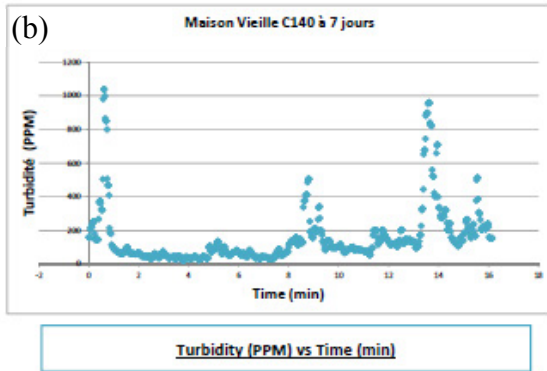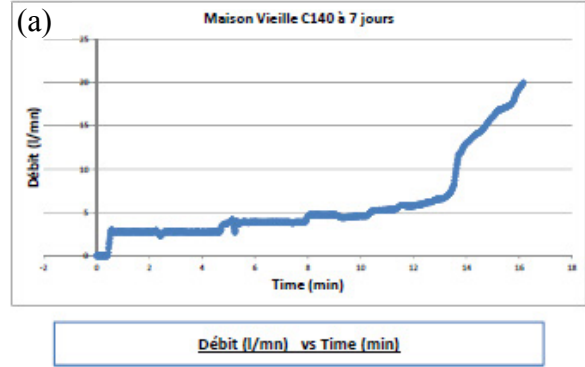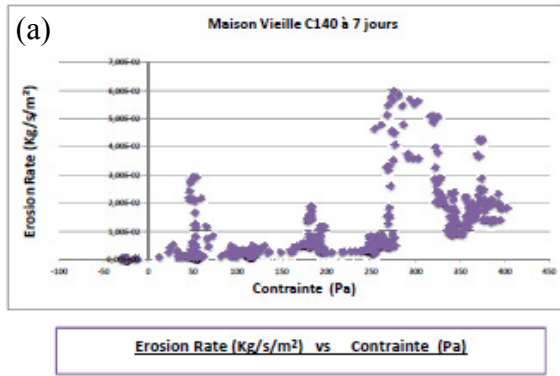
Figure 5. Hole erosion test set-up. (a) erosion rate vs stress, (b) turbidity vs time, (c) stress vs time

Figure 6. Hole erosion test set-up. (a) Flow, (b) variation of pressure vs time, (c) erosion rate vs time

4 CONCLUSIONS

As a conclusion:

- The treated soils at Sigloy and Maison Vieille present thresholds around 150-200 Pa and important erosion coefficients. It means that when the erosion starts, it rapidly increases. It does not represent a classical behaviour.
- The treated kaolinite at the same cement content as materials from the sites presents a much better erosion resistance. It could linked ε to the granulometry of the natural material : Sigloy and Maison Vieille have bigger grain sizes than pure clay (kaolinite) and are therefore naturally more erodible.
- Only one of the curves can be interpreted. It is not enough to finalize the analysis. However, the tested materials are erodible with a high threshold. It could represent a good opportunity to undertake a parametric study, treatment and erosion response at these sites.

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