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Report on the work concerning the comparison of the jet-test and hole-erosion test.

Abstract:

The purpose of this report is to present a comparison between the Hole Erosion Test (HET) and the Jet Erosion Test (JET). The difficulties encountered in conducting these two tests were both experimental and theoretical. From an experimental and practical point of view, it was difficult to manage the soil quality to obtain clearly the same soil behavior from test to test. From the theoretical point of view, the analysis used for the HET has to be improved to take advantage of all the information available from the test results. This report presents a comparison based on tests conducted on four soils at the Denver – USBR Laboratory.

The conclusions of the study focus on:

- the difference of scale between erosion with the JET and the HET.
- the same relative classification of erodibility obtained with the 2 devices.

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1 Introduction

The main objective of the study is to compare the jet erosion-test (JET) and the hole-erosion test (HET), 2 tools for an evaluation of the soil erodibility. The main difference consists in the applied state of stress on the soil. For the JET, a shear stress and impact take place. For the HET, only a shear stress is applied on the soil.

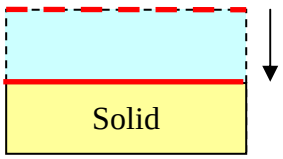
These 2 kinds of apparatus provide a measurement of the erodibility[1] of soils by considering an index for the HET and the parameters of the erosion law for the JET. The analysis for the HET and JET are based on a linear erosion law with a threshold and some identical hydraulic relations for modelling the hydraulic shear stress. A first formulation for the erosion law was defined in term of mass according to excessive shear stress.

Erosion law : $\dot{m} = k_{d,m} * (\tau - \tau_C)$ [1]

Équation An index is built with the coefficient pondering the excessive shear stress. This approach leads to neglect the shear stress threshold in the analysis.

$$I_{HET} = -\log(k_{d,m})$$ [2]

It is possible to change the variable mass by a variable length. It leads to a modification in the linear coefficient for the excess stress, refer equation 0.



dε : variation of position of the interface fluid/water ⇔ dV : removal of volume soil on a unit area ⇔ removal of solid mass (depends on the part of solid mass in a unit volume), dm = ρ_D * dV.

Figure 1: Illustration of the eroded length to the eroded mass.

$$\rho_D * \dot{\varepsilon} = \rho_D * k_d * (\tau - \tau_C)$$ [3]

The two tests give an idea of the "same erodibility characteristics" under different flow environments. The need of a comparison between the two tests exists for 2 reasons:

- to point out (or not) the correlation between the results of the two tests. The two apparatus quantifies erosion under two different flow environments but determine equivalent parameters.
- to show the inherent capacities of the two apparatus with the purpose in mind to determine if one test or both tests are required in testing materials for different flow environments.

The experiments took place at Denver (CO) from the 08/04/2007 to the 29/06/2007 in the USBR laboratory.

[1] The 2 measures for erodibility are considering the same kind of erosion laws. The difference is the treatment of the parameters for the erosion law.

2 The material tested at the USBR-Denver

Four materials were tested at the USBR Laboratory in Denver. According to a study conducted in 2004 (refer Wormer, 2004), the four soils cover a range of the HET erodibility index from3 to 4. The soils used in testing were taken from 4 sites and were stock piled in the USBR soil laboratory for 2 years prior to the series of tests conducted as reported in this report. The selection of soil is based on the assumption of a different erodibility regarding other analysis (Atterberg, project). In the USCS chart for fine soils, the soils have different position. This position is essentially defined by the Atterberg limits. The denomination for the different soils is defined in the table 1.

Letter	Kind of soil
G	Gravel
S	Sand
M	Silt
C	Clay
O	Organic
P	Poorly graded (Well sorted)
W	Well graded
H	High plasticity
L	Low plasticity

Table 1: USCS nomenclature.

The characteristics of the soil are registered in the table 2. They come from the report of Jeff Wormer (which is considered as a reference for the value of the soils), and are completed by the laboratory reports concerning the projects. Figure 2 is a display of the four soils in an air dried state prior to preparing for erosion testing.

The first soil tested was the soil used in the Teton Dam[1]. The soil is a CL-ML and based on the HET the index for erodibility is established as 2 to 3, indicating that it is quite erodible.

The second soil tested was the soil coming from the Many Farms site. The soil was tested for an embankment dam project for the Indian Affairs in 2003. The soil is classified as CL with an erodibility index of 3.

The third soil is coming from the Tracy Fish site. This soil was tested for a foundation and canal lining project. The soil is classified as CH with an erodibility index of 4.

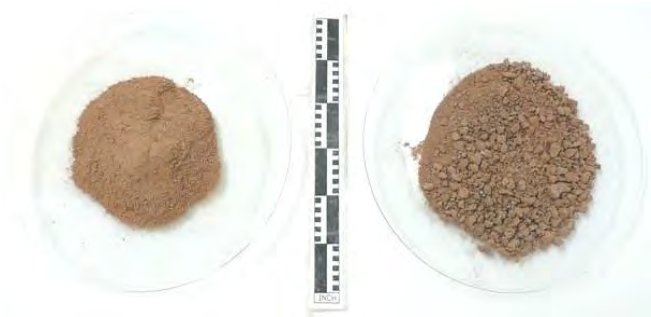
The last soil is from the Mountain Park site. This as a USBR project which includes a RCC dam and some dykes. The soil is classified as a CL-CH with an erodibility index of 4.

[1] Teton Dam failed on the 05/06/1976; 6 months after the dam was finished. The filling of the reservoir begin really on October 1975.

Soil name	Soil reference in the report and data	USCS[1]	Atterberg limits			Proctor state [25 blows]		Size curve distribution				
			Liquid limit [%]	Plastic limit [%]	Plasticity index [%]	Max dry density [kg/m^3]	W_{opt} [%]	0.05 mm % passing	d50 [mm]	d60 [mm]	d90 [mm]	Massic percentage < #40
Teton	TE	CL-ML	29	25	4	1694.75	17	15	0.03	0.04	0.08	97
Many farms	MF	CL	47	13	34	1742.809	17	40	0.01	0.02	0.18	95
Mountain park	MP	CH-CL	54	23	31	1681.938	20	86	0,0080	0,0154	0.07	97
Tracy Fish Facility	TF	CH	55	15	40	1685.142	18	55	0.035	0.01	0.05	98

Table 2 : Basic soil characteristics.

[1] Unified Soil Classification System, see the procedure USBR # 5000.



Tracy Fish

Many Farms

Teton

Mountain Park

(1) (2) (3)

Figure 2: Photos of the soil before compaction (1) blended, (2) "natural", (3) after drying.

3 The tests

3.1 Preparation of the samples

Test samples for this series were prepared at 1% less than the optimum water content. The position on the dry side was chosen to ensure that the same things were compared. Indeed, obtaining the proctor optimum density is very difficult. Each soil was relatively compacted on the same part of the proctor chart, and hopefully in the same relative state. The soil preparation consisted of preparing 2 samples, one for the HET, and one for the JET plus an additional mass for testing the water content (at least 10 %).

4 steps were required in the preparation of the soil samples.

1. A set amount of soil was mixed in the main tank. A sample was taken from this amount for determining the water content in a microwave (USBR #5315[2]).
2. Enough soil was taken from the main tank to prepare: 1 sample for the HET, 1 for the JET, and 2 smaller samples for water contents. The soil was mixed with additional water to obtain the targeted water content (optimum water content less 1 %).
3. Once mixing was completed the soil was preserved in a plastic bag. The plastic bag was set in the humidity room for a minimal time of 36 h (USBR procedure # 5500).

USCS[3]	Minimum storage [Hr]
GM, SM	3
ML,CL,OL,GC,SC	18
MH,CH,OH	36

Table 3 : Advised time to homogenize the moisture content in the soil.

4. Following step 3 the soil was compacted in a Proctor mold according to the USBR procedure #5500 and water content samples were taken at the beginning and at the end of compaction.

The compaction

The HET accommodates the proctor mold for testing. The mold consists of a steel cylinder:

- internal diameter of 10.13 cm (=3.99 inch);
- height of 11.7 cm (=4.59 inch).

All the characteristics of the mold are entered into an excel spreadsheet: weight, geometry, volume. The purpose is to determine the soil weight and volume in the mold.

The specimen is compacted in the mold using the following compaction effort: a standard hammer of 2.49 kg (=5.5 lbm) for a falling height of 30.48 cm (=12 inches – USBR

[2] Refer to the Earth Manual, USBR.

[3] Unified Soil Classification System, see the procedure USBR # 5000.

[5] It was observed that the erosion is also a function of the time variation of the hydraulic gradient.

procedures). The soil is placed in the mold in three equal layers and compacted with the 5.5 lbm hammer with 25 blows per layer. After compaction, the samples were weighted in the mold and stored in the humidity room for 12 hours before to be tested. The samples were preserved in a plastic bag. A part of the soil was taken prior to and following compaction to determine compaction water content using the USBR procedure #5300.

Collection of information concerning the samples

A sheet identifying the sample and its preparation information was filled out for each test. The mass of the intact mold sample was measured to define the density. The dry density was determined using the mass and the compaction water content as determined in step 4.

Following each test, the volume of the test sample was determined to quantify the erosion of the sample. For the HET, a basic measurement of the geometry was made including length and diameter.

The samples were dried and a mass measurement was made following each drying. For the HET, a plaster mold of the eroded sample was also made. All the geometry was described by surveying several diameter of the pipe (5) at different positions. A volume measurement by hydrostatic weighting was made. The plaster mold was essential for measuring and observing the erosion in the pipe.

For interpretation of the HET, the values required were the density; final diameter and sample flow length, which were measured from the plaster mold. Additional data was gathered in case re-interpretation was required, including masses and volumes.

3.2 The HET

In order to conduct the HET a preliminary test was conducted according to the USBR procedure which was started with a low head (50 mm). If no erosion occurred at this low head, the head difference was doubled each 15 min. No erosion was determined if the flow rate was not observed to increase versus time under a constant head setting. If no erosion was observed for head settings up to 800 mm then additional head setting were attained in step increases of 200 mm.

Once erosion was determined based on an observed increase in flow rate then the setting head was maintained for 45 min (USBR protocol[5]) or more.

Once the erosion threshold head was determined from the preliminary test, then this head was used as the target head for two additional longer tests. For these tests, I let the sample evolves as long as I could. The technical limit was the flow rate, roughly 20 l/min or the time (3-4 h test).

The main problem with this device & approach is that erosion is deduced. It is not measured directly but is inferred from the change in flow rate.

The different steps for the HET were:

1. Set up the apparatus to the appropriate head by using the blank test;
2. Prepare the sample by making a 6 mm diameter hole (or larger);
3. Set up the sample in the apparatus;

4. Fill by water the different pipe; opening of the air valve. Open slowly the downstream and upstream valve;
5. Open the valve for filling, and purging the air in the pressure transducers system. Close the downstream valve;
6. Fill above the weir, the downstream recipient, checking the scale for the flow rate evaluation (in case of the use of the scale);
7. Launch the software for the acquisition, wait for the first acquisition, and open the main valve.

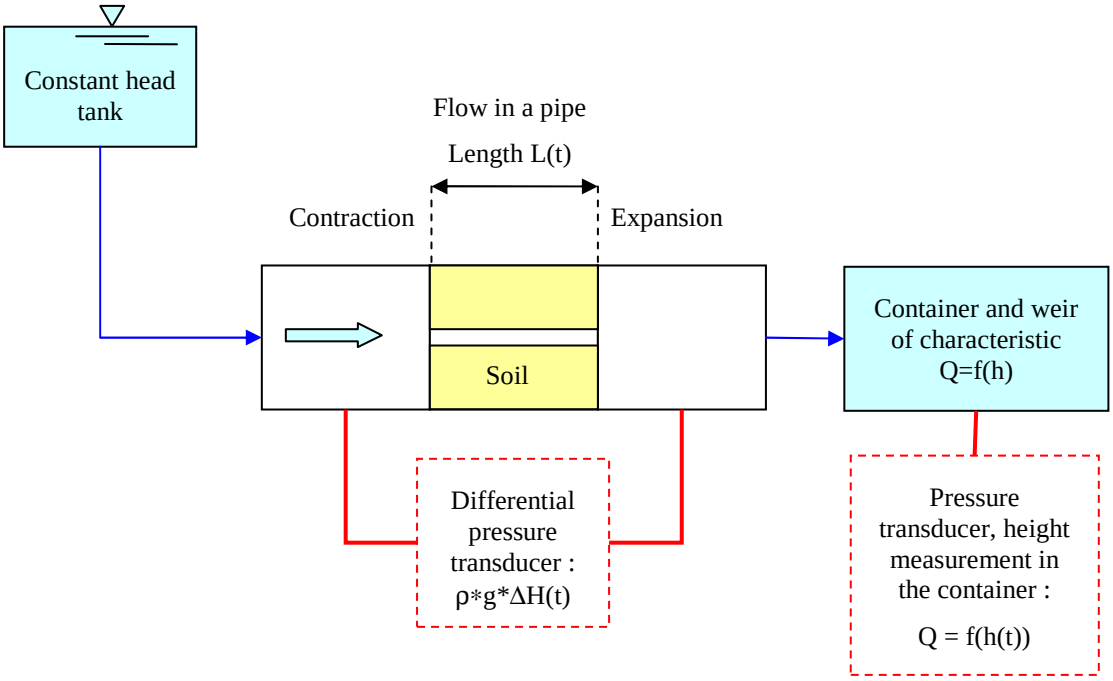


Figure 3 : Presentation of the HET and the acquisition chain for the HET.

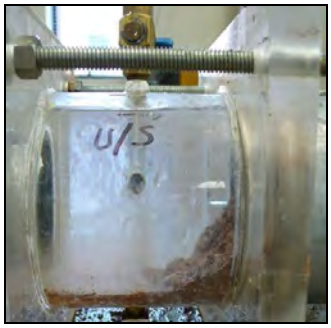


Figure 4 : Presence of crumbling on the upstream end, Tracy Fish soil.

Following many discussions and deliberations relative to boundary conditions at the upstream and downstream extent of the soil sample it was determined to conduct the tests without end plates. Initial tests were conducted with an end plate on the upstream end but it appeared that the presence of the plate interfered with the erosion and measurements of head loss. Therefore the plates were not used. If end plates are to be used they must be of a large enough diameter that they are larger than the final hole. The positive side to end plates is that they minimize crumbling, refer figure 4, but it must be determined if this out weighs the constraints they

impose on the erosion process. It was determined at this point of the testing that the end plates would not be used.

3.3 The JET

For the JET, the nozzle diameter, and head difference at the orifice were held constant during testing. The initial distance of the orifice from the soil surface was determined prior to initiating the testing sequence. The depth of scouring and head were measured at set times during the JET and timing of readings varied depending on rate of erosion.

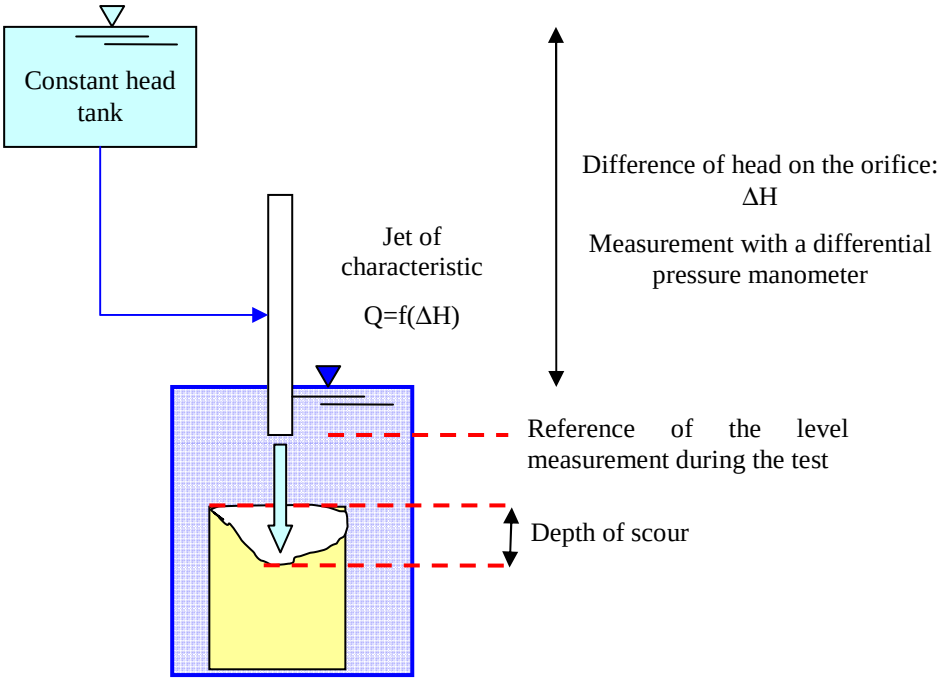


Figure 5 : Presentation of the jet and the acquired data.

The following steps were taken to conduct the JET (refer Hanson & Cook, ASTM D5852):

1. Fill of the sample and orifice submergence tank;
2. Place the sample under the jet with a plastic liner between the sample and the bottom of the container;
3. Take the following measurements using the JET point gage: nozzle and sample surface height. As a note: when the point gage is lowered it effectively obstructs the flow from the jet orifice, stopping erosion.
4. Open the upstream valve and set up the test head setting prior to initiating the erosion testing;
5. Raise the point gage above the orifice opening, allowing the jet to impinge on the soil sample surface and begin time measurement immediately;
6. At different times during testing, measure the amount of scour by lowering the point gage through the orifice opening, and also measure the head loss.

3.4 Data measurement and accuracy

The measurement on the sample

The accuracy of the different erosion measurements is partly a function of the amount of soil available for testing.

One of the concerns in measurement was determination of water content. It was very difficult to establish water content accurately and consistently. The exact water content in the actual soil sample was in question for 2 reasons. 1) The minimum time of waiting for drying in the oven was fixed to 24 hours. This may not have been a sufficient amount of time to completely dry the sample in the mold.2) Moreover, accuracy of water content is very sensitive to the amount of tested soil. The size of sample for determining the compaction water content in the tests conducted was limited by the size of the bag and the available soil.

Another measurement that was taken during this test series was the final wet mass. It was observed that the final wet mass was influenced by the amount of infiltration of water that may have occurred during testing. If little erosion occurred during testing, the mass may actually have increased during testing due to infiltration (essentially on Mountain Park soil).

Dry mass determination was essentially related to the time of drying (24-48 h) and the necessity for using the mold. A minimum time of 24 hours in the oven was established.

Concerning the hole geometry, it was very difficult to survey hole diameter in particular on the wet sample. The plaster print was easier but there were some concerns related shrinkage of the soil material during drying of the sample. The drying could affect the final measurements on the plaster print (+/- 1 mm).

The measurements during the experiments

During the HET, all the measurements were taken with a data logger. The chosen time step was 30 s, or 1 minute. It is recommended choosing 30 s to visualize clearly the kinetic of erosion and to be aware of any problems. The required measurements were:

- the outlet flow which is measured by weir Q(t);
- the head losses $\Delta H(t)$;
- time.

During the JET, measurements were taken manually. The required measurements were:

- the depth of scouring using the end of the nozzle as a reference;
- the head loss through the orifice;
- time.

Water quality was monitored during testing with an apparatus, Hydrolab DS5X, set up in the water tank. The parameters monitored were the temperature, the pH, the conductivity and the

dissolved oxygen. The parameters monitored were relatively constant during a test and during the entire period of testing.

Measurement	Accuracy	Unit	Comment
Initial water content	0,1	%	Depends heavily on the tested mass (if sufficient or not). Problems linked to this measurement are important.
Initial mass of sample	0,002	lbs	
Final mass of sample	0,01	lbs	Depends on the final soil consistency, loss when retiring the soil of the water.
Volume	0,005	l	Depends on the ability of the soil to go through the basket.
Dry mass after erosion	0,01	lbs	Depends on the time for drying of the sample and the losses during the mass measurement.
Final diameter	2	mm	Problem in determining the diameter.
Final length	2	mm	Problem in the protocol for doing it.
Diameter on plaster mold	0,5	mm	Problem for evaluating the correct position of the caliper.

Table 4 : Accuracy of the measurements for the sample.

Measurement	Average	Standard deviation	Maximum	Minimum	
pH	7,38	0,065	7,84	7,21	
Conductivity	178,39	21,71	256,6	152,3	mS/cm
Dissolved Oxygen	7,33	0,43	13,81	5,2	mg/L
Temperature	18,34	1,13	21,8	15,31	°C

Table 5 : Characterization of the water for the tests;

	Measurement	Accuracy	Unit	Comment
JET	*Time*	2	s	Depends a lot on the time of reaction of the operator.
	Head	+/- 0,25	inch	Depends on the water supply; there is some problems of variation of level in the head tank.
	Depth	0,001	ft	Some inaccuracies are due to the deepening of the point gauge in the soil.
HET	*Head*	1	mm	Fluctuation exists because of the turbulence.
	Time	0,02	s	Essentially based on the speed of the reading of the sensor and the writing in the text file
	Flow rate	+/- 3	%	The main unit is the l/min, but the accuracy for the flow rate is relative to a calibration curve.

Table 6 : Accuracy of the different measurements during the experimentations.

4 Data analysis: theory

4.1 The HET: the variation of flow rate versus time under a constant head for deducing an erosion law.

The main idea for analysis of the HET is to relate the variation of flow rate to the hole diameter. There are several assumptions related to this analysis. The description of the following part is based on the report made by J. Wormer (USBR), the software of B. Travers, and the report written by R. Fell.

The analysis consists in several assumptions concerning the experiment and the theory. It comes from the fluids mechanics/hydraulics in pipe. The shear stress is expressed according to a momentum analysis and also a friction factor model (Chezy). Then, the two expressions are equated for deducing a diameter.

Assumptions:

On the experiment:

1. the head remains constant versus the time;
2. the area of the hole is a disc of diameter ϕ;
3. the length of the sample is constant versus time;
4. homogeneous erosion on all the length of the pipe.

On a theoretical point of view:

1. all the flow is circulating through the pipe;
2. a constitutive law for the water is assumed;
3. homogeneous material of dry density ρ_D.

The constitutive law for the water: the expression of a shear stress.

The shear stress could be deduced from a "momentum analysis" on a piece of pipe of length L and the volume of water inside.

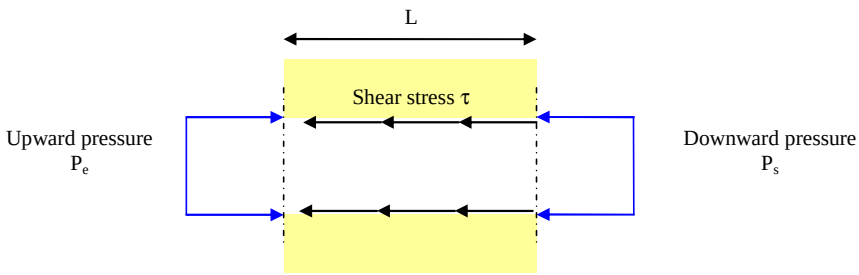


Figure 6 : Schema of the momentum analysis.

The following relation is established:

$$\frac{\Delta H * \rho * g}{L} * \frac{\phi}{4} = \tau \qquad [4]$$

ΔH : head loss through the pipe [m].

ρ : density of the water [kg/m^3] (=1000).

g: gravitational constant [m/s^(-2)] (= 9,81).

L: length of the sample [m].

It is also possible to build the constitutive law according to the fluid characteristics in the pipe as the speed. This constitutive law is based on classical expression used in fluid mechanics function of the Reynolds number (Re).

$$\mathrm{Re} = \frac{\rho * \overline{U} * \phi}{\mu} \qquad [5]$$

It exists two flow regimes[1]:

$$\begin{aligned} &\mathrm{Re} > 5000, \tau = f_T * \overline{U}^2 \\ &\mathrm{Re} \leq 5000, \tau = f_L * \overline{U} \end{aligned} \qquad [6]$$

, refer Fell, 2002, p. 3-15.

$\overline{U} = \frac{4 * Q_{pipe}}{\pi * \phi^2}$: mean velocity [m/s] of the flow in the pipe.

μ : dynamic viscosity [kg/(m.s) or Pa.s] (=1e-6).

f: friction coefficient. Units : [$kg.m^{-2}.s^{-1}$] for laminar and [$kg.m^{-3}$] for turbulent.

A parameter is lacking for deducing a shear stress (so a diameter) with time, a law is built for the evolution of the friction coefficient. It assumes a linear variation of the friction coefficient f between the beginning and the end of the test. The initial and final friction coefficients are deduced from the initial and final hydraulic conditions.

$$f = \frac{f(t_f) - f(t_0)}{t_f - t_0} * (t - t_0) + f(t_0) \qquad [7]$$

Two friction coefficient laws are computed one for f_L (laminar coefficient), one for f_T (turbulent coefficient). The following equations are used for computing the initial and final value.

$$f_L = \frac{\phi^3 * \pi * \rho * g * \Delta H}{16 * Q * L} \text{ for the laminar case} \qquad [8]$$

$$f_T = \frac{\phi^5 * \pi * \rho * g * \Delta H}{16 * Q * L} \text{ for the turbulent case} \qquad [9]$$

[1] The value for a Reynolds number of 5000 is high in regard of the literature. A value of 3000-4000 seems more reasonable.

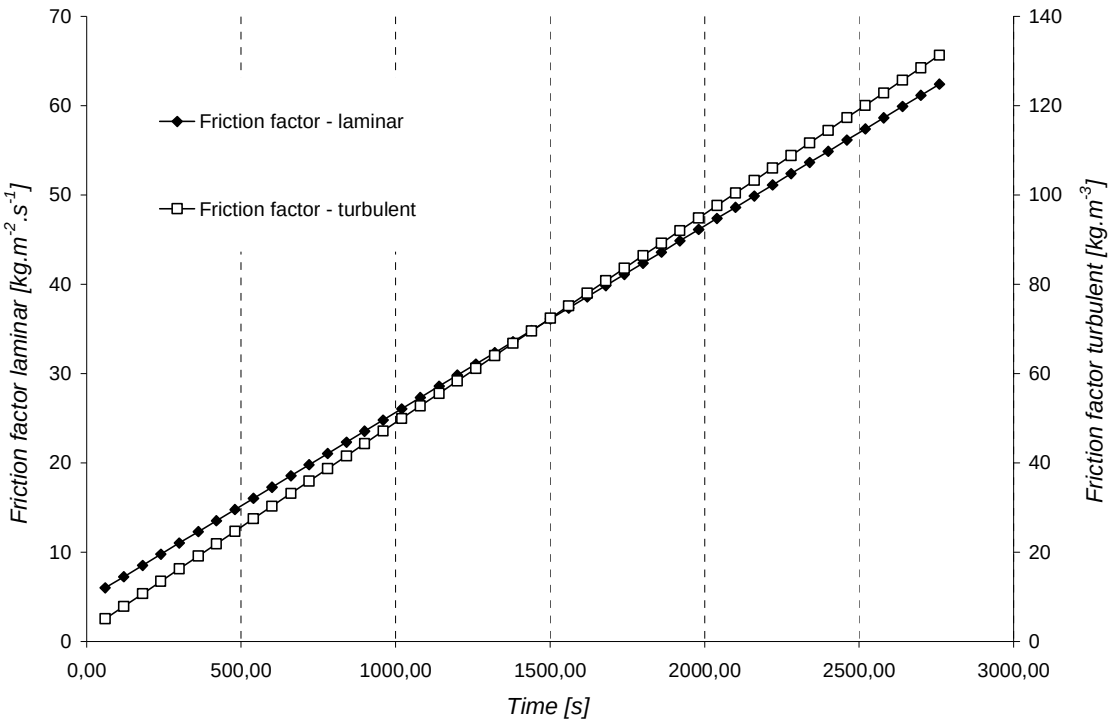


Figure 7 : Evolution of the friction coefficient for the laminar and turbulent case.

The steps in analysis:

By equating relationships in equations 4 & 6 at a given time, it is possible to deduce ϕ according to the hydraulic conditions.

1. A mean length ($\bar{l}$) and gradient[1] are evaluated for the tests;

   $\bar{l} = \frac{l_{initial} + l_{final}}{2}$, and the hydraulic gradient is computed by averaging the head losses with time & considering the mean length.

2. The initial and final friction factors are deduced from the hydraulic data. The used data are $\phi(t_0)$, $\phi(t_f)$, $Q_{pipe}(t_0)$, $Q_{pipe}(t_f)$; an evaluation is made for the laminar case and the turbulent case;

3. The friction law is constructed according to time by using the equations 7, 8 & 9; at the end, two friction laws versus time are available: turbulent & laminar. The friction laws are plotted on the figure 7.

4. A diameter $\phi(t)$ is deduced.

   - Evaluation of the diameter in turbulent and in laminar case by using the deduced friction coefficient with the equation 7, and the equation 10 and 11, for the diameter. If the two computations give different Reynolds regime (Laminar and Turbulent), an arithmetical average value is computed.

[1] It may be possible to use the gradient measured at the time t computed with an average length. But, our test is meaning to be at constant head, so I made an average according to time.

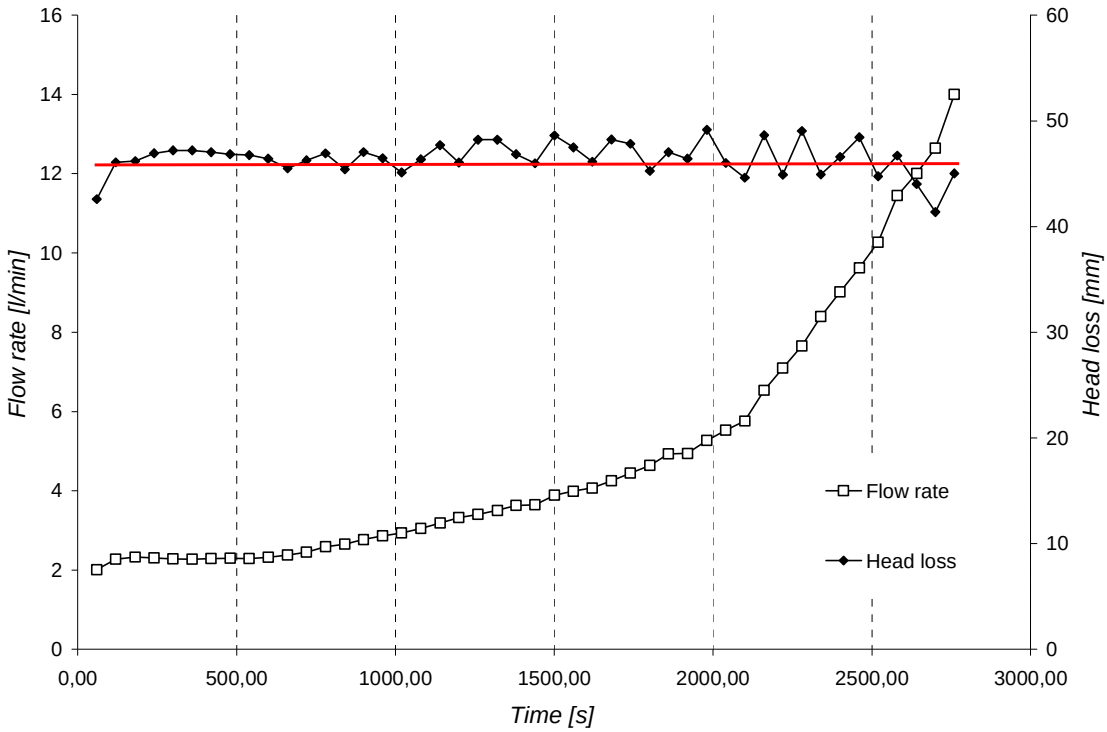


Figure 8 : The analyzed data for the soils MF-7.

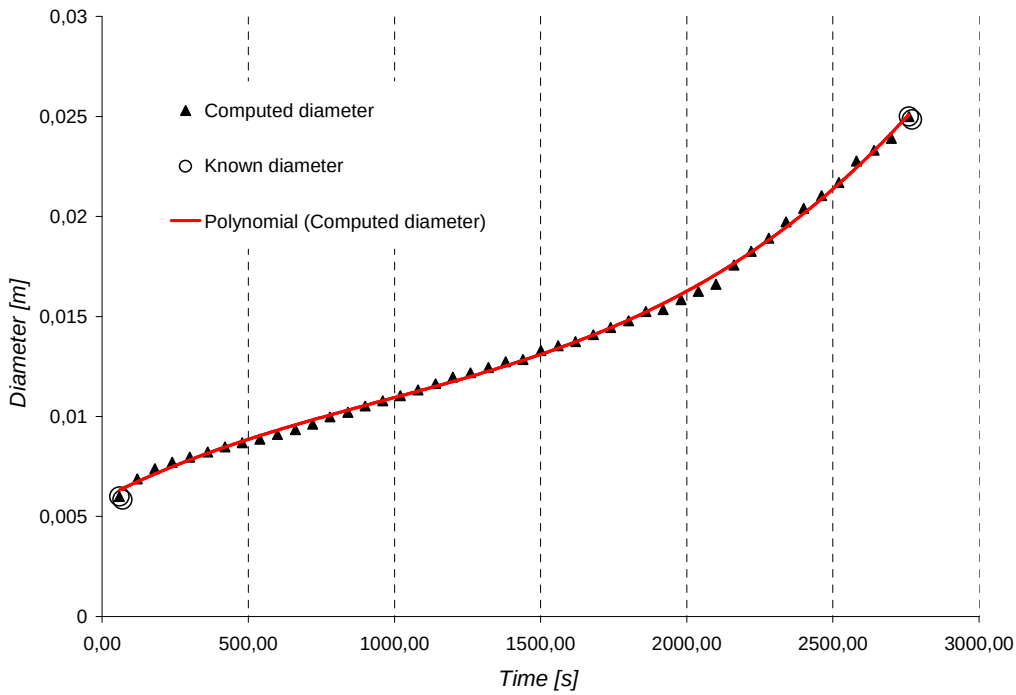


Figure 9 : The deduced diameter from the mean gradient, the flow rate and the initial & final geometry.

Laminar regime: the two Reynolds numbers are less than or equal to 5000:

$$\phi = \left(\frac{16 * Q * f_L * L}{\pi * \rho * g * \Delta H} \right)^{1/3} \qquad [10]$$

Turbulent regime: the two computed Reynolds numbers are greater than 5000:

$$\phi = \left(\frac{64 * Q^2 * f_T * L}{\pi^2 * \rho * g * \Delta H} \right)^{1/5} \qquad [11]$$

- Evaluation of the Reynolds number according to the computed diameter for the 2 regimes;
- Evaluation of a diameter for the time t.

5. A 3rd order polynomial function is interpolated from the ϕ(t) function. This function is differentiated according to time in order to obtain a rate of evolution for the hole. (refer Wormer, 2004). It is possible to build a numerical differentiation according to the computed values. The use of a correlation ensures the increase in diameter with time.

$$\phi(t) = A * t\text{^}3 + B * t\text{^}2 + C * t + D \qquad [12]$$

$$\frac{d\phi}{dt} = 3 * A * t\text{^}2 + 2 * B * t + C \Rightarrow \dot{m} = \rho_D * \frac{d\phi}{dt} * \frac{1}{2} \qquad [13]$$

6. The shear stress is deduced by using equation 4, the computed diameter and the average head. The equation 13 allows the determination of a mass rate by unit of area by using the diameter variation.

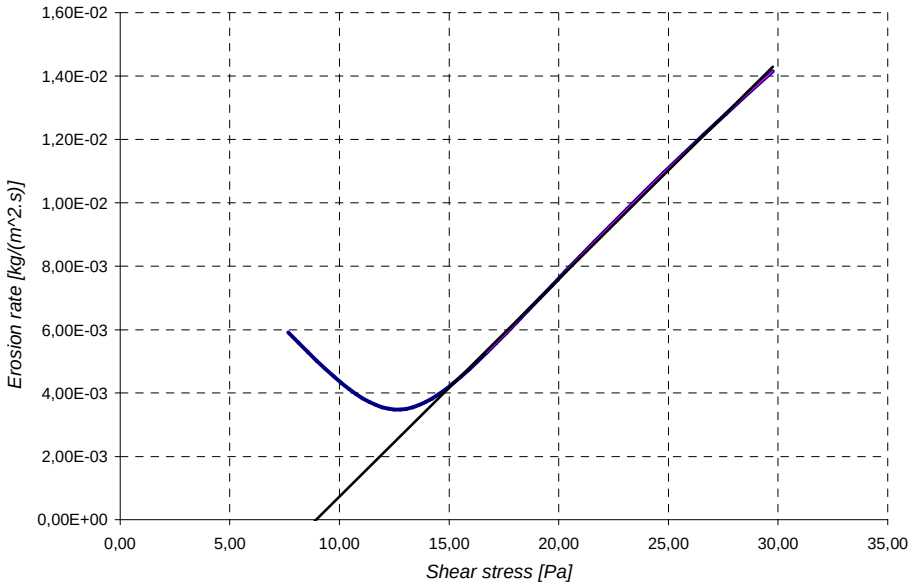


Figure 10 : The erosion law deduced from the analysis.

The result is plotted as the erosion law in terms of soil mass per second (refer figure 10). The tangent (or the linear interpolation) on the left side of the minimum is defined. Its slope corresponds to the $k_{d,m}$ coefficient. By taking the opposite decimal logarithm, it is obtained an erosion index.

$$I_{HET} = -\log(k_{d,m}) \qquad [14]$$

4.2 The JET: the depth of scouring versus the time for deducing an erosion law.

Studies made on scour, Albertson & al., 1950, and observations lead to the conclusion that an equilibrium depth exists. This equilibrium depth corresponds to the point where erosion does not exist any more (or equilibrium between deposition and pulling out of soil are balanced).

A first assumption of the JET is on the erosion behavior (the evolution of the depth with time) of the soil. It is governed by the linear erosion law described in equation 3. This assumption leads to a summary of the erodibility in the coefficients k_d & τ_c. Therefore a key assumption of the JET is that the shear stress at the soil boundary when the equilibrium depth is reached is equivalent to the critical shear stress.

With these assumptions, a set of equations are written to describe the erosion phenomena and deduce the erosion law for the JET. A detailed description of the development of these equations for circular jets refers to Hanson & al., 2002.

Assumptions and conditions:

On the experiment:

1. the variation of the interface position under the center of the jet is accounting for the erosion of the soil;
2. the jet is submerged.

On a theoretical point of view:

1. a constitutive law for the water is assumed[1] in term of kinetic energy diffusion and in the development of shear stress under a jet;
2. the existence of a equilibrium depth where the hydraulic shear stress is equating the shear threshold for the erosion;
3. homogeneous material of dry density ρ_D.

Presentation of the geometry:

The jet nozzle exit is the reference point for all scour measurements of the JET. The initial configuration is important because it leads to the evaluation of the erosion with time.

[1] These laws are coming from experiments, and are described in the article Hanson & al., 1990.

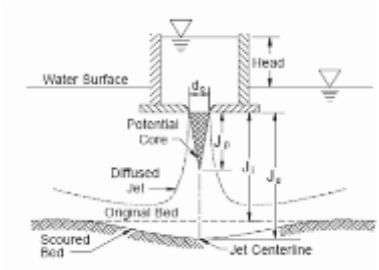


Figure 11 : Geometry description of jet for the analysis.

J: distance of the soil from jet orifice [m], $J_0 = J(t=0)$

J_e: distance of equilibrium for the test [m];

d_0: orifice diameter [m]

The constitutive law for the water:

As the jet of water leaves the orifice, and enters the water reservoir, the first behavior for the water is the transfer and absorption of kinetics energy as the jet travels through the water. The original velocity of the jet is maintained at the center of the jet for a distance J_p.

$$J_p = 6{,}2 * d_0 \qquad [15]$$

J_P: distance from the orifice where the speed of water is constant at the center of the jet [m].

Beyond J_p, the kinetics energy is diffused through the entire jet diameter and relationship for this diffusion is defined as [Albertson & al., 1950], on the centerline of the jet.

$$J \le J_P, U = U_0 \qquad [16]$$

$$J > J_P, \frac{U}{U_0} = \frac{J_p}{J}$$

In order to evaluate erodibility based on equation 3 a shear stress model is necessary for the interface soil/water. This modeling is based on the classic expression for shear stress in fluid mechanics (cf. equation 6 in the turbulent case). For the value of the coefficient, it is possible to refer Hanson & al., 1990.

$$\tau = C_f * \rho * U^2 \qquad [17]$$

$$C_f = 0{,}00416$$

C_f: Chezy coefficient for the soil/water complex.

Re_0: Reynolds number at the orifice according to the diameter of the orifice.

The velocity of water at the nozzle outlet is based on the head – discharge relation:

$$U_0 = \sqrt{2 * g * \Delta H} \qquad [18]$$

ΔH€: water head difference on the nozzle [m].

The analysis:

The first step of analysis is to determine the equilibrium depth for the scour which is deduced by using the time scour relationship developed by Blaisdell, 1981. The analysis consists of a correlation with water velocity, time, and scour depth using a hyperbolic logarithmic function.

The critical shear stress is deduced from the determination of the equilibrium depth based on equations 17 & 16.

$$\tau = C_f * \rho * \left(\frac{J_p}{J} * U_0 \right)^2 \text{ and } \tau_C = \left(\frac{J_p}{J_e} \right)^2 * \tau_0 \qquad [19]$$

τ_0 €: potential shear stress at the exit of the nozzle [Pa] computed by using the equation 18 and 17.

The second step in the analysis consists in a correlation of the data couple (depth, time) with an integration of the erosion law. An a-dimensional equation for erosion is written.

$$\frac{dJ}{dt} = k_d * \left(C_f * \rho * U^2 - \tau_C \right) \qquad [20]$$

$$\frac{dJ}{dt} = k_d * \left(C_f * \rho * \left(\frac{J_P}{J} * U_0 \right)^2 - C_f * \rho * \left(\frac{J_P}{J_e} * U_0 \right)^2 \right) \qquad [21]$$

$$\frac{dJ}{dt} = k_d * \tau_C * \left(\left(\frac{J_e}{J} \right)^2 - 1 \right) \qquad [22]$$

By expressing the depth with the equilibrium depth and an a-dimensional depth, the following equation is obtained:

$$\frac{dJ^*}{dt} * J_e = k_d * \tau_C * \left(\left(\frac{J_e}{J} \right)^2 - 1 \right) \qquad [23]$$

The integration of the equation 23 leads to a logarithmic function for solution, and the expression of some characteristic value for the problem, refer 24.

$$T_R = \frac{k_d * \tau_C}{J_e} \quad J^* = \frac{J}{J_e} \qquad [24]$$

The data couple (depth, time) are correlated using the equation 25 for deducing a k_d.

$$t = T_R * \left(-J^* \Big|_{J_i^*}^{J^*} + \frac{1}{2} Ln \left(\frac{1 + J^*}{1 - J^*} \right) \Bigg|_{J_i^*}^{J^*} \right) \qquad [25]$$

Equation 25 is valid for the condition $J > J_P$. For the condition $J < J_p$ another equation could be built. For most the experiments, this condition is checked. If it is not checked, some data are deleted to reach the condition and a change in the time reference is made.

The analysis is made in 2 times by using the same data; one for deducing the critical shear stress, and the other for deducing the k_d coefficient. An improvement could be the use of 1 correlation on the data set for deducing the 2 parameters.

5 Analysis

5.1 Comments about soil preparation

The first point on the preparation is a general overcompaction in comparison of the available data. This fact seems to be emphasized by the chart representing the compaction ratio in dry and wet density (refer figure 13). The percentage is defined as the ratio of the experimental density on the reference density (given in the report by Wormer). Our set of experimental points is describing by a straight line on the right position of identity. May be, there is a problem of compaction. The variation observed could be explained by a higher compaction rate because of the use of a different rammer than during the previous studies. It may be also caused by a long drying time for the soil.

MF	Moisture content [%]	Dry density [kg/m^3]	Wet density [kg/m^3]
Average value	14,9	1777,7	2037,1
Standard deviation	0,6	12,5	12,0
Minimum value	13,7	1752,1	2004,9
Maximum value	17,4	1815,9	2076,2

TE	Moisture content [%]	Dry density [kg/m^3]	Wet density [kg/m^3]
Average value	16,0	1697,7	1970,0
Standard deviation	0,4	3,7	6,1
Minimum value	15,2	1690,1	1954,3
Maximum value	16,6	1703,6	1982,8

TF	Moisture content [%]	Dry density [kg/m^3]	Wet density [kg/m^3]
Average value	17,4	1625,7	1908,1
Standard deviation	0,6	47,5	53,6
Minimum value	16,3	1498,4	1774,2
Maximum value	18,5	1707,9	1992,5

MP	Moisture content [%]	Dry density [kg/m^3]	Wet density [kg/m^3]
Average value	17,8	1662,0	1940,5
Standard deviation	0,6	6,3	25,9
Minimum value	16,6	1653,3	1887,1
Maximum value	19,2	1679,1	1975,7

Table 7 : Moisture content and dry density for the soils.

The water content determination which influences the determination of the dry density could partly explain the variation by underestimating the water content. The amount of soils used for water content (100 g) was not adequate to an accurate determination.

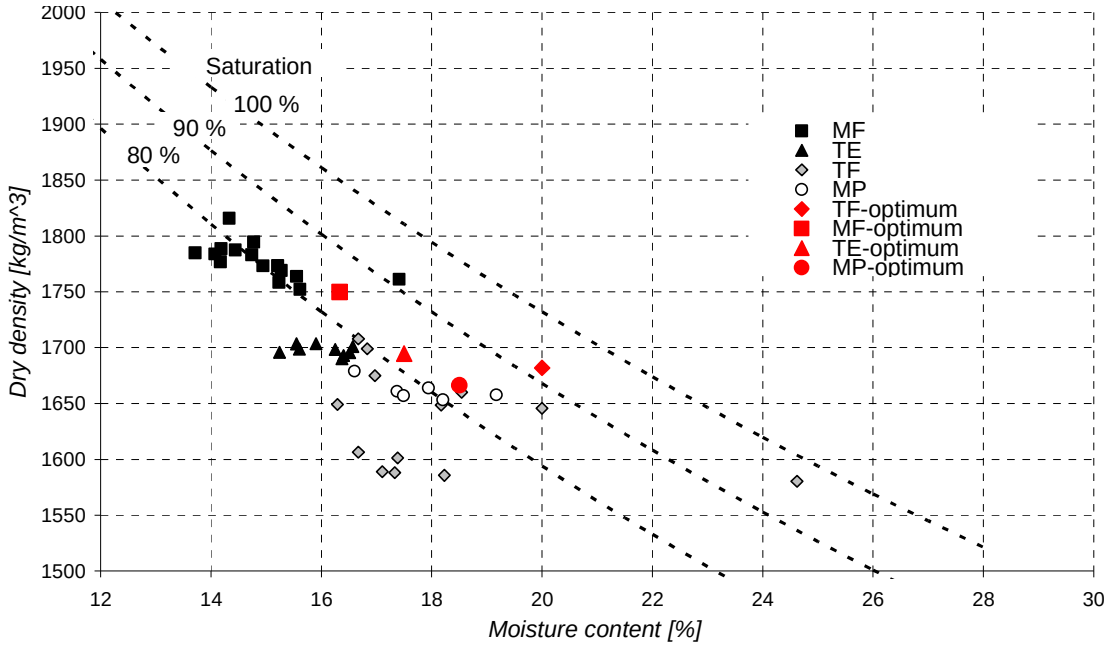


Figure 12: Dry density versus moisture content.

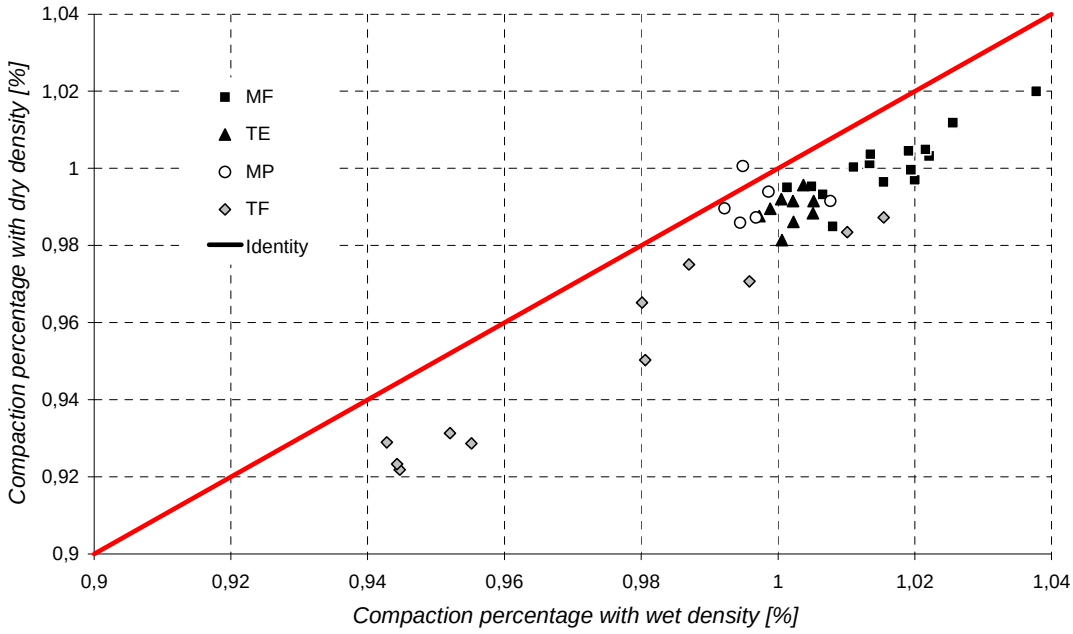


Figure 13: Compaction percentage for the dry density and the wet density.

The soil preparation seems correct when the characteristics are compared but some soils are presenting more discrepancies than others. Large variations are observed in the preparation of the Tracy Fish soil. The point on the left of the chart “dry density versus water content” is

explained by the fact that no water content was determined prior the fabrication of the soil. But, for the variation observed on the other points, I think it is due to compaction problems and the proper behavior of the soil.

Analysis was based on all the tests available with the exception of the first tests for Many Farms and Tracy Fish which were not included. They were made to define the protocol. At least, for each soil, 3 HET and 3 JET were considered for the analysis.

5.2 HET analysis

This section presents HET results for one test per soil to indicate and discuss typical results as well as the observed erosion behavior. The tests chosen for presentation of the HET test are based on constant head and enough time of erosion to describe observations and discuss results. The tests are the following:

- Tracy Fish : DEN-TF-HET-05-06-2007 – TF-5
- Many Farms : DEN-MF-HET-30-05-2007 – MF-7
- Teton : DEN-TE-HET-13-06-2007 – TE-3
- Mountain Park : DEN-MP-HET-25-06-2007 – MP-4

The two curves on the following pages present the flow rate and head versus time, which indirectly display the behavior of the soil. The increase of the flow rate represents the rate of erosion by indirectly indicating an increase in the hole diameter (for a trial at constant head). It is possible to see from these plots that the Teton soil erodes faster than the Many Farms soil. Observation of the Tracy Fish soil data indicates some discontinuities in the flow rate. These discontinuities are due to a clogging of the pipe as chunks are dislodged during erosion. This phenomenon was only observed for this soil.

Concerning the head necessary for erosion, it was 50 mm for Many Farms and Teton soils, 1000 mm – 1200 mm for Tracy Fish to 1600 mm for Mountain Park. This by itself gives some indication of the difference in erosion resistance of the four soils.

The initial shear stress equivalent to this head could be evaluated with the equation 6 using a diameter of 6 mm and the initial length of 115 mm.

Many Farms 10 Pa

Teton: 10 Pa

Tracy Fish: 130 Pa

Mountain Park: 200 Pa

So as a relative conclusion from the figure 15 and the previous critical shear stress, it is possible to establish a scale for erodibility of the four soils from more erodible to the less erodible : Teton – Many Farms – Tracy Fish – Mountain Park. This conclusion is based on the critical shear stress. In order to make a complete determination of order of erodibility requires an evaluation of the k_d, That is the objective of the following analysis.

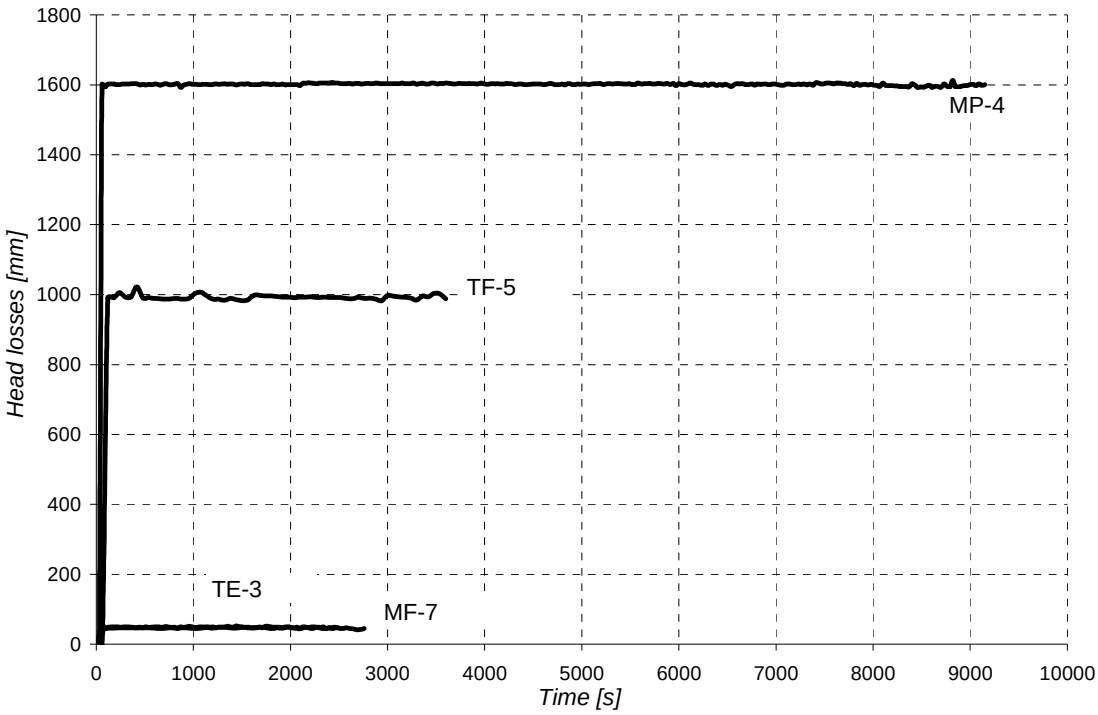


Figure 14 : Head loss versus time for different soils.

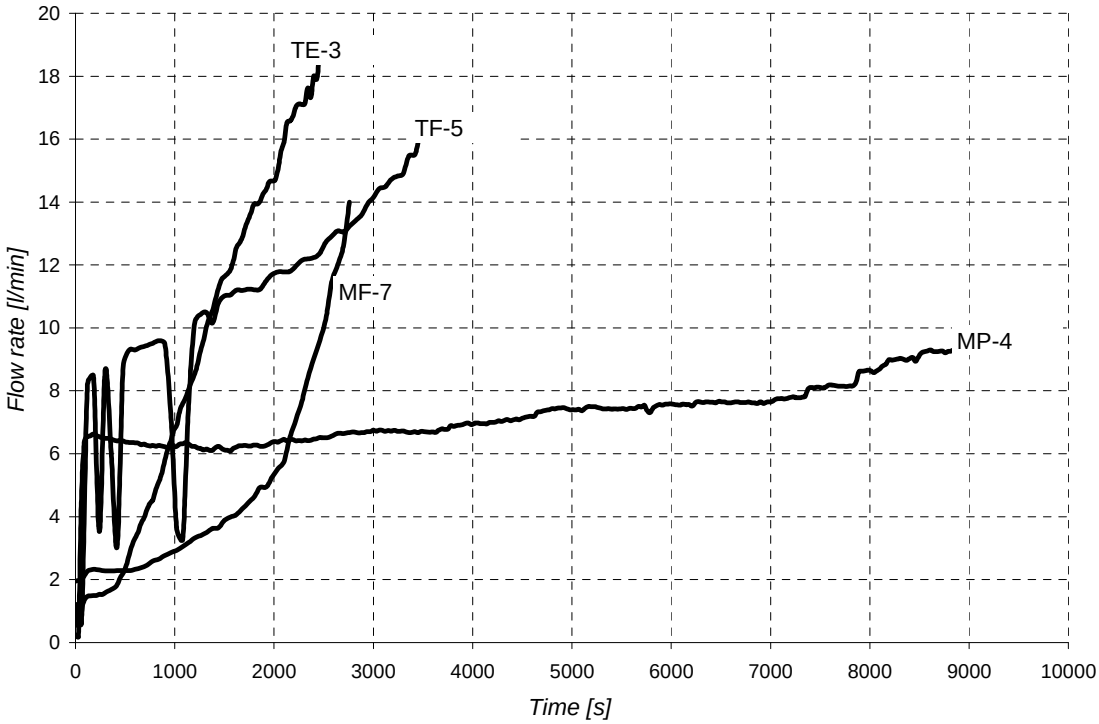


Figure 15 : Flow rate versus time for different soils.

The behavior of Tracy Fish could be observed on figure 16. Between 1000 s and 2000 s, the head loss is increasing associated with a decrease in the flow rate. The reason for the large changes in flow rate is due to “chunks” clogging the pipe. The fluid is eroding “chunks” of the soil in a dis-continuous way. Based on visual observations, the size of the eroded

“chunks” clogging the hole are larger than the size of the air dried material particles used for compaction.

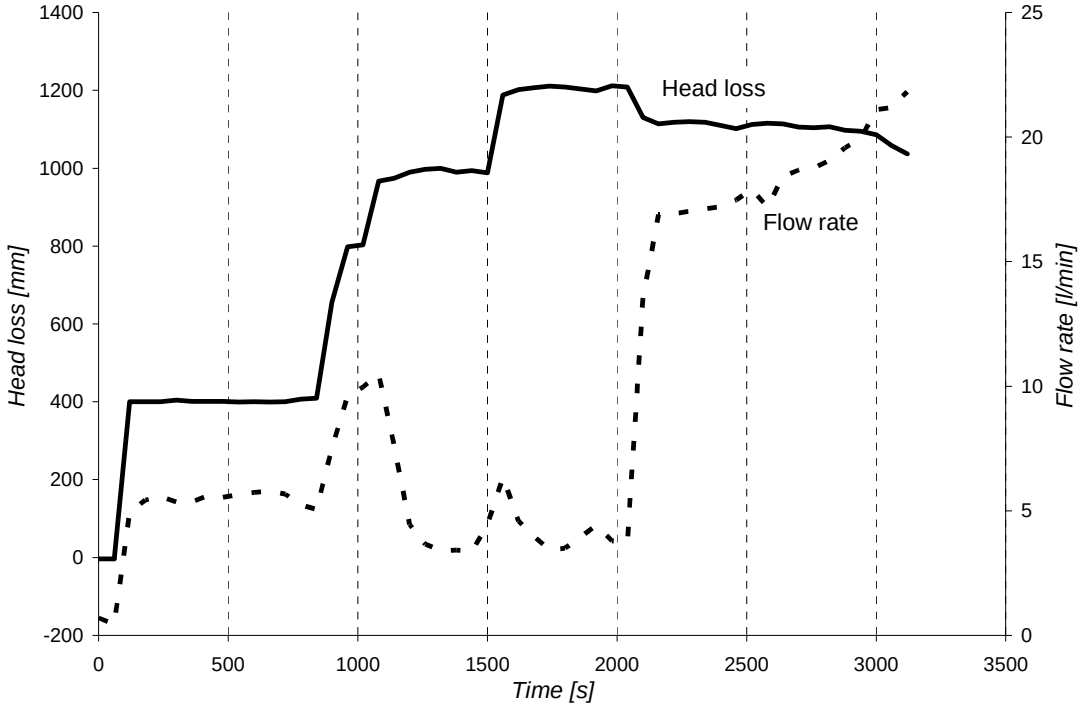
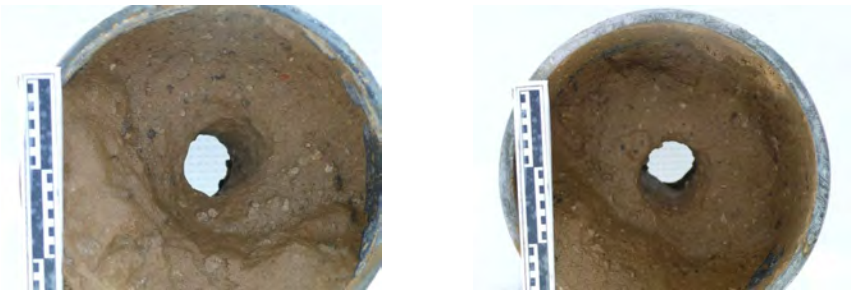


Figure 16: Behaviour of TF soil - trial on sample TF-4.

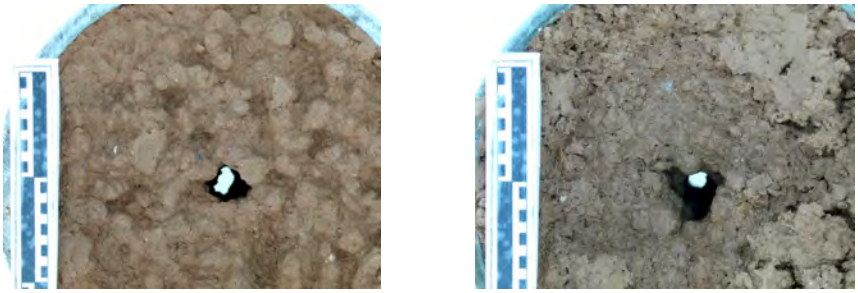
The shape of erosion:

In addition to the internal erosion of the pipe, erosion was observed to take place at the extremities. The erosion at the extremities is more remarkable at the downstream end of the sample than at upstream end. This is due to the energy losses at the expansion which are more important than in the contraction. On the pictures, it is also possible to see the texture of the soil. It goes from affine soil texture MF & TE to a coarse and irregular texture TF.

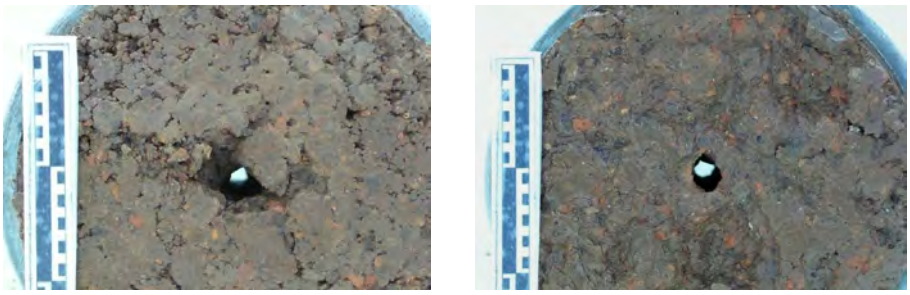
Many Farms soil – U/S D/S.



Teton soil – U/S D/S.

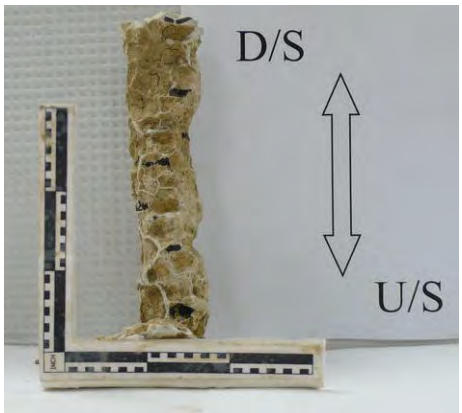


Tracy Fish soil – U/S D/S.

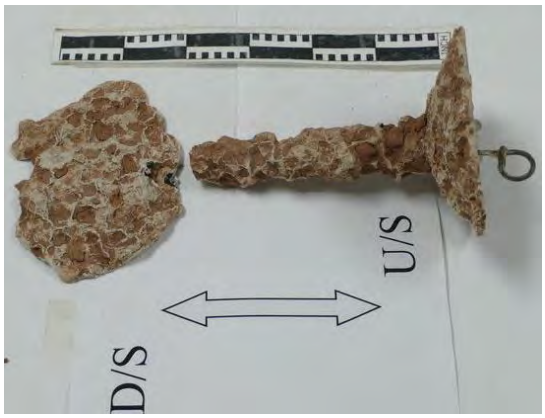


Mountain park soil – U/S D/S.

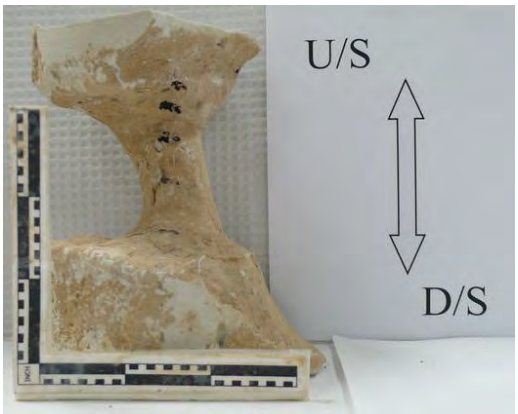
Figure 17 : Erosion of the soil - view of the extremities.



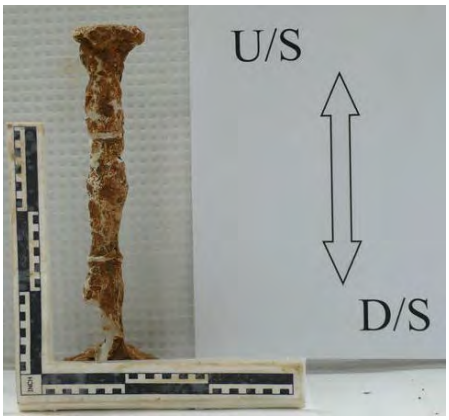
Many Farms soil



Tracy Fish soil



Teton soil



Mountain Park soil

Figure 18 : Photography of the plaster mold for the HET.

It is possible to observe the variation in length of the internal path of flow by evaluating the photographs taken during testing. This length variation leads to a hydraulic gradient variation. In order to minimize the impact of length variation on the computations, an average length is used. This leads to a computation of the shear stress on a 1-D geometry where only the diameters varies with time.

As it is possible to see on the plaster mold, the final diameter could be averaged only on a small length (4 cm for Teton soil). But, according to the experiments, these length variations are mainly explained by the erodibility of the soils.

The effects of erosion are:

- increase of the diameter;
- reduction of the length.

Some difficulties appear for the interpretation of the data. The variation of flow rate is not only related to the variation of the diameter.

Fell analysis for the HET tests

Conducting the test with a constant head improves test conditions and analysis because it eliminates the complexity that varying head would add to the analysis. A small time variation on the head difference is observed. This variation is not directly linked to the erosion, so it is used a time average head difference. The use of time averaged head impacts the computation of the diameter and the shear stress (equation 10, 11), but it filters the variations due to the experimental device.

A first step in analysis of the four soils is observing the data from all the available experiments. A summary of the HET analysis is given in the table 8.

	Erosion index	$k_{d,m}$ [m^3/(N.s)]	Critical shear stress [Pa]	Comments
MF-3 (2)	4,30	$2,81^{E-08}$	-200,79	Short trial - not a lot of points / Important head not included in the analysis.
MF-5	3,14	$4,05^{E-07}$	12,02	
MF-6	3,20	$3,55^{E-07}$	9,40	
MF-7	3,16	$3,85^{E-07}$	8,94	
TE-1	Impossible to deal with the analysis / Erosion too fast			
TE-2	3,11	$4,56^{E-07}$	10,08	
TE-3	3,41	$2,28^{E-07}$	-28,84	
TE-4	Impossible to deal with the analysis			
TE-5	Impossible to deal with the analysis			
TF-3	4,13	$4,53^{E-08}$	253,40	Clogging of the pipe / Included in the analysis by using the time when the applied head is maximum
TF-4	4,70	$1,24^{E-08}$	0,01	Clogging of the pipe
TF-5	4,96	$6,57^{E-09}$	186,42	No clogging
TF-6	Impossible to deal with the analysis			Clogging at 8 min - under a head of 1000 mm
TF-7	4,79	$1,03^{E-08}$	670,12	No clogging
MP-1	No interpretation because of USBR protocol & few erosion			
MP-2	5,40	$2,19^{E-09}$	248,62	
MP-3	5,80	$9,54^{E-10}$	84,09	
MP-4	5,33	$2,79^{E-09}$	343,80	

Table 8: Results for the analysis with the HET.

	kd [m^3/(N.s)]	% of variation
MF	$3,82^{E-07}$	35%
TE	$3,42^{E-07}$	33%
TF	$1,86^{E-08}$	71%
MP	$1,98^{E-10}$	35%

	Critical stress [Pa]	% of variation
MF	10,12	12,52%
TE	-9,38	-207,50%
TF	277,49	70,75%
MP	225,50	41,81%

Table 9 : Average value and observed deviation in percentage of the mean for the HET results.

First, in this table, it can be observed that it is difficult to conduct analysis for the HET on a significant number of tests, up to (30 %) in this set of tests. Analysis was considered

impossible if the computations results in erroneous erosion law[1], or if the speed of erosion is too fast and few points are available for the linear correlation on the erosion law.

Based on the computed erosion index results, it is possible to classify the soils. The most erodible soil of the four evaluated would be Many Farms with an erodibility index of 3,18, followed by Teton with an erodibility index of 3,24, Tracy Fish with an index of 4,52 and Mountain Park with an index of 5,47. This classification is strengthened by the crude classification made with a quick analysis of the flow curve of the HET. Between Many Farms and Teton, some doubt exists as to which material is more erodible. The erosion rate versus time seems to be greater for Teton versus Many Farms according to figure 15. This may be explained by the fact that Teton has a lower threshold and a lower k_d than Many Farms.

Concerning the value for the critical shear stress, more discrepancies are observed for the critical shear than for the k_d and some computed values are negative which is not mechanically possible. The Teton soil was observed to erode rapidly so it was normally possible to interpret the data but in some cases the rate of erosion was such that it led to negative values interpreted for critical shear stress. It is surprising. The interpretation of negative critical shear stress values may be explained by the fact that the analysis is not complete.

Comments on the Fell analysis

The analysis of the HET is heavily dependent on the geometry of the initial and final state of the hole. The analysis uses the constitutive law considering only the final and initial flow rate. Moreover, the computed friction coefficients used in the constitutive law analysis are simply not realistic. The values are too high for the final time with a relative roughness (median diameter of particles on the diameter of hole) of 0,02 and less (refer Nikuradse).

is a plot of the friction coefficient versus Reynolds number for each soil. It can be observed from this plot that friction coefficient ranges in value from 0,005 to 0,25 for a Reynolds number variation of 5000 to 20000. According to the Nikuradse's curve (figure 19), this variation should go from 0,02 to 0,1 for a Reynolds numbers up to 80000 and a constant relative roughness. Consequently, the value at the beginning of the tests seems to correspond with a realistic friction factor but at the end of the test, this value seems simply too high.

	Initial relative roughness	Maximal value for f	Initial value found for f [no unit]	Final value found for f [no unit]
MF-7	0,0017	0,02-0,025	0,03	0,13
TE-3	0,0050	0,032	No value / laminar model	0,23
TF-5	0,0006	<0,02	0,006	0,27
MP-4	0,0017	0,02-0,025	0,03	0,48

Table 10 : Value for the friction coefficient found with the Fell analysis.

As an additional observation, the friction factor increases with the Reynolds number for some soils which are quite surprising in the case of decreasing roughness[2]. An evolution law for the

[1] Erroneous law : the parabol is admitting a maximum.

[2] The dimension of the roughness is equal but there is an increase in diameter.

friction factors does not seem to be a valid approach for an analysis of the HET. Mechanically the variation of this one with time is not explainable. The variation is related to the variation of the relative roughness by an increase of the diameter and to the variation of the Reynolds.

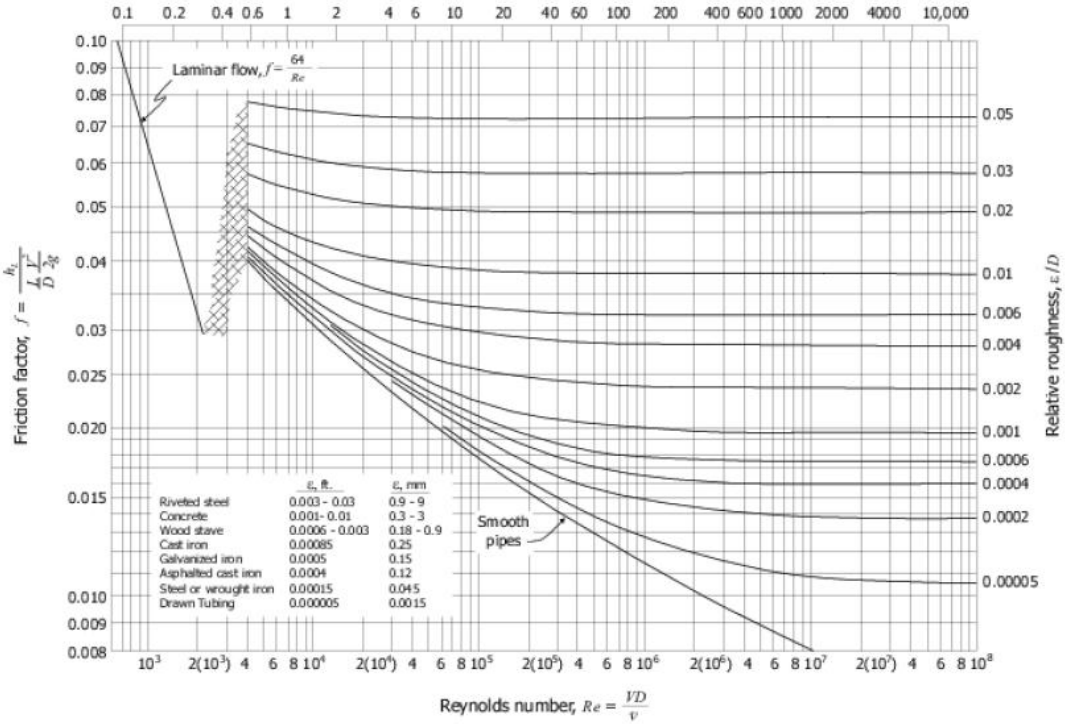


Figure 19 : Moody chart - Friction factor versus relative roughness and Reynolds.

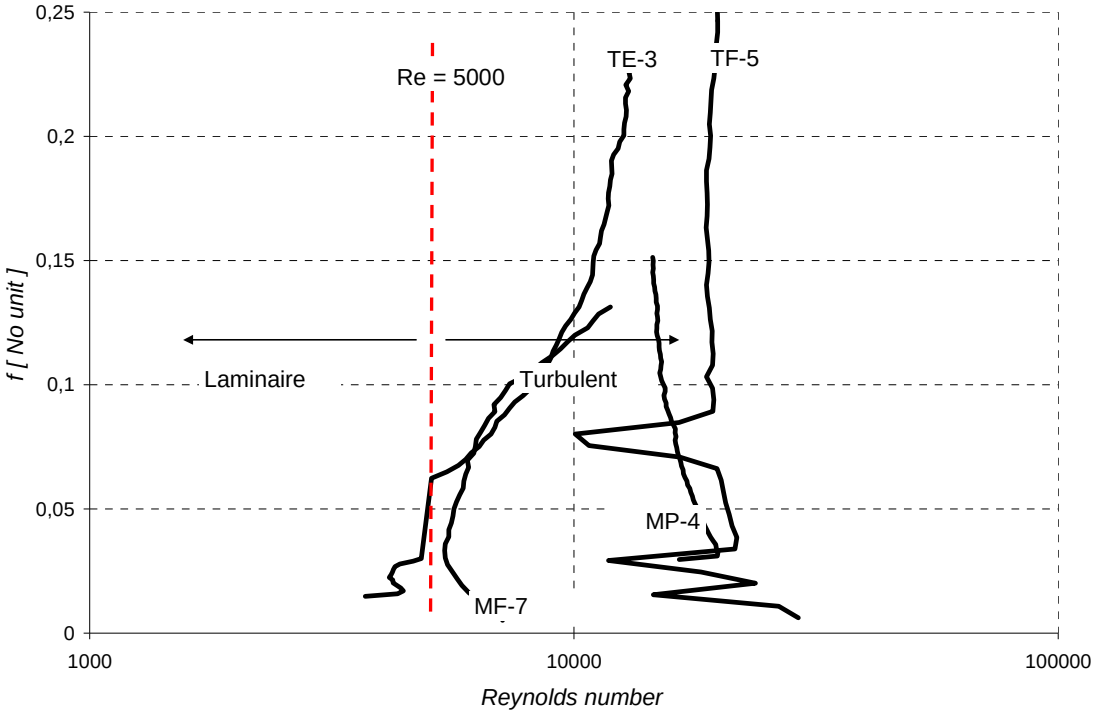


Figure 20: Friction coefficient versus Reynolds for the different soils.

At last, the transition between laminar and turbulent is proposed as a Reynolds number of 5000. In pipes, generally the transition is more at 2000-> 5000. The turbulent regime in a pipe is clearly established for a Reynolds number of 25000 (refer figure 19). I think, in the transition zone the results of the tests are difficult to interpret.

Concerning the erosion law, a minimal value for the rate of erosion is observed. It is surprising. The assumptions of a soil decohesion and transport can explain partly its presence. But, an analysis in time has to confirm it.

The proposed approach for analysis of the HET could lead to reasonable relative interpretations of erodibility coefficients but may be misleading for absolute values. This depends a lot on the interpretation of the friction coefficients and the deduced hole diameter.

The HET is interpreted by using equations written for permanent and steady flow. The deduction of the erosion is made by computing the hole diameter at a given time during the test. So each time step of the test is considered independent from the others. Therefore, it is possible to find some decreases in the hole diameter during the test even though increases would always be anticipated. The history of the flow rate is key in the analysis for determining the hole diameter. It has to be considered to use the gradient in the flow rate to deduce a gradient in the hole diameter. A better comprehension in the fluid mechanics and the hydraulic stresses of a HET is necessary.

5.3 JET analysis

This section presents the data results for the four soils tested using the JET at the USBR Laboratory in Denver. One test for each soil is summarized below in figure 21. The plot shows the depth of erosion (origin is the soil surface at time t = 0) versus time. It can be observed that for the most part, the rate of scour/erosion decrease with time. This would be expected if an equilibrium depth would eventually be attained with time. In my experiment, this observation was not made (not enough time of test).

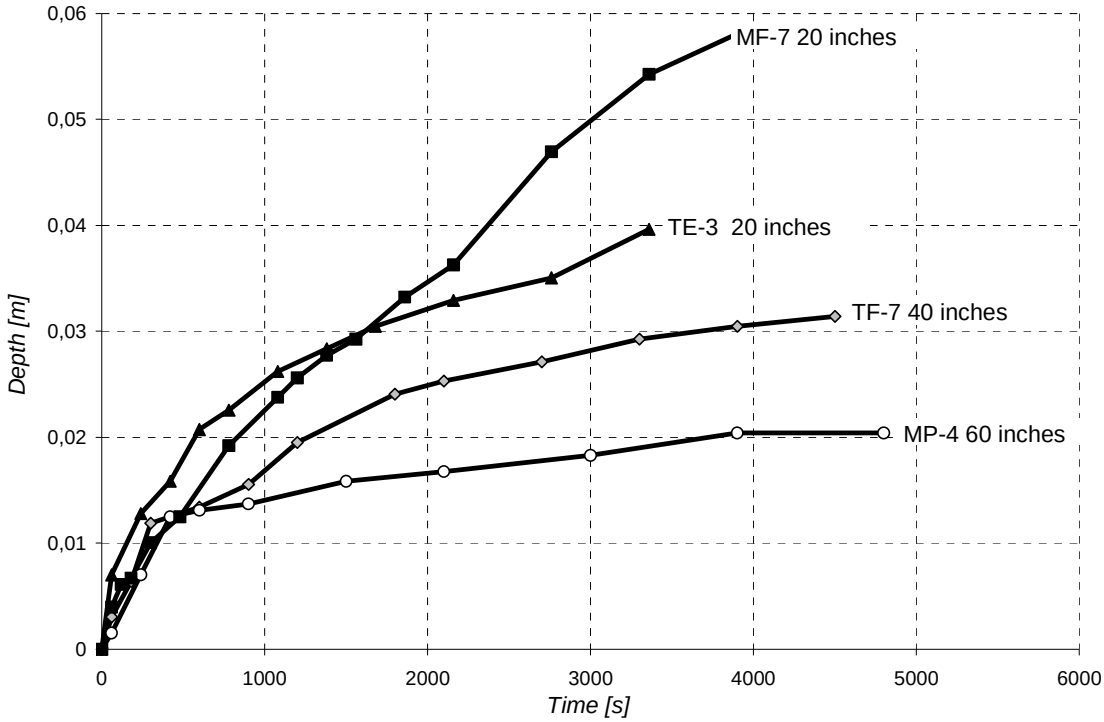


Figure 21 : Results for each soils of a jet test – head on orifice is varying with soil (1 inch = 0,0254 m of height of water).

It is also possible to observe the behavior of the soil on this chart. To be more comprehensive this curve should be built with the same head loss at the jet nozzle. This remark is also true for the HET. Using the same head loss for all tests allows relative erosion classification of the materials based on scour depth observations versus time. As for the HET, the classification is based on the initial shear stress and also rate of observed erosion. In order to obtain the real erosion law an analysis has to be made for both the HET and JET to deduce k_d and τ_C.

A relative classification of the soils based on scour test results of more erodible to the less erodible is: Teton – Many Farms – Tracy Fish – Mountain Park.

Many Farms and Teton results are not necessarily clear but it is possible to say that:

> $\tau_{c\ teton} > \tau_{c\ many\ farms}$ because the equilibrium depth appears to be closer to the original soil level for the Teton soil based on results in figure 14.;
>
> $k_{d\ teton} >= k_{d\ many\ farms}$ because the slope at t=0 is steeper for the Teton soil than for Many Farms.

Some problems were encountered with the Tracy Fish soil. During the JET, particles were removed in “chunks” periodically throughout the test, resulting in large shifts in depth measurements with time (figure 22).

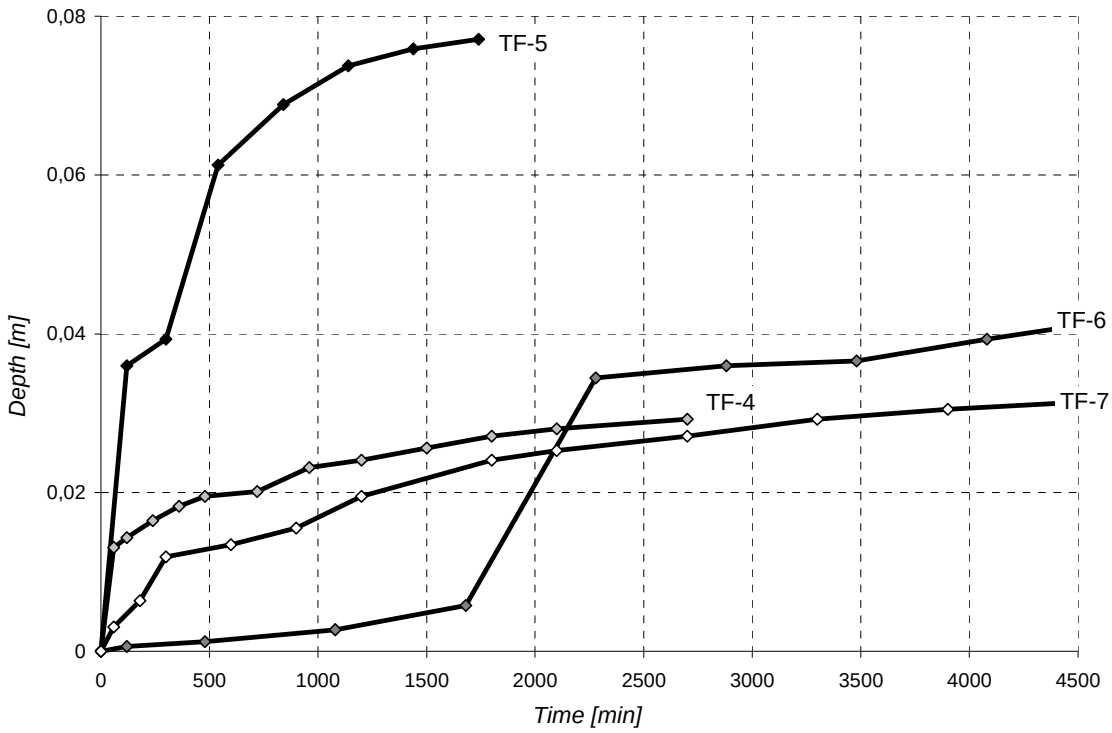


Figure 22 : Behavior of Tracy Fish soils.

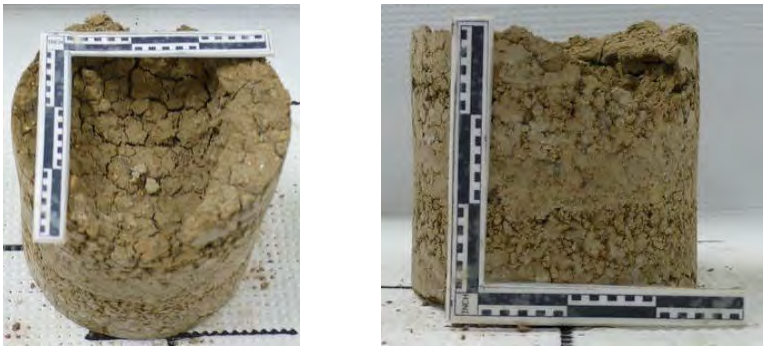
The behavior of soil TF-5 may partially be due to bad compaction in comparison to other compaction results. The compaction of TF-5 is 90% of the mean of the other compaction results. Concerning the jump observed in TF-7, it is mainly due to the presence of the compaction layer (depth = 0,12 ft). On the other soils some discrepancies could be observed with the erosion behavior during time, but they could be certainly explained by variation in compaction & preparation.

The shape of erosion:

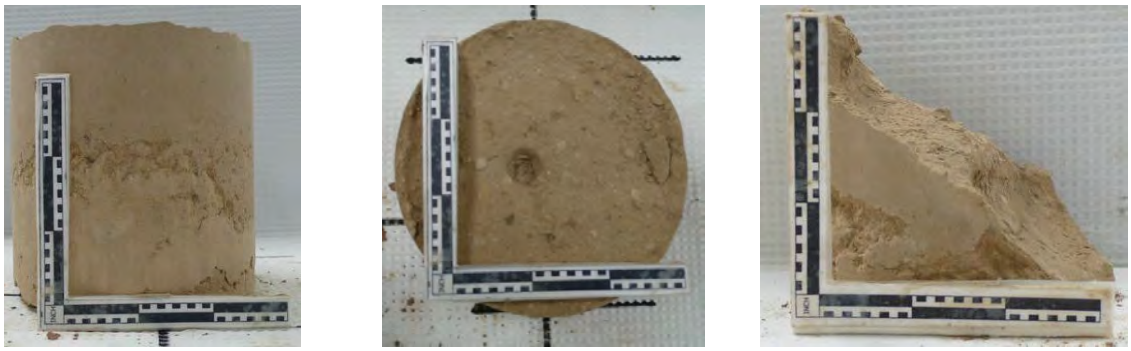
3 shapes of erosion profiles were observed in the case of the four soils tested at the USBR Laboratory in Denver. The erosion profile observed from the Many Farms JET samples was a parabola (or near). The erosion shape observed for the Teton soil samples was a scour hole with what appeared to be “waves of soil” around the perimeter of the hole. In one case rapid erosion was observed due to local compaction problems. The transition on the curves presented in the appendix is taking place near the compaction layer. Concerning the Tracy Fish soil and Mountain Park soil, the profile is flat.

The difference in shapes of erosion may be explained by differences in the erosion process for the different soils. For MF and TE, the erosion takes place with an eroded particle size equivalent to the size of the original particles in the air dried material prior to compaction. For TF & MP, the erosion takes place in the form of chunks greater than the original size of particles in the air dried samples. This might be due to the strength of cohesion and the

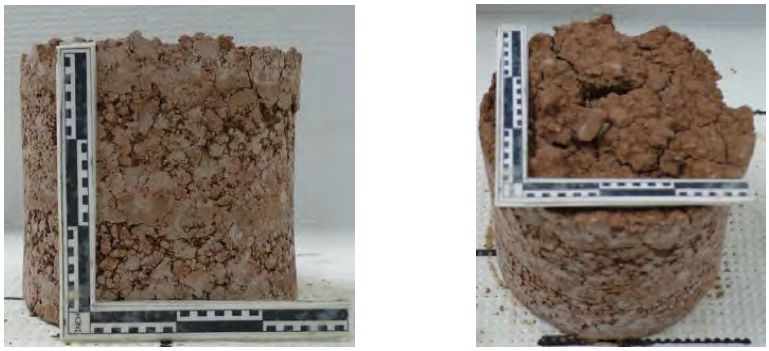
presence of fissures within the compacted samples leading to a jacking phenomenon during erosion.



Many Farms soil: MF-2



Teton soil : TE-2 & TE-4



Tracy Fish soil: TF-5

Mountain Park soil: TF-5

Figure 23 : Shapes (after drying) of erosion with the jet.

Use of the JET analysis

All the available data are analyzed with the Excel sheet for the erosion described by Hanson and Cook (2004). The value for the analysis of the different constant coefficients are C_d= 6,2, C_f=0,00416, d_0=0,25 inch. They are issued from an analysis made by Hanson and al. (2002). The data are summarized in the table 11.

	k_d [m^3/(N.s)]	Critical stress [Pa]	$k_{d,m}$ [kg/(N.s)]	Erosion index	Comments
MF-2	$1{,}09^{E-06}$	0,15	$1{,}91^{E-03}$	2,72	Using only a part of the data
MF-2	$1{,}12^{E-06}$	0,13	$1{,}96^{E-03}$	2,71	
MF-4 (1)	$2{,}34^{E-06}$	0,60	$4{,}19^{E-03}$	2,38	
MF-4-(2)	$5{,}52^{E-07}$	0,55	$9{,}79^{E-04}$	3,01	
MF-5	$1{,}09^{E-06}$	0,37	$1{,}93^{E-03}$	2,72	
MF-6	$1{,}50^{E-06}$	0,12	$2{,}68^{E-03}$	2,57	
MF-7	$1{,}94^{E-06}$	0,27	$3{,}45^{E-03}$	2,46	
MF-8	$1{,}89^{E-06}$	0,03	$3{,}35^{E-03}$	2,48	
TE-1	$1{,}67^{E-06}$	0,65	$2{,}83^{E-03}$	2,55	Head loss through the orifices = 14 inches
TE-2	$1{,}08^{E-06}$	0,90	$1{,}83^{E-03}$	2,74	
TE-3	$1{,}33^{E-06}$	0,66	$2{,}26^{E-03}$	2,65	
TE-4	$1{,}80^{E-06}$	0,33	$3{,}06^{E-03}$	2,51	Problem after 1/2 h / erosion till the bottom
TF-4	$8{,}64^{E-07}$	5,38	$1{,}42^{E-03}$	2,85	
TF-5	$3{,}82^{E-06}$	0,08	$5{,}72^{E-03}$	2,24	
TF-6	$4{,}36^{E-07}$	0,22	$6{,}93^{E-04}$	3,16	
TF-7	$3{,}92^{E-07}$	1,80	$6{,}23^{E-04}$	3,21	
MP-1	$2{,}37^{E-07}$	7,50	$3{,}93^{E-04}$	3,41	
MP-2	$1{,}59^{E-07}$	9,15	$2{,}63^{E-04}$	3,58	
MP-3	$1{,}55^{E-07}$	8,20	$2{,}55^{E-04}$	3,59	
MP-4	$1{,}63^{E-07}$	7,18	$2{,}71^{E-04}$	3,57	

Table 11 : Results of the jet tests for the different soils.

	kd [m^3/(N.s)]	% of variation
MF	$1{,}22^{E-06}$	34%
TE	$1{,}47^{E-06}$	18%
TF	$1{,}38^{E-06}$	89%
MP	$1{,}59^{E-07}$	2%

	Critical stress [Pa]	% of variation
MF	0,50	96%
TE	0,64	24%
TF	1,87	94%
MP	8,18	8%

Table 12 :Average value and observed deviation in percentage of the mean for the HET results.

The equivalent of the erosion index was computed for the jet. To compute it, the erosion coefficient $k_{d,m}$ is found by multiplying the coefficient k_d by the dry density refer equation 3. The final index is computed by taking the 10-logarithm of $k_{d,m}$.

So, by comparing, this different index, it is possible to obtain the following classification (built on an average value of k_d). TF[1] – 2,57; MF – 2,59; TE – 2,60; MP – 3,58. The soil of Tracy Fish appears as more erodible than Many Farms and Teton. As a side note: it is pointed out that the index is essentially based on the rate of erosion once it is emerced (k_d value), not on the global ability of the soil to erode. This classification results in some errors because a critical shear stress should also be determined and included in order to make a more accurate classification.

The JET analysis always allows for a determination of the critical shear stress which seems acceptable and the observed variations in results appear to be due to difficulties in consistent handling and preparation (TF). The results for the erosion coefficient and the critical shear stress are given in the . A lot of discrepancies are observed for the critical shear stress. The rate of erosion seemed to have the similar magnitudes from test to test for a given soil.

Comments on the JET analysis

The analysis is based on an experimental work lead at the ARS. It authorizes the deduction of erosion parameters in a clear way. The coefficients for the different laws used are coming from the experiences. A possible improvement in the analysis will be the correlation of our data directly with the erosion law. It will avoid the deduction of the equilibrium depth, and the parameters will come from the same fitting on the data.

The following comparison is not taking into account the different remarks made on the HET and the JET. It presents the data deduced by the analysis presented above.

5.4 Comparison of the two devices

The first comparison of the HET and JET is based on the initial state of the two apparatus relative to velocities of flow and hydraulic shear stress. The initial state for the HET is a flow selocity of 1 m/s and a shear stress ranging from 5 Pa (Teton and Many Farms) to 200 Pa (Mountain Park). The initial state for the JET is a flow velocity at the jet impact of approximately 3 to 5 m/s and a shear stress of 30 Pa to 105 Pa. The range of values covered by the two tests is roughly the same concerning the shear stress. But, there is a difference between the JET and the HET. In the first a pressure (impact) is applied on the soil. Maybe it lead to a different state of stress than the one proposed in the analysis.

The JET velocities of flow and values of shear stress decrease as the test progresses with time and the HET values increase with time. Concerning the JET, the stress is computed by a Chezy expression (equation 17), and for the HET the stress is computed by the expressions from the momentum balance (equation 4).

The second comparison of the tests is the different parameters obtained with the 2 tests. Unfortunately, some discrepancies are observed in the values of the different tests. For the HET, these discrepancies are due to the limitations and difficulties in analysis. For the JET, the observed discrepancies appear to be more due to the real behavior of soils and variations in the compaction state.

[1] For the interpretation of the erosion on the Tracy Fish soil, the trial TF-1, TF-2, TF-3 are neglected in the analysis because of a number of points insufficient. MF-1 is neglected in the analysis because of a variation of pressure during the test.

The table 13 provides a summary of the average values of all the tests for the different soils. , Figure 24, figure 25, present the different coefficients for the different preparations of the four soils tested.

One of the first points to be made is that the order of magnitude for the critical shear stresses and the erosion coefficients determined from the HET and JET are not the same. The factors varying with the kind of soil tested. The erodibility coefficient is 10 times greater for the JET test than the HET and the critical shear stress[1] is 100 times less for the JET than for the HET.

The relative order of the erodibility of the four soils tested is coherent between the two tests with the exception of the Many Farms and the Teton values which appear to be inverted for the two results. The Many Farms soil is less erodible than Teton according to the JET index. The opposite situation appears for the HET index.

The index does not integrate the critical shear stress in its computation. The HET analysis partially integrates the critical shear stress in the final results by the deduction of the friction law using the initial and final time. For the most part the erosion dynamic of the HET is driven by the friction law. By considering the critical shear stress for the JET & the index for the HET, the relative erodibility is conserved.

	JET			HET		
	k_d [m^3/(N.s)]	**Critical shear stress [Pa]**	**Erosion index**	**kd [m^3/(N.s)]**	**Critical shear stress [Pa] - theorical**	**Erosion index**
MF	1,22E-06	0,50	2,66	$3{,}82^{E-07}$	10,1 - < 10	3,18
TE	1,47E-06	0,64	2,60	$3{,}42^{E-07}$	-9,4 - < 10	3,24
TF	1,38E-06	1,87	2,67	$1{,}86^{E-08}$	277,5 - < 130	4,52
MP	1,59E-07	8,18	3,58	$1{,}98^{E-09}$	225,5 - < 200	5,47

Table 13 : Summary of the soil properties concerning the erodibility, comparison between the JET and the HET.

	k_d JET/k_d HET
MF	3,74
TE	4,31
TF	69,33
MP	77,57

Table 14 : Ratio on k_d between the JET and the HET.

	τ_C JET / τ_C HET
MF	0,05
TE	-0,07
TF	0,01
MP	0,04

Table 15: Ratio on τ_C between the JET and the HET.

[1] We consider for the HET, the shear stress on the initial diameter.

There does not appear to be a significant relationship between the k_d coefficient and the critical shear stress for the four soils tested between the 2 tests. This fact is mainly due to the interpretation of the HET which is difficult to handle and does not allow computation of the values of the mechanical parameters. Moreover, discrepancies in the soil preparation do not allow yet a direct comparison.

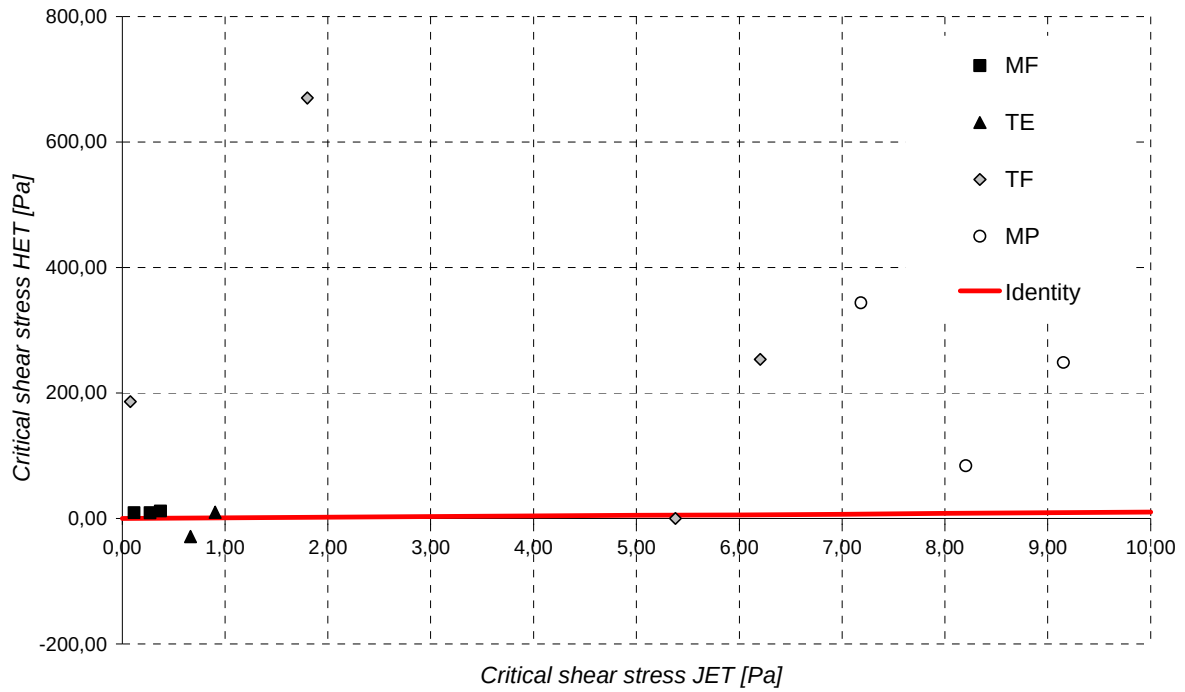


Figure 24 : Comparison of the shear threshold obtained with the HET and the JET.

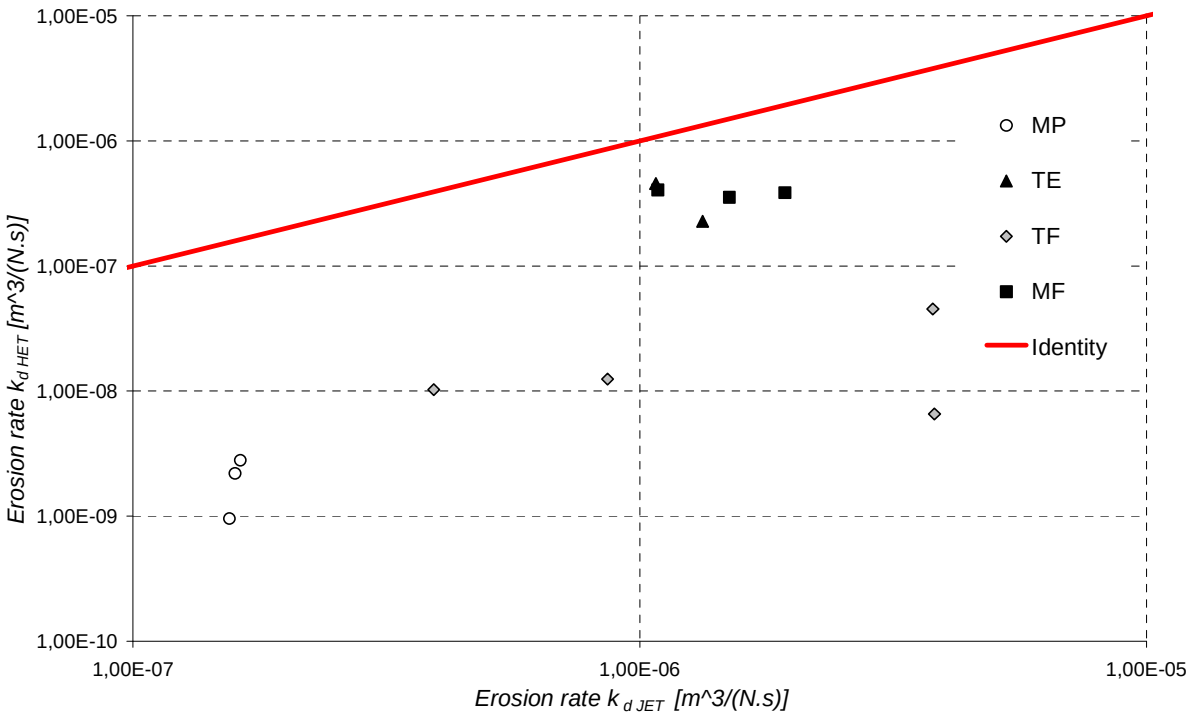


Figure 25 : Comparison of the erosion coefficient obtained with the HET and the JET .

Information extrapolated from the HET test comparing the flow rate from the Teton Dam soil and Many Farms points out a difference in the erosion behavior of the two soils (refer figure 26). Using the slope on the flow rate, Many Farms appears to erode faster at the end of the test than the Teton Dam soil. But at the beginning of the test, the Teton soil erodes faster than the Many Farms. It could be deduced from this observation that the $k_{d\ teton} >= k_{d\ many\ farms}$ and $\tau_{c\ teton} > \tau_{c\ many\ farms}$ or $k_{d\ teton} =< k_{d\ many\ farms}$ and $\tau_{c\ teton} < \tau_{c\ many\ farms}$. The first case is clearly described by the JET analysis.

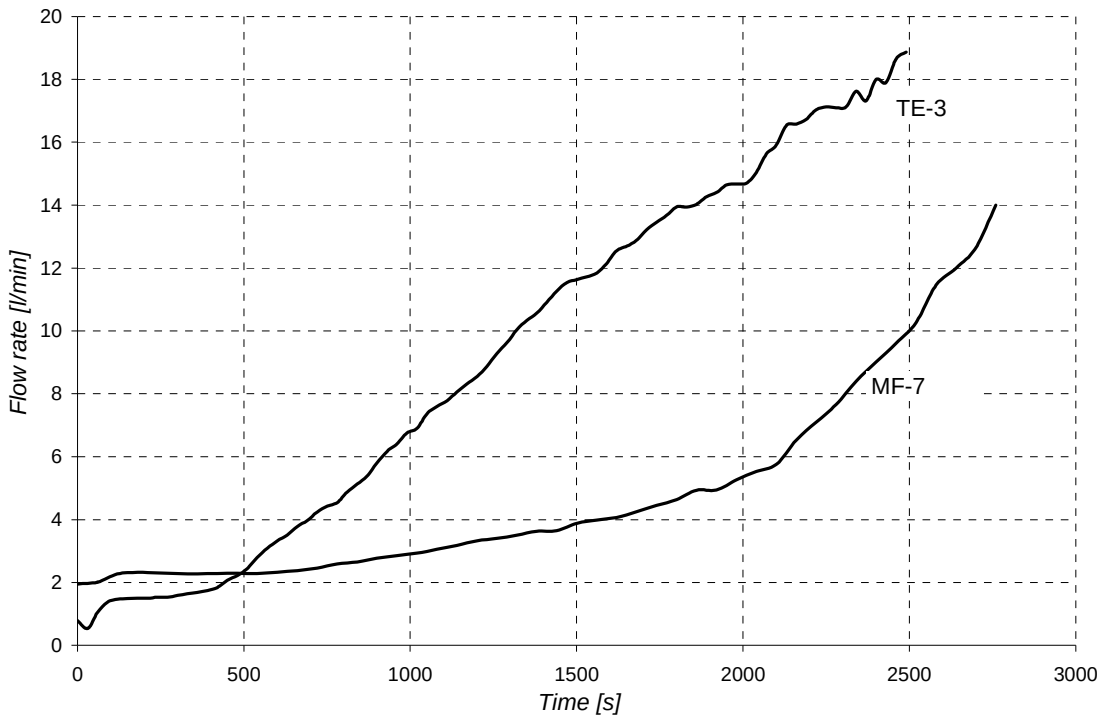


Figure 26 : Comparison of the behavior of Teton and Many Farms soils according to the time under 50 mm of head loss.

6 Conclusion

The experimental work has to be completed to be sure of the conclusions concerning the relation between the erosion with the JET and the erosion with the HET.

The two tests determine the soil erodibility and have the ability to give relatively the same erodibility classification. For the JET, the analysis and classification has to be made in two steps: first, with the critical shear stress and second, with the erodibility coefficient. The erosion index of the HET leads to the same conclusion. The HET gives some problems for the deduction of a critical shear stress. It is possible to find a negative one.

A complete erodibility analysis should include:

1. the critical shear stress (does it happen?);
2. the erosion rate coefficient (what is the rate?).

The use of the Hole Erosion Index only provides information about the rate of progression of the pipe, which is only a part of this information. It seems possible to develop an analysis procedure to include determination of the critical shear stress parameter. The analysis with the JET seems to be more complete in this aspect of the analysis because it determines both of these parameters.

In terms of soil behavior, in spite of the two approaches, HET and JET, being totally different, they appear to provide similar answers to relative but not for absolute comparisons. The erodibility coefficient for the HET appears to be 10 times smaller than the Jet and the critical shear stress appears to be 100 times greater. This indicates that the threshold value is less for the JET than the HET. This may be due to a bias introduced by the analysis and the comparison between the 2 tests.

Concerning the use of the two apparatus; the JET is very easy to handle and the HET is more difficult in a practical way and requires a lot of care. But, the HET test could bring a lot of information concerning the behavior of the soils if some improvements are brought to the analysis and the apparatus. It is more coherent with the physics of a piping phenomenon than the jet. The HET indirectly provides a continuous monitor of the erosion phenomena through the flow rate.

Different shapes of erosion are observed in the JET and the HET. The observed erosion shapes are clearly linked to the erodibility concerning the HET (variation in length and diameter). For the JET, it is more difficult to bring a conclusion to the erosion shapes. The depth is linked to the erodibility in the JET, but, the shape of the surfaces could not be explained in a clear way. A better comprehension in the effect of the JET on the soil, the state of stress, and an improvement in the HET analysis are necessary to conclude toward the behavior of the soil and to explain the shape.

7 Bibliography

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