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► **To cite this version:**

Katell Guizien, Francis Orvain, Jean-Claude Duchêne, Pierre Le Hir. Accounting for Rough Bed Friction Factors of Mud Beds as a Result of Biological Activity in Erosion Experiments. *Journal of Hydraulic Engineering*, 2012, 138 (11), pp.979-984. 10.1061/(ASCE)HY.1943-7900.0000627. hal-02955352

**HAL Id: hal-02955352**

**<https://hal.science/hal-02955352v1>**

Submitted on 2 Dec 2022

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Accounting for rough bed friction factors of mud  
beds due to biological activity in erosion  
experiments

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April 12, 2012

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# 1 **Abstract**

2       The average bed shear stress and bed friction factor of samples with any rough-  
3 ness was derived from the head loss between upstream and downstream of a test  
4 section in an erosion tunnel. The method was validated in both hydraulically smooth  
5 (plexiglass, Reynolds number less than 25,000) and rough regimes (calibrated par-  
6 ticles with known roughness). As a first step toward using this method on natural  
7 sediment, we tested this method with experimental mesocosms assembled from field  
8 collected materials (sieved sediments, diatoms). Bed shear stress measurement pre-  
9 cision was high enough in the experiments to detect a positive significant relationship  
10 between bed friction factor and core roughness. The observed bed friction factor  
11 increase could be related to diatom growth but not to diatoms biomass.

## 12 Introduction

13 Erosion of fine grained sediment and any living or dead benthic biota associ-  
14 ated with sediment particles are key processes in the control of coastal ecosystems'  
15 primary and secondary productivities and their morphodynamics which remain dif-  
16 ficult to predict for field situations. Sediment erosion flux results from the balance  
17 between bed shear stress induced by fluid forcing and sediment erodibility (that is  
18 the sediment resistance to erosion). Muddy sediment erodibility were first studied  
19 by focusing on abiotic factors (grain size, mineralogy, salt and water content, Mehta  
20 et al. 1982; Parchure and Mehta 1985; Mehta 1986). Devices for field studies  
21 of erosion opened the way in the 1990s for new investigations of biological parame-  
22 ters (biofilm, bioturbation) and sediment erodibility (e.g. Paterson 1989; Gust and  
23 Morris 1989; Amos et al. 1992; Widdows et al. 2000; Andersen et al. 2001;  
24 Black et al. 2002). Mud erodibility properties are expected to be best preserved  
25 with *in situ* flumes, although careful sampling technique and rapid transfer to the  
26 laboratory limit discrepancies between field and laboratory assessments (Tolhurst  
27 et al. 2000a,b; Widdows et al. 2007). Other concerns remained about the ability  
28 of either field or laboratory flumes to relate erodibility to fluid action (see review in  
29 Black & Paterson 1997, updated in Tolhurst et al. 2009). One criticism, which is  
30 cited repeatedly, is that flows are frequently non uniform in inverted benthic flumes,  
31 either across the flume section due to secondary flows in a horizontal annular re-  
32 circulating flume, or along the flume axis in straight flow-through flumes of finite  
33 length due to a partially developed boundary layer (Aberle et al. 2003). Another,  
34 more important, concern is that bed shear stresses are (in most cases) not measured  
35 during erosion experiments (Gust and Morris 1989), but derived from flow velocity  
36 using pre-deployment calibrations (Amos et al. 1997; Widdows et al. 1998; Ander-  
37 sen et al. 2001; Aberle et al. 2003; Orvain et al. 2007). Bed shear stress, however,  
38 depends not only on flow velocity, but also on the bottom roughness. Thus, a pre-  
39 deployment calibration implicitly assumes that field mud bed roughness is the same  
40 as the one used for calibration (generally hydraulically smooth, except in Andersen  
41 et al., 2001 and Aberle et al., 2003). Under low bed shear stresses ( $< \sim 0.5$  Pa), it is  
42 possible that the shear flow in small erosion devices remains hydraulically smooth,  
43 even in the presence of naturally rough beds (Cartwright et al. 2009). Nonetheless,

44 the hydraulically smooth assumption might not be valid in natural settings (Deb-  
45 nath et al. 2007) and at high Reynolds number during the erosion experiment.  
46 Hence, if one aims to investigate the relation between erodibility and ecological fac-  
47 tors or extrapolate erodibility measurements in erosion modelling, we must be able  
48 to relate erodibility to the actual bed shear stress applied and accounting for the  
49 effective mud roughness.

50 This study uses head loss between the upstream and downstream of a test sec-  
51 tion in a laboratory recirculating tunnel to derive the actual averaged bed shear  
52 stress over samples with any roughness. The sensitivity to bed roughness of the  
53 method was checked with smooth (plexiglass) and rough (made of calibrated par-  
54 ticles) beds. Finally, we investigated the relationship between bed friction factors  
55 derived from bed shear stress measurements over muddy sediment having growing  
56 diatoms and/or bioturbating fauna, and the roughness estimate derived from core  
57 surface topography.

## 58 **Material and Methods**

### 59 **The Erodimetre erosion tunnel and principles for measure-** 60 **ment of averaged bed shear stress over core samples**

61 The Erodimetre erosion tunnel of the *Institut Français de Recherche pour l'Exploitation*  
62 *de la MER* (IFREMER) is a small recirculating straight tunnel made of plexiglass  
63 (1.20 m long, a=8 cm wide and b=2 cm high, Fig. 1) designed to perform *ex situ*  
64 experiments (Le Hir et al. 2007). The hydraulic diameter of the duct's rectan-  
65 gular section is  $D_h = 2ab/(a + b) = 3.2$  cm. Erosion experiments can be done  
66 on duplicate sediment cores (8 cm diameter) placed flush with the bottom in a  
67 36 cm long section at the downstream end of the tunnel (Fig. 1). The test section  
68 is located 80 cm downstream from the tunnel entrance to ensure a fully developed  
69 and steady boundary layer at the entrance of the test section for flow discharge up  
70 to  $1.75 \text{ l s}^{-1}$  (Schlichting 1979). Sand paper with a roughness height of  $115 \mu\text{m}$   
71 was glued on the tunnel bottom upstream of the test section to diminish roughness  
72 changes at the tunnel bottom to test section transition for hydraulically rough sam-  
73 ples. A large artificial roughness was added to the top of the tunnel to homogenize

74 the bed shear stress across the tunnel (Le Hir et al. 2006; Calluad and Mouazé  
75 2007). The flow discharge delivered by the recirculating pump is continuously gauged  
76 by a flow meter. Discharge may be varied from 0 and 2.5 l s<sup>-1</sup> by steps of 0.1 l s<sup>-1</sup>,  
77 corresponding to a discharge velocity  $U$  ranging from 0 to 1.56 m s<sup>-1</sup>, by steps of  
78 0.0625 m s<sup>-1</sup> (Reynolds number  $Re = UD_h/\nu$  up to 50,000 using the kinematic  
79 viscosity  $\nu = 10^{-6}$  m<sup>2</sup> s<sup>-1</sup> for water). A differential pressure gauge measures the  
80 total pressure difference  $\Delta p$  between two sections 36 cm apart, (that is, upstream  
81 and downstream of the test section), with a resolution of 1 Pa. A negative total  
82 pressure difference indicates head loss  $\Delta h = \Delta p/(\rho g)$  in the test section, with  $\rho$ ,  
83 the fluid density and  $g$ , the Earth's gravity acceleration. Head loss between tunnel  
84 cross sections located upstream and downstream of the test section (Figure 2a) may  
85 be used to directly determine the average bed shear stress over the core samples  
86 (Briaud et al. 2001).

87 Subtracting equations of steady state momentum balance between upstream and  
88 downstream the test section with plexiglass caps and samples with any roughness,  
89 the average bed shear stress on rough samples  $\tau_{\text{rough}}$  yields:

$$\tau_{\text{rough}} = \tau_{\text{smooth}} + \frac{S_1}{2S_3}[\Delta h_{\text{caps}} - \Delta h_{\text{core}}] \quad (1)$$

90 where  $\tau_{\text{smooth}}$  and  $\Delta h_{\text{caps}}$  are the average bed shear stress and head loss, respectively,  
91 over hydraulically smooth plexiglass caps replacing cores in the test section,  $S_1$  is  
92 the tunnel cross-section area,  $S_3$  is the core area and,  $\Delta h_{\text{rough}}$  is the head loss with  
93 rough cores. The last term in equation (1) is the excess bed shear stress due to the  
94 core roughness compared to hydraulically smooth plexiglass caps (Fig. 2).

Bed shear stress  $\tau$  can be related to discharge velocity introducing a bed friction  
factor  $f$  defined as:

$$\tau = \rho f U^2 / 8 \quad (2)$$

95 In pipes,  $\tau_{\text{smooth}}$  can be calculated using the Reynolds dependent friction factor value  
96 given in the Moody chart for smooth walls (Moody 1944). In the Erodimetre,  $\tau_{\text{smooth}}$   
97 should be lower than the bed shear stress measured with plexiglass caps  $\tau_{\text{caps}}$ :

$$\tau_{\text{caps}} = \rho g \frac{S_1}{2(\Sigma + S_2)} \Delta h_{\text{caps}} \quad (3)$$

98 where  $S_2$  is the area of the smooth side-wall of the test section and  $\Sigma$  is the area of  
 99 the top-wall of the test section where roughness were added. At least, one "cap" ex-  
 100 periment was performed during each experimental series; a sixth degree polynomial  
 101 was fitted to describe the  $\Delta h_{caps}$  as a function of the flow discharge.

102 It should be noted that at zero discharge, the pressure gauge resolution of 1 Pa  
 103 limits the precision of bed shear stress determinations to 0.16 Pa. Moreover, dis-  
 104 charge fluctuations induce head fluctuations that may reach 0.1 cm at high flow  
 105 discharges (Fig. 2b), leading to practical uncertainties on the bed shear stress de-  
 106 termination that were estimated at  $\pm 0.5$  Pa for discharge ranging from  $0.1 \text{ l s}^{-1}$  to  
 107  $2.5 \text{ l s}^{-1}$ .

## 108 Shields experiments

109 Experiments with calibrated particles were carried out in tap water to test the  
 110 accuracy of the bed shear stress determination based on head loss. The core surface  
 111 was uniformly covered by a 1 cm thick layer of calibrated particles, ensuring a plane  
 112 surface flush with the tunnel bed and the discharge was increased. According to  
 113 Shields (1936) diagram, particles with median diameter  $D_{50}$  start to move when the  
 114 bed shear stress reach a critical value,  $\tau_{Shields}(D_{50})$ , defined as (Soulsby 1997):

$$\frac{\tau_{Shields}(D_{50})}{g(\rho_s - \rho)D_{50}} = 0.055 [1 - \exp(-0.02D^*)] + \frac{0.3}{1 + 1.2D^*} \quad (4)$$

115 where  $\rho_s$  is particles density and  $D^*$  is the dimensionless particle diameter,  
 116 defined as  $D^* = [g(\rho_s/\rho - 1)/\nu^2]^{1/3} D_{50}$ .

117 Characteristics of the calibrated particles, including the relative roughness height  
 118 value ( $D_{50}/D_h$ ), used in these Shields experiments are given in Table 1. Critical bed  
 119 shear stress and the corresponding particle Reynolds number  $RE_c = UD_{50}/\nu$  value  
 120 are also reported. These critical bed shear stress values were compared to the bed  
 121 shear stress values derived from the measured head loss when particles started to  
 122 move. For each experiment with calibrated particles, a mean value and standard  
 123 deviation of bed friction factor  $f$  was calculated by a linear regression between bed  
 124 shear stress and the square of flow velocity for discharges larger than  $0.15 \text{ L s}^{-1}$ .

## 125 Mesocosm experiments

126 Experiments were carried out in sea water using reconstructed cores from nat-  
127 ural sediment (10  $\mu\text{m}$  median grain size) collected on the intertidal mudflats of  
128 Marennes-Oléron Bay (French Atlantic coast). Sediment collected were sieved to  
129 1 mm to remove any macrofauna.

130 The experiments were designed to explore the relationship between the develop-  
131 ment stage of a microphytobenthic biofilm and mud surface roughness. To simulate  
132 different diatom biofilm development stages, twenty reconstructed mud cores were  
133 inoculated with benthic diatoms, twenty were not and all were pre-conditioned in  
134 the same tidal mesocosm for 5 days before an erosion experiment. Twenty cores  
135 without added diatoms were pre-conditioned at the same time. Two erosion experi-  
136 ments were then carried out every two days over a period of eight days, one with cores  
137 that had microphytobenthos added, and the second without. Two mud cores were  
138 placed in the Erodimetre and flow increased until mass erosion occurred (detach-  
139 ment of centimetric sediment aggregates, detected visually). The diatom biomass  
140 was estimated by analyzing the pigments present in the uppermost centimeter of  
141 mesocosm cores (Lorenzen 1967).

142 Before and after each of the experiments, a high resolution scan of cores' surface  
143 topography was done over a 5 cm  $\times$  5 cm area at the core center at a horizontal  
144 resolution of 200  $\mu\text{m}$   $\times$  200  $\mu\text{m}$ . The surface topography is the vertical deviation  
145 of the core surface from an average horizontal plane measured at a 15  $\mu\text{m}$  verti-  
146 cal resolution and core roughness was the square root of the variance of the core  
147 topography.

148 Finally, a bed shear stress-pump discharge curve was established for each exper-  
149 iment. One experiment was excluded as the cores surface was perfectly flush with  
150 the tunnel bed, presenting upward and downward steps to the flow (Briaud et al.  
151 2001) which produced unexpected large bed shear stresses. These outlying values  
152 highlight the difficulty in placing natural samples flush with the tunnel bed. Mean  
153 values and standard deviations for the bed friction factor were calculated after a  
154 linear regression between bed shear stress and the square of discharge velocity for  
155 discharges from 0.35 to 1.75  $\text{L s}^{-1}$  ( $Re$  from 7,000 to 35,000). The linear relationship  
156 between bed friction factor and core roughness was also tested.



158 This paper uses head loss measurement to derive bed shear stress as a function  
159 of discharge in both hydraulically smooth and rough regimes (Fig. 3). Briaud et al.  
160 (2001) also attempted to use head loss measurements to derive bed shear stress, al-  
161 though no details were given on how the authors dealt with the differential roughness  
162 between the tunnel walls and the sample when deriving bed shear stress from head  
163 loss measurements. After comparing erosion flux measurements in tunnel and flume  
164 experiments, they argued that using the Moody chart (Moody 1944) was more ap-  
165 propriate to relate erosion flux to bed shear stress in the tunnel. However, using the  
166 Moody chart in a hydraulically rough regime requires knowing the sample rough-  
167 ness which is generally not the case in natural settings, particularly when roughness  
168 arises from biological activity and along an erosion experiment. The method pre-  
169 sented in this study derives bed shear stress along erosion experiments over samples  
170 with unknown roughness. The method performance was checked over a wide range  
171 of sample roughness (plexiglass, calibrated particles, mud with biological activity).  
172 Bed shear stress derivation from head loss measurement when the test section was  
173 made of plexiglass deviated by less than a few percent from bed shear stress calcu-  
174 lated with equation (2) using the hydraulically smooth Moody chart friction factor  
175 if the Reynolds number was less than 25,000 (Fig. 3a). Smooth bed shear stress  
176 values ranged from 0 to 6 Pa at  $2.5 \text{ L s}^{-1}$  but remained below 1 Pa for discharges  
177 lower than  $1 \text{ L s}^{-1}$ . For Reynolds numbers greater than 25,000, bed shear stress  
178 values were larger than Moody chart smooth regime predictions and varied by 30  
179 % between different repeated experiments. Deviation may be due to the develop-  
180 ment of a rough boundary layer on the top wall and the adaptation of the rough  
181 bed boundary layer that had established over rough sand paper between the tunnel  
182 entrance and the test section to the abrupt roughness change over smooth plexiglass  
183 caps. Thus, Moody chart prediction was used for the smooth bed shear stress value  
184 in equation (1).

185 When the plexiglass caps were replaced by surfaces made of calibrated particles,  
186 bed shear stress values increased by around a factor 10, reaching the hydraulically  
187 rough regime (Fig. 3a,  $RE_c > 70$ ). Average bed friction factors derived using  
188 equation (2) were close for beds made of either sand or steel particles but having the

189 same median diameter and increased significantly when median diameter increased  
190 (Table 1). The hydraulic roughness of plane beds formed by particles with uniform  
191 size (Nikuradse 1933) was derived from these bed friction factor after integration  
192 of the velocity logarithmic profile over its thickness (6 mm according to, Calluad  
193 and Mouazé 2007)). Hydraulic roughnesses ranged from 2.1 to 2.6 times the mean  
194 diameter of bed particles, which is within values generally observed over a plane  
195 bed made of sand grains (Guy et al. 1966). Finally, the values of measured bed  
196 shear stress when calibrated particles start to move agreed fairly well with bed shear  
197 stress values predicted by Shields criteria (equation 4, deviation lower than 20 % at  
198 high flow, Fig. 4), demonstrating the accuracy of bed shear stress determinations  
199 based on head loss measurements. This validation accounted for uncertainties of  
200 about 1 Pa due to the observer difficulty in appreciating when particles start to  
201 move. A similar method was used to convert into equivalent bed shear stress either  
202 the eroding pressure of the pulsating jet of a Cohesive Strength Meter (Tolhurst et  
203 al. 1999) or the propeller revolution velocity for the EROMES device (Andersen  
204 et al. 2001). In the present study, validation of the method covered a wide range  
205 of bed shear stress values (from 0.15 to 12.7 Pa) which may prove to be useful to  
206 study the erosion of consolidated muds. In any case, bed shear stress range was  
207 larger than the usual range (up to 3 Pa) of erosion devices calibrated with smooth  
208 walls (Amos et al. 1997; Widdows et al. 1998), and close to bed shear stress values  
209 obtained when calibrating the NIWA flume with an artificial rough surface (Aberle  
210 et al. 2003). In summary, the method based on head loss between upstream and  
211 downstream, a test section with reduced length (ten times the hydraulic diameter) in  
212 the Erodimeter performed better in the hydraulically rough regime (20 % precision  
213 on bed shear stress determination) than in the hydraulically smooth regime. This  
214 should be attributed to the effort in reducing roughness change at the transition  
215 between the sample and the tunnel bottom covered with sand paper of intermediate  
216 roughness. Precision could be increased using a longer test section to ensure a fully  
217 developed boundary layer in the test section.

218 Six bed shear stress-flow discharge curves were measured over mud cores, three  
219 of which were enriched with diatom (Fig. 3). Bed shear stresses over muddy sediment  
220 supporting diatom growth increased by up to a factor of 4 compared to the smooth  
221 bed shear stresses that may be expected for a 10  $\mu\text{m}$  mud grain size. Meanwhile,

222 smooth bed shear stress predictions have been used extensively, in both field (Amos  
223 et al. 1997; Widdows et al. 1998; Orvain et al. 2007) and laboratory (Orvain  
224 et al. 2003; Ravens 2007) studies of natural mud beds' stability. Bed shear stress  
225 underestimation may have passed unnoticed when, for instance, lower critical bed  
226 shear stresses were found over bioturbated beds compared to non bioturbated beds  
227 and were interpreted as erodibility increase (Orvain et al. 2007). However, bed  
228 roughness enhancement after bioturbation would also lead to lower critical bed shear  
229 stress values if derived from calibration versus flow velocity over a smooth bed. In  
230 addition, flow velocity may indicate an erroneous hierarchy of sediment erodibility  
231 as bed roughness evolves during an erosion experiment (Maa et al. 1998).

232 The experimental series of the present study clearly showed a large variability  
233 (by a factor two) in bed shear stress values for the same discharge. Bed shear stress  
234 were lower when cores were not enriched with diatoms. Chlorophyll *a* concentration  
235 increased from 100 to 210 mg Chl *a* m<sup>-2</sup> in the uppermost cm of sediment cores  
236 indicating diatom growth during the first 7 days of experiment. These values cover  
237 the range of chlorophyll *a* concentration observed over intertidal mudflats (Blanchard  
238 et al. 2001). Growth was slower in cores without diatom enrichment. Bed shear  
239 stress increased after 5 and 7 days of diatom growth and strongly decreased when  
240 diatom biomass stabilized 9 days after inoculation.

241 Bed friction factor *f* values ranged from 0.04 to 0.09, and were significantly  
242 correlated with core roughness ( $R = 0.95$  and  $p = 0.35\%$ ). Core surface topography  
243 was generally bumpy in its center mainly due to the way it was cored and slid into  
244 the tunnel bottom. Core roughness were larger on average with diatoms enrichment  
245 (3.1 mm) than without (1.8 mm). Rough bed friction factors found over mud cores  
246 in the present study indicated hydraulic relative roughness ranging from 0.012 to  
247 0.05 using Moody chart predictions. Hydraulic roughnesses ranged from 2 to 4 times  
248 the roughness estimated from topography variance.

249 In any case, hydraulic roughness increase could be related to the microphy-  
250 tobenthic biofilm development but not to microalgal biomass integrated over the  
251 uppermost sediment centimeter. Biological enhancement of cohesive sediment hy-  
252 draulic roughnesses have frequently been attributed to bioturbation by infauna or  
253 small epibenthic species (Nowell et al. 1981; Wright et al. 1997; Ciutat et al.  
254 2007). To our knowledge, hydraulic bed roughness enhancement of mud interface

255 by biofilm coatings has never been shown, although previous studies have reported  
256 spatial micro-heterogeneity linked to discontinuous patches of diatoms at the sedi-  
257 ment surface (Grant et al. 1986).

## 258 **Conclusion**

259 Head loss between the upstream and downstream of a test section in an erosion  
260 tunnel was used to derive the averaged bed shear stress and bed friction factor of  
261 samples with any roughness. The method was validated in both the hydraulically  
262 smooth regime (plexiglass,  $Re < 25,000$ ) and rough regimes (calibrated particles  
263 with known roughness). The present study confirmed that *a priori* calibration of  
264 experimental devices relating bed shear stress to flow discharge assuming hydraulically  
265 smooth beds may be inadequate for studying erodibility of natural intertidal  
266 bare mudflats supporting diatom growth, especially at high stress conditions. How-  
267 ever, reliable estimates of bed friction factor requires to repeat experiments when  
268 studying natural samples to detect any artefactual roughness due to sample not per-  
269 fectly flush with the tunnel bed. Bed shear stress measurement precision was high  
270 enough to detect a relationship between bed friction factor and roughness produced  
271 by diatom biofilm growth. However, any roughness change should rather be related  
272 to biota activities than to biomass.

## 273 **Acknowledgments**

274 This work was supported by the French ANR (National Research Agency) through  
275 the VASIREMI project "Trophic significance of microbial biofilms in tidal flats"  
276 (contract ANR-06-BLAN-0393-01). The assistance of Caroline Nérot for the meso-  
277 cosms experiments is gratefully acknowledged. We also thank Jennifer Coston-  
278 Guarini and Ian Salter for language correction.

## 279 **Notation**

280 The following symbols are used in this technical note:

	$a =$	tunnel width (cm)
	$b =$	tunnel height (cm)
	$D_h =$	tunnel hydraulic diameter (cm)
	$D_{50} =$	particles median diameter (mm)
	$D^* =$	particles median diameter (dimensionless)
	$f =$	bed friction factor (dimensionless)
	$g =$	Earth gravity ( $\text{m s}^{-2}$ )
	$Re =$	tunnel Reynolds number (dimensionless)
	$RE_c =$	particle Reynolds number (dimensionless)
	$S_1 =$	tunnel cross section area ( $\text{m}^2$ )
281	$S_2 =$	test section side wall area ( $\text{m}^2$ )
	$S_3 =$	core area ( $\text{m}^2$ )
	$U =$	tunnel discharge velocity ( $\text{m s}^{-1}$ )
	$\Delta h =$	head loss between upstream and downstream of test section ( $m$ )
	$\Delta h_{caps} =$	head loss between upstream and downstream of test section with plexiglass caps ( $m$ )
	$\Delta h_{rough} =$	head loss between upstream and downstream of test section with rough sample ( $m$ )
	$\Delta p =$	pressure difference between upstream and downstream of test section ( $Pa$ )
	$\nu =$	fluid kinematic viscosity ( $\text{m}^2 \text{s}^{-1}$ )
	$\rho_s =$	particle density ( $\text{kg m}^{-3}$ )
	$\rho =$	fluid density ( $\text{kg m}^{-3}$ )
	$\Sigma =$	test section top wall area ( $\text{m}^2$ )
	$\tau =$	bed shear stress ( $Pa$ )
	$\tau_{caps} =$	average bed shear stress derived from equation (3) ( $Pa$ )
282	$\tau_{rough} =$	average bed shear stress over rough sample ( $Pa$ )
	$\tau_{smooth} =$	bed shear stress over hydraulically smooth plexiglass caps ( $Pa$ )
	$\tau_{Shields}(D_{50}) =$	bed shear stress value when particles with diameter $D_{50}$ started to move ( $Pa$ )

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397 **List of Figures**

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Material	Diameter range (mm)	Density (kg m <sup>-3</sup> )	Relative roughness $D_{50}/D_h$	$Re_c$	$f$
Sand	0.19-0.21	2700	0.0063	2.5	NC
Sand	1.25-1.6	2700	0.0445	41	0.13±0.03
Steel	1.25-1.6	7650	0.0445	89	0.14±0.03
Lead	1.6-2.0	10965	0.0563	164	0.18±0.03
Lead	2.0-2.5	10965	0.0703	237	0.22±0.02

Table 1: *Characteristics of the five categories of calibrated particles used in Shields experiments (Fig. 4) and the bed friction factors derived from bed shear stress vs pump discharge curves.*

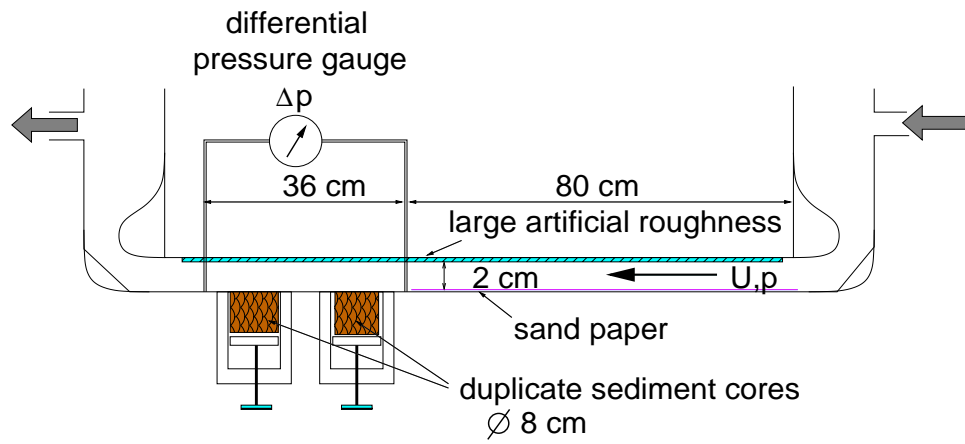


Figure 1: *Schematic of Erodimetre erosion tunnel, designed by the Institut Français de Recherche pour l'Exploitation de la MER (Le Hir et al. 2006).*

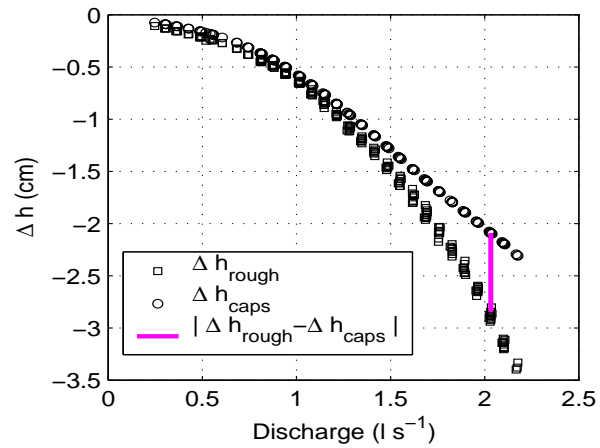


Figure 2: Head loss for increasing flow discharge with plexiglass caps (circle) and with mud cores (square): excess of bed shear stress due to mud roughness for a given discharge is proportional to the distance between the two curves as displayed by the thick vertical line.

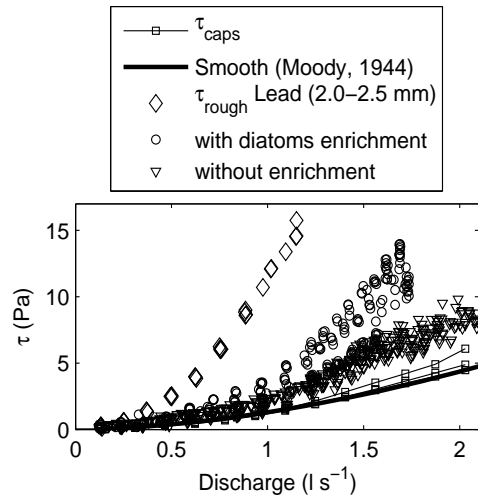


Figure 3: *Bed shear stress ( $\tau$ ) versus pump discharge in the mesocosm experiments. Bed shear stress measured in three different experiments with plexiglass caps (open squares), in the experiment with a plane bed formed by 2.25 mm calibrated particles (open diamonds), and the smooth bed reference (thick line, using Moody (1944) smooth friction factor in equation 2) are displayed.*

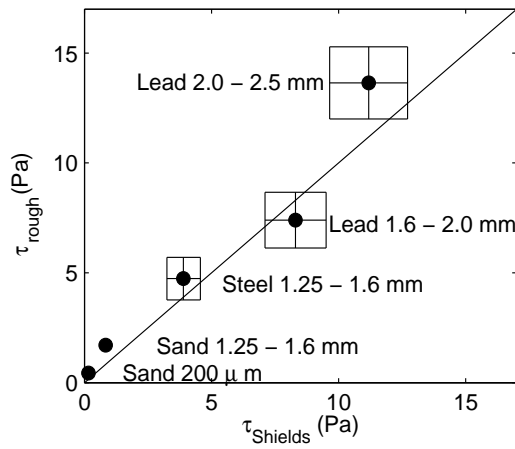


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