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► **To cite this version:**

Abdelwadoud Mehenni, Olivier Cuisinier, Farimah Masrouri. Impact of Lime, Cement, and Clay Treatments on the Internal Erosion of Compacted Soils. *Journal of Materials in Civil Engineering*, 2016, 28 (9), pp.04016071. 10.1061/(ASCE)MT.1943-5533.0001573 . hal-01409044

HAL Id: hal-01409044

<https://hal.univ-lorraine.fr/hal-01409044v1>

Submitted on 5 Jul 2019

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Impact of lime, cement and clay treatments on the internal erosion of compacted soils

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Keywords

Soil stabilization, internal erosion, lime, cement, clay treatment

44 **Abstract**

45 The aim of this paper is to study the impact of certain soil treatments on the internal erosion
46 characteristics of treated compacted silt. The experiments measured the internal erosion using
47 the hole erosion test (HET). This study aims to describe the effects of clay, lime and cement
48 soil treatments on the internal erosion, specifically with regard to the amount of treatment
49 used and the curing time. The internal erosion resistance was quantified by the coefficient of
50 soil erosion and the critical shear stress. The results demonstrated that clay treatment could
51 reduce the coefficient of soil erosion depending on the nature and percentage of clay added to
52 the soil. The results also showed that lime and cement treatment primarily increased the
53 critical shear stress of the tested silt. This increase was higher with cement treatment and was
54 dependent on the amount of the added product. The impact of the curing time (up to 30 days)
55 on the evolution of the erosion characteristics was not relevant for the lime-treated silt,
56 whereas that of the cement-treated silt was dependent on the amount of cement added to the
57 soil.

58

59 **Introduction**

60 Soil treatment with different types of clays, lime or cement is widely used in geotechnical
61 engineering to improve soil characteristics and thus achieve a higher design strength, elastic
62 modulus, and lower hydraulic conductivity, among other features. The main effects of these
63 treatments on the geotechnical characteristics of compacted soils are relatively well known.

64 Clayey soils are often used as treatment product specifically to reduce the hydraulic
65 conductivity of soils in order to reach a target design. The reduction of the hydraulic
66 conductivity depends on the percentage and the nature of the clayey soil employed (e.g.,
67 Sivapullaiah et al., 2000, Chapuis, 2002). Several authors (e.g., Eades and Grim 1966, Brandl,
68 1981, Bell 1996) showed that lime treatment improves mainly the soil workability as well as
69 the soil strength. Lime effects on the hydraulic conductivity of soils depend on the
70 compaction conditions (McCallister and Petry 1991, Le Runigo et al., 2009, Cuisinier et al.,
71 2011). Several studies showed the enhancement of mechanical characteristics of soils after
72 cement treatment (e.g., Al-Amoudi 2002, Sariosseiri and Muhunthan 2009). The addition of
73 cement is often related to a decrease of the hydraulic conductivity. However some authors
74 (e.g., Bellezza and Fratolocchi, 2006) showed that the evolution of the hydraulic conductivity
75 is mainly related to the nature of soil, and may increase or decrease after treatment.

76 Nevertheless, using compacted treated soils to build hydraulic earth structures (e.g., earth
77 dams, levees, water retaining structures) raises some specific issues. Several objectives must
78 be met simultaneously; specifically, low permeability and the overall stability of the earth
79 structure are paramount. Moreover, these structures can be affected by different internal or
80 external erosion phenomena. Erosion may affect soils, reducing the life of the structure or
81 even leading to its destruction. Soil treatment with clays, lime or cement could be of interest
82 to increase the strength and reduce soil erodibility, extending the service life of an earth
83 structure. Therefore, the impact of these common treatments on erosion characteristics must

84 be determined. After the description of the erosion process and its experimental
85 characterization, a literature review on the effects of treatments on the internal erosion
86 characteristics is presented.

87 **Background**

88 Erosion phenomena occurring on hydraulic earth structures can be classified into two
89 categories: external erosion and internal erosion. External erosion concerns the outer surfaces
90 of structures, whereas internal erosion occurs within the body of the structure. This study is
91 focused on piping, which is an internal erosion mechanism. According to Fell et al. (2003),
92 the process of internal erosion and piping can be divided into four phases: the initiation of
93 erosion on a concentrated leak, the continuation of erosion, the progression of erosion by the
94 enlargement of the concentrated leak to form a pipe, and the formation of a breach leading to
95 the destruction of the structure.

96 To study internal erosion and piping, Wan and Fell (2002, 2004) developed the hole erosion
97 test (HET), which was derived from other experimental erosion devices, such as the pinhole
98 test (Sherard et al., 1976; ASTM D-4647), the drill hole test (Lefebvre et al., 1985 and Rohan
99 et al., 1986), and the flow pump test (Reddi et al., 2000). The HET characterizes the behavior
100 of soils only once a pipe is completely formed. The test does not allow for the study of the
101 initial phase of the internal erosion process (i.e., the formation of the pipe in the soil). In fact,
102 in the HET, a preformed hole in a soil sample is created to simulate a pipe; erosion of the pipe
103 is then studied by subjecting the hole to a flow of water. The growth of the diameter of the
104 hole is monitored by measuring hydraulic parameters (i.e., the pressure drop between the
105 areas upstream and downstream of the sample and the flow through the hole). The results
106 determine the empirical erosion law of the material, which can be expressed as follows:

$$107 \quad \dot{\varepsilon} = k_{er} (\tau - \tau_c) \quad (1)$$

108 where:

109 $\dot{\epsilon}$ is the erosion rate per unit surface area of the hole at time t (kg/s/m²),

110 τ is the hydraulic shear stress along the hole at time t (Pa),

111 k_{er} is the coefficient of soil erosion (s/m),

112 τ_c is the critical shear stress (Pa).

113 The HET yields two parameters that characterize the soil erosion behavior: *i*) the critical shear
114 stress τ_c , corresponding to the minimum shear stress necessary to initiate the departure of soil
115 particles; and *ii*) the coefficient of soil erosion k_{er} , which expresses the erosion rate during
116 the erosion process.

117 To compute $\dot{\epsilon}$ and τ , it is necessary to determine the variation of the diameter of the hole
118 during the test; several assumptions are made following this measurement. It is assumed that
119 erosion occurs on a uniform circular cross section along the length of the soil sample during
120 the test. Wan and Fell (2004) proposed a method to determine the growth of the hole diameter
121 during erosion based on the friction factor. This method required the determination of the
122 final hole diameter after erosion, which is typically difficult to evaluate because the final
123 shape of the hole is often irregular. Wan and Fell (2004) assumed that the friction factor in
124 laminar or turbulent flow varies linearly with time. Two problems with this approach can be
125 noted: 1) during the drilling step, the hole is disturbed, and thus, the initial friction factor used
126 in the calculations is not representative of the real situation; and 2) the hypothesis of the linear
127 variation of the friction factor on the hole during the test is not realistic (Haghighi et
128 al., 2013). Another method uses the turbidity signal to compute the growth of the hole
129 diameter during the test (Pham, 2008; Indraratna et al., 2009; Benahmed and Bonelli, 2012;
130 Haghighi et al., 2013).

131 To classify soils by their resistance to internal erosion, authors often use the method proposed
132 by Wan and Fell (2004), which is based on k_{er} . The Erosion Rate Index is calculated as $ERI =$

133 $-\log(k_{er})$, and soils are classified by extremely rapid erosion (1) to extremely slow erosion
134 (6), as shown in Table 1. However, this method does not consider τ_c , which qualifies the
135 shear stress needed to initiate soil erosion along the pipe; this parameter is not included
136 because the HET does not yield good repeatability of τ_c (Wan and Fell, 2002). Indeed, for
137 specimens prepared under the same conditions, different studies indicated that both k_{er} and τ_c
138 might vary from one test to another for the same soil. k_{er} can vary by a factor of 2 (e.g., Wan
139 and Fell, 2002; Farrar et al., 2007), whereas τ_c may vary by a factor of more than 10 (e.g.,
140 Wan and Fell, 2002). The use of the *ERI* allows for the classification of different samples of
141 the same soil in the same erosion group even if k_{er} varies from one test to another. Another
142 method to overcome these repeatability issues is to use all results for $\dot{\epsilon}$ and τ_c obtained from
143 several specimens, prepared under the same conditions, to determine a unique erosion law
144 (Pham, 2008; Haghghi, 2012).

145 In the last decade, several optimizations were made on the HET to allow for more control of
146 the hydraulic parameters, such as the hydraulic pressure drop across the sample or the water
147 flow rate (Pham, 2008; Indraratna et al., 2009; Wahl, 2010; Benahmed and Bonelli, 2012;
148 Luthi et al., 2012; Haghghi et al., 2013).

149 The HET was used to assess the impact of the compaction parameters (i.e., the initial water
150 content, initial dry density and compaction energy) on the erodibility of compacted soils.
151 Attom (2012) showed that at the same initial dry density, soils exhibit a higher *ERI* if they are
152 compacted on the wet side of optimum. This observation has been confirmed by Wan and Fell
153 (2002) and Lim (2006). The increase in the initial dry density of soil induces a higher *ERI*
154 (Wan and Fell, 2002; Lim, 2006) and a higher τ_c (Benahmed and Bonelli, 2012). For
155 compacted soils, the effects of the initial dry density, on increasing the *ERI*, are also related to
156 the initial water content; the increase of the *ERI* is more pronounced on the dry side of
157 optimum (Attom, 2012). Wahl (2010) and Attom (2012) have also shown that along the

158 compaction curve, the highest *ERI* values are obtained for coupled values of the optimum
159 initial water content and maximum dry density.

160 The percentage of clay particles can modify the internal erosion resistance of soils. Several
161 authors showed that increasing the clay percentage induces a higher τ_c and lower k_{er}
162 (Bennabi et al., 2012; Benahmed and Bonelli, 2012; Haghghi et al., 2013).

163 A limited number of studies considered the improvement of soil internal erosion
164 characteristics by lime or cement treatment. To study the internal erosion of a specific soil, it
165 is necessary to use a device capable of applying the necessary inlet pressure and hence the
166 necessary pressure drop across the soil sample required to initiate the erosion of the studied
167 soil. However, the existing devices are not convenient to fully characterize the impact of these
168 treatments on erodibility due to technical limitations. In fact, the study of erosion in treated
169 soils requires a high level of applied hydraulic shear stress that few devices can provide.
170 Chevalier et al. (2012) showed that a 2% lime-treatment of silt can increase τ_c by a factor of
171 at least 4. Herrier et al. (2012) studied a 2% lime-treated soil with a curing time of 14 days
172 and observed that τ_c increased by a factor of 20, whereas k_{er} was reduced by a factor of 10.
173 Indraratna et al. (2009) worked on silty sand treated with cement with a τ_c near zero before
174 treatment; they showed that treatment with 3% cement increased τ_c by up to 50 Pa and
175 decreased the k_{er} by two orders of magnitude. Additionally, they found that the decrease in
176 erosion by cement treatment is directly related to the percentage of cement added to the soil.

177 Thus, the literature has shown that the HET could be a convenient method to quantify soil
178 erodibility. Furthermore, treatment with clays, lime or cement could reduce soil erodibility.
179 However, the limited data available did not provide a sufficient amount of information
180 regarding the impact of clay treatment on silty soils or the impact of lime and cement
181 treatments, the curing time and the percentage of admixture.

182 The main focus of this study is to investigate the impact of soil treatments on erosion
183 characteristics. A new enhanced HET device was created to quantify the effects of different
184 treatments. In the following sections, the testing procedures and theoretical models are
185 presented, and the modifications produced by the treatments are discussed.

186 **Materials and experimental setup**

187 In this section, details regarding the tested materials and experimental setup are presented.

188 **Materials**

189 The studied soil was a silty soil from northern France; Table 2 summarizes the main physical
190 and geotechnical properties of the soil. Four types of commonly used treatment products were
191 considered: kaolinite (2 and 9%), bentonite (2%), quicklime (1 and 3%) and cement (3 and
192 6%). These percentages refer to the quantity of the product calculated on a dry soil weight
193 basis. These choices were made based on usual field uses of these treatment products in
194 France (SETRA-LCPC, 2000). The bentonite was sodium smectite clay. The lime used in this
195 study contained 94% of quicklime (CaO). The category of the cement was CEM II (i.e., 65%
196 of clinker, 35% of limestone and fly ash).

197 **Specimen preparation**

198 First, the compaction characteristics of the different mixtures were determined. For specimen
199 preparation, the water content of the soil was adjusted to the desired water content for
200 compaction. After a storage period of 24 h, during which the moisture content homogenized,
201 the soil and treatment product were thoroughly mixed. When the lime treatment was added,
202 the mixture was left for 1 h in an airtight container before compaction. When the cement
203 treatment was used, compaction was carried out within a few minutes (maximum of 30 min)
204 after treatment to account for the setting time of the cement. When clay treatments were used,
205 no specific time was needed between the mixing and compaction; the mixture was statically

206 compacted in the cell test to the target dry density. When a curing period prior to testing was
207 required, the compacted samples were wrapped in plastic sheets and kept at $20.0 \pm 1.5^\circ\text{C}$ to
208 prevent any water loss. The compaction characteristic curves were determined for each type
209 and percentage of treatment according to the standard ASTM-D 698; the results of these
210 experiments are summarized in Table 3.

211 **Experimental strategy**

212 Several authors (e.g., Mitchell et al. 1965; Benson and Daniel 1990; Watabe et al. 2000)
213 showed that soil hydraulic conductivity reaches its minimum value on the wet side of
214 optimum; thus, the investigations were focused on one specific compaction state for each
215 treatment and each percentage. This state was defined by $w = w_{\text{OMC}+3\%}$ and $\rho_d = 0.96 \rho_{\text{dmax}}$,
216 depending on the nature and percentage of each treatment, where w is the compaction
217 moisture content (%), w_{OMC} is the optimum moisture content (%), ρ_d is the dry density
218 (Mg/m^3) and ρ_{dmax} is the maximum dry density (Mg/m^3) (Table 3). The soil, untreated and
219 treated, was statically compacted directly in the cell mold. After treatment and compaction,
220 the soil specimens were sealed in airtight bags and cured at 20°C for different periods (e.g., 0,
221 7, and 30 days) before starting the erosion tests.

222 **Experimental procedures**

223 In this section, the enhanced HET device, test procedure and theoretical calculation methods
224 are described.

225 **HET device**

226 An enhanced HET device was developed to measure the internal erosion of the compacted
227 treated soil specimens. This device included several optimizations that allowed for the
228 application of a high inlet pressure, producing a large pressure drop across the sample and
229 hence a high hydraulic shear stress along the hole.

230 Major improvements were made to the pressure system: the water pressure at the inlet of
231 sample was applied with a special air-water reservoir; an electromechanically operated valve
232 controlled the air flow in the air-water reservoir during the experiment; the inlet pressure was
233 controlled by a sensor at the entrance of the sample; and the water pressure was also measured
234 at the outlet of the sample. The maximum inlet pressure exceeded 650 kPa, producing the
235 necessary pressure drop of 650 kPa between the flows upstream and downstream of the soil
236 samples.

237 Other optimizations were made to the configuration of the testing cell. A detailed view of the
238 testing cell is provided in Figure 1. The soil samples were strongly held within the testing
239 device from both sides. This prevented any loss of pressure and water leakage and also
240 allowed for better holding of the soil specimen during the test under the large pressure drops.

241 The water flow was measured with an ultrasonic flowmeter and ranged from 0 to 1.4 L/s. A
242 turbidimeter was connected to the outlet of the test cell to measure the effluent turbidity to
243 determine the diameter of the hole during the test.

244 The initial diameter of the hole in the sample was between 3 and 6 mm. The tested samples
245 were cylindrical, with a diameter of 70 mm and a length between 70 and 150 mm. When
246 using a sample of 70 mm length and an initial hole of 6 mm, the device allowed for the
247 application of a hydraulic shear stress of approximately 10,000 Pa (calculated with
248 equation 6).

249 **Test procedure**

250 The initial hole was made by drilling into the specimen center; the specimen was then placed
251 in the testing cell. Saturation of the whole system ensured that no air bubbles were trapped
252 inside the cell or pipes; this saturation was established under a low flow while the vent valves
253 were open. The erosion test was conducted by controlling and monitoring hydraulic

254 parameters (i.e., the pressure applied to the sample, the pressure drop between the upstream
255 and downstream of sample, and the flow through the hole).

256 In the literature, three different methods were used depending on which hydraulic parameter
257 was applied and controlled during the test: i) applying a constant pressure at the upstream side
258 of the sample (Wan and Fell, 2002 and 2004; Muttuvel, 2008); ii) applying a constant drop
259 pressure across the sample (Pham, 2008; Haghghi, 2012); and iii) maintaining a constant
260 flow through the hole (Bonelli and Benahmed, 2007; Benahmed and Bonelli, 2012). The
261 methods of the tests performed are related to technical constraints only and do not influence
262 the erosion law of the soil, which is independent of the hydraulic conditions of the test.

263 In this study, tests were performed by applying a constant pressure at the inlet of the sample.
264 Some preliminary tests were performed for each treatment to define the necessary range of
265 applied pressure to initiate erosion by detaching soil particles. This pressure was related to the
266 nature of the soil and the treatment product used. Table 4 provides some examples of the
267 initial inlet pressure necessary to begin erosion for different treatment products and
268 percentages. The erosion starting process was determined by the turbidity signal which
269 increased when the erosion of soil particles increased.

270 A typical set of the test parameters monitored during a test performed on untreated soil is
271 shown in Figure 2. The system can maintain a constant inlet pressure (Figure 2.a). At the
272 beginning of the test, and after the clear-out of the hole from the soil particles detached during
273 the drilling process, soil erosion increased rapidly due to the large pressure drop between the
274 inlet and outlet of the sample (Figures 2.b and 2.c). Detachment of soil particles produced an
275 increase in the hole diameter, creating an increase in the flow through the sample (Figure 2.d)
276 and a progressive decrease in the pressure drop between the inlet and outlet of the sample.
277 The evolution of the erosion rate is shown in Figure 2.e. After the increasing soil erosion
278 phase, as also shown in the turbidity signal, the detachment of soil particles decreased

279 progressively, likely because of the decrease in the hydraulic shear stress along the hole
 280 (Figure 2.f). The changes of the hydraulic shear stress are related to both the increase of the
 281 hole diameter and the decrease of the pressure drop between the inlet and outlet of the sample
 282 (equation 6). The test ended when the turbidity reached a lower asymptote. At the end of each
 283 test, the cell was dismantled, and the hole in the specimen was filled with liquid wax to
 284 determine the final characteristics of the eroded hole.

285 **Theoretical model**

286 *Integration of the final shape of the hole*

287 For all the successful tests, the cross section of the eroded hole at the end of the test was in
 288 general circular or in some cases slightly ellipsoidal. These observations lead to suggest a
 289 general theoretical model that accounts for the real final shape of the hole and accurately
 290 compute the erosion rate and hydraulic shear stress. This model was based on the two radii of
 291 the hole (a and b) to better approximate the real shape of the hole. a and b are equal for a
 292 circular hole.

293 The erosion rate $\dot{\epsilon}$ (kg/s/m²) for a given hydraulic shear stress can be expressed by the eroded
 294 soil mass (kg) per unit surface area of the hole at time t (s):

$$295 \quad \dot{\epsilon} = \frac{\text{mass of eroded soil}}{\text{surface area of the hole} * \text{unit of time}} \quad (2)$$

296 Considering an ellipsoidal hole, the cross section is $S = \pi ab$ and the perimeter is $p_r =$
 297 $\pi\sqrt{2(a^2 + b^2)}$, where a and b are the smaller and larger radii of the ellipsoid, respectively.

298 The erosion rate can then be expressed as follow:

$$299 \quad \dot{\epsilon} = \frac{\rho_d}{2} \sqrt{\frac{2}{a(t)^2 + b(t)^2}} [a(t)db + b(t)da] \frac{1}{dt} \quad (3)$$

300 where ρ_d is the dry density of the soil (Mg/m³); $a(t)$ and $b(t)$ are the radii of the hole (m) at
 301 time t ; and db and da are the variations of the radii at the elementary time dt .

302 Using the principle of the equilibrium forces carried out on a volume of fluid between the
 303 inlet and outlet of the hole, the applied shear stress to the surface of the hole is related to the
 304 hydraulic gradient measured across the hole (Wan and Fell, 2002, Muttuvel, 2008).
 305 Considering the ellipsoidal shape, the hydraulic shear stress along the hole can be expressed
 306 as:

$$307 \quad \tau = \frac{1}{\sqrt{2}} \cdot \frac{\Delta P(t)}{L} \cdot \frac{a(t) \cdot b(t)}{\sqrt{a(t)^2 + b(t)^2}} \quad (4)$$

308 where L is the length of the sample (m) and $\Delta P(t)$ is the pressure drop between the inlet and
 309 outlet of the sample (Pa). To solve this equation, it is assumed that there is a unique
 310 relationship between the radius of the hole: $a = \alpha b$. The factor α is measured at the end of the
 311 test and assumed to remain constant during the test. The final radii a and b are taken as the
 312 mean values along the hole, and only specimens with a uniform shape along the hole were
 313 considered. Then, $\dot{\varepsilon}$ and τ are obtained as follows:

$$314 \quad \dot{\varepsilon} = \rho_d \cdot \sqrt{\frac{2\alpha^2}{\alpha^2 + 1}} \cdot \frac{db}{dt} \quad (5)$$

$$315 \quad \tau = \frac{\Delta P(t)}{L} \cdot \frac{\alpha}{\sqrt{2(\alpha^2 + 1)}} \cdot b(t) \quad (6)$$

316 Equations 5 and 6 account for the general shape of the hole. For a circular hole, a is equal to
 317 b ; the coefficient α is then equal to 1.

318 ***Determination of the evolution of the radius***

319 To compute the erosion parameters (k_{er} , τ_c), it is necessary to determine the evolution of the
 320 radius of the hole (db) during the test, which can be related to the soil eroded mass.

321 Two assumptions were made to determine the evolution of the cross-sectional shape of the
 322 hole: *i*) erosion is uniform along the hole and *ii*) the factor α relating the radii of the hole is
 323 constant. The soil eroded mass can be expressed as follows:

$$324 \quad dm(t) = 2 \cdot \alpha \cdot \pi \cdot \rho_d \cdot L \cdot b(t - 1) \cdot db \quad (7)$$

325 where $dm(t)$ is the soil eroded mass (kg).

326 The soil eroded mass during time step dt is also related to the measured concentration of soil
327 particles as follows:

$$328 \quad dm(t) = c(t) \cdot q(t) \cdot dt \quad (8)$$

329 where $c(t)$ is the concentration of soil particles (kg/m^3) and $q(t)$ is the water flow passing
330 through the hole (m^3/s).

331 From Equations 7 and 8, db is given as follows:

$$332 \quad db = \frac{c(t) \cdot q(t)}{2 \cdot \alpha \cdot \pi \cdot \rho_d \cdot L} \cdot \frac{dt}{b(t-1)} \quad (9)$$

333 Given the initial radius of the hole b_0 , the radius at each time step can then be expressed as
334 $[b(t) = b(t - 1) + db]$.

335 The turbidity signal was used to determine the instantaneous concentration during the erosion
336 process (Reddi et al., 2000; Pham, 2008; Muttuvel, 2008). The relationship between the
337 concentration of soil and the turbidity of the effluent concentration was also calibrated. These
338 calibrations were performed for each treatment and each percentage of treatment product.
339 Some examples of the relationship between the soil concentration and turbidity signal are
340 given in Figure 3. The results indicated a bilinear calibration curve for all samples. Hence,
341 two relationships were considered for each treatment, one for each concentration range. The
342 threshold concentration value was approximately 1 kg/m^3 and depended on the nature and
343 percentage of treatment.

344 ***Validation of the calculation method***

345 Figure 4 presents the final eroded diameter measured at the end of the test versus the final
346 diameter calculated from the turbidity signal (Equation 9). The slight differences could be due
347 to inaccuracy of initial and final drilled hole measurements and the turbidity sensor response.
348 The results showed the relevance of the technique used to determine the hole diameter during
349 the test using the soil detachment particles.

350 **Impact of treatment on soil erodibility**

351 **Untreated soil**

352 The repeatability of the erosion parameters obtained with the new HET device was verified
353 with the untreated soil by performing several tests. Two sets of these results are shown in
354 Figure 5. Table 5 shows the erosion parameters determined from six tests. k_{er} varies between
355 1.13×10^{-04} and 3.04×10^{-04} s/m, and τ_c varies between 291 and 615 Pa. This dispersion is of
356 the same order of magnitude as has been found in previous studies. As an example, Wan and
357 Fell (2002) found that τ_c for a clay-sandy soil varied between 85 and 327 Pa. Haghghi (2012)
358 also found a similar range of τ_c (i.e., from 152 to 541 Pa) for a similar silty soil.

359 The mean values for the untreated silt are $k_{er} = 2.07 \times 10^{-04}$ s/m and $\tau_c = 429$ Pa. The *ERI* of
360 the tested materials is between 3.59 and 3.95; therefore, all untreated specimens are classified
361 as having “moderately rapid” erosion according to the classification of Wan and Fell (2002).

362 The studied silt has a high critical shear stress compared to the values typically observed in
363 untreated soil (Wan and Fell, 2002). This can be related to the high percentage of the fine
364 particle fraction ($< 80 \mu\text{m}$), 99.2%, and to the compaction conditions. In fact, compaction on
365 the wet side of optimum allows for a better rearrangement of the soil particles, than the dry
366 side of the optimum, and reduces porosity (e.g., Benson and Daniel 1990). Compaction on the
367 wet side ($w = 17.5\%$) combined with the high dry density ($\rho_d = 1.73 \text{ Mg/m}^3$) induces a dense
368 arrangement of soil particles. This arrangement hinders the detachment of soil particles and
369 requires a greater level of hydraulic shear stress to start the erosion. However, once this value
370 of hydraulic shear stress is reached, the erosion rate progresses rapidly, as shown by the value
371 of the coefficient of soil erosion ($k_{er} = 2.07 \times 10^{-04}$ s/m).

372 **Clay treatment**

373 Examples of the erosion law for the clay treatments are shown in Figure 6, and Table 6
374 summarizes the erosion characteristics for the clay-treated soil obtained from the other tests.
375 The use of 2% kaolinite did not significantly change k_{er} ; however, τ_c tended to increase and
376 had a mean value of 607 Pa. The addition of 9% kaolinite decreased k_{er} by one order of
377 magnitude and induced a small increase in τ_c with a mean value of 513 Pa. According to the
378 classification of Wan and Fell (2002), the silt treated with 2% kaolinite was in the
379 “moderately rapid” group, whereas the silt treated with 9% kaolinite became “moderately
380 slow”. Therefore, 9% kaolinite was required to significantly modify soil erodibility.

381 For the treatment with 2% bentonite, k_{er} is of the same order of magnitude for all samples
382 and is approximately 5.00×10^{-05} s/m (Table 6) which is less than one order of magnitude less
383 than that of the untreated soil. τ_c varies between 123 and 483 Pa, which are included within
384 the interval of variation of τ_c for untreated silt. Thus, the silt treated with 2% bentonite is
385 classified as “moderately slow”.

386 The enhancement of the silt internal erosion characteristic induced by clay treatment is then
387 characterized mainly by the reduction of the coefficient of soil erosion depending on the
388 nature and percentage of the added product.

389 **Lime treatment**

390 To study the internal erosion of lime-treated silt, it was necessary to apply an inlet pressure of
391 up to 250 kPa for 1% and 300 kPa for 3% lime to initiate soil erosion.

392 A typical set of results for the lime-treated silt is presented in Figure 7. Two phases can be
393 distinguished during the test. The erosion process was initiated for a hydraulic shear stress of
394 926 Pa with a slope k_{er} of 3.76×10^{-04} s/m until a maximum erosion rate of 0.30 kg/s/m² was
395 reached. Then, the erosion rate decreased and stopped for a hydraulic shear stress of 1,500 Pa
396 with a mean slope of approximately 2.65×10^{-04} s/m. This behavior was observed with 1%
397 and 3% lime after 7 days of curing time. τ_c at the ending phase was higher than during the

398 starting phase (Figure 7), indicating that the soil resisted erosion more at the end of the test
399 than at the beginning. Such behavior could be explained by the type of material used. Indeed,
400 lime-treated soil can be considered as brittle material. The drilling is a mechanical process
401 which may damage the brittle material by inducing small cracks. A small area of the soil
402 around the hole could have been damaged during the drilling of the hole after the curing
403 period. This damaged part is then the first to be easily eroded during the test, leading to a
404 higher erodibility than the undisturbed part of the sample.

405 To verify this hypothesis, some tests were conducted on 3% lime-treated silt with the hole
406 being drilled just after sample compaction. The drilled sample was then left for curing until
407 the erosion test was performed. The results in Figure 8 showed that the effects of the drilling
408 process were less pronounced when the drilling was made before the curing time; this
409 observation was made for both specimens after 7 days of curing (Figure 8.a and 8.b) and after
410 30 days of curing (Figure 8.c and 8.d). The results also indicated that the erosion law was
411 identical at the starting and ending phases of the test. In fact, soil drilling occurred before the
412 beginning of the formation of the cementitious compounds that bind the soil particles. The
413 soil is then less disturbed by the drilling just after compaction than when drilling occurs after
414 curing. The drilling step after curing significantly modified the soil and produced different
415 behaviors between the starting and ending phases of erosion. To examine the impact of
416 treatment on the erosion characteristics, only the characteristics stemming from the ending
417 phase will be considered; these characteristics correspond to the erosion of the soil that is less
418 disturbed by the drilling process.

419 Some results for lime-treated soil are shown in Table 7, and examples of the erosion law are
420 shown in Figure 9. For treatment with 1% lime, k_{er} varied between 1.09×10^{-04} and 2.87×10^{-04}
421 s/m regardless of the curing time. For treatment with 3% lime, k_{er} varied between
422 1.54×10^{-04} and 4.52×10^{-04} s/m regardless of the curing time. Lime treatment increases the τ_c

423 of the untreated soil, yielding values of up to 1,770 Pa for 1% lime and 1,889 Pa for 3% lime.
424 Moreover, τ_c tended to increase with curing time but not in any common progression.
425 The erosion rate during the test was higher for samples treated with 3% lime than for the
426 untreated silt (Figure 9). This observation could be explained by the maximum coarse grain
427 size in the treated soil, which is higher than the untreated soil; furthermore, during the erosion
428 of the treated soil, the detachment of particles accompanied aggregates of larger size than for
429 the untreated silt. It was also observed during the tests, that the erosion of lime treated soil
430 particles often occurs by the detachment of aggregates of soil and not only individual soil
431 particles. Hence, the erosion rate will be higher for the lime-treated silt.
432 The erosion of the lime-treated silt is classified as “moderately rapid,” as is that of the
433 untreated soil, regardless of the lime percentage or curing time. The impact of the lime
434 treatment cannot be observed in these tests because the classification of Wan and Fell (2002)
435 does not consider the critical shear stress.
436 The improvement of the silt internal erosion characteristics induced by lime treatment is then
437 characterized mainly by the increase in the critical shear stress regardless of the curing time
438 and the percentage of the added product.

439 **Cement treatment**

440 Some results from the HET for the cement treatment are shown in Table 8. For 3% cement, it
441 was necessary to apply an inlet pressure of up to 450 kPa to initiate the soil erosion; this is
442 reflected by the high hydraulic shear stress. For most tested samples, erosion started at a
443 hydraulic shear stress of 2,000 Pa, and the erosion was mainly independent from the curing
444 time. For the lime-treated silt, the erosion law exhibited a different behavior between the
445 beginning and end of the tests. Therefore, the same selection process was used to compute the
446 erosion parameters for each step as described for the lime treatment cases. In case of
447 treatment with 6% cement, the applied inlet pressure was more than 500 kPa, and the length

448 of samples was reduced to 70 mm to apply a higher hydraulic shear stress. Detachment of soil
449 particles started after 4,000 Pa for most specimens; however, the erosion law exhibited non-
450 linear characteristics for most specimens, especially after 7 days of curing. Thus, it was
451 difficult to compute k_{er} for some samples, and in such cases, τ_c was reported as the threshold
452 of the hydraulic shear stress at the end of erosion.

453 Examples of the erosion law for cement-treated specimens are shown in Figure 10. For
454 treatment with 3% cement, k_{er} varied between 1.13×10^{-04} and 1.67×10^{-04} s/m, regardless of
455 the curing time. For treatment with 6% lime, k_{er} varied between 1.00×10^{-05} and $8.00 \times 10^{-$
456 05 s/m. Furthermore, for treatment with 3% cement, τ_c varied between 2,850 and 3,619 Pa,
457 and the curing time appeared to have no effect on the evolution of τ_c . In the case of 6%
458 cement, τ_c varied between 4,400 and 6,800 Pa for a curing time of 1 day and reached
459 9,893 Pa after 7 days of curing. Thus, the erosion of cement-treated silt is classified as
460 “moderately rapid” for 3% cement and “moderately slow” for 6% cement.

461 The main enhancement of the silt internal erosion characteristic induced by cement treatment
462 is then characterized by the increase in the critical shear stress and may also result in a
463 decrease in the coefficient of soil erosion depending on the percentage of the added product.

464 **Discussion**

465 Figure 11 shows the erosion characteristics (k_{er} and τ_c) obtained for both treated and
466 untreated silt.

467 The addition of kaolinite induced a relatively small increase in τ_c , and the addition of
468 bentonite did not significantly change the range of τ_c . This observation can be explained by
469 the fact that the initial compaction states (ρ_d , w) were similar for untreated and clay-treated
470 silt.

471 The addition of 9% kaolinite and 2% bentonite decreased k_{er} by one order of magnitude. The
472 nature of the clay particles appears to have an important effect on the erosion behavior of soil.
473 Indeed, the addition of only 2% bentonite has similar effects to the addition of 9% kaolinite.
474 A higher percentage of clay fraction increases the resistance of sandy soils to erosion (e.g.,
475 Bennabi et al., 2012; Benahmed and Bonelli, 2012). This study showed that this trend is also
476 valid for silty soil.

477 The lime treatment resulted in an increasing τ_c , even with a short curing time (1 day) (Figure
478 11), indicating that the increase in erosion resistance by lime treatment is a short-term effect
479 of lime. The development of longer-term (pozzolanic) reactions for increasing the hydraulic
480 shear stress appears to be less important. One of the short-term mechanisms responsible of
481 these changes could be the flocculation-aggregation of soil particles caused by lime addition.
482 The coefficient of soil erosion k_{er} maintained the same level with or without lime treatment
483 regardless of the lime percentage or curing time, indicating that once erosion has started, the
484 rate of soil detachment will be the same as untreated silt. This result can be explained by the
485 detachment process of soil particles. As it was observed during the tests, the erosion of soil
486 particles often occurs by the detachment of aggregates of soil and not only individual soil
487 particles; this indicates that erosive forces can break more easily the weaker bonds between
488 aggregates.

489 The main impact of cement treatment was the increase in τ_c in proportion to the percentage
490 of cement (Figure 11). Furthermore, the increasing cement percentage was accompanied by a
491 decrease in k_{er} . The enhancement of the erosion characteristics induced by cement treatment
492 is related to the cement setting and the development of cementitious compounds, which
493 induce strong bonds between soils particles. The detachment of soil particles becomes more
494 difficult, making the soil more resistant to erosion. When treated with 3% cement, this
495 improvement came in early ages of curing time, and no further significant modification was

496 observed until 30 days. At higher percentages of cement (6%), an increase in the critical shear
497 stress was obtained with increasing curing time. This behavior could be related to the soil-
498 cement setting time, which may be longer for a higher amount of cement treatment.

499 **Conclusion**

500 The main objective of this paper was to study the impact of soil treatment on the internal
501 erosion resistance of treated compacted silt. A new enhanced HET device was developed to
502 determine the erosion characteristics of treated materials. A modified interpretation method
503 that considered the final shape of the eroded hole has been proposed.

504 The results showed that the studied silt had a higher critical shear stress compared to the
505 values typically observed in the untreated soil. This higher critical shear stress was primarily
506 caused by the compaction conditions on the wet side of the optimum water content. However,
507 the mean coefficient of soil erosion was 2.07×10^{-04} s/m, which may accelerate detachment
508 due to erosion once it has begun. The solution to this issue could be the treatment of soil by
509 adding clay, lime or cement. The following conclusions can be made based on the results
510 obtained:

- 511 • The use of clay soil as a treatment product reduces the erosion rate of soil particles.
512 This effect is related to the nature of the clay, and the use of bentonite further reduces
513 the coefficient of soil erosion than the use of kaolinite at the same percentage.
- 514 • Lime treatment increases the internal erosion resistance of soil by increasing the
515 critical shear stress. This effect is similar to either 1 or 3% lime treatment and occurs
516 rapidly, with no significant change with increased curing time up to 30 days.
- 517 • Cement treatment increases the critical shear stress, and the increase in erosion
518 resistance is proportional to the percentage of cement used. A high percentage of
519 cement will also provide a smaller coefficient of soil erosion. The enhancement occurs

520 rapidly for 3% cement, whereas higher percentages require additional curing time to
521 yield greater erosion resistance.

522 Additional works are required to relate the evolution of erosion characteristics to the
523 microstructure of the treated soil which may give more information about the factors
524 responsible of the changes of the erosion characteristics.

525 Although the short-term effects seemed to be positive, the use of these treatments for
526 hydraulic earth structures should consider their long-term behavior. In fact, such products
527 require specific studies to assess the evolution of these parameters over time when the
528 structures are submitted to climatic conditions, which can affect the sustainability of
529 treatments and decrease their initial performances. The impact of these different treatment
530 products on other hydro-mechanical parameters (e.g., hydraulic conductivity, unconfined
531 compression strength) of the tested soil should also be considered in the framework of the
532 selection of the most cost effective treatment product.

533

534

535 **Acknowledgment**

536 The authors would like to thank S. Bonne, E. Lavallée and T. Le Borgne from DTP -
537 Bouygues Construction - France for their valuable support of this study.

538

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636

637 **Tables**

638 **Table 1: Method of the classification of soils based on their erodibility (Wan and Fell,**
639 **2002).**

640 **Table 2: Physical and geotechnical properties of the studied soil.**

641 **Table 3: Optimum Proctor compaction characteristics for silt treated with different**
642 **products and the compaction characteristics for the HET samples.**

643 **Table 4: Example of the range of the initial applied inlet pressures for different**
644 **treatments.**

645 **Table 5: Erosion characteristics for the untreated silt calculated from 6 tests.**

646 **Table 6: Impact of clay treatments on the erosion characteristics of the studied silt.**

647 **Table 7: Erosion characteristics of lime-treated silt calculated from several tests after 1,**
648 **7 and 30 days.**

649 **Table 8: Erosion characteristics for cement-treated silt calculated from several tests**
650 **after 1, 7 and 30 days.**

651

652 **Figures**

653 **Figure 1: Schematic of the enhanced HET testing cell.**

654 **Figure 2: Example results for a HET performed on a sample of untreated silt.**

- 655 a) pressure applied at the inlet of the sample.
- 656 b) pressure drop between the inlet and outlet of the sample.
- 657 c) turbidity signal of the effluent.
- 658 d) flow through the sample.
- 659 e) erosion rate.
- 660 f) hydraulic shear stress.

661 **Figure 3: Relationship between the soil concentration and turbidity signal.**

- 662 a) concentration interval [0 - 1.5 kg/m³].
- 663 b) concentration interval [0 - 15 kg/m³].
- 664 The best fit line is drawn for each treatment.

665 **Figure 4: Representation of the calculated and measured diameter at the end of the**
666 **different tests.**

667 **Figure 5: Two examples of erosion law for the untreated silt.**

668 **Figure 6: Impact of clay treatment on the erosion characteristics of silt.**

669 The lines represent the erosion law drawn from the best fit line for the selected data of each
670 treatment.

671 **Figure 7: Example of the erosion law for lime-treated silt (1%) with 7 days of curing.**

672 **Figure 8: Impact of the drilling on the erosion law of 3% lime-treated soil.**

- 673 a) drilling after 7 days of curing
- 674 b) drilling before 7 days of curing
- 675 c) drilling after 30 days of curing
- 676 d) drilling before 30 days of curing

677 **Figure 9: Examples of the erosion law for lime-treated samples.**

678 The lines represent the erosion law drawn from the best fit line for the selected data of each
679 treatment.

680

681 **Figure 10: Example of the erosion law for cement-treated silt.**

682 The lines represent the erosion law drawn from the best fit line for the selected data of each
683 treatment.

684

685 **Figure 11: Effect of treatment on the erosion characteristics of the studied silt.**

686 The vertical small bar refers to samples where the coefficient of soil erosion was calculated at
687 the starting phase only.

688

689

690 **Table 1: Method of the classification of soils based on their erodibility (Wan and Fell,**
691 **2002).**

Group number	Erosion Rate Index (<i>ERI</i>)	Description
1	<2	Extremely rapid
2	2 – 3	Very rapid
3	3 – 4	Moderately rapid
4	4 – 5	Moderately slow
5	5 – 6	Very slow
6	>6	Extremely slow

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694 **Table 2: Physical and geotechnical properties of the studied soil.**

Soil properties	Value
Liquid limit (%)	28.5
Plastic limit (%)	20.5
Plasticity index (%)	8.0
Passing sieve 80 μm (%)	99.2
Clay size content (<2 μm) (%)	6.0
Specific gravity G_s (-)	2.64

695

696 **Table 3: Optimum Proctor compaction characteristics for silt treated with different**
 697 **products and the compaction characteristics for the HET samples.**

Types of treatment	Notation	Optimum Proctor compaction characteristics		Compaction characteristics for the HET samples	
		ρ_{dmax}	w_{OMC} (%)	ρ_d (Mg/m ³)	w (%)
		(Mg/m ³)			
Silt	S	1.82	15.0	1.73	17.5
+ 2% kaolinite	SK 2%	1.80	15.5	1.73	18.0
+ 9% kaolinite	SK 9%	1.79	15.8	1.74	18.3
+ 2% bentonite	SB 2%	1.78	15.3	1.74	17.8
+ 1% lime	SL 1%	1.75	17.5	1.70	20.0
+ 3% lime	SL 3%	1.73	17.5	1.68	20.0
+ 3% cement	SC 3%	1.81	15.0	1.75	17.5
+ 6% cement	SC 6%	1.82	15.0	1.75	17.5

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700 **Table 4: Example of the range of the initial applied inlet pressures for different**
701 **treatments.**

Type of treatments	Range of initial applied pressure (kPa)
Silt	70-80
+ 2% kaolinite	70-80
+ 9% kaolinite	100-120
+ 2% bentonite	75-85
+ 1% lime	150-250
+ 3% lime	200-300
+ 3% cement	400-500
+ 6% cement	500-650

702

703 **Table 5: Erosion characteristics for the untreated silt calculated from 6 tests.**

Test	k_{er} (s/m)	τ_c (Pa)	Mean values	
			k_{er} (s/m)	τ_c (Pa)
1	2.58×10^{-04}	391		
2	2.16×10^{-04}	389		
3	2.22×10^{-04}	398		
4	1.13×10^{-04}	491	2.07×10^{-04}	429
5	3.04×10^{-04}	615		
6	1.30×10^{-04}	291		

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707 **Table 6: Impact of clay treatments on the erosion characteristics of the studied silt.**

Test	Nature of treatment	k_{er} (s/m)	τ_c (Pa)	Mean values	
				k_{er} (s/m)	τ_c (Pa)
1	+ 2% kaolinite	1.54×10^{-04}	586	1.99×10^{-04}	607
2		2.68×10^{-04}	754		
1	+ 9% kaolinite	4.62×10^{-05}	668	6.92×10^{-05}	530
2		8.10×10^{-05}	391		
3		5.05×10^{-05}	519		
1	+ 2% bentonite	5.66×10^{-05}	357	5.62×10^{-05}	316
2		5.71×10^{-05}	511		
3		5.13×10^{-05}	123		

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711 **Table 7: Erosion characteristics of lime-treated silt calculated from several tests after 1,**
 712 **7 and 30 days.**

Test	Nature of treatment (curing time)	Erosion characteristics from the ending phase		Mean values	
		$k_{er}(s/m)$	$\tau_c(Pa)$	$k_{er}(s/m)$	$\tau_c(Pa)$
1	+ 1% lime (1d)	1.20×10^{-04}	618	1.25×10^{-04}	745
2		2.62×10^{-04}	836		
1	+ 1% lime (7d)	2.87×10^{-04}	1725	2.63×10^{-04}	1660
2		2.35×10^{-04}	1770		
1	+ 1% lime (30d)	2.53×10^{-04}	1538	2.11×10^{-04}	1279
2		1.09×10^{-04}	963		
1	+ 3% lime (1d)	2.47×10^{-04}	1409	2.24×10^{-04}	1200
1	+ 3% lime (7d)	1.75×10^{-04}	1863	2.46×10^{-04}	1707
2		4.52×10^{-04}	1889		
3		2.15×10^{-04}	1567		
4		2.28×10^{-04}	1522		
5		3.07×10^{-04}	1648		
6		1.81×10^{-04}	1608		
1	+ 3% lime (30d)	2.27×10^{-04}	1035	1.71×10^{-04}	1362
2		1.78×10^{-04}	1197		
3		1.68×10^{-04}	1 845		
4		2.42×10^{-04}	1 365		
5		1.67×10^{-04}	1 405		

713

714 **Table 8: Erosion characteristics for cement-treated silt calculated from several tests**
 715 **after 1, 7 and 30 days.**

716 NE: not established at the ending of the erosion phase.

Test	Nature of treatment (curing time)	Erosion characteristics from the ending phase		Mean values	
		$k_{er}(s/m)$	$\tau_c(Pa)$	$k_{er}(s/m)$	$\tau_c(Pa)$
		1	+ 3% cement (1d)	1.13×10^{-04}	2850
2	NE	2850			
1	+ 3% cement (7d)	1.22×10^{-04}	2520	1.31×10^{-04}	2985
2		1.47×10^{-04}	3619		
1	+ 3% cement (30d)	1.43×10^{-04}	2531	1.47×10^{-04}	2886
2		1.67×10^{-04}	3150		
1	+ 6% cement (1d)	8.00×10^{-05}	6475	4.83×10^{-05}	5891
2		1.00×10^{-05}	6800		
1	+ 6% cement (7d)	NE	9734	NE	9814
2		NE	9893		

717







































