Analysis of the dispersivity in soils by applying a modified test based on the pinhole method

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Abstract. The Pinhole test is an empirical probe with a qualitative classification foundation that identifies fine-grained soils with dispersive potential using hydraulic heads. However, the original technique was designed to identify dispersive clays. In some cases, it is misused as a quantitative test for measuring subsurface erosion rates. This paper presents a physicochemical modification to the exact test, based on adding a dispersant in the sample compaction water. For the quantitative evaluation of the susceptibility of the soil to generate internal tubification or piping, the effects of hydraulic load, flow, and orifice diameter before and after the execution of the test are explored—both for the samples treated with deflocculant and for those compacted using distilled water. Additionally, to complete the identification results, physical and chemical approaches were applied as methods of comparison. The results obtained from the altered soils indicate a significant increase in the clay fraction among the samples at the end of the test and gains of 3.7 and 6.2 times the initial diameter. The study demonstrates that the modified test is suitable for identifying non-dispersive soils before raising the percolation pressure. This modification is helpful for the improvement of the test because it helps to understand the procedure better and allows to calibrate the apparatus used.

1. Introduction
Dispersivity in clays is mainly attributed to interchangeable sodium ions within the lamellar microstructure [1,2]. Dispersive cohesive soils retain high sodium cation contents versus other common ions such as calcium, potassium, or magnesium [3]. Under saturation conditions, the sheet fractions usually called "tactoids," are transformed into monogrannular agents with lower electrochemical attraction and particular adhesion. In simpler words, the lamellar bodies undergo deflocculation and are transformed into individual colloidal suspensions [4]. This behavior depends on the infiltration velocity and generates internal erosion processes and tubification channels known as piping. In general, erosive phenomena occur when the shear stress induced by the flow exceeds the friction among particles, causing surface abrasion [5]. Erosion can extend itself along a drying crack, settlement, hydraulic fracture, or other high permeability channels in a soil mass.

The main problem when considering existing studies that address dispersion mechanics lies in the erosional quantification limited only to the presence of sodium [6], being classified into dispersive and non-dispersive samples concerning their exchangeable sodium percentage. However, dispersive erosion of soil is a physicochemical process influenced by several other variables, such as mineralogy, electrolyte concentration, dissolved salt content, and thixotropy; [7] identified Potassium-dominant clay soils with dispersive potential at low electrolyte concentrations, [8] recorded dispersive behavior in aqueous solutions with low sodium ion concentrations.
According to [9], the ionic bond between particles is weak for soils where the proportion of magnesium ions exchangeable with other cations is high. For this reason, several methodologies and devices have been designed to estimate dispersivity using a wide range of constitutive parameters. Although dispersive clays cannot be identified using conventional tests such as visual analysis, gradation, specific gravity, Atterberg limits, or hydraulic conductivity [10]. It can be roughly determined through standardized methods such as the crumb test [11], pinhole [12], sometimes called double hydrometer test (SCS) [13], and pore water chemical analysis; individually and in combination to obtain more reliable results. In addition, a significant number of additional empirical tests [14-19]. However, the dispersive nature of the soils is not truly identified under any of these tests. [20] provides a detailed module of many of these mechanisms and techniques commonly used.

Chemical identification methods are fundamental since sodium in pore water directly controls the dispersion mechanism. Some of these systems empirically use developed graphical interpretations that feed on data obtained from interstitial water analysis [21]. Some research is based on mineral and acidity theory [22] to answer the dispersive nature; [23] showed that, with further increases in sodium sulfate concentration, the dispersion potential decreases. Results reported in [24,25] confirm the occurrence of dispersivity at low electrolyte concentrations; [26] combined results from chemical tests with pinhole data to demonstrate the inaccuracy of the equation; guidance practiced by [27] detailed the change under a total dissolved solids (TDS) analysis. This relationship generates false negatives in the pinhole test.

The pinhole device and its subsequent modifications are currently considered the most accurate nuclear trajectory for identifying dispersivity in fine-grained soils. Percolation flow is allowed at pressures of 50 mm, 180 mm, 380 mm, and 1080 mm water column through an artificial 1 mm diameter tubing in the center. The recorded parameters are the flow rate, effluent turbidity, and orifice size at the end of each test [12]. However, the phenomenon should be noted that all dispersive soils may be erodible, but not all erodible soils are necessarily dispersive [28].

Therefore, to reduce the uncertainty of false negatives in tests, non-dispersive samples can be converted entirely into dispersive soils by imposing artificial dispersivity through modifications in conventional tests; [29] executed pinhole and crumb tests using test waters with varying values of total dissolved solids in five selected samples to find the impact of water chemistry on dispersivity, [30] developed a particular metal disk with a short conical inlet tube that prevents erosion inside the pinhole device; [31] propose an approach that assesses mass loss at the water-soil interface using a simplified numerical erosion archetype based on the Pinhole mechanism and assumes "instantaneous" activation of erosion. Modifications to the crumb test consist of automation [32], assessment of self-healing of filtering materials through the sandcastle test [33,34], and an improved version proposed by [35] called the enhanced crumb test.

Given the constant generation of modifications to the conventional tests, a chemical modification to the pinhole test based on artificial dispersivity is proposed. In non-dispersive samples, sodium hexametaphosphate was added through the water of compaction in different scales of values. The dispersivity results obtained using this new approach compared with those obtained using crumb, SCS, and chemical variants, generated one of the main contributions to the new knowledge. In summary, the proposed modification will allow the user to understand the dispersive behavior of a sample better and even rule out false negatives stated in the regulations.

2. Materials and methods
The alteration for the pinhole test [12] is mainly based on chemical transformation. A 5% deflocculant or dispersive solution (sodium hexametaphosphate) in the compaction water is used to generate induced erosion in non-dispersive soils. For this purpose, the current study appropriates the hydrometric concept to separate silt and clay particles. The modification applied to the interparticle contact water allows exploring the impact of water chemistry on dispersivity. In addition, the inclusion of synthetic sodium ions affects the mechanics of the results in non-dispersive soils, reducing the uncertainty of false negatives in the original pinhole test (Figure 1).
2.1. Sample preparation and compaction

A total of ten (10) soil samples were prepared, dispersive and non-dispersive, to test the dispersivity behavior using the new chemical modifications. The identification and classification of clay soil dispersion were carried out following ASTM D4647, which details the pinhole test procedures [36]. Compaction of the samples was performed on molded specimens, in three different layers, with eight blows per layer using the energy calculation required for the standard proctor in a test volume of 62.3 cm³. The specimens treated with 5% sodium hexametaphosphate were cured (inside the molds) for 24 hours at 18 °C and relative humidity of over 78%.

![Figure 1. Mechanism of soil dispersivity due to water. (a) natural conditions, (b) saturated conditions.](image)

2.2. Materials

The results of the soil classification test are presented in Table 1. The clay used in the investigation was obtained from the North-Central zone of Colombia, near the municipality of Girón, Santander, Colombia; according to ASTM D2487 [37], soils with percentages higher than 50% on sieve No. 200 (0.075 mm) and liquid limit lower than 50% correspond to low plasticity silts (ML). The reduced amount of clay can expose a high dispersive potential. For soil configurations with small dispersive clays, low proportions of exchangeable sodium are required to trigger the erosive phenomenon. Disturbed samples were collected in sufficient quantity to complete all tests. The samples were taken in a non-altered condition because the pinhole dispersivity test does not distinguish this issue.

| Table 1. Physical properties of the clay. | Clay sample |
|------------------------------------------|-------------|
| Liquid limit (%)                         | 22.5        |
| Plastic limit (%)                        | 16.8        |
| Plasticity index (%)                     | 5.7         |
| Specific gravity                         | 2.8         |
| Silt (0.002 mm < diameter < 0.075 mm) (%)| 35.1        |
| Clay (diameter < 0.002 mm) (%)           | 23.5        |
| Proctor compaction stress (kN/m³)        | 18.2        |
| Proctor optimum moisture content (%)     | 15.0        |
| Unified soil classification system class | ML*         |

* Low plasticity silt

Physical and chemical methodologies complemented the identification results. The dispersive soil category was also determined through two additional physical tests: (i) crumb [11], used as a visual evaluation of the tendency of soil particles to deflocculate, both in the original solution and in the synthetic solution after 60 and 360 minutes and (ii) double hydrometer test (SCS), whose classification module is based on the "dispersion percent-age," obtained through the comparison of the hydrometric curves of the soil without and with chemical dispersant. The performance procedures for both systems are described in ASTM D6572 [38] and ASTM D4221 [39], respectively. Chemical tests for pH based
on the standard [10] were applied to specimens dispersive with 5% sodium hexametaphosphate. However, the parametric dispersion alterations were investigated, mainly using the hydraulic conductivity (EC) test to analyze and compare the results between natural and induced dispersion samples.

3. Results and discussion

Table 2 shows the results obtained for the original altered samples and those modified employing the solution with 5% sodium hexametaphosphate in the compaction water. As shown in the exploratory tests, the in-situ material is not dispersive. According to the classification chart proposed by [10], the dispersivity measure categorizes the soil as completely non-dispersive (ND1), a classification mainly due to the low clay content present in the samples. However, this clay fraction is greater than 12% in particle diameters greater than 0.005 mm, enough to exclude the method's inability. On the other hand, when a dispersing agent is added to the sample (hexametaphosphate at 5% solution), the concentrations of synthetic sodium rise, increasing both the ionic attraction power at the water-soil interface and the dispersive properties. For this case, a designation slightly dispersive (ND3) corresponds.

When the soil reaches a percolation pressure of 380 mm water column and the flux is increased to a range of 1.8 ml/s to 3.2 ml/s, the diameter of the holes increases between 3.7 and 6.2 times the initial diameter of 1 mm, indicating the existence of intra-particle drag and piping spectra within the sample (Figure 2(a) and Figure 2(b)). This directly proportional relationship between sodium content and piping is exclusively observable for samples altered with sodium hexametaphosphate or highly erodible origin.

Soil particles were mobilized at pressure heads above 800 mm in distilled water, but they were not exported from the soil sample due to the tubing's low flow carrying capacity. Hydraulic gradients of 380 mm produced intense through-flow rates in the samples disturbed with sodium hexametaphosphate; [40] suggest using two different and contrasting hydraulic heads (180 mm and 1020 mm) to produce different pipe shear stress. However, the samples with chemical dispersant required flow pressure elevations lower than 380 mm, since a small piezometric loading value in samples with high sodium content identifies horizons susceptible to low hydraulic loads and high erodibility. The artificial dispersion effect is beneficial to study this physicochemical phenomenon since the possibility of finding natural dispersive samples is not very high; therefore, calibrating the pinhole apparatus properly with dispersive samples is essential for its understanding; this modification was not considered in state of the art before. The process is analogous to what is done with the SCS method.

| Table 2. Pinhole test results. |
|-------------------------------|
| Sample number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Natural samples |
| Final hole (mm) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Classification (ND) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Final flow (m/s) | 2.4 | 3.1 | 1.4 | 2.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Final head (mm) | 1020 | 1020 | 1020 | 1020 | 1020 | 1020 | 1020 | 1020 | 1020 | 1020 |
| Dispersive samples |
| Final hole (mm) | 6.2 | 5.5 | 4.5 | 4.1 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 |
| Classification (ND) | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Final flow (m/s) | 3.3 | 1.8 | 1.2 | 1.4 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| Final head (mm) | 1020 | 380 | 380 | 380 | 380 | 380 | 380 | 380 | 380 | 380 |

Figure 2. Hole (pinhole) in samples after testing; (a) non-dispersive sample, (b) dispersive sample.
3.1. Double hydrometer test
The 24-hour readings for the dispersing agent and the original sample in hydrometric processes are shown in Figure 3. The test results show that there is a significant variation in the fraction of clay present among the samples at the end of the test, reflected in higher dispersion potentials due to the increase in the contact surface between the clay tactoids and the sodium ions. The samples dispersed with sodium hexametaphosphate produced a 21% increase in the volume of finer particles at a diameter of 0.005 mm for those diluted in distilled water. Theoretically, the 0.005 mm fraction for the basic test cannot be higher than that of the standard test using a chemical dispersant [41]. On the other hand, the highest disaggregation of soil flocs occurred with the aggregation of the chemical dispersant. The dispersion percentage of 16% calculated through the equation proposed by ASTM D4221 [39] is relatively low. It indicates that the synthetic dispersant in the standard test did not fully disperse the particles or possibly caused particular deflocculation to occur to a small degree.

![Figure 3. The double hydrometer test results on the in-situ clay samples and samples dispersed with sodium hexametaphosphate.](image)

3.2. Crumb test
The results obtained using the crumb test were developed in this research as well. It can be seen from the results that, after 2 minutes, the distilled water solution samples are classified as dispersive to some extent (grade 2 and grade 3), a classification obtained with the number of colloids in suspension. However, the suspension settles after 60 minutes at grade 2, although the 2-minute reading classifies the sample as non-dispersive (grade 1). This effect indicates that the experimental values of the crumb test after 2 minutes are not reliable for non-dispersive samples since some of the fine particles, which are not necessarily disintegrative, may still be in suspension and achieve a false criterion erodibility. The sodium hexametaphosphate sample showed a non-dispersive behavior in the first 2 minutes of drying in solution and high dispersive potential after 60 min from the initial settling. The rapid erosive growth of the sample in short periods indicates the presence of synthetic segregation derived from external dispersing agents and not due to the intrinsic characteristics of the material.

3.3. pH and electrical conductivity
According to the methodology proposed by [42], pH tests to measure dispersivity require additional electrical conductivity tests to verify the values obtained. Initially, the condition of alkalinity or acidity is not an aspect that controls dispersivity. However, some types of soils in acidic conditions may lose ion exchange capacity, which in theory favors the dispersivity of the soil. For the samples immersed in distilled water and sodium hexametaphosphate, there are slight differences between the pH and EC tests.
(Table 3); according to [42], pH and EC values lower than 7.80 and 250 µS/cm, respectively, correspond to non-dispersive samples, a classification partly in line with this study. However, dispersive samples have a slightly acidic pH do not show agreement with this technique.

| Sample | EC (µS/cm) | pH   | Test Value |
|--------|------------|------|------------|
| ND1    | 202 – 214  | 7.0 – 8.0 |
| ND3    | 99 – 105   | 5.0 – 6.5 |

4. Conclusions

The behavior of the pinhole test results proves to be unreliable for identifying dispersive soils; according to the results, flow and final diameter results below 50 mm water column are the primary differentiation between dispersive and non-dispersive soils, showing that it is not strictly necessary to perform the test up to a maximum flow height of 1080 mm water column. If soil does not exhibit dispersivity greater than ND1 at pressures less than 50 mm water column, it is possible to increase the head to 180 mm, 380 mm, or 1080 mm to verify that assumption. However, additional pressure increases may give rise to false classifications of erodible soils; thus, the imposition of artificial dispersivity utilizing external agents with high exchangeable sodium content allows corroborating that the material is effectively non-dispersive in pressures lower than 380 mm of the water column, eliminating the verifications that require raising the percolation pressure.

Adding an artificial dispersion allows comparing the non-dispersive natural sample with a dispersive one and comparing its results to how it is done with the double hydrometer. In this case, it was helpful to calibrate the equipment and demonstrate that any clay sample can be dispersive. It is only to locate sodium ions in the interstitial water, either naturally or artificially. Because finding soil with a dispersive pathology, it is not a very frequent case. There may be some uncertainty when it comes to knowing if the equipment adequately detects the phenomenon. The current modification lets us know if the sample is dispersive and its degree of dispersivity, especially when we want to be sure of a true negative.

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