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ASSESSMENT OF COARSE SOIL'S STABILITY TOWARDS INTERNAL EROSION CASE OF BISKRA'S DAM SOIL

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Abstract

Internal erosion is a phenomenon that occurs in soils constituting hydraulic structures under the influence of internal flow. This erosion occurs because of pipe erosion which becomes widespread, leading in some cases to the rupture of the structure. Soils susceptible to piping, generally have particle size instability. This study aims to provide an empirical understanding of the initiation and development of erosion in coarse soil obtained near Biskra's dam in Algeria. To assess the soil's dispersiveness chemical analyses such as SAR and PS were conducted, as well as the particle size criteria were verified. The soil was examined in-depth using a double hydrometer test along with Crumb tests. A Hole Erosion Test (HET) device is developed to investigate the effect of certain parameters, such as the compaction degree and the hole diameter on internal erosion's onset and progression. The results have shown the instability of the soil toward internal erosion given the considerably eroded particles. furthermore, an inverse relationship between the eroded particles mass and the degree of compaction and the initial hole's diameter is observed.

Keywords:

Hydraulic structures;
Coarse soil;
Internal erosion;
HET;
Pipe.

1 Introduction

Several failures in the last decade have shown the susceptibility of earth hydraulic structures such as, quays levees, and dams to erosion [1] and [2].

Furthermore, internal erosion is one of the main concerns involving embankment dams, accounting for 46% of all reported collapses [3]. Internal erosion groups any process by which soil particles are teared and transported by the flow in water retaining structure or its foundation [4] and [5]. It can be initiated by concentrated leak erosion, backward erosion or piping, soil contact erosion, or suffusion [6]. Since it deflocculates in the presence of running water, dispersive soils are highly vulnerable to erosion and piping. Dispersive soils are clayey soils that are highly susceptible to erosion due to its high percentages of exchangeable sodium ions Na+ [7]. Chemical and mineralogical tests performed at the Asian Institute of Technology and the Royal Irrigation Department of Thailand found that dispersion does not occur in the absence of montmorillonite, even at high sodium levels in pore water. Thus, sodium adhering to montmorillonite appears to be more important than the presence of Na+ in the pore water in causing dispersiveness [8]. Even at low seepage rates, these soils can be eroded quickly by segregation of individual particles, generating pipelines and deep gullies, due to a process in which individual clay particles go into suspension in moving water. Numerous earth dams, slope, and foundation failures have all been recorded in these kinds of soils [9].

Considering that hydraulic structures require the use of stable soil to prevent internal erosion, it is appropriate to assess this stability to be exploited without posing a risk of instability.

The internal stability of a soil is affected by geometric, hydraulic, and mechanical conditions [10], [11], [12] and [13]. Geometric and mechanical conditions affect the potential of internal instability whereas hydraulic conditions govern the onset of any instability [14]. Good efforts have been made to investigate the internal stability of soils from the geometric point of view [15],[16], [17], [18],[19] and [20]. Using the coefficient of uniformity (Cu) as a variable, [21] suggested an internal stability criterion for

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granular soils. with reference to the concept of Terzaghi's filter rule [22], a geometric criterion was proposed by [23] to assess the internal stability of soils. [24] presented an internal stability criterion for well compacted granular soils. [8] in their turn recommended a criterion to assess the internal stability of broadly graded soils and [25] presented a geometric criterion for granular soils.

Many previous studies in different parts of the world [26], [27], [28], [29], [30] and [31A] have assessed the erosivity of soils using several methods. Algeria disposes of 80 dams, projections to 2030 predict that the number will increase to 139 dams. Even though, no study has been carried out to investigate on the erosion behaviour of soil in any dam or site.

In the present work, the erosivity of a soil from the Fountains of Gazelles dam in the Wilaya of Biskra was investigated. For this purpose, the internal stability of the soil was assessed using geometric criterion, chemical analyses of Ca^{++}, Mg^{++}, exchangeable sodium percentage (ESP**)** Na^{+}, and K^{+} concentration as well as Sodium Absorption Ratio (SAR) and Percent Sodium (PS) of the soil were determined. The dispersive character of soil was examined using double hydrometer, modified Crumb test, as well as a parametric study was carried out to figure out the influence of the initial pipe diameter and the compaction degree (density and compaction water content) on soil's piping erosion behaviour a series of tests was performed using hole erosion test (HET), which was derived from other experimental erosion devices, such as the pinhole test [32] and [33], however a new approach of measuring the erosion rate (and eroded mess) and instantaneous hole diameter was applied in this study.

2 Materials and methods

The soil was collected from Biskra region, The grain size distribution curve indicates that it is composed of 10% clay, 23.09% silt, 56.91% sand and 10% gravel (Fig. 1). The uniformity factor is187 and a curvature factor is 6.9. It is classified as very silty medium gravel (B5) according to the French standard [34]. Atterberg limits of the soil are found to be as follows: liquidity limit W_L = 31, plasticity limit W_P = 15 and a plasticity index (I_P = 16), according to French classification AFNOR XP P 94-011 [35] is classified as low plastic and consistent soil (I_c =0,69). with important activity of its clayey fraction (A_{CB} N 1.25; presence of calcic montmorillonite). The chemical analysis showed that the dominating elements are silica (SiO_2), calcium oxide (CaO) and alumina (Al_2O_3). X-ray diffractogram shows that the dominant crystalline minerals are quartz (Q) and calcite (Cl) (Fig. 2). The geotechnical proprieties of soil and its chemical composition are listed in Table 1. As well, SEM aspects of the fine fraction are exposed in Fig. 3.

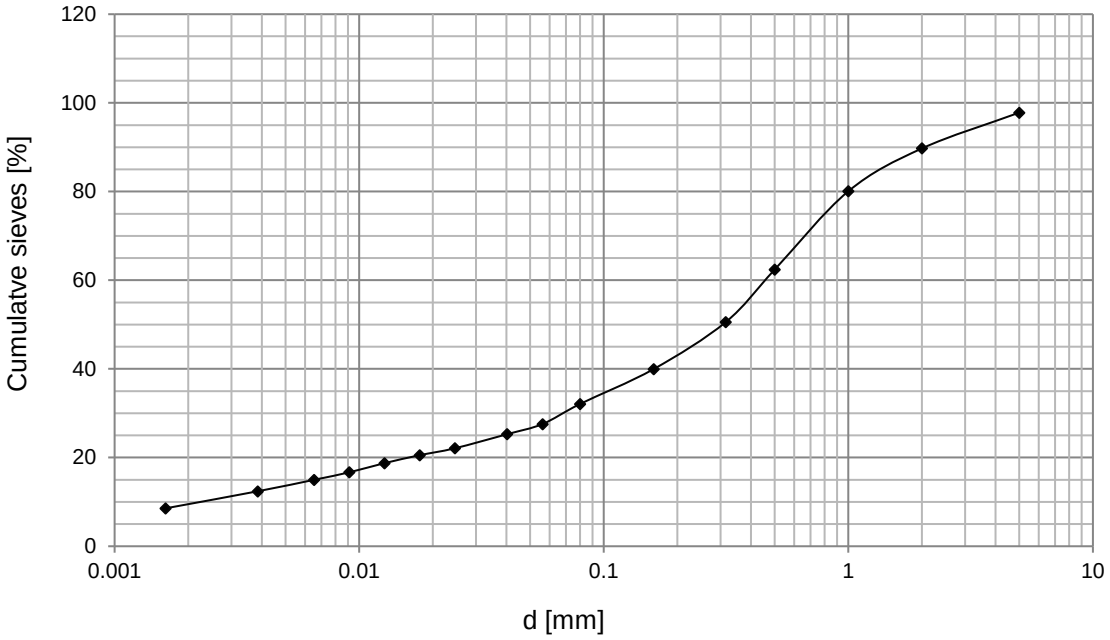


Fig. 1: Particle size distribution of the soil.

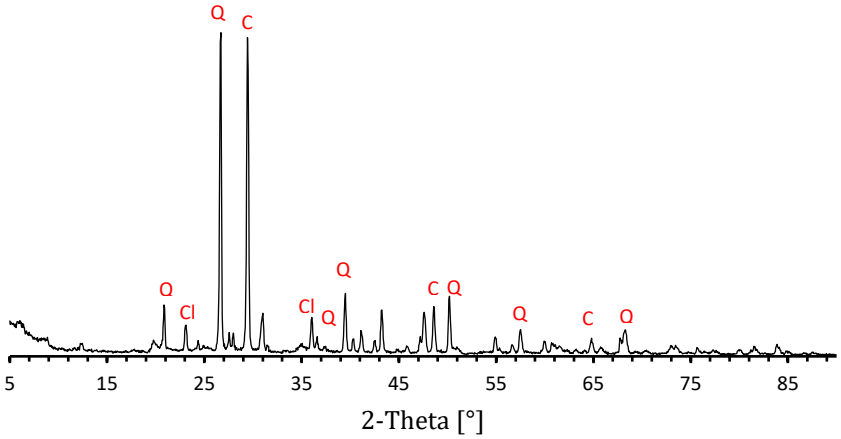
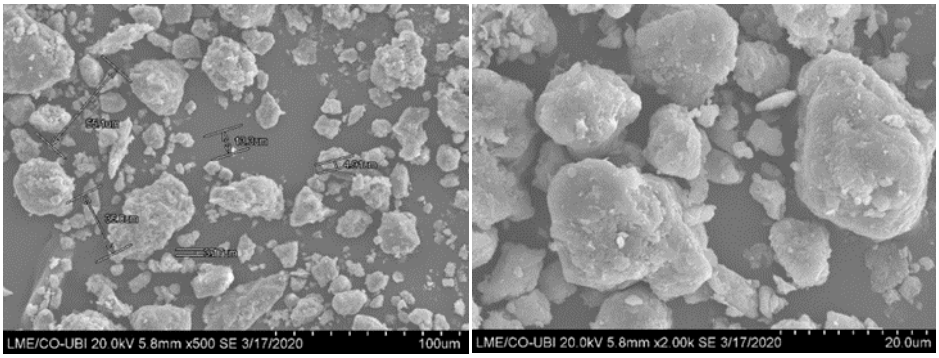


Fig. 2: X-ray diffraction analysis.



a) b)

Fig. 3: SEM Aspects of the fine fraction of soil: (a) magnification x500. (b) magnification x2000.

Table 1: Geotechnical and chemical properties of the soil.

Physical properties		**Physical properties**	
%80 µm	33.09	Na_2O	0.77
%<4 µm	12.5	MgO	3.38
% <2 µm	10	Al_2O_3	12.43
D_{10} [µm]	2	SiO_2	36.15
D_{30} [µm]	70	K2O	2.05
D_{60} [mm]	0.45	CaO	37.06
C_u	187	TiO_2	0.73
C_c	6.9	$Fe2O_3$	6.54
M_{BV}	0.5	SO_3	0.60
I_P	16		
A_{CB}	1.6		
ρ [t/m3]	2.66		

2.1 Soil chemical tests (cations)

To determine the concentration of different ions, the soil pore water is chemically analyzed. This is important as there is a relationship between electrolyte concentration of the soil pore water and the exchangeable ions present [36]. The presence of high salt concentration increases the dispersiveness of the soil.

Sodium Absorption Ratio (SAR) and Percent Sodium (PS) are the two parameters which are frequently used to verify chemical compatibility [37] and [38]. "Sodium adsorption ratio" (SAR) is the ratio of the Na concentration divided by the square root of one-half of the Ca + Mg concentration. PS and SAR are calculated from the following equations:

$$TDS = Ca^{2+} + Mg^{2+} + Na^{+} + K^{+} \quad (1)$$

$$\mathrm{PS} = \frac{\mathrm{Na}^{+}}{\mathrm{TDS}} \times 100 \quad (2)$$

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (3)$$

The soil's samples were acid digested, then the extracts were used to conduct chemical analysis. The concentration of Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} were determined by atomic absorption spectroscopy method. The values of SAR and PS were compared with Sherard Curve [39]. Soils having sodium adsorption ratio of 13 or more may have an increased dispersion of organic matter and clay particles, reduced saturated hydraulic conductivity and aeration, and a general degradation of soil structure [40]. The soil's erosivity decreased as sodium adsorption ratio of the pore water increased [41].

By comparison, it was observed that the values of SAR and PS were low, and the soil is classified as non-dispersive. The results of the chemical analysis are given in the Table 2.

Table 2: Chemical analyses of Soil.

Eliments	Na^{+}	K^{+}	Ca^{++}	Mg^{++}	TDS	PS%	SAR
Concentration(mg/L)	190	27	395	37	649	29.27	-
Exchangeable Cations [meq/L]	8.26	0.69	9.85	1.52	-	-	**3.47<13**

2.2 Double hydrometer test

As described in the standard [42] the main idea of this method is to compare the grain size of the soil's fine part in two different ways. The first way is by carrying out a particle size analysis by sedimentation using a dispersing agent of sodium hexametaphosphate and a mechanical agitator (Fig. 4). The second way is to carry out the same test without using a dispersing agent and without an agitator.

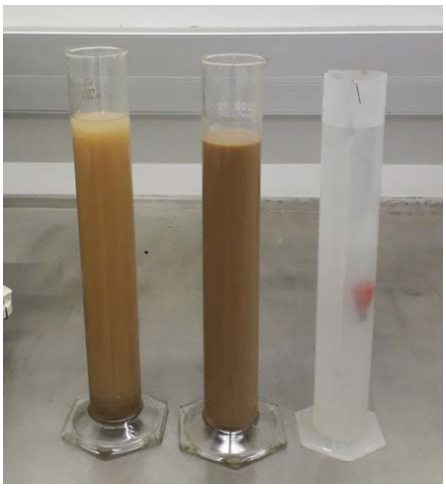


Fig. 4: Double hydrometer test.

The test consists of evaluating the dispersion rate D defined by the ratio between the percentages of fines less than 5 microns without dispersant (A) and with dispersant (B), according to the following formula:

$$D = \frac{A}{B} = \frac{\%<5\mu m\ without\ dispersant}{\%<5\mu m\ with\ dispersant} \times 100 \quad (4)$$

2.3 Specimen preparation for HET test

The specimens are prepared in a rigid cylindrical PVC mold of 100 mm in diameter and 200 mm in length. To obtain uniform compaction, the soil is dynamically compacted into three layers of equal

thickness inside the PVC mold with a normal Proctor hammer (Fig. 5). The soil is prepared in advance to a given water content and left to mature for 24 hours in airtight bags. The amount of material required for each layer is determined from the desired final dry density. The water content and final density are defined using a standard Proctor test NF P 94-093 [43].

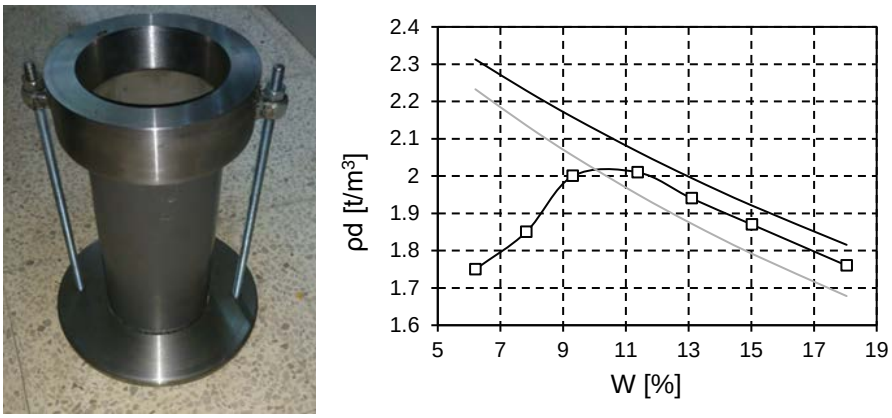


Fig. 5: Normal Proctor Curve and compaction mold.

The specimens are compacted to a final dry density corresponding to 95% and 90% of the maximum dry density at the wet side of the standard Proctor curve. To simulate pipe erosion, an initial hole of 10, 7, and 4mm in diameter in the middle of the specimen is made vertically with metal wicks. The characteristics of specimens are summarized in Table 3. The test samples are then stored with a plastic film to maintain the water content of the compaction and avoid its evaporation and kept in an ambient temperature of approximately 20°c until the test time.

Table 3: Characteristics of specimens.

Specimen	d10-95	d7-95	d7-90	d4-95	d4-90
ρd [t/m3]	1.92	1.92	1.82	1.92	1.82
w [%]	13.6	13.6	16.4	13.6	16.4
Initial hole diameter [mm]	10	7	7	4	4

2.4 Dispersion test (modified Crumb test)

The principle of this test is based on that called Crumb Test described in standard [44]. However, it is adjusted to fit the specimen dimension. The specimens reserved for this test were prepared with the same method as that of the erosion (HET) test. The specimens were deposited on a metal support allowing the contact of water below the specimen and then emerged in a glass tank whose dimensions are 500×500×500 mm. The test consists of immersing a specimen of known density and dimensions in a tank of water and following its morphological evolution over time and assessing its dispersion in water as it is illustrated in Figure (6).

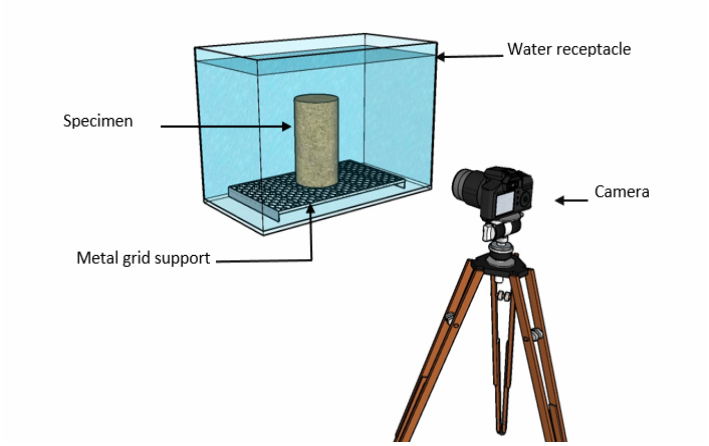


Fig. 6: Sketch of crumb test device.

2.5 Hole Erosion Test (HET)

To carry out laboratory piping erosion tests, an experimental device has been developed, it is inspired from the pinhole test [39] and [33]. and the Hole Erosion Test (HET) device designed by [45] and [12], It can be considered as efficient tool to assess the initiation piping erosion and to characterize the internal erosion of soils [46].The test consists of eroding a drilled soil specimen by water flow with a constant pressure drop at the boundaries of the specimen while recording the flow rate and studying the hole enlargement [28]. To determine the final hole diameter, melted paraffin is poured into the test hole and then removed once it has cooled.

The internal erosion is monitored by measuring hydraulic parameters (i.e., the pressure drops between the areas upstream and downstream of the sample and the flow through the hole). The results determine the empirical erosion law of the material, which can be expressed as follows:
The rate of erosion which relates to erodibility of soil is defined by [47] as:

$$\dot{\varepsilon}_t = c_e(\tau_t - \tau_c) \tag{5}$$

where, $\dot{\varepsilon}_t$ is the erosion rate [kg/s/m^2], ce is the coefficient of soil erosion obtained from the slope of the erosion curve [s/m], τ_t is the hydraulic shear stress along the hole at time t [N/m2], and τ_c is the minimum hydraulic shear stress for the initiation of erosion, also referred to as the critical shear stress [N/m2].

The erosion rate $\dot{\varepsilon}$ [kg/s/m2] is expressed by the eroded soil mass mt [kg] per unit area of the hole at time t [s]:

$$\dot{\varepsilon}_t = m_t/(a_t \times t) \tag{6}$$

Several previous studies measured the erosion rate based on the estimation the instantaneous hole diameter, it was estimated by [41] from the pipe-line flow theory that estimate flow rate using the “Moody diagram”, in this case it’s not guaranteed that the flow regime is constantly turbulent or laminar. [48] suggested a general theoretical model, considering the hole as ellipsoidal however it still unrealistic, [49] tried to estimate the instantaneous diameter using the turbidity measurements, however they introduced the grain solid density instead of dry density which is inaccurate since the eroded mass is a part of the specimen which is compacted to a given dry density.

In the present study, the erosion rate is calculated using the eroded mass for every applied shear stress which is related to the hydraulic gradient measured across the hole and doesn’t involve any hypothesis on flow laws. The erosion rate can then be expressed as follows:

$$\dot{\varepsilon}_t = \frac{m_t}{2\pi r_t l\, t} \tag{7}$$

The hydraulic shear stress along the hole can be expressed as:

$$\tau = \rho_w g s_t \frac{\phi_t}{4} = \rho_w g s_t \frac{r_t}{2} \tag{8}$$

where:
ρ_w – the density of the eroding fluid [kg/m^3],
g – the gravitational acceleration [9.81 m/s^2],
s_t – the hydraulic gradient across the soil sample at time t and
r_t – the average diameter of the erosion hole assumed to remain circular at time t.

Thus, the hole diameter is calculated as the following:

$$v_t = \pi\, r_t^2\, l = v_i + \Delta v \tag{9}$$

$$\pi\, r_t^2\, l = \pi\, r_i^2\, l + \frac{m_t}{\rho_d} \tag{10}$$

$$r_t = \sqrt{\frac{m_t}{\rho_d \pi L} + r_i^2} \quad (11)$$

$$\phi_t = 2r_t \quad (12)$$

where:
v_t – the volume of the hole at time t.
v_i – the volume of the hole.
Δv – the volume variation.
r_t and r_i – the hole rayon at time t and the initial hole diameter respectively.

2.5.1 Het device

A hole Erosion apparatus inspired from the one of [47] was developed to carry out laboratory tests, it can be considered an efficient tool to assess piping erosion initiation and to characterize the internal erosion of soils [50].

The different elements of device are connected using sections set of tubes fitted with quick couplings and valves as it is illustrated in Fig. 7. The erosion cell consists of three parts, the first one is an upstream base with an inlet diameter of 30 mm, which ensure a constant inflow for each hydraulic load. The central (second) part is a PVC cylinder of 100 mm in diameter and 250 mm in length, 50 mm of it is reserved to receive gravels which the role is to make the inflow homogeneous, and 200 mm for the specimen; Separated by means of a metal grid of 1 mm from the gravels. Downstream there is another base, with an outlet which measures 30 mm as well in diameter.

After drilling of the hole, the central part was placed into the erosion cell and well fixed by tie beams. To avoid any water leak, the water tightness of the cell, it was thought to put O-rings at the contact points between the PVC tube and the bases.

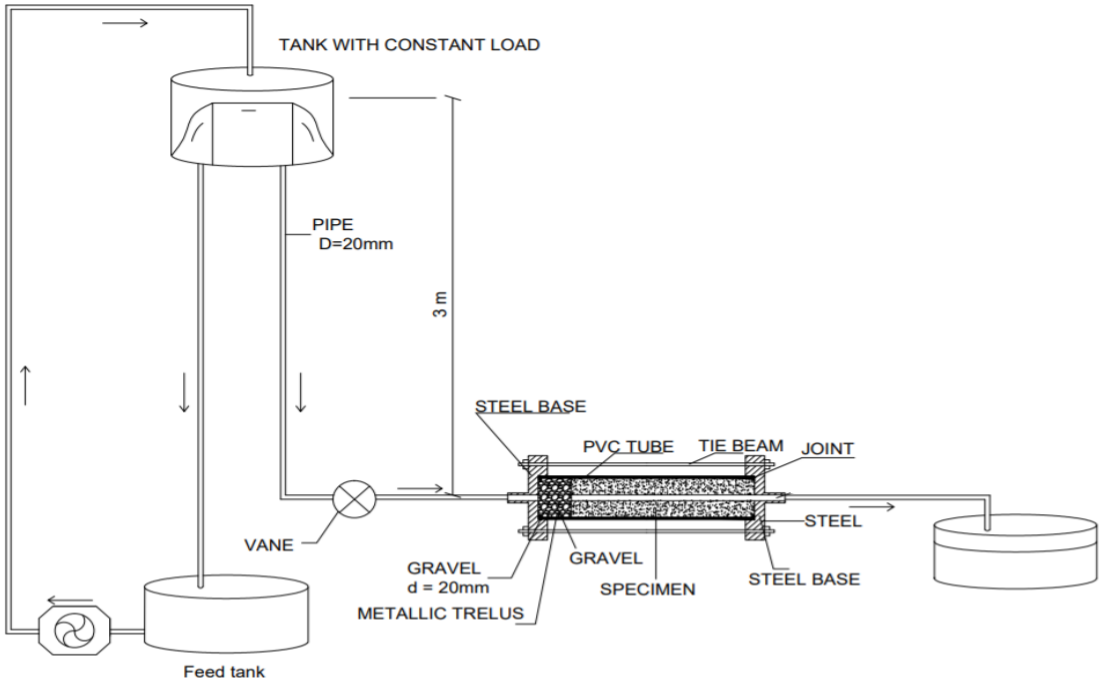


Fig. 7: General schema of the developed device.

3 results and discussion

3.1 Validation of the calculation method (results)

The final diameter which is calculated from the measured eroded mass is displayed in Fig. 8 versus the final eroded diameter which measured at the end of the tests from the extracted candles. The small discrepancies might be caused by imprecise mass calculations and hole diameter

measurements at the beginning and end of the test. The results demonstrated the applicability of this method to predict the hole diameter during the test using soil's eroded particles mass.

In this work, the average hole diameter is measured directly using the extracted candles obtained after pouring the melted paraffin wax to determine the volume of the hole, and then the diameter average over the length of the hole.

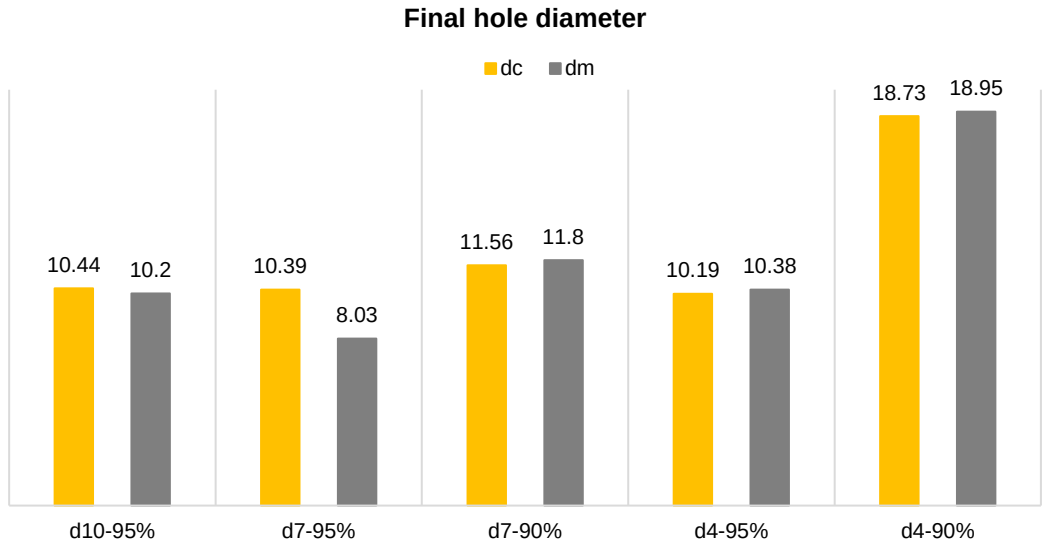


Fig. 8: comparison of the calculated and measured final diameters.

3.2 Verification of criteria for soil instability with respect to internal erosion phenomena (particle size criteria)

3.2.1 Initiation of internal erosion

The existing particle size criteria are based on the shape of the tested material's particle size curve and its particles size [51]. Using the particle size distribution curve of the soil, these criteria was verified, the obtained results are summarized in Table 4. Given these findings, it was concluded that the soil is unstable.

Table. 4: Properties of soil.

Criterion	Istomina (1957) [21]	Terzaghi [22]	Kenney and Lau (1984, 1985) [24]	Lubochkov (1965) cited by [23]	Sail (2012) [51]	BURENKOVA (1993) [17]
Stability	**US**	**S**	**US**	**S**	**US**	**US**

3.2.2 Double hydrometer test

[52] provided the first inspiration for this method, then [36] subsequently gave the test process for the first time.

The results of double hydrometer test are shown in Fig. 9. The distinction of these two curves demonstrates the natural dispersion tendency of the tested soil. (A) is found to be equal to 42 and (B) equal to 16. By calculating the rate (D) presented above, the results indicate that Biskra soil has dispersion rate of about 38 percent. Thus, it indicates that this soil's degree of dispersion is in the intermediate range.

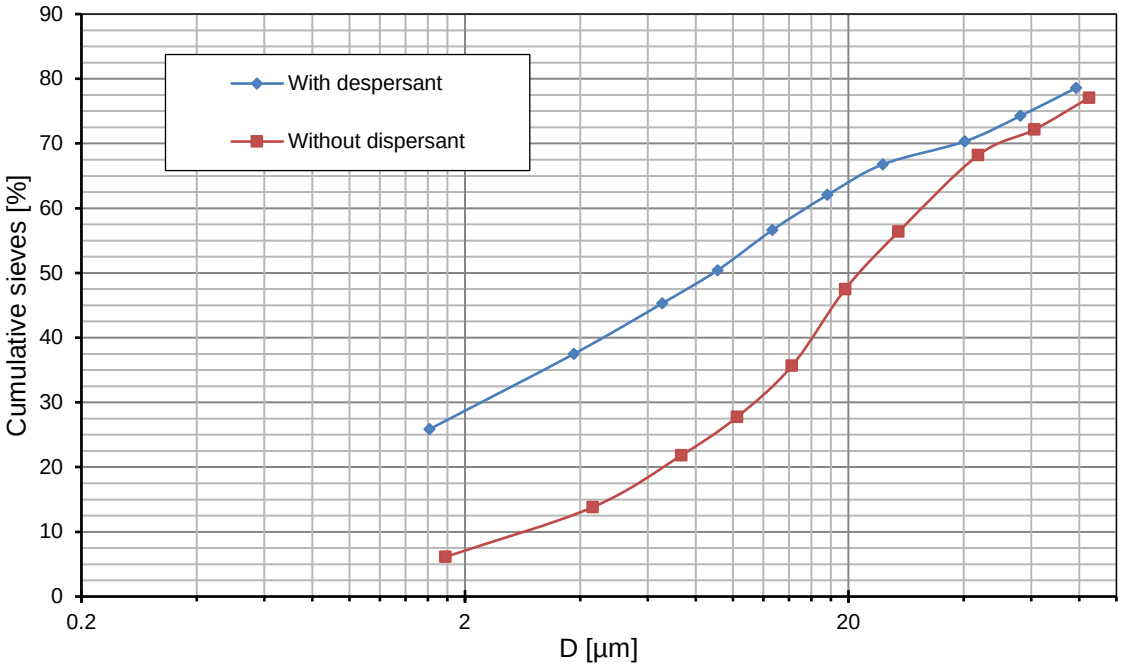


Fig. 9: Double hydrometer test.

3.2.3 Immersion test (Crumb test)

As mentioned previously, many works have been conducted on clay soils only, composed of colloidal particles clipped to Dmax= 3mm using cylindrical specimens of 15 mm in diameter and 20 mm in height [53] and [54]. As part of the present study, specimens of 10 cm in diameter and 20 cm in height were used to investigate the influence of: clays proportion in the studied soil (10%), the dry density, compaction water content and the degree of saturation on the triggering of the dispersion phenomena are examined.

The results of this configuration showed that the soil completely disintegrates after 7 hours in case of specimen which is compacted to 95% of the optimum dry density, while the specimen which is compacted to 90 % disintegrates after 12 hours (Fig. 10). It should be noted that for both cases, the detachment of the particles from the solid mass starts from the first minutes of the specimen being immersed in water. The separation of larger flocs was observed after about one hour of immersion, with absence of the turbidity effect which is a halo of particles in suspension around the sample, when compared to the tests conducted by [55]; However, it was observed when the specimens were entirely dispersed, this indicates that the behavior of submerged soil in water tends to both slaking and dispersion. The obtained results reveal the influence of the degree of compaction (dry density and water content) on the dispersive character of Biskra's soil where the dispersion of soil is faster (higher) in case of specimen characterized by high dry density and low water content than the specimen characterized by low dry density and high water content where the soil is actually in contact with water, this process usually takes only a few minutes [49], [53] and [56] In the case of the Biskra soil, the dispersion of the specimen takes much more time this maybe is due to water content and the electromagnetic and electrostatic interparticle forces, which are influenced by the dry density. Moreover, soil structure and fabric, as well as pore-water chemistry, particle size distribution, and clay mineralogy seem influence the slaking preces during the dispersion test as [57] has stated (reported).

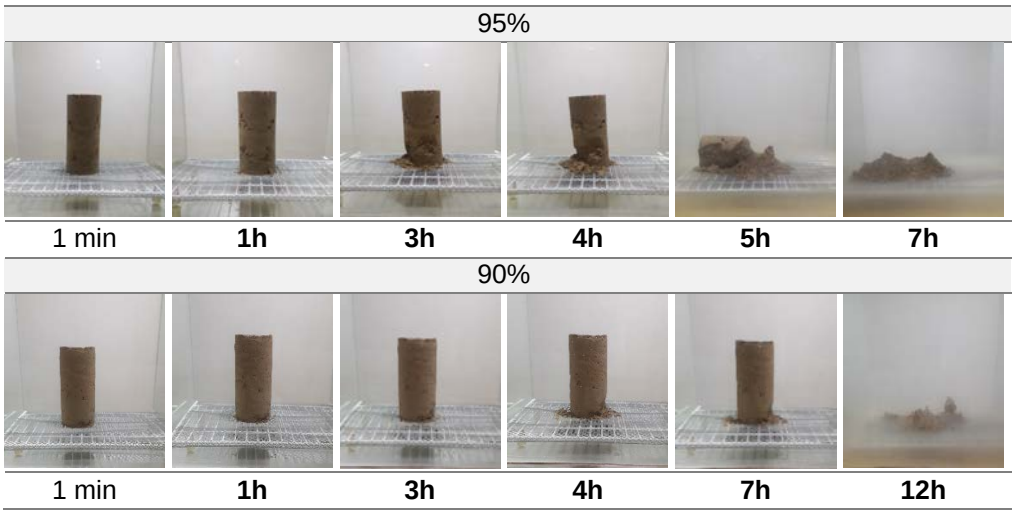


Fig. 10: Evolution of soil samples over time during immersion in water.

3.3 HET results

A parametric study was carried out to determine the influence of the compaction degree and the hole's initial diameter on the initiation of piping erosion. The onset and progression of internal erosion mechanism occurring under the application of a horizontal unidirectional flow will be described and illustrated in this section.

Fig.11 shows the variation of eroded particles mass as a function of hydraulic gradient. It is obvious that this mass is affected by the degree of compaction and the initial hole's diameter. Considering the cases (d10-95, d7-95 and d4-95) and (d7-90 and d4-90), in which group has the same dry density and compaction water content however, has a decreasing hole diameter, the results showed that the instability or the erodibility of soil increases with the decrease of the hole diameter, which leads to an increased pressure and as a result an increased water shear stress in the interface water-soil. Taking the case of (d7-95, d7-90) and (d4-95, d4-90), where the erosion instability of soil is increased with the decrease of compaction degree, in other words decreased density and increased compaction water content. The obtained results have shown that the soil is unstable towards this phenomenon of internal erosion or piping in view the considerable departure of particles. As well as the mass of eroded particles is inversely proportional to the compaction degree and the diameter of the hole.

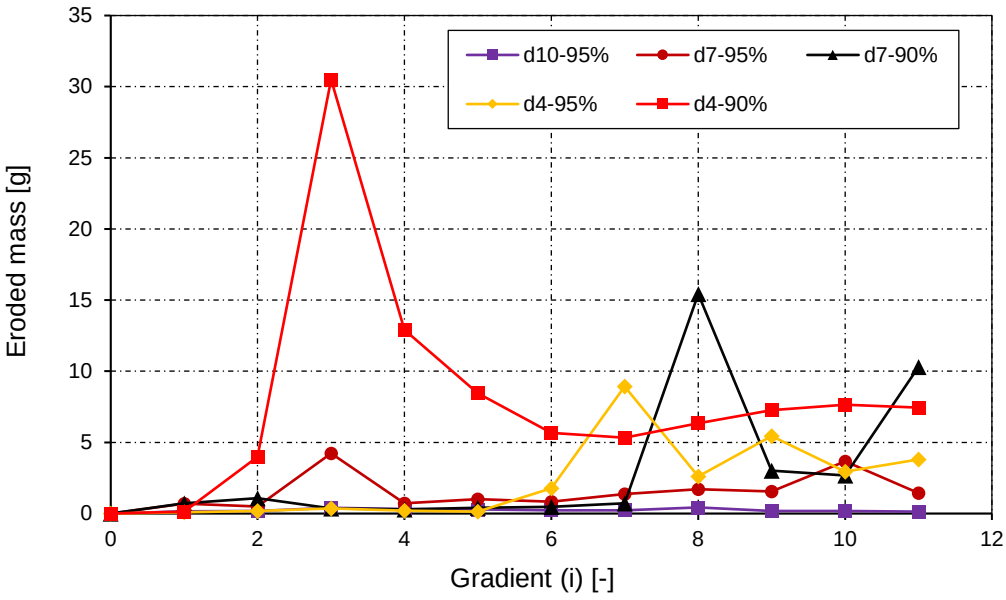


Fig. 11: eroded mass evolution.

Fig.12 presents the evolution of cumulative eroded mass the as a function of hydraulic gradient. It varies quasi linearly in the case of soil d10-95% and d7-95%, while the variation for the other cases is

not linear. The final cumulative eroded mass is influenced by compaction conditions and the initial hole diameter, the highest values were recorded during HET test curried out on the specimen d4-90%, which is characterized by a lower density and a higher compaction water content, thus considered as the most unfavourable case of Biskra's soil resistance to pipping erosion.

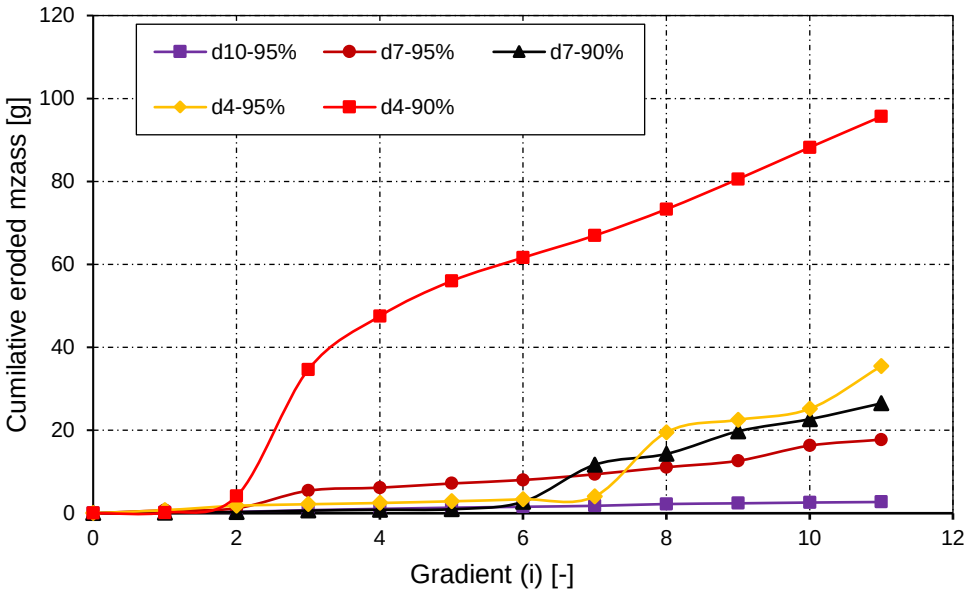


Fig. 12: Evolution of the cumulative mass of the eroded particles soil.

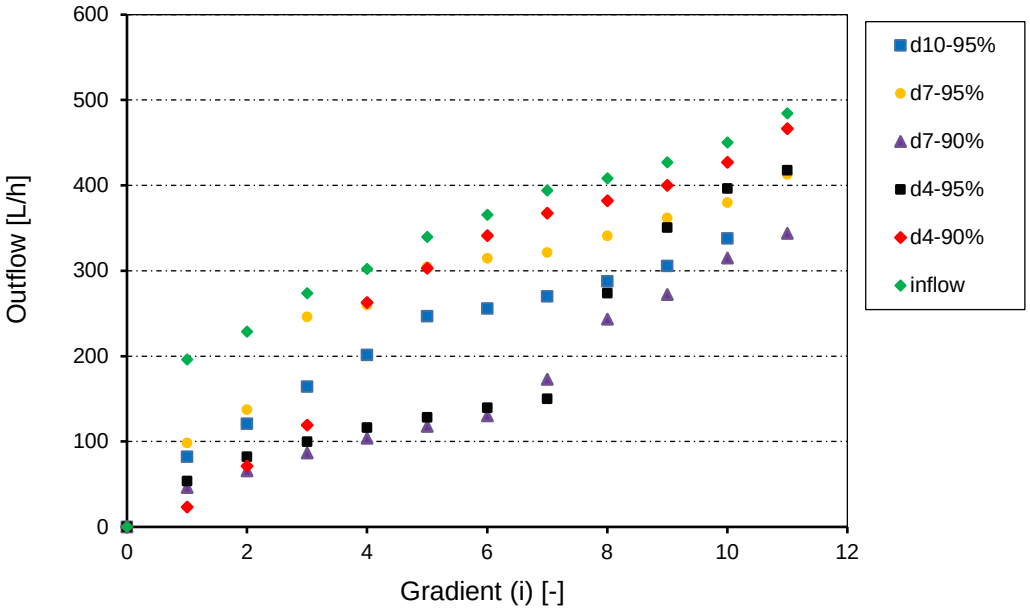


Fig. 13: Evolution of the outflow during HET test.

The outflow (the flow rate) is a function of the instantaneous diameter of the hole Fig.13. Regarding in the case of d4-90% test, which is considered the most unfavorable case, the flow rate was at 23 L/h in the beginning of the experiment; then under the increasing hydraulic loading therefore the shear stress is increased resulting in more particles detachment and consequently in enlargement of the hole diameter, which leads to a larger flow rate ends up to 459 L/h. The flow rate seems to be depended to the initial hole diameter and the cumulative eroded particles mass (instantaneous diameter). In other words, the rise in cumulative eroded particles mass is coupled with greater outflow.

The instantaneous diameter is calculated using the equation (12), as it is shown in Fig.14 the variation of the calculated instantaneous diameter is plotted versus time, the most affected specimens

by diameter variation between start and end of test are those with 4 mm initial diameter, and a significant deference was observed in case of specimen (d4-90%).

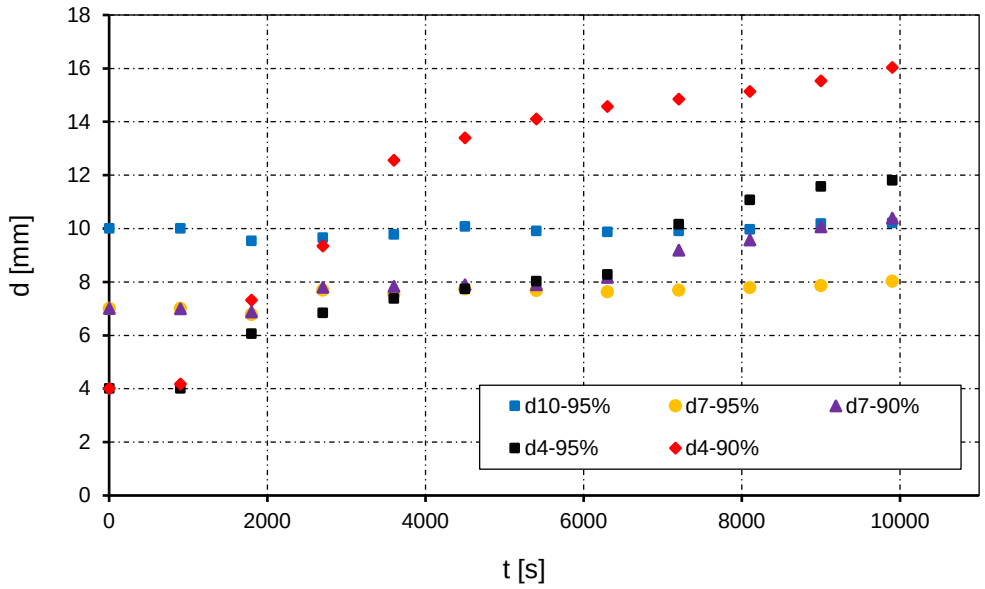


Fig. 14: Evolution of the hole's diameter during HET test.

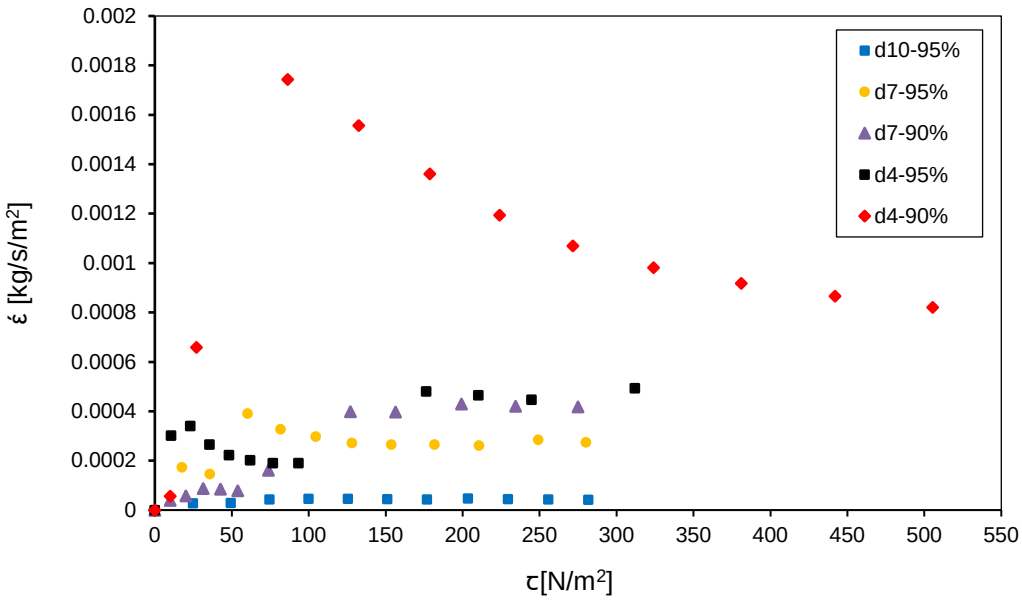


Fig. 15: Erosion curves.

Results of the Hole Erosion Test on different cases are depicted on Fig.15 where the erosion rate έ is represented as a function of the shear stress τ at the interface.

Repeatable tests and various pressure drop (shear stress). were used to collect experimental data points for each case. These data are also adjusted for a linear fit in accordance with the erosion law (2) in case of (d10-95%), however it is not observed in the other cases especially (d4-90%). No critical shear stress is measured the same was observed in the [47] or [58] methods.

Results are represented on Fig.15 The varying parameters are the initial diameter and the compaction degree. Experimental data for different specimens can be easily differentiated, and HET allows to distinguish of the different cases.

As compaction degree is decreased, the erosion rate decreases, and the erosion coefficient (ce) tends to increase, thus the texture becomes more resistant to erosion and vice versa. However, as the

initial diameter is decreased, the erosion rate usually tends to increase. The highest erosion rate values were recorded in case of specimen (d4-90%), which considered the most unfavourable case of this soil erosion resistance.

3.3.1 Estimation of final hole diameter

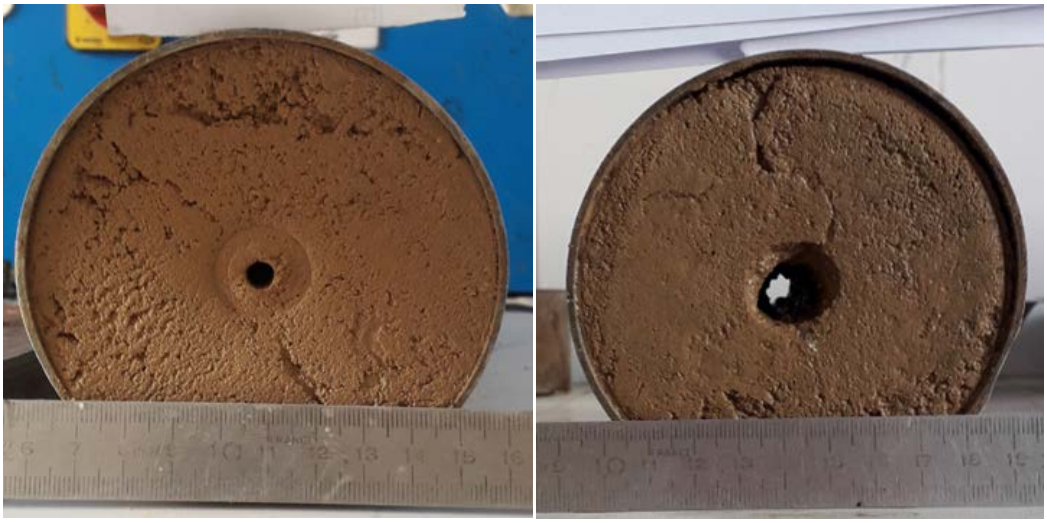


Fig. 16: Hole's diameter before and after HET test (d4-90%).

To calculate the hole's volume in the current work, the hole's diameter is measured using molten paraffin once the test is complete. The average hole diameter is then calculated based on the volume of the extracted paraffin witch takes the from the hole.



Fig. 17: Extracted candle (d4-90%).

The extracted paraffin takes the shape of the eroded hole, it was found to be the irregular, the diameter of the latter measures approximately three times the initial diameter in the case of d4-90% test. Generally, the diameter of the hole at the upstream part is relatively a little larger than at downstream part (Fig.17).

The final hole diameter has an inverse proportion with the initial diameter and the compaction degree as it is presented in figure (18). In other words, the lower initial hole diameter and compaction degree the lager final hole diameter.

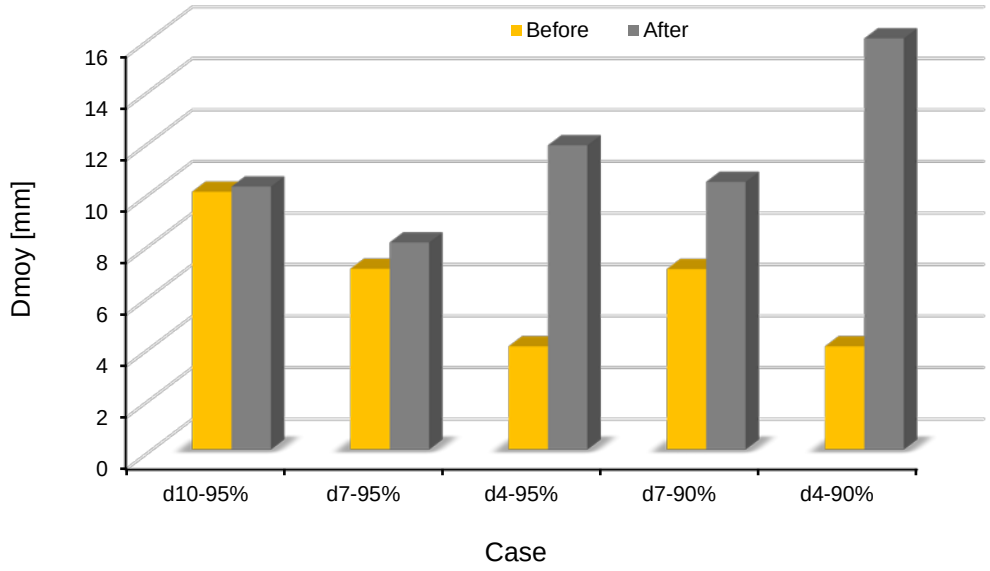


Fig. 18: Final versus initial hole's diameter.

A comparison of the final diameter to the initial diameter for each case can be used to quantify the soil's erodibility. The change in final diameter for specimens with an initial diameter of 4 mm is obviously greater than for specimens with an initial diameter of 7 and 10 mm. Regarding specimens with identical initial diameters and different degree of compaction, the final hole diameter is larger when the degree of compaction is lower.

4 Conclusion

The aim of this study was to evaluate the hydraulic properties (the erosivity and dispersity) of a representative coarse soil, as well as the ability to be used in hydraulic earthworks. The obtained results showed that the soil was found to be unstable towards internal erosion phenomenon.
Chemical analyses showed that the values of SAR and PS were low, and the soil is classified as non-dispersive, however after the verification of instability particle size criteria, it was concluded that the soil is dispersive and therefore unstable towards erosion.

To deep dive into the investigation, the soil was tested using Double hydrometer test where the degree of dispersion was found to be in the intermediate range, alongside Crumb tests revealed that the soil fully disintegrates when submerged in water, the compaction conditions determine how long this process will take.

HET tests revealed a relation between the initial hole's diameter and degree of compaction, which influences internal erosion onset and progression.

The results are more meaningful with specimen in which the hole is 4mm (d4) diameter, and the soil is compacted to a dry density of 90% of the normal proctor curve (opt90).

The obtained results provide more data for future studies on the behavior of compacted coarse soils, regarding the lack of understanding about this type of soil in terms of its behavior to the phenomenon of erosion.

Future research will be based on this case (the choice was for the most unfavorable case), to make the soil more resistant to erosion, many approaches are being used to stabilize the soil.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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