Open Journal of Civil Engineering, 2023, 13, 155-170
https://www.scirp.org/journal/ojce
ISSN Online: 2164-3172
ISSN Print: 2164-3164

Soil Erodibility Rates through a Hydraulic Flume Erosometer: Test Assembly and Results in Sandy and Clayey Soils

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How to cite this paper: Stresser, C. and de Brum Passini, L. (2023) Soil Erodibility Rates through a Hydraulic Flume Erosometer: Test Assembly and Results in Sandy and Clayey Soils. *Open Journal of Civil Engineering*, **13**, 155-170.
https://doi.org/10.4236/ojce.2023.131011

Received: January 5, 2023
Accepted: March 27, 2023
Published: March 30, 2023

Abstract

This paper presents a proposal for erodibility quantitative evaluation through a hydraulic flume based on the Inderbitzen erosion test. The equipment scheme and procedures for result calculation are described, following a review of literature. Through the proposed procedure, 24 tests are conducted, in order to study the erodibility of a sandy soil and a clayey soil, in undeformed and reconstituted conditions. These are conducted using grass roots in controlled quantities, to quantify root effects on erodibility. The results of soil loss by elapsed time and the definition of the erodibility K factor shows that clayey soil is 90% less erodible compared with sandy soil. Also, roots show no significant relationship with K factor and the undeformed sample is less erodible, compared with reconstituted sample. The test methodology and the results allowed soil classification, analytical data and comparative results between different cases.

Keywords

Erosion Rates, Procedures, Low-Cost, Criteria

1. Introduction

Nowadays, accelerated erosion is considered one of the most significant socioeconomic and environmental problems of the world [1] [2]. For example, in a range of 11 years (1991 to 2012) in Brazil, landslides caused by erosion correspond to 0.24% of death by environment disasters, whereas floods correspond to 43.19% of occurrences [3]. These two phenomena are intimately related, since in urban landscapes, erosion causes reductions in drainage systems capability, moving loose soils from private lots to a public pluvial system, reducing flow rate capability [4]. Because of these impacts, in big cities, water courses have gradually loosed their role as an element of the landscape, generating responses in the form of environmental and socioeconomic damage [5].

As erosion is a multidisciplinary issue, having subject in biology, geology and geography. It is important a knowledge combination of areas, in order to obtain more suitable approach to problems [6]. This paper focuses on erosion in an engineering approach, in order to quantify the erodibility in soils located in an artificial macro drainage channel thought lab tests.

Erodibility is one of the most complex properties of soil. A great number of variables are involved, such as particle size, Attemberg Limits, geological origin, chemical composition, void ratio, suction, and mechanical extern reinforcement [7]. In an analytical approach, erosion phenomena can be expressed by an interaction between three main components: the erodible material, the eroding fluid (in most cases, water), and the channel geometry that contains the flow [8]. In other ways, erodibility can be evaluated in terms of a relationship between soil erosion rate and fluid velocity or hydraulic shear stress.

Recent approaches have established a relation between erosion rate (ε), in a time unit of measurement, with the critical hydraulic shear stress (τ_c) and applied shear stress (τ_a) [8] [9]. The erosion and shear stress rate can be represented by Equation (1), known as DuBoys equation [10].

$$\varepsilon = \alpha\left(\tau_a - \tau_c\right)^{\beta} \tag{1}$$

where: ε = erosion rate; τ_a = applied shear stress; τ_c = critical shear stress; α and β = adjustment parameters.

The process of movement and particles detachment occurs after the application of a certain magnitude of stress. The concept of critical shear stress (τ_c) is defined as a threshold, who represents the beginning of the erosion process. From this point, the erosion rate is proportional to the difference between the applied shear stress and the critical shear stress [11].

A similar approach is presented by Equation (2), which relates erosion rate to applied hydraulic shear stress [11]. The authors used a series of tests, inserting two adjustment coefficients that take into account the type of soil. The formulation also includes the critical velocity, measured in point of critical shear stress. Equation (2) can be defined as the constitutive law of erosion problems [8].

$$\frac{\varepsilon}{v_c} = \alpha\frac{\left(\tau_a - \tau_c\right)^{\beta}}{\tau_c} \tag{2}$$

where: ε = erosion rate; v_c = critical velocity; τ_a = applied shear stress; τ_c = critical shear stress; α and β = adjustment parameters.

In order to categorize the behavior of different soil types, considering erodibility as a relation between erosion ratio and applied shear stress, authors made an abacus of categories for erodibility [12] [13]. In the graphs, the erosion rate (mm/h) has a relationship with the flow velocity (m/s) (**Figure 1(a)**) or the

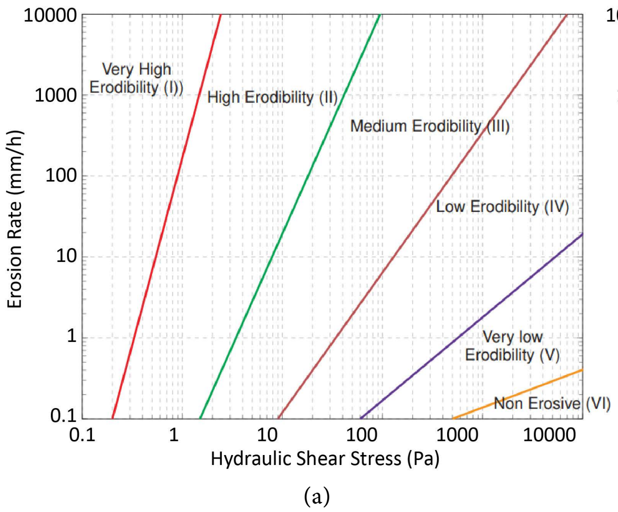


Figure 1. Abacus of erodibility classification, (a) categories by hydraulic shear stress; (b) categories by velocity. Source: Adapted from [8].

applied hydraulic stress (Pa) (**Figure 1(b)**). The contours that defined the categories are originated from tests made by the authors in various types of soils and rocks.

There are several tests that aim to simulate erosive processes, each one for a specific type or purpose. Some tests have only qualitative results, quick execution, for preliminary tests (*i.e.*, crumb test [14] and pinhole test [15]). Other tests quantify the variables, with a series of complex tests proposed in recent years (*i.e* Erosion Function Apparatus (EFA) [16] [17], *Ex-Situ* Scour Testing Device [17], Jet Erosion Test (JET) [18]).

The mainly goal of all tests aims to apply a known solicitation and evaluates soil detachment rates. In this sense, is common to use a hydraulic flume, where flow rates and pressures are determined by instrumentation. Values of erodibility thought open channel test are present in some research, including equipment scheme and test procedures [19] [20]. Effect of roots in a hydraulic flume and the relationship between shear stress and erosion rates show significant relation between grain size, root area ration (RAR), bulk density and hydraulic stress [21] in erodibility. Effects of grass roots in soil shear strength, and erodibility, are described in studies [22] [23], respectively.

In practice of geotechnical engineering, common labs, complex apparatus to value soil erosion is not a reality. In this regard, the described test into this paper is based on hydraulic flume originally proposed by Inderbitzen [24]. The test allows a quantitative analysis of the soil response against erosion agent. The sample is positioned on an inclined ramp, where a constant flow coming by top of the ramp is applied in order to disperse the material. The particles detached are collected on the base, through a system of sieves. Proceedings of test, results database and modifications are described in several Brazilian researches [7] [23] [25] [26] [27] [28] [29].

Given the mass accumulated in the sieves during the test and the shear stress applied, the results can be plotted on a graph, relating shear stress applied and the losses of mass. By performing 3 (three) or more rounds, it can be adjusted a line to the points, where the angular coefficient expresses the erodibility coefficient (K) [23] [30], as shown in **Figure 2**.

This behavior is described by Equation (1), with the coefficient β equal to unity. The intersection of the line with the x-axis defines the critical shear stress (τ_c), the point where the erosion process begins.

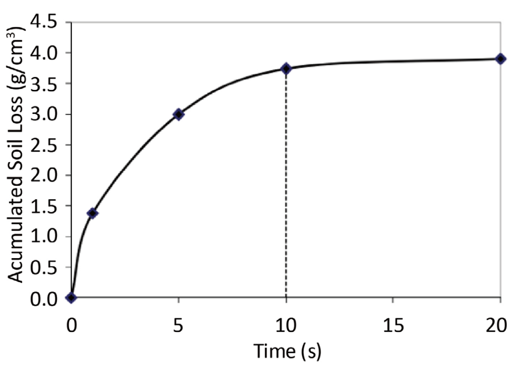
Therefore, the overall objective of this study is proposed a routine to perform Inderbitzen hydraulic flume test, quantify shear stress and compare the results in different cases. It was carried tests on samples in undisturbed and reconstitute states. Into this last, the effects of grass roots in erodibility were evaluated thought inclusion of roots fibers in controlled quantities [16].

2. Methodology

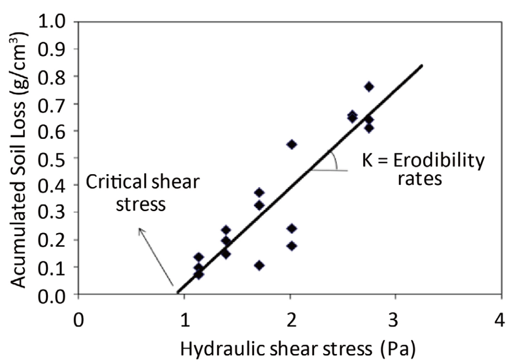
The developed hydraulic flume based on Inderbitzen test aims to improve the measurement of the hydraulic stress in the sample and to change the dynamics of the test, in order to facilitate its execution.

In relation of the original test, the main modifications consist in a water level sensor inputted close to the sample; a digital rotameter positioned in the flow release system; a microcontroller to automate data collection, and a water recirculation system. The design of a prototype was subject of several tests and experiments in order to correct errors and problems, in addition to verifying the entire system. A schematic representation of the erosometer developed are presented in **Figure 3**.

The main structure of the equipment is composed of an 80 cm steel tower, which serves as a support for a galvanized steel basement, with length, central shaft dimensions similar to the original project by Inderbitzen. The ramp has 70 cm of extension, 25 cm of width, 10 cm of height and a chamfer of 60˚ at the base.



(a)



(b)

Figure 2. Definition of K-Factor and critical hydraulic stress in Inderbitzen tests. Source: Adapted from Pinheiro *et al.*, [29].

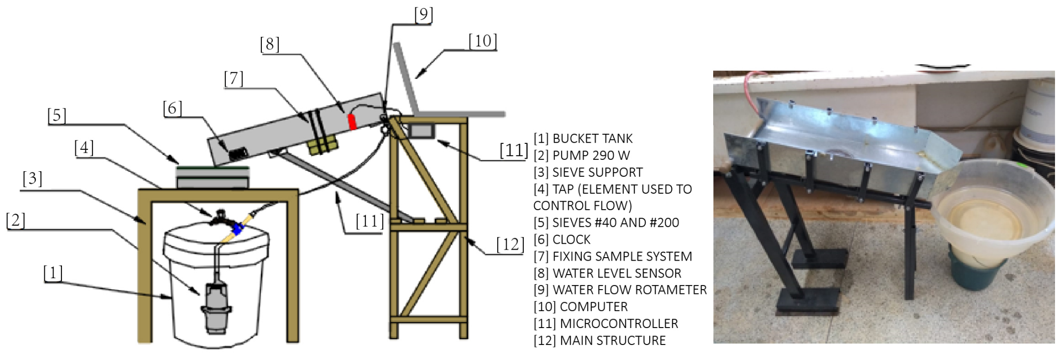


Figure 3. Equipment schematic representation. Source: The authors.

In the original test, the ring that contains the sample has approximately 15.2 cm (6") in internal diameter and height. Some other researchers use 10 cm rings [25] [26]. In this research, samples with diameter of 9.7 cm were used.

The hydraulic system is composed of a 25 mm diameter tube, with 6 mm holes in total along its length. The tube is connected to a threaded joint with a digital rotameter installed. Complete the system a flexible tube that connects to the water pump in a bucket that also serves as a tank. A water recirculation system comes by this bucket, with the advantage of water needed reduction. The equipment reservoir consists of a 25 L bucket, with a 290 W submerged pump. This pump has a flow rate of up to 30 liters per minute for the bucket pressure. A set of two taps was installed at the pump outlet, with drills facing the reservoir itself, in order to control the flow in standard rate of 12 L/min.

As the pump provides low flow variation, the standard flow rate stipulated throughout the test was facilitated. As a disadvantage of the recirculation method, there is a mixture of fines of soil in the water of the reservoir, that is sent back by the pump. As a way of circumventing this disadvantage, the water in the reservoir was replaced whenever it reached a high turbidity, with could be visually identified. Some studies suggest a use of a sedimentation test, after performed, in order to quantify fines grain sizes [7]. This procedure was considered unnecessary, since detachment of particles due to flow occur majorly in fine and coarse sand fractions [31].

In order to determine the shear stress applied on the sample, it used an equation based on the water depth. The shear stress applied to the sample can be expressed by $\tau_a = \gamma_w hd$, where τ_a is the applied shear stress (Pa), γ_w is the fluid specific weight, h is the water depth, and d is the degree of ramp. The electronic system for estimating the water depth in the ramp is composed of a rotameter and a water level gauge. This gauge varied the electrical resistance in its body according to the submersion of the equipment in the water.

The eroded material was collected using a pedestal to attach a set of 5 (five) pairs of sieves, each on with #40 (0.42 mm) and #200 (0.075 mm) openings.

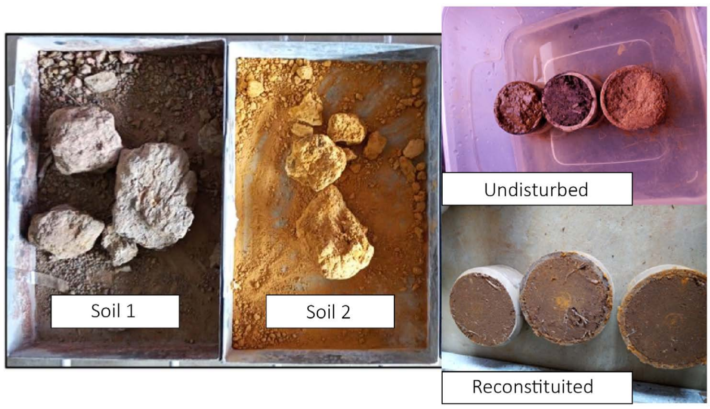
The sieves were replaced at 2 min, 4 min, 6 min and 10 min, for a total test time of 18 min. This interval between changes considers a typical test curve, described by [7].

More details about equipment description, as well as summary of test procedures and interpretation can be found in more details in Stresser [32].

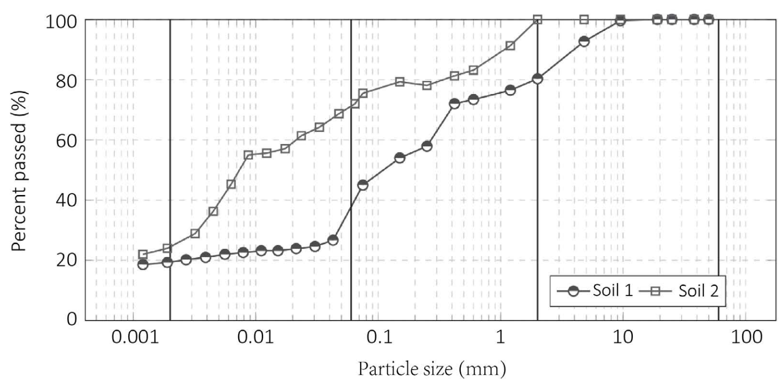
2.1. Soil Origin and Sample Preparation

Two types of alluvial soils were tested, coming by a drainage channel located in Curitiba, Parana, Brazil, at geographical coordinates 25˚32'36.4"S and 49˚20'39.6"W. The channel in question shows several erosive processes indicators, with material losses, margin verticalization and mass movements. The spatial arrangement of deposits in the region is quite heterogeneous, due to the origin of alluvial deposits combined with landfills, sourced by anthropic interventions.

The two soils collected in the field received names, as shown in **Figure 4(a)**, which also presents the aspects of specimens with and without roots after sample preparation. The granulometric curves of the soils are shown in **Figure 4(b)**. Complete the classification the following tests: Liquid Limit (LL), Plastic Limit (LP), Specific Gravity (Gs) and Organic Matter Index (MO). The results are shown in **Table 1**. Soil 1 was classified as sandy, defined as SUCS (Unified Soil



(a)



(b)

Figure 4. Soil grain size characterization. (a) tested identification and sample aspect. (b) Grain size distribution. Source: The authors.

Table 1. Geotechnical classification of tested soils.

ID	LP	LL	IP	*Gs*	MO	SUCS
Soil 1	15%	21 %	6%	2.650	5.15%	SC-SM
Soil 2	38%	55%	17%	2.225	6.72%	MH

Source: The authors.

Classification System) by the symbol of SC-SM; the Soil 2 were classified as clayey (defined as HM in SUCS).

The tested soils contain a high level of organic matter. The Soil 1 has an average index of 5.15%. Soil 2 contains the highest average, with a medium index of 6.72%. Both determinations were made using method described in ASTM D2974-14 [33]. The high organic matter is attributed to the depth of the soil collection and sedimentary origin. The samples collected in an undisturbed form were extracted from a plateau excavated on the slope of channel bank, through the setting of a beveled ring.

Two types of samples were used in tests: those extracted in the field in an undeformed form (I) and those reconstituted in lab by static compaction-Reconstituted (R).

In order to produce the reconstituted samples, the process of static compaction was used [34]. This procedure is demonstrated to be feasible for production of specimens in the lab [35]. Standard Proctor test was applied to determine the maximum soil unity and optimum water content—ASTM D698-12 [36]. The specimen is compressed into a ring with rigid side walls using a press fitted with a top cap that has the same diameter as the sample. The movement of the press continues until it reaches the previously stipulated height.

From those samples that contains roots, it was primarily extracted from the plant and dried in an oven at 100˚C. The mixed with roots is made before soil compaction. Defining root quantity was realized using its dry unit weight, obtaining a value of 0.479 g/cm^3. The medium area of a unity root is determined by measuring a group and determining a medium value. It was calculated the root mass that is necessary to obtain the stipulated quantities, obtaining 0.405 g for the R05 case (0.5% RAR) and 0.817 g for the R10 case (1% RAR). The parameter root area ratio (RAR) is commonly used in other soil-root behavior studies [19] [26].

A summary of the sample conditions is presented in **Table 2**, which shows the samples' geometric dimensions, soil bulk density and the roots theory quantity.

2.2. Test Procedures

Each test consisted in a sequence of steps, namely: (a) sample positioning and fixing; (b) equipment preparation of with inclination adjustment, wetting the ramp to avoid surface tension, followed by covering with plastic film; (c) start of data collection, with the removal of the plastic film when flow were stabilize and

Table 2. Compaction parameters compared in undisturbed and reconstituted case and roots measures.

Parameter	Soil 1	Soil 2
Sample diameter (d)	9.7 cm	9.7 cm
Sample height (h)	4.92 cm	4.92 cm
Proctor Normal water content (wp)	13.80%	29.80%
Water content in undisturbed samples (U) (wnat)	23.00%	47.65%
Water content in reconstituted samples (R) (wnat)*	13.80%	29.80%
Dry unity weight of reconstituted (R) samples (ρd)	1.82 g/cm^3	1.34 g/cm^3
Dry unity weight of undeformed (I) samples (ρd)	1.74 g	1.33 g/cm^3
Dry unity weight roots (ρr)	0.4792 g/cm^3	
Medium quantity of roots in R05 case (0.5% RAR)	82 units	
Medium quantity of roots in R05 case (1% RAR)	194 units	

*Optimal water degree from standard proctor test [37]; Source: The authors.

the activation of the stopwatch, initiating the test; (d) replacement of the sieve set by another at previously established times (2 min, 4 min, 6 min, 10 min and ending test in 18 min); and (e) after 18 min, removal of sieves material collected and transportation to pots with de-aired water, followed by oven drying.

After 24 h, the dry pot was measured, using a balance. The difference between full and empty pots weight determines the detached mass at each stage. In all tests, the flow value was 10 L/min, in order to generate water depths detected by the electronic system, without equity order with real rainfall intensities. Similar flow rates were used in other studies on the simulation of hydraulic channels [19] [21].

Overall, 24 valid erodibility tests were performed, three in each type/condition of soil analyzed. Inclinations of 5˚, 10˚ and 15˚ were used.

3. Results and Discussion

The tests carried out on the developed equipment allow an evaluation in four different scenarios, as follows: undeformed samples (U), reconstituted with no roots (R), reconstituted in a ratio of 0.5% (R05) and with a ratio of 1% (R10). The individual results of Inderbitzen are given in mass collected over time. It was carried out tests in 3 samples, varying the ramp degree in order to obtain different hydraulic shear stresses. The K erosion factor was adjusted using a linear equation, whereas the inclination represents that factor interpreted as the erosion velocity measurement, in unity of g/cm^2/min/Pa.

The results of the three tests performed in undeformed (U) condition for Soil 1 are shown in **Figure 5**, that also represents the K-factor for these two cases. The Soil 2 case are presented in **Figure 6**.

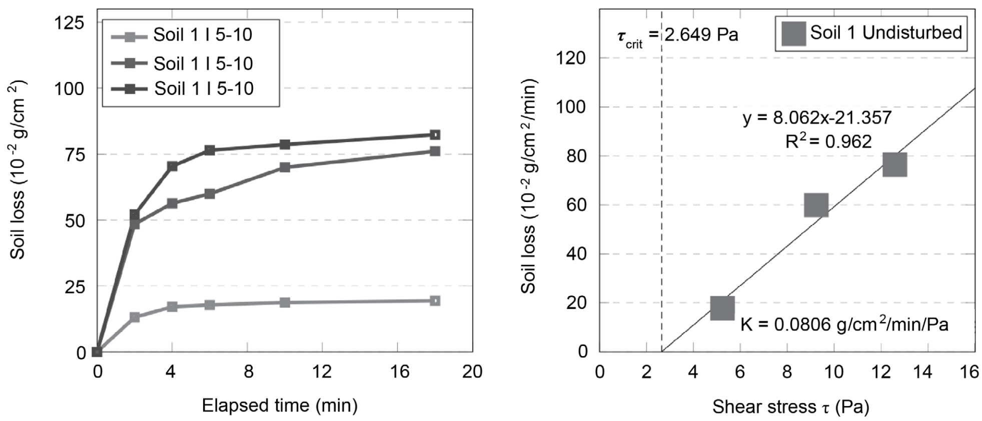


Figure 5. Soil 1 Undisturbed: determination of the erodibility factor K for Soil 1; Source: The authors.

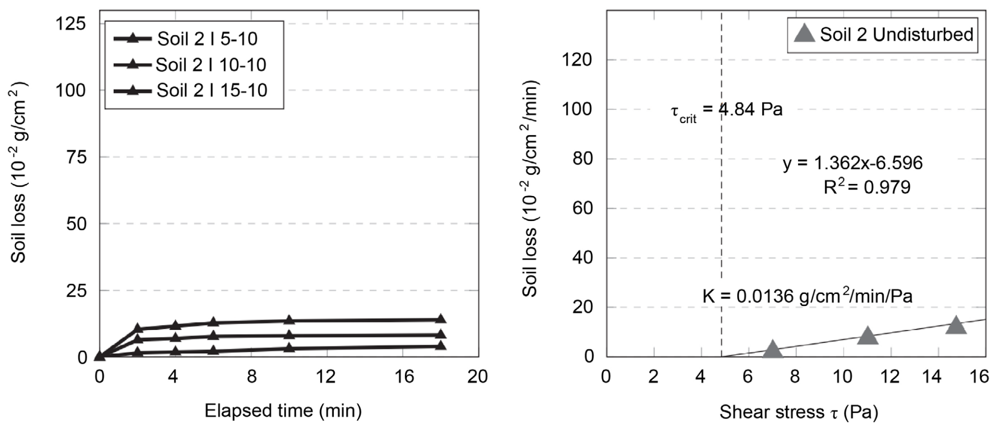


Figure 6. Soil 2 Undisturbed: determination of the erodibility factor K for Soil 2; Source: The authors.

Samples are identified in the results with a nomenclature that indicates soil type, condition, slope and flow. As an example, the denotation Soil 1 R 5 -10 indicates a reconstituted Solo 1 sample, with a 5˚ slope inclination in test and a flow rate of 10 L/min.

The fitted equation corresponds to the DuBoys equation (Equation (1)), with an exponential coefficient β equal to unity. According to [19], the unit coefficient is valid in the simulation of erosion in pits. The K-factor of Soil 2 is in average 84% smaller than Soil 1.

The curve obtained had a format like the typical one defined by Bastos [7], with greater variations in the first minutes. Soil 1 and 2 shows different behaviors, verifying that Soil 1 has a higher erosion rate compared to Soil 2.

Tests are procedures in reconstituted samples, in 3 (three) different conditions: No roots, 0.5% RAR (root-area-ratio) and 1% RAR. By defining the applied shear stress, it is possible to calculate the erodibility factor K, through the rate adjustment method presented in Figure 2. The K-factor for three conditions with roots are presented by Figure 8.

The Soil 1 reconstituted sample suffered a meltdown before the conclusion of the test, where the last recorded sieve exchange occurred within 10 minutes. This occurrence is related to the low initial degree of saturation. The sample was reconstituted under the same compaction conditions as the Proctor test. Likewise, for an apparent dry unity weight of 1.82 g/cm³ and a void ratio of 0.45, it presented a saturation degree of saturation of 80.18%. This behavior was observed in other studies [30] [38].

In general, it was possible to observe in the curves that the magnitude of the loss is proportional to the slope of the ramp and, consequently, to the applied shear stress, which can be calculated through Equation (4).

The reconstituted samples with roots are compared in terms of total soil loss per root quantity. Results indicated in **Figure 7** show that soil reduces erosion proportionally to roots quantity, in the range evaluated. It also presented the shear stress applied in each case. Results indicate that, in same range of applied shear, roots act like a reinforcement, reducing the flow effects. However, no significant changes on erodibility K factor were obtained. The Soil 1 in 10-10 conditions shows more root dependency, a fact that can be related to the reduction in shear strength applied in each case during tests.

The system proved to be feasible in maintain a relatively constant applied shear in each case evaluated. In comparison to undisturbed samples, all reconstituted soils have more total soil loss, even those that receive more roots, despite the high unity weight in reconstituted samples (see **Table 2**). This can be related to cementation effects in undisturbed samples. K values vary in the range of 0.01 to 0.1 g/cm²/min/Pa. The hydraulic shear stresses are within the range of other

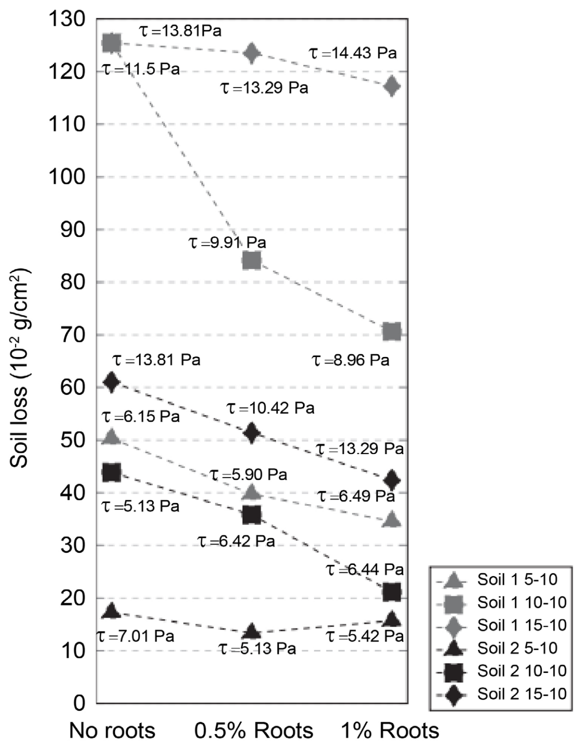


Figure 7. Relation between Soil Loss and Root quantities, on reconstituted samples (R). Source: the authors.

studies, with values from 1 Pa to 9 Pa [7] [19] [21] [23].

The lowest values of K correspond to the undeformed condition. Soil 2 I presented K of 0.0136 g/cm²/min/Pa, the lowest value found, followed by the K factor of Soil 3 (0.0248 g/cm²/min/Pa) and of Soil 1 with K of 0 .0806 g/cm²/min/Pa. These parameters indicate that the undeformed condition is less erodible compared to the reconstitution situation.

In relation of critical shear stress obtained, provided by the intersection point with the adjustment grid, it generates uncertainty results in some cases, because it crosses the x-axis in negative quadrant, which does not have physical sense. This fact also observed in other studies [7] [23] [25]. Valid values vary from 2.92 Pa in Soil 1 to 5.089 Pa in Soil 2. Reconstituted soils present a minor value in critical shear stress, varying from 2.01 Pa to 2.92 Pa.

The adjustment made for the reconstituted Soil 2 presented a lack of definition in the critical shear stress, since the challenge crosses the non-quadrant negative abscissa axis, also a result without physical significance. This uncertainty was also found in the tests carried by Bastos [7] and Venturini [23].

The erosometer tests were applied on two soil erodibility criteria proposed in the literature. The criteria chosen were those proposed by Bastos [7], developed for Inderbitzen-type tests, and those proposed by Briaud [13], developed for various types of erosion tests. **Figure 8** presents the results of the erodibility coefficients K determined for each case analyzed in the criteria of Bastos. The graph consists in a semi-logarithmic scale on the y-axis, with the plotting of the values obtained for factor-K. The author states that the limits between erodibility categories are not fixed, but are indicative of the behavior, given tests and parameters from other studies. The Bastos criteria presented in **Figure 8** compares data with the results of [23] (who used roots on a sandy soil) and Bastos [7], that evaluated unsaturated residual soil from Porto Alegre, Rio Grande do Sul, Brazil.

Analyzed cases indicates that Soil 1 is at the limit between the High Erodibility

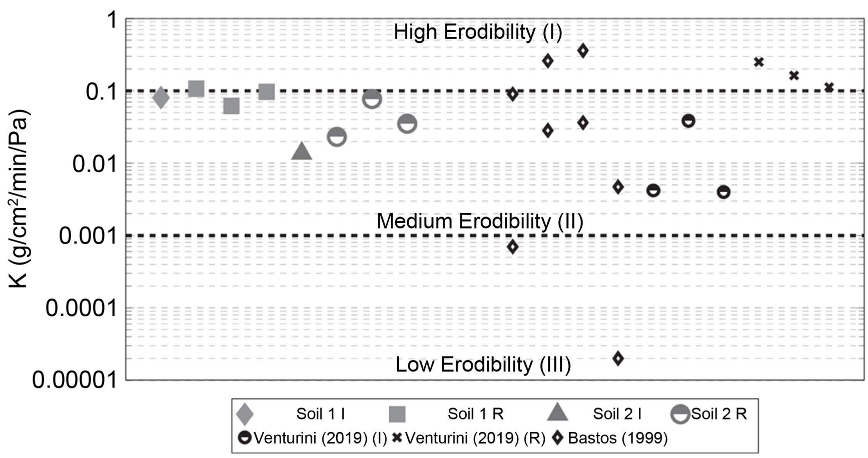


Figure 8. Application of results in erosion criteria; Source: Data from authors, using criteria by Bastos [7].

(I) and Medium Erodibility (II) categories, with a small reduction in the erodibility of the sample with 0.5% of roots (R05). Solo 2 features values within the range of average erodibility, with the highest value for the case R05, opposite to the results for Soil 1. Reconstituted samples show a small increase in K factor. The evaluated soils show less different between undisturbed samples and reconstituted samples, compared with reference data from [23].

The results were also applied to the erodibility criterion proposed by Briaud. The criterion uses a bi-log graph, where the erosion rate (length/time) is plotted on the y-axis and the test's hydraulic shear stress is plotted on the x-axis. The criterion was designed to unify results from different types of erodibility tests; However, the authors do not cite results from Inderbitzen-type tests. To apply the results in the criteria, a method was developed, based on the calculation of an erosion velocity (rate). The equation to define the erosion rate, in units of length/time is based in the soil dry unit mass. The proposed equation is presented in Equation (3).

$$\varepsilon = 600\frac{m\left(0-t_6\right)}{AA\cdot t\left(6\right)\cdot \gamma_d} \tag{3}$$

where: ε = erosion rate (mm/h); $m\left(0-t_6\right)$ = soil mass collected from 0 to 6 min (g); AA = specimen area (cm²); $t\left(6\right)$ = time considered (6 min); γ_d = apparent dry unity weight (g/cm³); 600 = unit conversion factor (from cm/min to mm/h).

Figure 9 presents the results in Inderbitzen test using the described methodology of classification. The reconstituted condition is grouped on the same category.

Compared the two criteria, it appears that the results are quite similar. In both, the tested soils will remain in the medium erodibility zone, with the Soil 1 being samples closer to the limit between medium and high erodibility, and

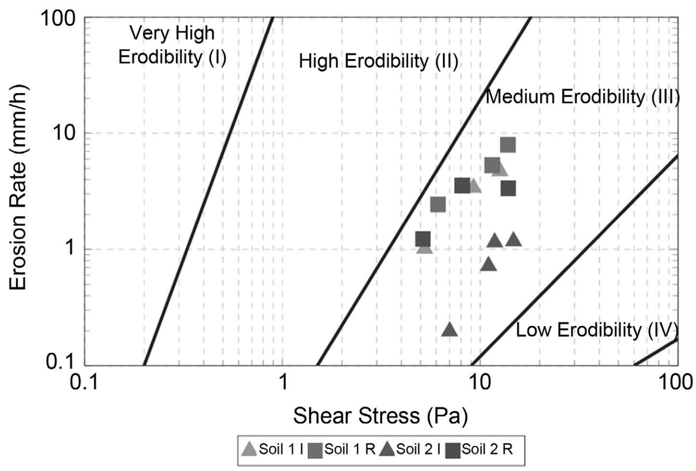


Figure 9. Application of results in Briaud criteria; Source: Data from authors, using criteria by [7].

the undeformed Soil 2 and Soil 3 samples being the least erodible. Thus, the analysis of the results of two tests seeks to present a form of evaluation and comparison between the cases in order to guide the selection of mitigation techniques.

An important point of the analyses performed was that all samples were in conditions of intermediate humidity: the undisturbed samples had preserved field humidity, and the reconstituted samples were produced in the optimal humidity of the Normal Proctor test. Other studies have shown that samples with higher levels of saturation seem to be more resistant to erosion, with higher losses of soil with higher initial suction values [25] [30] [38] [39]. Flooding the sample could eliminate the influence of suction. Therefore, the conditions analyzed would be different from those of the field, since soil more subjected to the erosive action of water are found in more superficial horizons, usually in the unsaturated zone.

4. Conclusions

The present paper presents a methodology for the Inderbitzen erosion test, which includes the assembly of equipment, procedures, and analysis of results. The procedure aims to enable a method of analytical extraction of the results, following constitutive erosion equations and classification criteria.

The results of the two tests performed will allow classifying Soil 1 as erosive, or Soil 2 as moderately erosive. Soil 2 is, in average, 90% less erodible than Soil 1. Erosion rates are directly proportional to the inclination of the equipment and, consequently, to the applied hydraulic shear stress. The samples not in their natural state present lower erodibility when compared to the reconstituted samples. For the application of the methodology in Bastos criteria, it is necessary the parameter K, where the theoretical basis and the procedures are described on paper. A formulation was presented to estimate the erosion rate for the application of results on Briaud criteria. The results were close on both criteria. Roots added to reconstituted samples (R) reduce soil losses but show no significant changes on the erodibility K-factor, which shows a stronger correlation with the hydraulic critical shear stress. Therefore, the method needs to be validated through other studies and tests that contain a wider range of soils types.

The values used for the slope and flow rate of the Inderbitzen are not intended to simulate real conditions, but to allow the measurement of erodibility under controlled conditions, reducing the total time of the natural erosion process and allowing a comparison between different cases. In general, the Inderbitzen erosion test has the potential to evaluate soil erodibility in a quantitative way, with an easily implementation. In an erodibility assessment of field samples, the data can complement preliminary analyses performed with qualitative tests, generating graphs and enabling the application of erosion criteria, in order to compare the results with a database of other tests performed.

Acknowledgements

The authors want to acknowledge the Program of Postgraduate in Civil Engineering (PPGEC) and the members of the Geotechnical Studies Group (GEGEO), both from Federal University of Parana (UFPR), for the support of this research.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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