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Soil susceptibility to accelerated hydric erosion: geotechnical evaluation of cut slopes in residual soil profiles

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ABSTRACT. The experimental research program was developed in the Alto Paraopeba region, state of Minas Gerais, Southeastern Brazil. The main objective was to promote the geotechnical evaluation of soil samples from four cut slopes in residual soil profiles of highways and local secondary roads in order to assess the potential of the anthropic impact on the soil susceptibility to accelerated erosion processes. Soil samples were named: red residual soil (RRS); pink residual soil (PRS); yellow residual soil (YRS); and white residual soil (WRS). The methodology used consisted of geotechnical characterization tests, infiltration rate and modified mass loss by immersion tests performed on soil samples from these profiles, using the physical parameters and indirect assessment of erodibility proposed in 2000 by Bastos et al. The results of indirect assessment of erodibility, which were derived from tests based on the MCT methodology, highlighted the different susceptibility of the investigated soils to hydric erosion. The parameters proposed by the referred authors were complementary to conventional criteria for an adequate classification of tropical soils into their respective classes of erodibility. Among the tested soil samples, the highest erodibility was associated with the YRS and PRS, respectively, in the natural and pre-moistened conditions, as well as it was not detected erodibility in the RRS and WRS.

Keywords: geotechnical characterization, soil classification, erodibility.

Suscetibilidade de solos à erosão hídrica acelerada: avaliação geotécnica de cortes rodoviários em perfis de solos residuais

RESUMO. O programa experimental de pesquisa apresentado se desenvolveu na região do Alto Paraopeba, no Estado de Minas Gerais, na região Sudeste do Brasil. O objetivo principal foi promover a avaliação geotécnica de perfis de solos residuais de cortes de rodovias e estradas vicinais, quanto à potencialidade da interferência antrópica sobre a suscetibilidade desses solos aos processos erosivos acelerados. A metodologia aplicada neste estudo consistiu na realização de ensaios de caracterização geotécnica, de infiltrabilidade e de perda de massa por imersão modificada de amostras de solos desses perfis, utilizando os parâmetros físicos e de avaliação indireta de erodibilidade apresentados na proposta de 2000 de Bastos e outros autores. Os resultados para avaliação indireta de erodibilidade, oriundos de ensaios baseados na metodologia MCT, destacaram as diferentes suscetibilidades dos solos investigados à erosão hídrica. Considerando-se os resultados obtidos no presente trabalho, os parâmetros utilizados pelos referidos autores apresentaram-se como complementares aos critérios convencionais, permitindo um adequado enquadramento dos solos tropicais estudados às suas respectivas classes de erodibilidade. Dentre as amostras estudadas, detectou-se maior erodibilidade nas amostras YRS e PRS, respectivamente nas condições natural e pré-umedecida, bem como não se observou erodibilidade nas amostras RRS e WRS.

Palavras-chave: caracterização geotécnica, classificação de solos, erodibilidade.

Introduction

The erosion term comes from the Latin *erode-erodere* meaning to corrode, with several definitions in the literature. In general, erosion is a term that represents a series of actions, including the loosening, dragging and deposition of soil particles caused by erosive agents such as ice, wind, gravity and water.

When erosion is a natural process, it is considered a geological agent that changes terrestrial landscapes, in a slow mechanism measured by geological time. Human interference modifies this natural process and usually accelerates its action and increases its intensity. When human action is characterized as promoting and intensifying the processes of water erosion, the term used is accelerated hydric erosion (BASTOS et al., 2000).

Rainfall is the erosive agent of water erosion, and manifests its action on two ways: by the impact action of drops and the action of runoff. Both act on the particle pull out and transport (BASTOS et al., 2000). When a drop of rain strikes the surface of the soil, it detaches particles and moves them at short distance. This is called drop impact erosion.

Runoff occurs when the rainfall intensity exceeds the infiltration capacity of the soil. In this case, there is a diffuse surface flow on the ground surface, which causes a progressive and uniform removal of surface horizons.

From a geotechnical point of view, erodibility characterizes the susceptibility of a soil to erosive action. One of the major difficulties in studying this phenomenon is that the erosion actually observed may not be related directly to the soil grain size distribution. For example, a clean, non-cohesive sand is highly erodible under the erosive action of water sheet but in appropriate slope angle it can be a non-erodible material, as observed in sand dunes (NOGAMI; VILLIBOR, 1995).

With respect to erosion control, soil conservation through mandatory policies often do not reach their goals (FRANCO et al., 2002). However, knowledge and quantification of the factors that may influence water erosion are of utmost importance in the planning of roads (CORREA; CRUZ, 2010).

The main factors influencing soil erosion include the net rain excess, the water depth, the velocity, the shear stress of overland flows, and the erosion-resisting capacity of soil (LIU et al., 2001).

The importance of the inherent resistance of soil to erosional processes, or soil erodibility, is generally recognized, but the full implications of the dynamic soil properties that affect erodibility are seldom considered (BRYAN, 2000).

Given the context described previously, this study investigated, via geotechnical laboratory tests, the susceptibility to accelerated erosion of cuts in residual soil profiles in some highways and local secondary roads of the city of Ouro Branco, Alto Paraopeba, state of Minas Gerais, southeastern Brazil.

Material and methods

Ouro Branco has an area of 260.766 km² and is located in the micro-region of the Alto Paraopeba in the state of Minas Gerais, 95 km from Belo Horizonte, Brazil. The city presents average latitude and longitude of 20° 31' 15''S and 43° 41' 31''W, respectively, at an average altitude of 1,100 m, and is bordered by the municipalities of Congonhas, Conselheiro Lafaiete, Itaverava and Ouro Preto.

Soil samples studied herein are from four cut slopes of roads in residual soil profiles typical of the region of the Alto Paraopeba in the state of Minas Gerais. They were named as follows: red residual soil (RRS); pink residual soil (PRS); yellow residual soil (YRS); and white residual soil (WRS). Disturbed soil samples for geotechnical characterization tests and soil classification, as well as undisturbed soil samples for indirect assessment of erodibility, were collected, respectively, the PRO 003 (DNER, 1994d) and the PRO 002 (DNER, 1994d). Disturbed soils samples were air-dried and sieved through a 2 mm mesh (sieve #10) before testing.

The following geotechnical characterization tests were performed: Disturbed soil samples preparation - NBR 6457 (ABNT, 1986); Standard test method for particle-size analysis of soils - NBR 7181 (ABNT, 1984d); Atterberg limits: Liquid limit - NBR 6459 (ABNT, 1984a) and Plastic limit - NBR 7180 (ABNT, 1984c); Specific gravity of soil solids- NBR 6508 (ABNT, 1984b).

For soil classification purpose, it was used empirical coefficients obtained in two tests of the MCT Methodology as prescribed in CLA 259 (DNER, 1996), currently regulated by road standards of the National Department of Transports Infrastructure (Dnit), as follows: (i) Mini-MCV dynamic compaction test - ME 258 (DNER, 1994b); and (ii) mass loss by immersion test - ME 256 (DNER, 1994a). In the MCT Methodology, soils are classified as presenting lateritic behavior (groups LA, LA' and LG') or non-lateritic behavior (groups NA, NA', NS' and NG'), as defined by Nogami and Villibor (1995).

The Mini-MCV test consisted of a compaction test with variable energy, where soils with different moisture contents were compacted into cylindrical molds (diameter $\phi = 5$ cm and height $h = 5$ cm) by an increasing number of hits, until the maximum dry apparent specific mass. The Mini-MCV test provides the MCT classification coefficients c' and d'. The coefficient c' is determined from the deformability curve slope while the coefficient d' represents the curve slope of the dry side of the compaction curve corresponding to 12 hits.

The test of mass loss by immersion consisted of submerging specimens compacted in the Mini-MCV test. The mass loss by immersion (*Pi*) in conjunction with the coefficient d' enabled the calculation of the classification index e', as shown in Equation 1.

$$e' = \sqrt[3]{[(P_i/100) + (20/d')]} \quad (1)$$

where:
Pi: Mass loss by immersion in water;
d': Inclination of straight part of the dry branch of the compaction curve, corresponding to 12 blows in the Mini-MCV test.

Using the MCT methodology (NOGAMI; VILLIBOR, 1995), it is possible to predict the erosion susceptibility behavior of the soils analyzed in this study. This prediction is based on two parameters, as follows: the sorption coefficient (s) obtained in the infiltration rate test, and the modified mass loss by immersion (*Pi*) obtained in the specific erodibility test. Soils are classified as erodible when the *Pi* s^{-1} ratio is greater than 52 (NOGAMI; VILLIBOR, 1979; BASTOS et al., 2000).

In this paper, prediction of soil erosion susceptibility was based on Bastos et al. (2000) criteria, where potentially erodible soils show less than 55% passing through the 200 mesh sieve, and their plasticity index is less than 10% and *Pi* s^{-1} ratio (relationship between the mass loss by immersion and sorption coefficient) is higher than 52.

The infiltration test aimed to quantify the rate of capillary rise in the soil samples analyzed. In this test, undisturbed soil samples presented the following conditions: natural moisture, air-dried (for at least 72 hours) and pre-moistened (by capillary rise, at least for 24 hours), being confined in cylindrical PVC rings, 5 cm high and 5 cm diameter.

The equipment used in the infiltration rate test consists of a wooden plate equipped with graduated rulers and glass capillary tubes (6.0 mm diameter) and connected to a water reservoir with an open-graded porous-stone and the soil specimen resting on its top. The capillary tube was filled with water until overflowing at the top of the reservoir and reaching the base of the porous stone, being placed a filter paper on the top of the porous stone. Undisturbed soil samples were confined into their PVC rings and placed on the top of the filter paper.

The displacements of the meniscus were measured in cm within the capillary tube, at a quadratic time frequency (1, 2, 4, 9, 16, 25, 36, 49, 64, and 81 min. and so on) to the time at which the displacement has ceased, that is, until the moment that the soil samples proved to be fully saturated by the capillary rise of water.

With data corresponding to the displacement of the meniscus, in cm, and to the square root of time, in min., it was possible to draw up a chart showing a typical curve where its initial rectilinear sections provided the sorption coefficient sin cm min.$^{-1/2}$ determined by the relationship shown in Equation 2:

$$s = \frac{(L_2 - L_1).S}{10.(t_2 - t_1).A} \quad (2)$$

where:
S: area of the capillary tube section, in cm^2;
A: area of the specimen section, in cm^2;
L_2: reading at time t_2 and L_1: reading at time t_1.

The modified mass loss by immersion test (Pi), also called specific erodibility test, provides a quantitative assessment of the potential breakdown of undisturbed soil samples when submerged in water. For this test, undisturbed soil samples were used in the following conditions: natural moisture; air-dried (for at least 72 hours) and pre-moistened (by capillary rise, at least for 24 hours), being confined in cylindrical PVC rings, 5 cm high and 5 cm diameter. For the tests, samples were reduced to 2.5 cm high in the laboratory, placing a filter paper on the top of the porous stone at the base of the soil specimen in the ring.

By the completion of the test, water was carefully drained from the container supporting the samples. The loosened soils and remaining soils of the rings were collected, taken to the oven and subsequently weighed. The parameter *Pi* was determined by the Equation 3:

$$Pi = \frac{p_{d_{dry}}}{p_{t_{dry}}} \quad (3)$$

where:
Pd_{dry}: loosened dry soil weight, in g, and
Pt_{dry}: total dry weight of the soil sample in g.

Then, it was used a geotechnical approach to predict the erodibility of the unsaturated residual soils. At this step, the results were analyzed according to the physical parameters and indirect assessment of erodibility procedure proposed by Bastos et al. (2000). For analysis of the proposed geotechnical approach, parameters of the physical characterization tests (Standard test method for particle-size analysis of soils and Atterberg limits) and of the MCT methodology were used.

Results and discussion

Table 1 presents information regarding particle size distribution, Atterberg limits and specific weight of solid grains of the four soil samples analyzed.

Table 1. Results of tests for geotechnical characterization of studied soils: particle size, Atterberg limits and specific gravity of soil solids.

Properties analyzed (Geotechnical characterization)		Soil samples			
		RRS	PRS	YRS	WRS
Particle-size analysis of soils (%)	Clay (φ ≤ 0.002 mm)	4	8	0	8
	Silt (0.002 < φ ≤ 0.06 mm)	61	22	58	41
	Fine sand (0.06 < φ ≤ 0.2 mm)	22	42	9	13
	Medium sand (0.2 < φ ≤ 0.6 mm)	12	24	29	32
	Coarse sand (0.6 < φ ≤ 2 mm)	0	3	4	5
	Gravel (φ > 2 mm)	1	1	0	1
Atterberg Limitg (%)	Liquidity limit (LL)	59	35	46	35
	Plasticity limit (LP)	38	31	40	30
	Plasticity index (IP)	21	4	6	5
Specific gravity of soil solids (kN m^{-3})	γ_s	28.65	29.72	28.65	28.65

The RRS soil (red residual soil) was classified as MH by the Unified Soil Classification System - USCS (DNIT, 2006) and as A-7-5 by the Transportation Research Board System – TRB (DNIT, 2006). The PRS soil (pink residual soil) was classified as ML and A-4, the YRS (yellow residual soil) was classified as ML and A-5 and the WRS (white residual soil) was classified as SM and A-4, respectively, by the USCS and TRB, respectively. For the studied soils, the specific gravity of soil solids ranged from 28.65 to 29.72 kN m^{-3}.

Based on conventional soil classification systems, all materials studied belong to the class of fine materials, except for WRS soil that was classified as silty sand according to the USCS. In all these soils, there is predominance of silt and sand fractions, as well as the limited percentage of clay in these materials.

Despite some of these soils are classified as fine by the conventional classification, it should be noted that this is mainly due to the high percentage of silt in their respective particle size compositions. As for consistency indices derived from Atterberg tests, they showed orders of magnitude consistent with the characteristics of the samples analyzed.

Physical indices obtained from undisturbed samples, which were used in the tests of infiltration and mass loss by immersion, are presented in Table 2. Particular emphasis may be given to the respective values of void ratio of these soils, all with magnitude greater than unity.

Information on the classification of the samples according to the MCT Methodology is also presented in Table 2. According to such methodology, PRS and WRS samples were classified as belonging to the group NA', and RRS and YRS samples were classified as belonging to the groups LG' and NS', respectively.

Samples PRS and WRS belong to the group NA', presenting non-lateritic behavior, which in accordance with the particle size characterizes soils of quartz sand or similar mineral properties, with fines passing through the sieve of 0.075 mm. According to Nogami and Villibor (1995), genetically, the most representative types of this group are saprolite soils derived from quartz-rich rocks, such as granites, gneisses, sandstones and impure quartzites.

Table 2. Soil classification according to the MCT Methodology: **i**ndex properties, classification indices and soil classification.

Index properties*	Soil samples			
	RRS	PRS	YRS	WRS
w (%)	19.24	18.57	23.12	11.06
γ (kN m^{-3})	15.59	14.31	17.38	15.12
γ_d (kN m^{-3})	13.07	12.07	14.11	13.62
e	1.19	1.46	1.03	1.10
n (%)	54.34	59.35	50.74	52.38
S (%)	47.21	38.54	65.54	29.36

Soil samples	Classification indices				MCT Classification
	c'	d'	Pi (%)	e'	
RRS	1.88	64.15	0.00	0.68	LG'
PRS	1.06	19.90	52.20	1.15	NA'
YRS	1.04	5.18	32.00	1.61	NS'
WRS	0.93	19.46	52.00	1.16	NA'

*w: water content; γ: natural specific weight; γ_d: dry unit weight; e: void ratio; n: porosity; S: degree of saturation.

The RRS sample belongs to the group LG', in which the most frequent members are clays and sandy clays, which constitute the B horizon of the Oxisols, Argissols and Latosols.

In turn, the YRS sample belongs to the group NS', which comprises mainly the peculiar silty-sandy saprolite soils, resulting from tropical weathering on igneous and metamorphic rocks, predominantly of quartz-feldspar-micaceous constitution.

The varieties richest in quartz sand may have mechanical and hydraulic characteristics close to soils of the group NA'.

Considering the classification indices and the classification of soil samples based on the MCT Methodology, described in detail by Nogami and Villibor (1995), the coefficient c' is correlated approximately with the particle size. Thus, low values of c' (below 1.0) characterize the sands and non-plastic or little cohesive silt, and values of c' between 1.0 and 1.5 characterize soils of various particle sizes, which may comprise silty sands, clayey sands, sandy clays, silty clays, among others.

The four samples investigated have these particle size characteristics, with the coefficient c' ranging between 0.93 and 1.88. Among the studied soils, PRS, YRS and WRS had coefficients c' near unity (typical of sand or little cohesive silt), while the RRS soil showed coefficient c' far above the unity. It is noteworthy that the soils rich in silt and sand may have greater potential for water erosion, a trend that can be restricted by the clay fraction due to its ability to enhance the cementation of larger particles in the soil structure.

Concerning the values of the sorption coefficient (s) and modified mass loss by immersion (*Pi*) for different moisture conditions of the soil samples studied, the tests were conducted using as reference the criteria for assessing soil erodibility following the method of Bastos et al. (2000) for the three conditions of initial moisture content of the samples: natural moisture (nm), air-dried (ad) and pre-moistened (pm).

The results of the infiltration and specific erodibility tests performed in three specimens per soil are presented in Tables 3 and 4, represented by the sorption coefficient (s) and the modified mass loss by immersion (*Pi*) according to the criterion of erodibility of the MCT Methodology for RRS and PRS soils and the YRS and WRS soils, respectively.

According to Bastos et al. (2000) classification criteria of erodible soils and analyzing the data presented in Tables 3 and 4, for samples RRS and WRS, the *Pi* s^{-1} ratios were below 52, regardless of the initial moisture content considered. Among the soils studied, the RRS soil sample presented the lower *Pi* s^{-1} ratio at the natural condition linked to the higher percentage of fines (65%), which probably gave to soil structure a higher cementation capacity at the inter-particle contact points and consequently improved its potential ability to resist hydric erosion.

For all tested soils, the *Pi* s^{-1} ratio greater than 52 was only found for samples PRS and YRS, respectively, in the pre-moistened and natural conditions. Thereby, considering only the *Pi* s^{-1} ratio, the results highlight the increased susceptibility of the sample YRS to erosion. It should be emphasized that this sample presented 58 of silt and 42% of sand, which probably made it more vulnerable to the erosive phenomenon, explaining its poor performance compared to the other soil samples.

Table 3. Sorption coefficient (s) and modified mass loss by immersion (*Pi*) parameters for different moisture conditions of RRS and PRS soils samples.

RRS Soil									
	Natural moisture (nm)			Air-dried (ad)			Pre-moistened (pm)		
Samples	s (cm min.$^{-1/2}$)	*Pi* (%)	*Pi* s^{-1}	s (cm min.$^{-1/2}$)	*Pi* (%)	Pi/s	s (cm min.$^{-1/2}$)	*Pi* (%)	*Pi* s^{-1}
SP1	0.0251	0.0290	1	0.0268	0.8039	30	0.0001	0.0033	33
SP2	0.0162	0.0180	1	0.0349	0.2226	6	0.0001	0.0006	6
SP3	0.0169	0.0663	4	0.0376	0.2001	5	0.0001	0.0014	14
Mean value	0.0194	0.0378	2	0.0331	0.4089	14	0.0001	0.0018	18

PRS Soil									
	Natural moisture (nm)			Air-dried (ad)			Pre-moistened (pm)		
Samples	s (cm min.$^{-1/2}$)	*Pi* (%)	*Pi* s^{-1}	s (cm min.$^{-1/2}$)	*Pi* (%)	*Pi* s^{-1}	s (cm min.$^{-1/2}$)	*Pi* (%)	*Pi* s^{-1}
SP1	0.0223	0.594	27	0.0159	0.287	18	0.0001	0.0159	159
SP2	0.0177	0.514	29	0.0106	0.442	42	0.0002	0.0399	200
SP3	0.0267	0.566	21	0.0245	0.555	23	0.0002	0.0397	199
Mean value	0.0667	0.558	26	0.0170	0.428	27	0.0002	0.0318	186

Table 4. Sorption coefficient (s) and modified mass loss by immersion (*Pi*) parameters for different moisture conditions of samples of YRS and WRS soils.

YRS Soil									
	Natural moisture (nm)			Air-dried (ad)			Pre-moistened (pm)		
Samples	s (cm min.$^{-1/2}$)	*Pi* (%)	*Pi* s^{-1}	s (cm min.$^{-1/2}$)	*Pi* (%)	*Pi* s^{-1}	s (cm min.$^{-1/2}$)	*Pi* (%)	*Pi* s^{-1}
SP1	0.0064	0.4561	71	0.0234	0.8209	35	0.0001	0.5703	5.703
SP2	0.0120	0.6478	54	0.0247	0.5228	21	0.0001	0.4267	4.267
SP3	0.0057	0.6698	118	0.0224	0.6097	27	0.0001	0.1564	1.564
Mean value	0.0080	0.5912	81	0.0235	0.6511	28	0.0001	0.3845	3.845

WRS Soil									
	Natural moisture (nm)			Air-dried (ad)			Pre-moistened (pm)		
Samples	s (cm min.$^{-1/2}$)	*Pi* (%)	*Pi* s^{-1}	s (cm min.$^{-1/2}$)	*Pi* (%)	*Pi* s^{-1}	s (cm min.$^{-1/2}$)	*Pi* (%)	*Pi* s^{-1}
SP1	0.0276	0.7575	27	0.0355	0.7745	22	0.0001	0.4618	4.618
SP2	0.0311	0.6641	21	0.0292	0.9212	32	0.0001	0.4600	4.600
SP3	0.0257	0.8305	32	0.0348	0.9012	26	0.0001	0.4915	4.915
Mean value	0.0281	0.7507	27	0.0332	0.8656	26	0.0001	0.4711	3.089

The curves representing the relationship between the volume of infiltrated water ($cm^3\ cm^{-2}$) and the square root of time (in $min.^{1/2}$) for each soil studied are illustrated in Figure 1. These curves represent the mean values derived from three tests for the same type of soil.

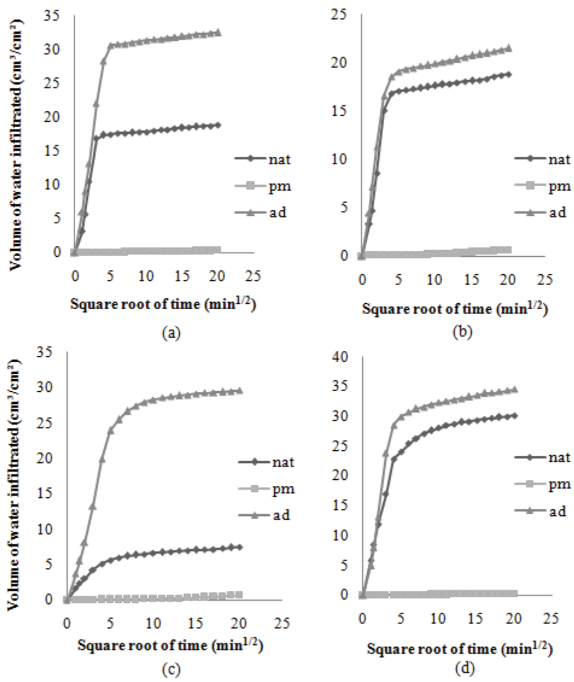

Figure 1. Curves of variation in the volume of infiltrated water ($cm^3\ cm^{-2}$) versus the square root of time ($min.^{1/2}$) determined in the infiltration rate tests conducted on soil samples: (a) RRS; (b) PRS; (c) YRS; and (d) WRS.

Based on Figure 1, it can be observed that for all soil types, air-dried samples absorbed greater amounts of water over time, when compared to natural and pre-moistened soil samples. Consequently, there is an increasing trend in the rate of capillary rise for dry samples, induced by the greater magnitude of the suction resulting from low initial saturation.

Considering the physical parameters and indirect assessment of erodibility relevant to the geotechnical approach for predicting the erodibility of unsaturated residual soils proposed by Bastos et al. (2000), among the four soils tested herein, those strictly classified as erodible materials, according to their respective percentage of fines, plasticity index and *Pi* s^{-1} ratio, correspond to PRS, YRS and WRS soils, confirming previous assessments that pointed out the RRS soil as the one with lower erosive potential.

Thus, it is clear that, with regard to the tropical soils studied herein, the proposal of Bastos et al. (2000) for using physical parameters and indirect assessment of erodibility represents an adequate alternative to predict the erodibility of soils, complementing the conventional geotechnical criteria used for such prediction.

Conclusion

Geotechnical data obtained from the MCT Methodology and data following Bastos et al. criteria for erodible soils presented convergence, considering the purpose of the classification of soils into erodibility classes. Taking into account the soils analyzed in this study, the parameters used by Bastos et al. were complementary to the conventional criteria, allowing an adequate classification of the tropical soils into their respective erodibility classes.

The YRS and PRS soils samples showed the highest susceptibility to erosion, respectively, in the natural and pre-moistened conditions, as well as erodibility was not observed in samples RRS and WRS.

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