On the Erosive Potential of Some Weathered Soils from Southern Brazil

R.A.R. Higashi, M. Maccarini, R. Davison Dias

Abstract. This paper presents a parametric study on erodibility of soils which occurs in Southern Brazil. Different methodologies were carried out and soils more vulnerable to these phenomena were identified. The research lays mainly on erodibility criteria based on infiltrability tests, weight loss by immersion, direct shear tests and modified Inderbitzen tests. Results obtained allowed a comparison and interpretation of the erosive potential of some soil units from the states of Paraná, Santa Catarina and Rio Grande do Sul. By the applied methodologies and their respective criteria, it was observed that Cambisols units present a high erosive potential compared to other soils studied, like Latosols and Red-Yellow Podzolic soils. It was also observed that fine sandy soils were more vulnerable to erosion despite the fact of belonging to the same group. This was due to the different degree of weathering of the stratum from where samples were obtained. Finally, the results also showed that it seems to be possible to successfully correlate the erosive potential of soils with simple indices, which may reflect the characteristics related to certain peculiarities of the soil, such as specific gravity.

Keywords: erosion, tropical soils, laboratory tests.

1. Introduction

Erosive processes caused by water are of great interest, especially in areas of high pluviometric indices and intense use and occupation, as occurs in the south region of Brazil. The siltation mechanism, reflex of erosion phenomenon, tends to accelerate with the expansion of urban areas, mainly due to the suppression of vegetation, exposing high vulnerable soils to erosion. This process results on the decrease of the superficial thickness of soil horizons and on the rising of river water levels during catastrophic climatic events.

Although several studies have been carried out to analyze erosive potential of soils from other parts of Brazil, the relationship between geotechnical parameters obtained by laboratory tests and the tropical soil units have not usually been done.

Due to this reason, a diagnostic study was carried out between the erosive potential of soils determined by different mechanisms of evaluation of geotechnical parameters involved in the process (Criterion of erodibility - Nogami & Villibor, 1979; Modified Inderbitzen - Freire, 2001 and Direct Shear Tests - Bastos *et al.*, 2002) and their pedologic classification.

2. Soil Samples Location

All studied soil samples come from south Brazil, which is formed by states of Paraná, Santa Catarina and Rio Grande do Sul. Fig. 1 shows the map details.

Despite all three states of south Brazil are well away from the equator line, they present soils with tropical characteristics, with thick residual soil layer showing intensive weathering action. In this region, apart from sedimentary soils, which are not the subject of this study, the more important units are formed by Latosols (Oxisols), Cambisols and Red-Yellow Podzolic soils originated from several geologic formations.

The main characteristics of Latosols from this region are that, despite their high permeability (average of 10^{-4} cm/s, mainly due to their structures formed by micro-aggregates - Davison Dias, 1987) they present a high percentage of clay size particles. They also show a deep and relatively homogeneous B horizon with water table well below from soil surface.

Cambisols and Red-Yellow Podzolic soils, which tend to be developed in steep topographic areas, show some similar geotechnical characteristics. Among them, they present a deep C horizon containing low weathered minerals and high strength increasing with depth. They also show deep water table and a significant variability of others geotechnical properties as the matrix rock changes.

Lithologically, the studied areas are composed of basaltic rocks (Serra Geral Formation), granites (Granite-Gneiss Complex) and sedimentary rocks (Guabirotuba Formation).

3. Tests Procedures

Laboratory erodibility tests have been carried out more frequently from the sixties on. They allow to analyse

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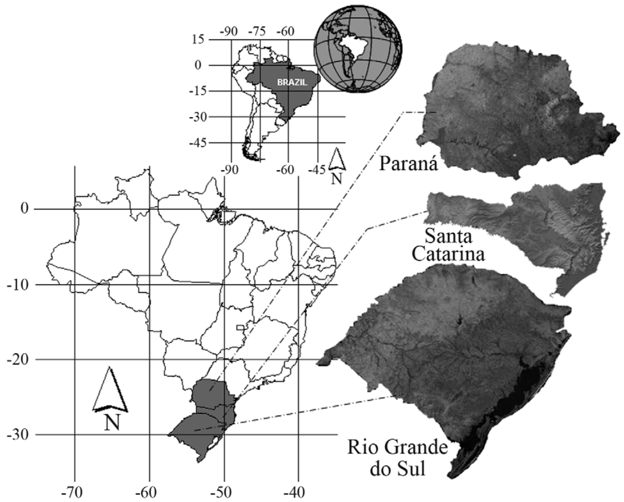

Figure 1 - Studied area Location.

the influence of the several states the soils experiment, such as humidity during erosion is taking place, the rain drops impact energy or water percolation (Chamecki & Silva, 2004).

Several papers on erodibility have been published, among them, Moore and Masch (1962), the Inderbitzen tests (Inderbitzen, 1961), pinhole test and crumb test (Sherard *et al.*, 1976a and 1976b), desegregation (Brazil, 1979; Fonseca & Ferreira, 1981), the MCT erodibility criterion (Nogami & Villibor, 1979) and the Modified Inderbitzen criterion (Freire, 2001).

Due to the high variety of existing geotechnical tests, only three different procedures have been chosen by this research to evaluate the mechanisms influencing soils erosive potential, as follows:

- MCT erodibility criterion (Nogami & Villibor, 1979);
- Erodibility criterion based on Modified Inderbitzen tests (Freire, 2001) and;
- Erodibility criterion based on direct shear tests (Bastos *et al.*, 2002).

The paper searched for relationship between results obtained by the three methodologies and also between physical indices, such specific gravity, taking account samples of Cambisols, Latosols and Red-Yellow Podzolic soils from South Brazil.

3.1. MCT erodibility criterion (Nogami & Villibor, 1979)

Erodibility criterion using the MCT methodology, as been proposed by Nogami & Villibor (1979) is essentially empirical and is based on correlations with the behaviour of a great number of tropical soils observed in roads cuts.

Nogami & Villibor (1995) stress the complexity of erodibility due to the great number of factors involved and because they are generally interdependent. According to these authors, erodibility depends mainly on the following characteristics: grain size distribution, structure and macro-fabric, permeability, infiltration rate and cohesion.

According to the authors, the prediction of the behaviour of tropical soils against hydric erosion can be obtained by infiltrability tests which determines the water absorption index (s) and the specific erodibility (modified loss of mass by immersion) which indicates the percentage of dry weight loss in relation to the total weight of the sample (pi).

From results of these two tests, the relationship called erodibility index ($E = 52s/pi$) is obtained, which establishes the limit of the erodibility criterion, based on field observations. This way, soils presenting $pi/s > 52$ are considered of high erodibility and soils showing $pi/s < 52$ are classified as medium to low erodibility.

Despite the erodibility criterion proposed by Nogami & Villibor (1979) has been used for decades and by different studies, Pejon (1992) presented a criterion using as boundary the value $pi/s = 40$ for some deep tropical soils from southern Brazil. This condition is emphasized by this paper for some tropical soils whose origin and formation are similar to those studied by Pejon (1992), as for example, Latosols.

3.2. Erodibility criterion by direct shear tests (Bastos *et al.*, 2002)

The methodology proposed by Bastos *et al.* (2002) is based on considerations made by Nascimento and Castro (1976). These authors consider that the most important parameters affecting the erosive processes of tropical soils are: grain size distribution (for sandy soils), expansion and *petrification* (the last one representing the ability of a clayey soil to maintain its cohesion immediately after submersion). Therefore, Bastos *et al.* (2002), evaluate the potential erodibility of tropical soils by the analysis of the decrease in cohesion due to submersion of the soil samples during the stage of consolidation in the direct shear tests. According to the authors, a change in cohesion (Δc), given by Eq. (1), of at least 85%, classify soils as potentially erodible.

$$\Delta c = \frac{(c_{nat} - c_{inu})}{c_{inu}} \tag{1}$$

where c_{nat} and c_{inu} are, respectively, the cohesion determined by samples under natural water content and after submersion.

3.3. Erodibility criterion based on modified inderbitzen tests (Freire, 2001)

The erodibility criteria of soils presented so far, evaluate with efficiency the erosive effects by loss of solid particles and modification of soil structure due to submersion. Nevertheless, these tests are not able to simulate the soil particles desegregation due to the impact of rain drops and superficial running water after intensive rains.

The importance of rain drops impact in the erosive processes can be observed directly by laboratory tests developed by Laws (1940), Ellison (1947a-e), Musgrave (1947), Guerra & Cunha (1995) and Chamecki & Silva (2004).

In this way, Freire (2001) presents the modified Inderbitzen test which adds to the superficial running water effect (Inderbitzen, 1961), the rain drops impact effect. In the authors opinion, the latest one is considered to be the most representative of all the three methodologies presented.

The test apparatus is mainly composed of an inclined plane structure which serves as a bed to set up undisturbed samples on it. In addition, there are two parallel lines of "showering" made of perforated tubes which lies, on average, 0,20 m above the undisturbed samples.

The samples, with dimensions 10.16 cm x 10.16 cm x 2 cm, are submitted to showering at constant water flow for a period of 2 h, under different humidity conditions.

Water and sediments are collected under the inclined plane structure in a first recipient. Afterward, they are oriented to a second recipient where sedimentation process occurs. After the sediments are separated from water, it is sieved to determine the grain size distribution of the eroded soil.

Figure 2 presents the apparatus setup for infiltrability tests, weight loss by immersion and modified Inderbitzen tests.

Through field observations and laboratory tests, Higashi (2006) obtained a value of 6% loss of weight by water dropping for residual samples that occur in some coastline regions of south Brazil. According to the author, this value should be considered the limiting value defining the erosive potential of soils. Despite this, studies involving this type of tests are recent and there is no agreement among researchers about the criteria which define erosive potential of soils. Some variations are expected for soils from different places.

4. Soil Erodibility Evaluation

A laboratory test program was conducted to study the erodibility of typical tropical soils, such as Latosols, Cambisols and Red-Yellow Podzolic from southern Brazil by several tests, as mentioned previously. The main geotechnical soil properties are presented in Table 1.

In this study, 898 samples were tested, from which, 380 specimens according to MCT methodology, 38 by Inderbitzen Modified tests and 160 by Mohr-Coulomb failure envelope (with at least three specimens for each envelope), carried out by direct shear test.

The same criterion was applied for collecting all samples, that is, three sun shining days after the last rain stopped.

4.1. Erodibility evaluation by MCT criterion

It was observed from results obtained by MCT testing procedures that there is a tendency towards a relationship, between pedologic evolution and the erosive potential of soils.

Figure 3 shows the relationship between *pi* and *s* for Cambisols and Red-Yellow Podzolic soils, based on pa-

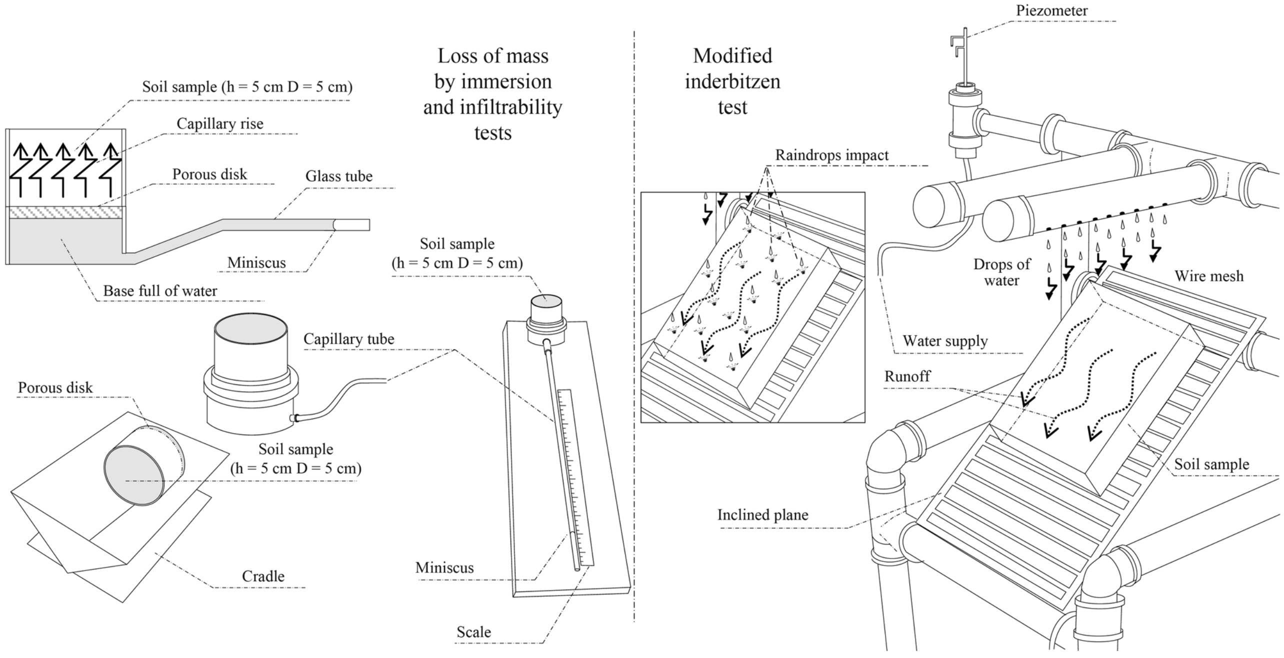

Figure 2 - Apparatus setup for infiltrability tests, weight loss by immersion and modified Inderbitzen tests (Modified from Nogami & Villibor, 1979 and Freire, 2001).

Table 1 - Main geotechnical properties for soils such Latosols, Cambisols and Red-Yellow Podzolic soils from southern of Brazil.

Property		Cambisols	Red-Yellow Podzolic	Latosols	
				Dusk	Dark Red
Medium grain size distribution (%)[1]	Sand	48.51	36.43	6.52	48.83
	Silt	42.39	23.21	29.73	19.62
	Clay	9.10	40.36	63.75	31.55
Origin rock		Granite	Granite	Basalt	Sandstone
Horizon sampling		C	B/C and C	B	B
Average specific gravity		2.67	2.77	2.83	2.74
Water content (%)		14.23-15.31	19.24-25.18	29.42-49.61	7.50-24.25
Optimum moisture content[2] (%)		10.5-32.7	13.7-35.4	32.3-36.9	10.9-16.5
Maximum dry density (kN/m3)		12.2-18.6	13.1-19.8	12.4-13.7	14-19.5
Natural cohesion (kPa)		8.1-104.1	22.3-74.1	17.4-57.0	8.0-54.0
Submerged cohesion (kPa)		36.5-0	17.5-6.4	6.3-37.9	2.5-17.5
Natural friction angle (degrees)		31.9-46.1	28.7-37.3	11.8-35.0	23.8-32.1
Submerged friction angle (degrees)		23.2-41.3	20.1-35.6	21.1-31.2	21.1-28.4
Average CBR[2] (%)		18	16	11	13

Notes: (1) With deflocculating agent; (2) Normal proctor energy.

rameters obtained by Nogami & Villibor (1979) and Pejon (1992).

Soils with higher degree of weathering (Red-Yellow Podzolic and mainly Latosols soils) showed lower values of *pi*/*s*. This behaviour indicates a lower tendency to erodibility, especially based on criterion of $pi = 52\ s$.

Despite this and the fact that the great majority of results obtained by Cambisols indicated a high erosive potential, most of the data obtained fell in between the interval $40 < pi/s < 52$. For these soil samples, the authors observed a direct relationship between grain size distribution and erosive potential. More erodible soils presented a higher content of sand particles size.

Despite the high depths of C horizon in Cambisols soils of Southern Brazil, even the top part of these strata presents a low degree of weathering. In many cases, a significant number of samples collected from different places presented a significant percentage of quartz, a mineral known to be more resistant to weathering. This aspect ensures to these soils a higher percentage of sand in their composition, with an unstable structure, which by its turn may trigger the process of erosion.

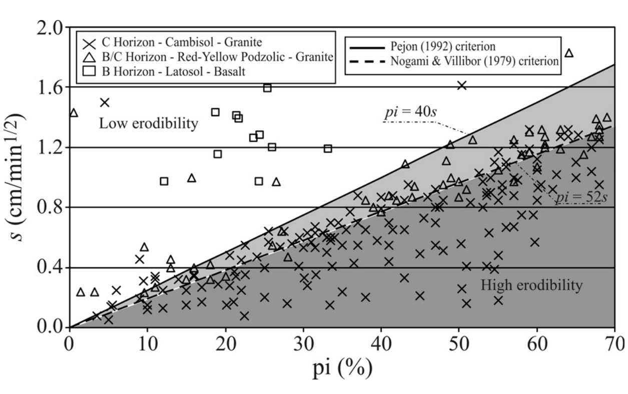

Figure 3 - Water absorption index (s) *vs.* loss of mass by immersion (pi).

Based on the data studied, it seems clear that the weight loss by immersion is the main parameter separating the erodibility of soils samples. More important than the water absorption index.

Nevertheless, Pejon and Silveira (2007) emphasize that there is a relationship between specific gravity of particles (ρ_s) in the range between 25.1 to 27 kN/m^3 and high erodibility index.

Based on data presented by Fig. 4 and comparing results with those obtained by the MCT criterion, it was observed that soils with ρ_s in between 25.31 to 26.69 kN/m^3 show higher erodibility. This range was determined by a statistical analysis.

4.2. Erodibility evaluation by direct shear tests

Fig. 5 shows the relationship between natural and submerged cohesion, according to criterion presented by Bastos *et al.* (2002) and Bastos *et al.* (1998).

The behaviour of cohesion, under these two conditions, is reflected on the desegregation of superficial particles, especially in less weathered soils, the Cambisols. As already mentioned previously, though Cambisols and Red-Yellow Podzolic soils do present a structure more similar to that of the origin rock, these soils also present their superficial strata with considerable quantities of quartz,

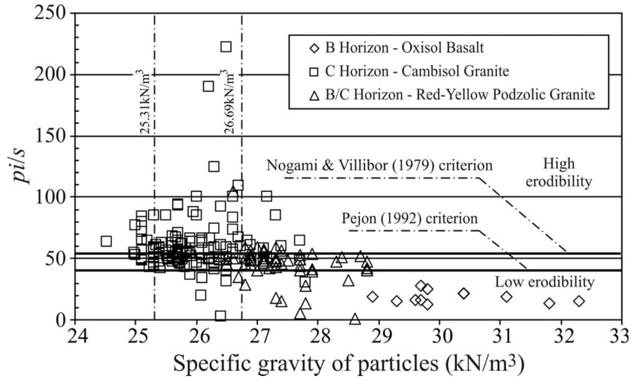

Figure 4 - Relationship between specific gravity, loss of mass by immersion and water absorption index.

which due to this aspect turn them more vulnerable to erosion. Even Cambisols, considered the most structured ones, which present high natural cohesion, showed significant decrease after being submerged. For these cases, in many times the criterion proposed by Bastos *et al.* (2002), was reached.

By the other hand, results obtained with samples collected from B horizon, formed by basaltic and sandstones Latosols, showed low erodibility. Despite structural instability, typical to these types of soils, originated from a structure formed by strongly bonded clayey micro-aggregates and weakly bonded micro-aggregates formed by clay-bridges, the variation of cohesion intercept was considered low, especially when interpreted by criterion proposed by Bastos *et al.* (2002).

Nevertheless, it was noticed that samples collected from very weathered soil strata, like sandstones, showed lower values of natural cohesion and higher cohesion drops after submersion, compared to results obtained from very weathered Latosols derived from basaltic rocks. This characteristic is associated to the bigger amount of fine sand particles present in the Latosol B horizon derived from the sandstone. The fine sand fraction in this case, was above 40% in all samples, while in samples derived from basaltic rocks this value was less than 25%.

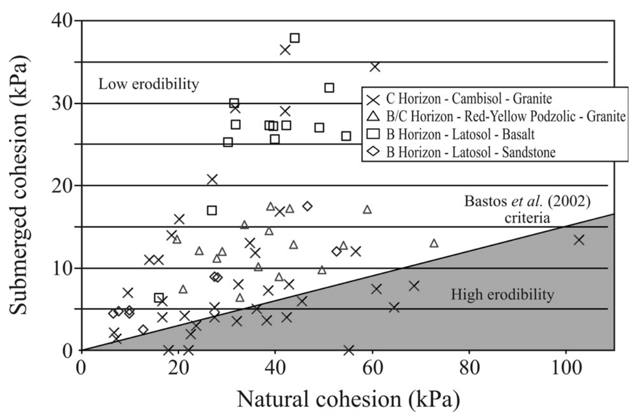

Figure 5 - Relationship between values of submerged and natural cohesion.

Related to variation in friction angles, one assume that minor changes were due to new spatial arrangements of particles after submersion and are not indicative of erosive characteristics.

4.3. Erodibility evaluation by modified inderbitzen tests

Modified Inderbitzen tests were carried out on samples at natural water content and air dried for 72 h, as recommended by Freire (2001). Figure 6 shows the results.

The soil behaviour determined by this test, considered by Higashi (2006) the most representative method to evaluate the erosive potential, confirms the results obtained by other methodologies used in this research.

Besides the fact that the majority of the samples show considerable weight loss, under a constant simulation of dripping rain water, it was observed that for granitic Cambisols samples the loss of solid particles was more significant.

Though Latosols derived from basalt show structural instability (Davison Dias, 1987), simulation under constant dripping process on these samples has indicated a weight loss considered low, compared to other soils studied. This aspect emphasizes the necessity of some adjustment in the criterion proposed by Higashi (2006). This author establishes as 6% the weight loss of solids as the limit between low and high erodibility (Fig. 6).

Referring to grain size distribution of eroded soil, though some samples did not present enough material for the test, in order to comply with the standards, it was observed a tendency for the curves, under different conditions, to be somewhat parallel. This indicates that the weight loss, during the tests, has occurred approximately with the same intensity for the whole range of diameter particles, and for different soil types.

Figure 7 shows a comparison between grain size distribution for Red-Yellow Podzolic soils before Modified Inderbitzen tests under conditions of natural water content and for its respective eroded material. Figure 8 presents this comparison for the same soil after being dried out for 72 h.

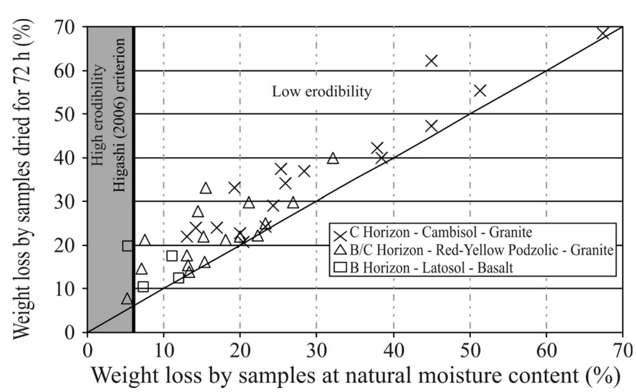

Figure 6 - Weight loss of soils under different conditions of humidity.

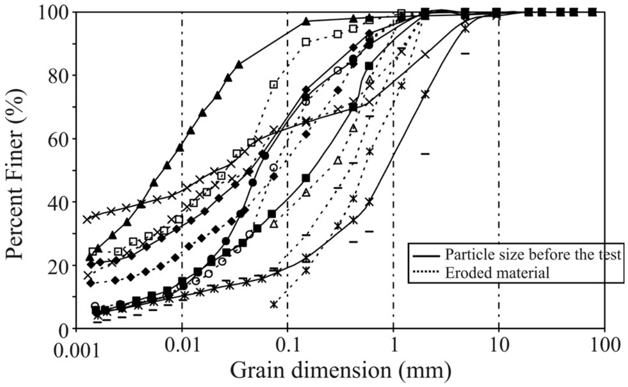

Figure 7 - Comparison of grain size distribution for soil and respective eroded material for Red-Yellow Podzolic soils under Modified Inderbitzen tests - samples tested at natural water content.

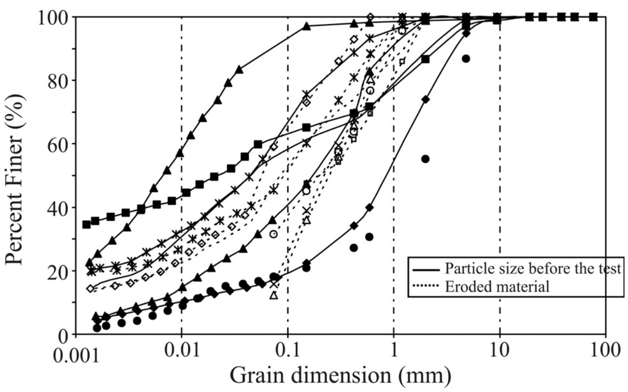

Figure 8 - Comparison of grain size distribution for soil and respective eroded material for Red-Yellow Podzolic soils under Modified Inderbitzen tests - samples tested after being dried for 72 h.

5. Conclusions

There is a great variety of tropical residual soils in Brazil, which underwent intensive processes of weathering. The most common ones in southern part are Latosols, Cambisols and Red-Yellow Podzolic soils. Under present climate conditions, these soils suffer a continuous weathering, which results in structures in constant changes. Therefore, due to the differences of weathering, from where samples have been collected and the different types of parent rocks, to establish a parameter defining the erodibility of soils is a very complex task.

Nevertheless, the analysis of the erosive potential, based on the methodologies applied and their respective criteria, carried out in this research, showed high values of erosive potential for Cambisols, especially when compared to other soils studied. This aspect is still more significant due to the high slopes in which these units are formed.

Furthermore, it was also observed that soils composed of grain size fraction of fine sand, are more vulnerable to erosion, as for instance, the dusk and dark red Latosols. It is important to emphasize that in the field, these soils present their structures in the form of micro-aggregates, in the range of fine sand particles, strongly bonded. Despite this characteristic, the micro-aggregates also present weak bonding, especially in the B horizon of Latosols derived from sandstones.

Finally, it was also observed that methods applied to differentiate soils of high and low erodibility presented coherent results by their classifications. All methods classified Cambisols as highly erodible, Latosols as less erodible and an erodibility medium to high to the Red-Yellow Podzolic soils. Besides, this work has shown also that simple indices, as specific gravity, can be successfully used to evaluate tropical soil erodibility and thus aid the prevention of erosion and the losses of its entails.

References

Bastos, C.A.B.; Gehling, W.Y.Y. & Bica, A.V.D. (1998) Some considerations about the shear strength an erodibility of unsaturated residual soils. In: Proc. International Conference on Unsaturated Soils, ISSMGE/CISMGE-CCES, Beijing, v. 1, pp. 19-24.

Bastos, C.A.B.; Gehling, W.Y.Y. & Milititski, J. (2002) Avaliação geotécnica da erodibilidade de solos residuais - Uma proposta metodológica. Anais XII Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica, São Paulo, v. 2, pp. 1193-1203.

Brasil, Ministério dos Transportes (1979) Recomendações para Proteção de Taludes Contra a Erosão. Instituto de Pesquisas Rodoviárias, Rio de Janeiro, 59 pp.

Chamecki, P.R. & Silva, E.T. (2004) Erosão hídrica em argilas da Formação Guabirotuba: comportamento e parâmetros em ensaios e simulações em laboratório. Proc. GEOSUL - Simpósio de Prática de Engenharia Geotécnica da Região Sul, Curitiba, pp. 131-138.

Davison Dias, R. (1987) Aplicação de Pedologia e Geotecnia no Projeto de Fundações de Linhas de Transmissão. Tese de Doutorado em Engenharia, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 309 pp.

Ellison, W.D. (1947a) Soil erosion studies - Part I. Agricultural Engineering, v. 28:4, p. 145-146.

Ellison, W.D. (1947b) Soil erosion studies - Part II: Soil detachment hazard by raindrop splash. Agricultural Engineering v.28:5, p. 197-201,.

Ellison, W.D. (1947c) Soil erosion studies - Part III: Effects of soil erosion on infiltration and surface runoff. Agricultural Engineering, v. 28:6, p. 245-248.

Ellison, W.D. (1947d) Soil erosion studies - Part IV: Soil erosion, soil loss, and some effects of soil erosion. Agricultural Engineering, v. 28:7, p. 297-300.

Ellison, W.D. (1947e) Soil erosion studies - Part V: Soil transportation in the splash process. Agricultural Engineering, v. 28:8, p. 349-351, 353.

Fonseca, A.M.M.C.C. & Ferreira, C.S.M. (1981) Metodologia para determinação de um índice de erodibilidade dos solos. Proc. I Simpósio Brasileiro de Solos Tropicais em Engenharia, COPPE, CNPq e ABMS, Rio de Janeiro, pp. 646-667.

Freire, E.P. (2001) Ensaio Inderbitzen modificado: Um novo modelo para avaliação do grau de erodibilidade do solo. Proc. VII Simpósio Nacional de Controle de Erosão, Goiânia, CD-ROM, pp. 1-8.

Guerra, A.T. & Cunha, S.B. (1995) Geomorfologia, Uma Atualização de Bases e Conceitos. Ed. Bertrand, Rio de Janeiro, 443 pp.

Higashi, R.A.R. (2006) Metodologia de Uso e Ocupação dos Solos de Cidades Costeiras Brasileiras Através de SIG com Base no Comportamento Geotécnico e Ambiental. Tese de Doutorado em Engenharia Civil, Universidade Federal de Santa Catarina, 486 pp.

Inderbitzen, A.L. (1961) An erosion test for soils. Materials Research Standards, v. 1:7, p. 553-554.

Laws, J.O. (1940) Recent studies in raindrops and erosion. Agricultural Engineering, v. 21, p. 431-433.

Moore, W.L. & Masch, F.D. (1962) Experiments on the scour resistance of cohesive sediments. Journal Geophysical Research, v. 67:4, p. 1437-1446.

Musgrave, G.W. (1947) The quantitative evaluation of factors in water erosion, a first approximation. Journal of Soil and Water Conservation, v. 2, p. 133-138.

Nascimento, U. & Castro, E. (1976) Erosão: critérios de seleção de solos. Geotecnia, n. 20, p. 17-33.

Nogami, J.S. & Villibor, D.F. (1979) Soil characterization of mapping units for highway purposes in a tropical area. Bulletin of IAEG, n. 19, pp. 196-199, DOI 10.1007/BF02600475.

Nogami, J.S. & Villibor, D.F. (1995) Pavimentação de Baixo Custo com Solos Lateríticos. Ed. Villibor, São Paulo, 240 pp.

Pejon, O.J. (1992) Mapeamento Geotécnico de Piracicaba 1:100.000: Estudo de Aspectos Metodológicos, de Caracterização e de Apresentação dos Atributos. Tese de Doutorado, Escola de Engenharia de S. Carlos, Universidade de São Paulo.

Pejon, O.J. & Silveira, L.L.L. (2007) Index properties to predict erodibility of tropical soils. Bulletin of Engineering Geology and the Environment, v. 66:2, DOI 10.1007/s10064-006-0067-9.

Sherard, J.L.; Dunningan, L.P. & Decker, R.S. (1976a) Identification and nature of dispersive soils. Journal of the Geotechnical Engineering Division, ASCE, v. 102:GT4, p. 287-301.

Sherard, J.L.; Dunningan, L.P.; Decker, R.S. & Steele, E.F. (1976b) Pinhole test for identifying dispersive soils. Journal of the Geotechnical Engineering Division, ASCE, v. 102:GT1, p. 69-85.