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Unconfined strength of an unsaturated residual soil struck by replicated lightning

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Abstract It is well known that different triggering factors are related to landslides occurrence. However, in many cases, it is not possible to identify main factors that may contribute to start a landslide. Following that, lightning phenomena is herein considered as a possible factor that may promote changes in the structure, and eventually, in the strength of soils. The current study aims to analyse the influence of laboratory simulated lightning in the structure of undisturbed granite-gneiss residual soil samples. The main focus is to compare the peak strength of unsaturated samples that were not struck by replicated lightning with the peak strength of soil samples struck by replicated lightning. The methods used are: Soil sampling and physical characterization; unconfined compression strength tests on unsaturated undisturbed samples; submission of soil samples to replicated lightning; unconfined compression strength tests on samples struck by replicated lightning and micro tomography of samples submitted to lightning. As results, it is seem that lightning may cause a hole with irregular geometry inside the soil. Analysing the tests of the samples struck by laboratory simulated lightning, a peak strength reduction with the charge incidence was observed. Comparing the variation of soil matric suction on the peak strength of the soil that was not struck by replicated lightning with that of the soil struck by the higher charge of the replicated lightning, it is observed that the samples struck by high-voltage presents lower values of peak strength.

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1 Introduction

In January of 2011, the mountainous region of the state of Rio de Janeiro, Brazil, suffered what was considered as one of the worst natural disasters of the Brazilian history, counting hundreds of landslides that caused more than 900 deaths (see Figure 1).

In this event, failure mechanisms were not fully understandable, opening a wide discussion on the theme and suggesting the existence of triggering factors not considered before.

Interviews with local-people indicated a large occurrence of lightning and of ground shacking at the flashing moments. Based on that, investigations were started at PUC-Rio trying to understand the lightning-soil interaction.

Lightning is a natural phenomenon that involves a huge transfer of energy. Rakov and Uman [1] highlights that an overall flash has 200-300 ms time duration and its temperature is of circa 30.000 ºC [2] of magnitude. According to these authors, lightning can propagate through the air with velocity of 220.000 km/h.

The objective of the present work is to analyse if laboratory replicated lightning may cause strength reduction in an unsaturated soil higher than a strength reduction promoted by a decrease of the matric suction of the soil due, for instances, an increase in its degree of saturation.

Figure 1. Rio de Janeiro mountain region. The landscape after disaster

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2 Material

The material chosen for testing is from a site named Condomínio do Lago – Nova Friburgo – RJ (coordinates 742961.31 m E; 7539347.23 m S), which was destroyed in the 2011 event.

It comprises a granite-gneiss residual soil, with e = 0.715, ρ_d = 1,49 g/cm³ and Gs = 2.66. Average grain size of the material is shown in Table 1. The soil is classified as SM - silty sand, according to the Unified Soil Classification System.

Table 1. Distribution of particle sizes

Gravel (%)	Sand (%)	Silt (%)	Clay (%)
1.4	60.5	31.9	6.2

The filter-paper [3], Haines' funnel [4] and potentiometer WP4C (Decagon Devices Inc.) techniques were employed to define the soil water retention curve of the undisturbed soil (Figure 2). It can be seen in this figure that a quite reasonable unimodal relationship was obtained using these three different techniques.

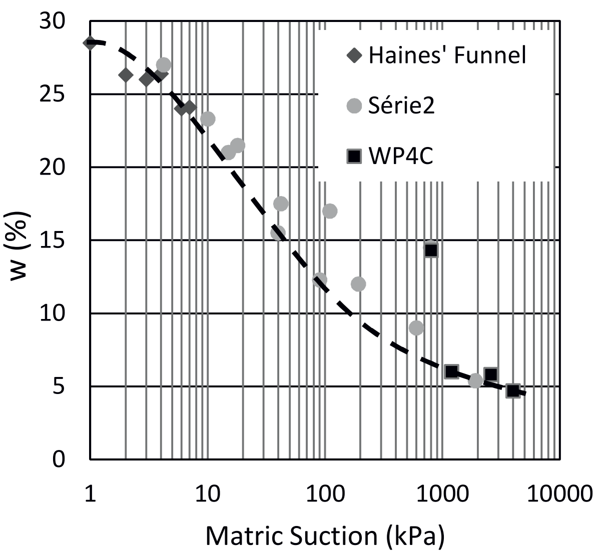

Figure 2. Water retention curve (WRC)

3 Methods

Cylindrical samples, with 38 mm of diameter and 76 mm in height were used in the experiments, comprising:

a) pulse generator submission, where the granite-gneiss soil samples were struck by different charges of replicated lightning;
b) test on a computerized micro tomographer, to analyse structural characteristics of the samples [5];
c) unconfined compression strength tests performed under different soil matric suction.

3.1 Pulse generator

To analyse possible lightning influences, a cooperation between the Pontifical Catholic University of Rio de Janeiro - PUC-Rio and the Electrical Energy Research Center - CEPEL-ELETROBRAS was developed. Replicated lightning were created in the CEPEL laboratory, enabling to submit the soil samples to high-voltage electrical pulses.

Figure 3 shows the overall pulse generator schema containing the layout of the set composed of seven stages and the place where soil samples were located along the tests.

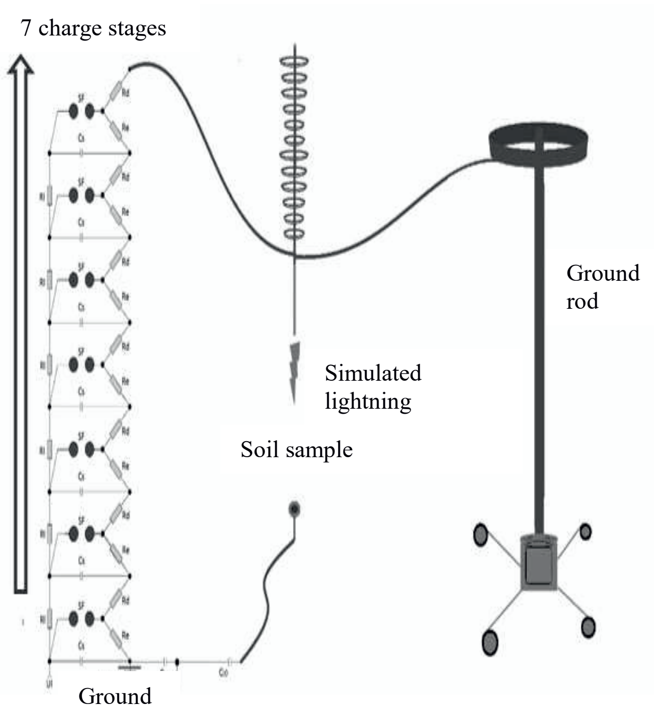

Figure 3. High-voltage pulse generator scheme

The first step of the experimental programme was to submit the undisturbed soil to simulated lightning. Following the pulse generator Series L from HIGHVOLT [6], the samples were struck by 300 kV, 450 kV and 600 kV electric charges.

It is important to note here that the discharges induced by the electrical impulses in the laboratory are considered to replicate lightning, as they are in agreement with the time to reach the peak (1,2µs) and tail (50 µs) of the impulses [7].

Figure 4 shows the response emitted by the lightning equipment simulator, where channel 1 presents the kV (voltage) response and channel 2 presents A (amperage) response along time. The data sheet also reveals the time (in µs) and the negative characteristic of the charge, which represents a negative lightning.

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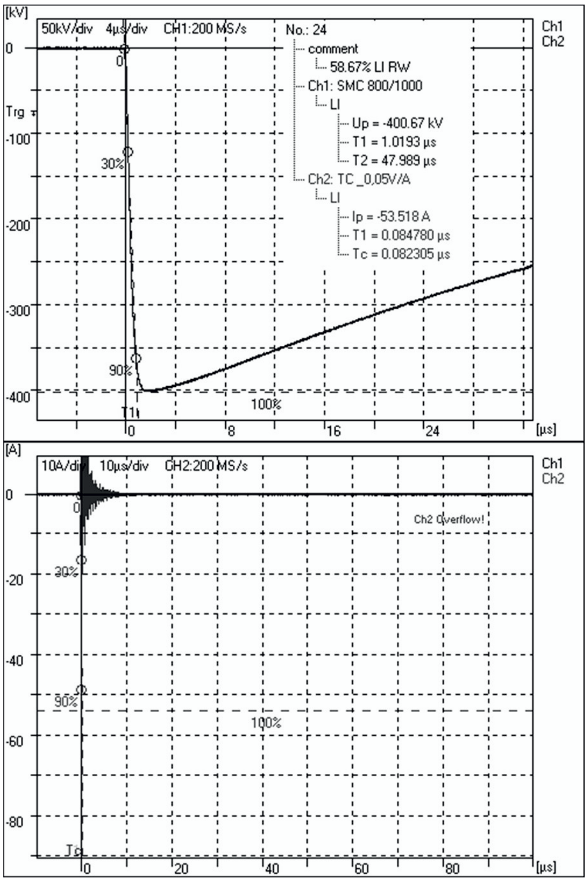

Figure 4. Simulated lightning developed in the lab

If the electrical signal is higher than the air resistance, it is formed a heated luminous channel that crosses the soil sample, discharging the high-voltage in the ground rod. At this time, it is possible to see the replicated lightning (Figure 5).

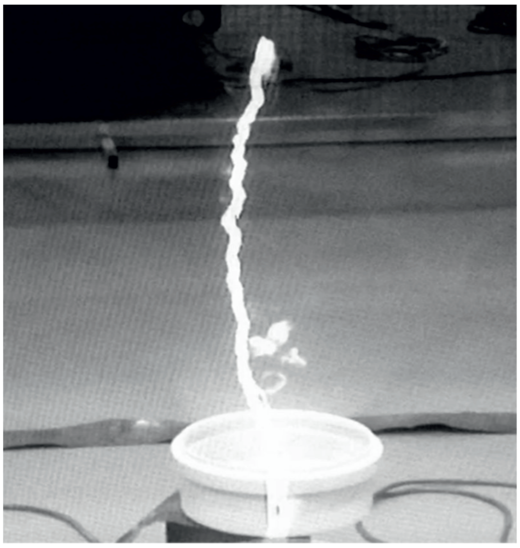

Figure 5. Simulated lightning developed in the lab

It is interesting to notice here that saturated samples were initially tested. However, they presented catastrophic failure under the incidence of replicated lightning (Figure 6). So it was chosen to work just with unsaturated samples, under their natural water contents.

Figure 6. Catastrophic failure of saturated samples

3.2 Micro tomography

The effects of atmospheric impulses in the soil samples are until now undiscovered. Thus to better understand what happens with the soil when it is struck by a huge electric energy, this study used computerized micro tomography, with 22.12 resolution, to obtain 3-D internal images (Figure 7)

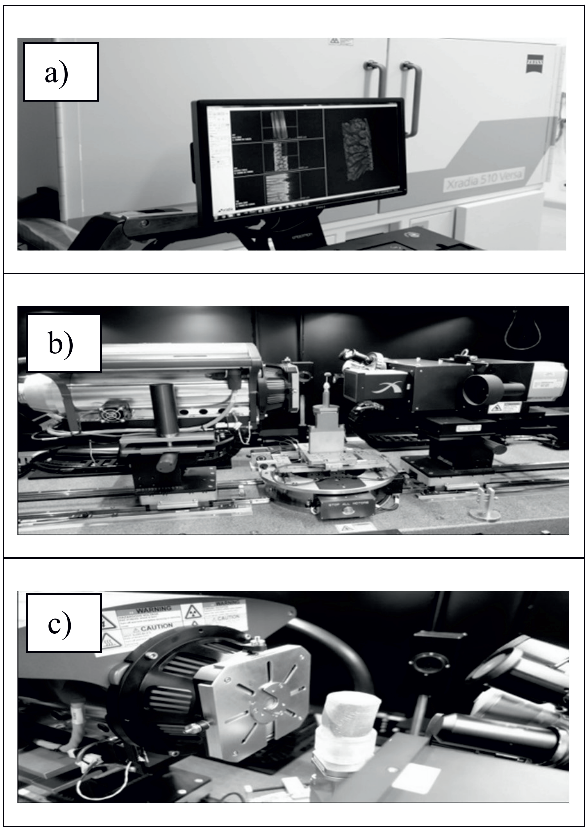

Figure 7. Micro tomography equipment and internal configuration a) Computer graphic analysis, b) X-ray emission mechanism and c) Soil cylindrical sample on the adapted support

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3.3 Unconfined compression strength tests

Unconfined compression strength tests (Figure 8) were carried out under a strain rate of 0.4 mm/min.

Undisturbed samples non-struck by replicated lightning were wetted and dried before the unconfined strength tests. Table 2 shows the initial moisture content of such samples. The samples submitted to replicate lightning were at their natural water content before being struck by 300 kV, 450 kV and 600 kV. Such water contents are also included in Table 2.

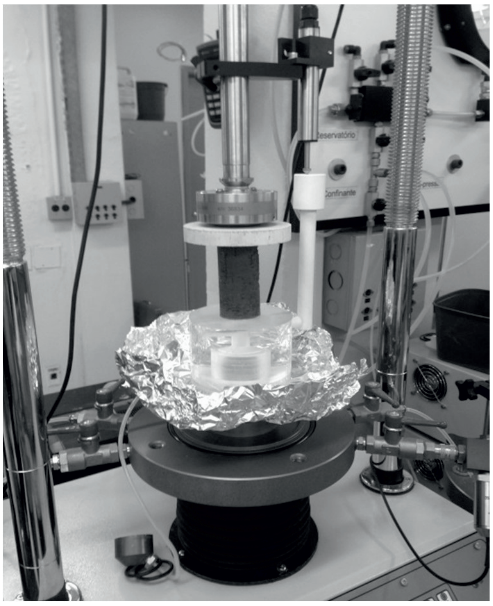

Figure 8. Unconfined compression strength tests

Table 2. Initial moisture content of the samples struck and non-struck by lightning

Sample			Moisture w (%)
Struck by Lightning	1	300 kV	15,83
	2	300 kV	16,11
	3	450 kV	15,8
	4	450 kV	15,77
	5	600 kV	16,26
	6	600 kV	16,13
Non-struck	7		22,1
	8		19,89
	9		17,68
	10		12,3
	11		10
	12		6,4
	13		6,33

4 Results and discussion

On using the micro tomography technique it was observed that the electric discharge affected only the samples struck by 450 kV and 600 kV. The simulated lightning caused an irregular tortuous hole with some radial cracks (Figure 9) in the central area of the sample (which was the selected principal path of the lighting experiment|).

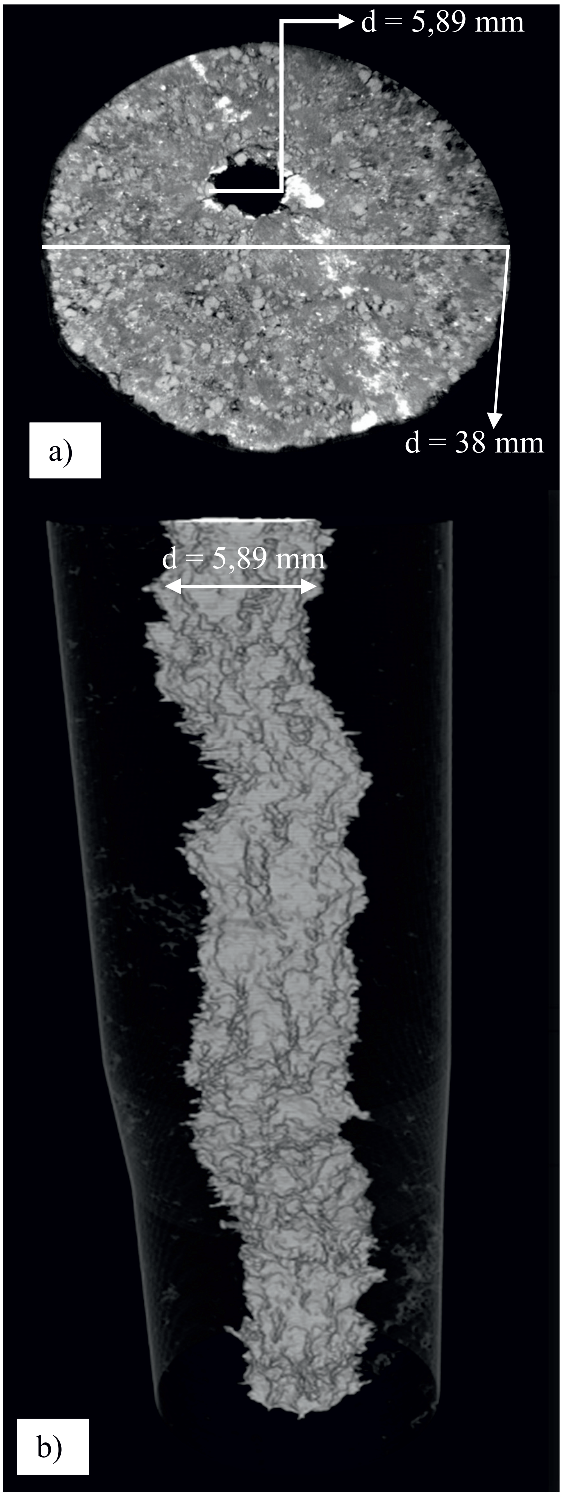

Figure 9. Micro tomography. (a) Top and (b) central hole images

For the 600 kV sample, the hole size distribution was analysed and it was possible to observe a higher size in the sample top. Analysing the figure 10 it is possible to observe a 6 mm maximum variation of the hole size diameter. Another observation is related to the spiral behaviour shown in Figure 9, which indicates that the simulated lightning crossed the soil sample following a zig-zag path.

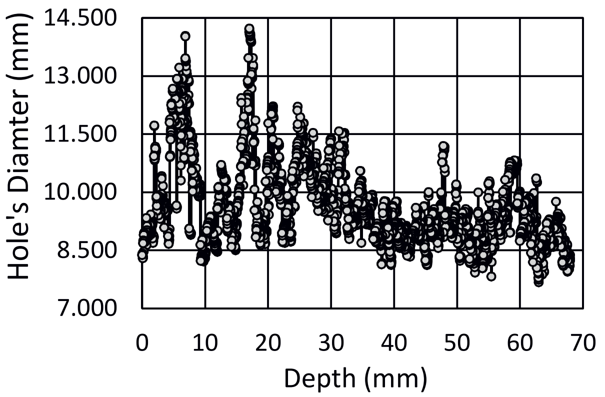

Figure 10. Variation of the hole size diameter

Figure 11 shows the results of the unconfined strength tests performed on the samples non-struck by replicated lightning under variable initial matric suction. Such suction (MS in Figure 11) was estimated based on the measured initial moisture content of the samples and on the water retention relationship shown in Figure 2. As expected, higher peak strengths were obtained in the tests performed in the samples with lower degree of saturation (or moisture content).

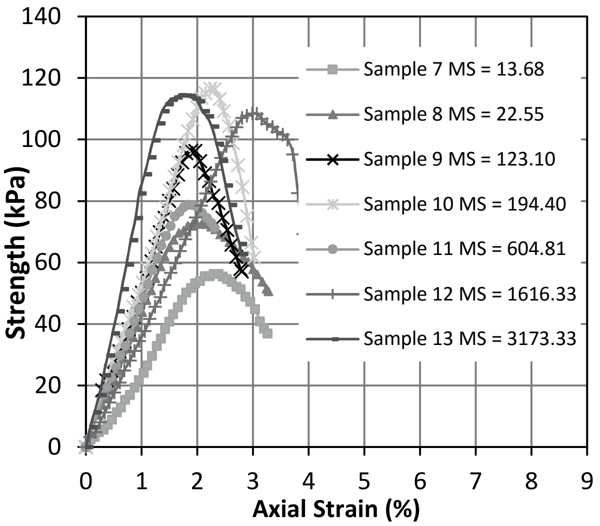

Figure 11. Unconfined strength tests for the samples non-struck by replicated lightning

Analysing the unconfined strength tests results for the samples struck by replicated lightning (Figure 12), it is notable that, for the samples in which holes were formed (samples 3 to 6), the peak strengths were much lower than the peak strengths of the samples submitted to 300 kV replicated lightening (samples 1 and 2), which did not show a continuous hole in their central portion.

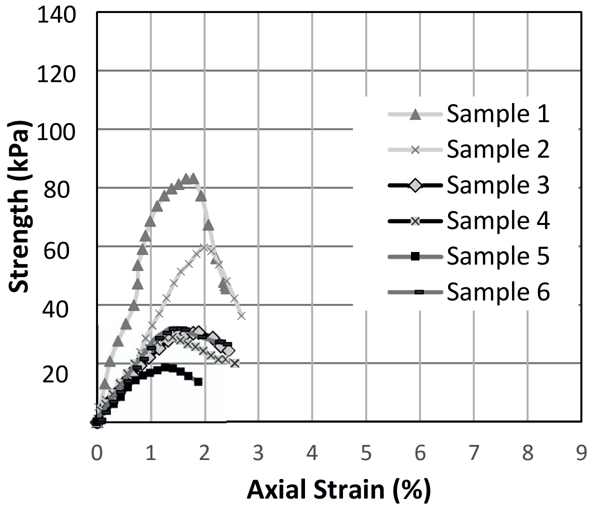

Figure 12. Unconfined strength tests for the samples struck by replicated lightning

Table 3 shows the unconfined strength of all tested samples and the matric suction related to each one of the samples before lightning struck and / or strength testing, estimated as mentioned before. Based on these data and on the data shown in Table 2, Figures 13 and 14 were produced.

Table 3. Unconfined compression strength results

Sample			Strength (kPa)	Matric Suction (kPa)
Struck by Lightning	1	300 kV	85	41,21
	2	300 kV	60	35,49
	3	450 kV	32,8	42,33
	4	450 kV	29,9	41,61
	5	600 kV	36	34,57
	6	600 kV	19,5	36,32
Non-struck	7		56,3	13,68
	8		73,1	22,25
	9		96,8	123,10
	10		118	194,40
	11		79,5	604,81
	12		109	1616,33
	13		116	3173,33

Taking as a basis the range of initial soil suction of the tested samples, Figures 13 and 14 indicates that the matric suction (plotted in log scale) decreases in an approximately linear way with an increase in moisture content (plotted in natural scale) for the non-struck samples. In that case, shear strength (plotted in natural scale in Figure 13 and in log scale in Figure 14) decreases with moisture content, following a law not clearly defined. Figure 13 also indicates that the unconfined strength tends to decrease with an increase of the lightning charge (in natural scale) for the samples with initial moisture content of circa 16%, that corresponds to an initial suction of circa 40 kPa.

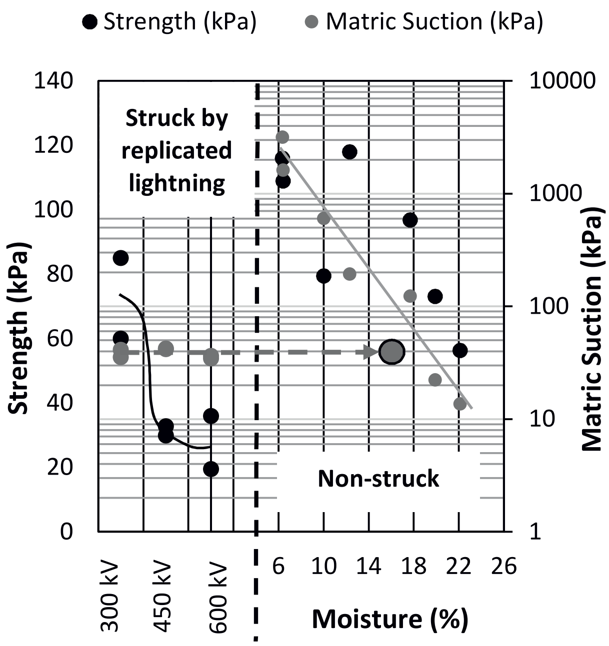

Figure 13. Peak strength and matric suction data versus replicated lightning charges (300 kV, 450 kV and 600 kV) and moisture content.

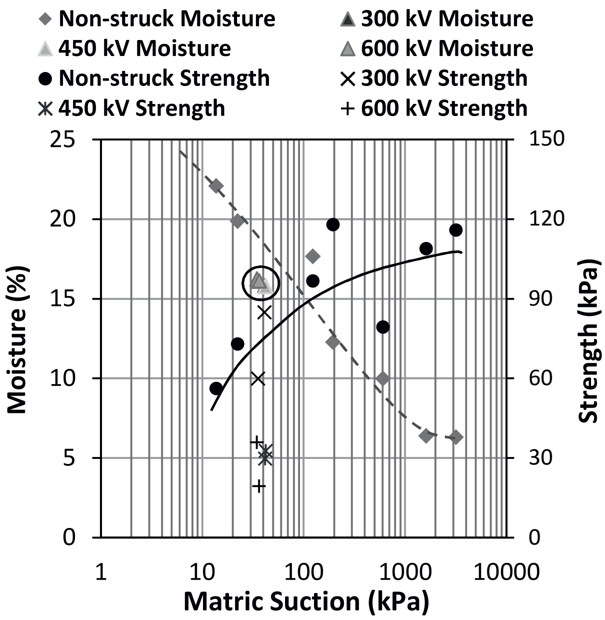

Figure 14. Variation of initial moisture content and peak strength with initial matric suction

Samples struck by a 300 kV simulated lightning showed an unconfined strength higher than the strength of non-struck samples at equivalent initial suction (see Figure 14). As in the present stage of the investigations it was not yet possible to evaluate the potential change in suction that might be promoted by the lightning inside the soil sample, such result must be seen with care.

5 Conclusion

This work presents preliminary results obtained in a large investigation under way at PUC-Rio on effects of lightning on the shear strength of unsaturated soils. These results indicate that lightning tend to promote a decrease of the shear strength of the soil; the larger the lighting energy, the lower the strength.

Also, it was found that depending on the lightning energy, a sinuously hole, with a nearly constant radius, occurs in the soil sample.

Further investigations are required in order to understand the hole of suction in the soil response after being struck by lightning.

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