Investigation of Soil Ionization Propagation in Two-Layer Soil Samples

A. Elzowawi
Cardiff University, UK
ElzowawiA@cf.ac.uk

A. Haddad
Cardiff University, UK
Haddad@cf.ac.uk

H. Griffiths
Cardiff University, UK
GriffithsH@cf.ac.uk

D. Clark
Cardiff University, UK
ClarkD@cf.ac.uk

***Abstract*- High current lightning strikes into earthing systems can result in ionization in the soil surrounding the earthing electrode. Most of the published studies investigating this phenomenon have assumed uniform one-layer soil, but soil ionization propagation in a multilayered soil sample has not been extensively addressed. Practical soils may consist of several layers with different water contents, and hence soil resistivity will vary continuously with depth. This investigation considers several sand samples, consisting of two layers with different water contents subjected to standard lightning impulse voltages. A rod-plane electrode configuration was constructed inside a cylindrical plastic test rig, in order to house both wet and dry soil test samples. In order to quantify the propagation of ionization inside the test sample, voltage probes were installed along the tube at specific positions. Localized changes in the ionization zone potential could, therefore, be monitored in real time.**

***Index Terms*—Lightning impulse, soil breakdown, soil ionisation, soil ionisation propagation, two-layer soil**

I. INTRODUCTION

Multilayer soils with variable resistivity values are a common feature of real earthing systems, due to variations in soil composition with depth, localized inhomogeneity and numerous hydrological and geological processes. The resulting distribution of soil resistivity can thus be highly non-uniform. Therefore, in the literature, several research investigations have been reported in which two–layer soil scenarios were studied for steady state performance and resistivity measurements [1-5]. However, the high impulse current performance and the soil ionization phenomenon have not been extensively investigated with two-layer soils. While soil ionization in earthing systems has been intensively studied [6-8], the majority of these investigations consider a uniform soil in the vicinity of the earthing electrode, which may not always be fully representative of practical soils.

Variations in weather conditions lead to changes in water content within the soil strata. This means that the upper and lower layers may have either high or low resistivity, thus affecting soil ionization initiation and propagation in these layers. This, in turn, affects the localized soil resistivity and the earth potential rise (EPR) due to current injection at the earth electrode [9]. The simplification proposed in [10], considering a bulk resistivity for all layers rather than each layer individually, could be acceptable where high water contents (more than 10%) in all soil layers keep the resistivity low. In the case of poor soil conditions (high resistivity soil), this simplification may not be applicable.

The resistivity and thickness of the layers are significant factors that influence the impulse behavior of earthing systems in two-layer soils. Taking advantage of the current's tendency to flow in the lower resistivity soil layer will help understand the behaviour of the current dissipation in each layer. For better electrical safety, it is preferable to have the lower resistivity layer just below the upper surface layer, with an electrode long enough to reach this layer to allow the majority of the current to be dissipated in this layer rather than in the upper surface layer. Soil ionization is thus encouraged to initiate and propagate to a greater depth, reducing the EPR at the ground surface.[9]

In this paper, a variety of sand samples representing common soil configurations were considered to investigate the initiation and propagation of soil ionization in two-layer soils with different water contents. Two voltage probes installed inside the test sand sample at selected positions were used to measure dynamic changes in the ionization zone potentials. These measurements allow determination of the position along the sample column to which the soil ionization has propagated. From this measurement, an estimate of the velocity of the ionization propagation between the two probes may be determined.

II. TEST ARRANGEMENT

A. *Test Setup:*

A test rig with consisting of a rod-plane electrode configuration was used in these series of tests connected with the test circuit shown in Fig. 1. The two-layer sample was placed in a vertical plastic tube between the two electrodes. A four-stage 400 kV Haefely impulse voltage generator was used to generate the lightning impulse 1.2/50 wave shape. A capacitive voltage divider with ratio 27931:1 was used to measure the applied voltage, and two other dividers with ratios 2000:1 and 1000:1 were used to measure the voltages inside the sample during the discharge (see Item 7 in Fig. 1 depicting a voltage probe installed in the tube and connected to the voltage divider. A current transformer with a sensitivity 0.1 V/A was used to measure the current flowing through the sample. The voltages and current signals were captured and recorded on a LeCroy digital oscilloscope.

B. *Sample Preparation*

Medium grain size (0.25-0.6) mm sand was used in all the samples. Tap water was also used to make the wetted sand layer, where the water content (wc) was calculated as a percentage of the mass of the dry sand as stated in [11]. The sand and water were thoroughly mixed so that a good moisture distribution among the sand grains is achieved.

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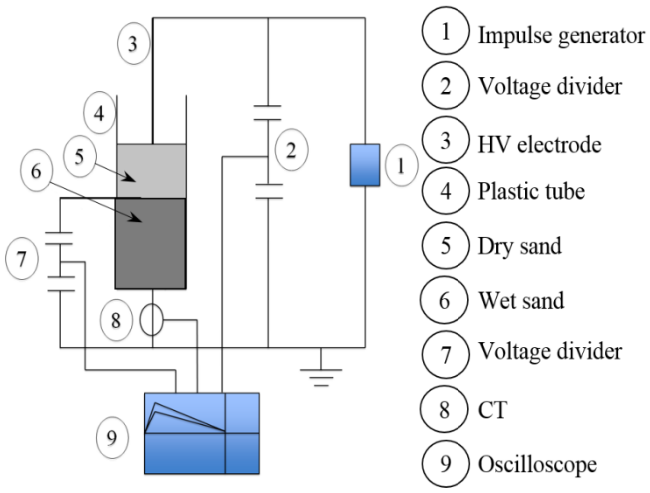

Fig. 1. Test circuit

This wet sand mixture is placed in the tube and then moderate pressure was applied to the sample to ensure adequate compaction and uniformity of distribution within the tube; this is thought to prevent formation of gaps inside the sample. A similar procedure was followed when setting each layer.

III. PROPAGATION OF IONIZATION ZONE IN DRY AND WET LAYER SAMPLES

Soil ionization may have different initiation and propagation processes in dry and wet conditions; hence, it has different effects on the soil in both cases. In this test, the electrode is embedded in the upper layer only. Therefore, by changing the positions of the voltage probes in the upper dry and lower wet layers, the propagation of the ionization zone can be tracked in both layers.

A. Propagation in Dry Soil

In this experiment, the sample consists of a 10 cm column of dry sand above 15 cm of wet sand with 5 % water content (wc). The first voltage divider is connected to the active electrode and the second is connected to the probe installed in the middle of the dry column. The last divider is connected to the probe installed at the interface between the dry and wet layers, as depicted in Fig. 2. The voltage probes are so located to measure the development of the ionisation propagation in the upper dry layer. An increasing lightning impulse voltage was applied in steps to the point where a current was detected by the CT.

From the waveforms in Fig. 3, it can be seen that the current did not flow until the ionisation has crossed the whole dry layer up to the second voltage probe between the two layers. Hence, the ionisation discharge current flowed from the highest field region at the HV electrode, crossing the dry layer to reach the wet layer. The voltage (V_1) can be seen to rise as the ionisation extends to the probe in the middle of the dry layer. Then, the current and the voltage (V_2) start to increase at the same instant when the ionisation discharge arrives at the second probe, as seen in Fig. 3. The total voltage developed across the dry layer ($V_d = V_t - V_2$) collapses at the instant when the ionisation reaches the dry-wet boundary. This indicates a sharp drop in resistivity caused by the soil ionisation in the dry sand layer.

Also visible from Fig. 3 there are two different delay times (t_1, t_2), which represent the propagation times for the ionisation expansion in each probe interval. The delay time (t_1) represents not only the propagation, but also the initiation time of the ionization at the electrode surface. The delay time for current initiation (t_1+t_2) was found to depend mainly on the applied voltage and the thickness of the dry layer. The above delay times indicate that the propagation of the ionization region in the dry layer has various successive stages. The first stage is the initiation of the ionisation phenomenon around the electrode; the second stage being the initiation of a streamer discharge from the electrode, and the third stage is the propagation of the discharge through the sand with what appears to be to a variable velocity which may be attributable to the driving local electric field.

When the dry layer breaks down, nearly the full applied voltage will appear across the wet layer. This explains why the applied voltage did not show any sign of breakdown. After about 3.88µs from the initiation of the current flow, a full breakdown of the sample occurred, causing the collapse of the three voltages due to the breakdown of the wet layer as well.

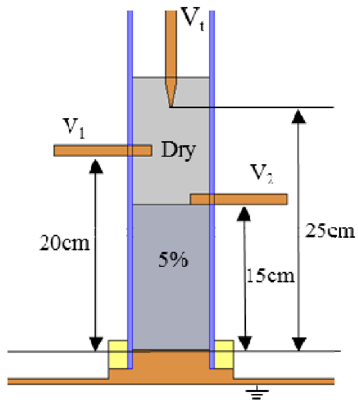

Fig. 2. Sample and voltage probe arrangement for III-A

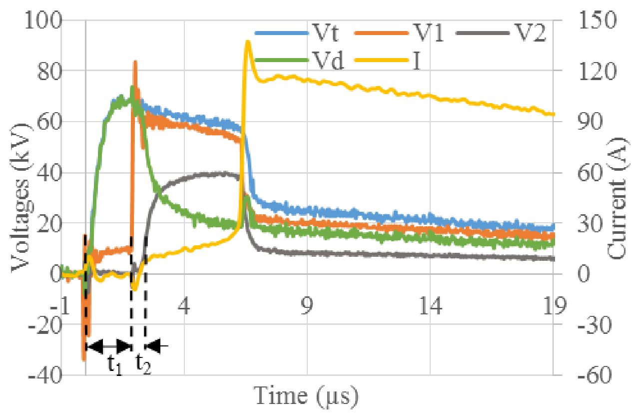

Fig. 3. Voltages and current traces in dry sand (10cm) above wet sand (15cm, 5% wc)

B. Propagation in Wet Soil

Fig. 4 shows the configuration of the sample and the voltage probes, where the upper dry layer has a height of 10 cm as in the previous test, but the lower 20cm wetted layer contains higher wc (10%). A voltage probe is installed at the interface between the dry and wet layers, with a second installed at the middle of the wetted layer. Thus, these two voltage probes will measure the potentials in the expected ionisation zone in the wetted layer. When the applied voltage is sufficient to break down the upper dry layer, soil ionisation is initiated in the lower wetted layer and the current exhibited the second peak. The voltage (V_1) can be seen to rise very quickly at the instant when the streamer reaches the dry-wet boundary. This voltage then decreases, indicating the initiation of ionisation at the top of the wet layer.

The voltage (V_2) increased at the same time as (V_1) but it continued to increase as the current increased (indicating a linear resistive behaviour) up to the instant when the ionisation propagation reached the second probe, then V_2 started to decrease, as can be seen in Fig. 5. The propagation time (t_p) between the two peaks of (V_1 and V_2) represents the propagation velocity of the ionisation zone boundary between the two probes in the lower layer.

This test shows that, despite the distance between the active electrode and the wet layer (10 cm dry sand layer), soil ionization is initiated in the lower layer, which may be driven by the local electric field magnitude provided by the discharge to further ionise the soil, allowing the ionisation to continue its propagation from the upper dry layer to the wetted lower layer. In a similar test, where 1% wc was used instead of 10% wc, soil ionisation did not initiate in the bottom layer. Therefore, it can be inferred that soil ionisation could be initiated in areas well below the electrode given the right conditions of field and water content.

IV. Propagation of Ionization Zone in Two Wetted Sand Layers with Different Water Contents

This investigation examine the scenario of two wetted layers with various water content in each layer, the water contents considered in this test are 1% and 10%. These percentages have been chosen to obtain a clear difference in the performance of the two layers under the applied voltage. In separate one layer soil sample tests, it was found that 1% wc was not enough to help initiate soil ionization in this test configuration, whilst 10% was very appropriate for the ionization. Therefore, these series of tests will investigate the initiation and propagation of soil ionization in two layer samples, where one layer contains (10% wc) and the other (1% wc). The thickness of these two layers will also be changed as in the following sections.

A. Lower Layer of Higher Water Content

The upper layer contains 1% wc with 10 cm height, and the bottom layer contains 10% wc with 20 cm height. The first voltage probe (V_1) was installed at the interface between the two layers, and the second voltage probe (V_2) was installed in the middle of the lower layer as in Fig. 6. When the applied voltage was around 42 kV, a linear behaviour was dominating the current conduction. However at 54kV, a second peak started to appear in the current trace as can be seen in Fig. 7. It is obvious from the voltage trace (V_1) that the soil ionization only extended from probe (V_1) to the lower layer but it did not propagate to the second probe, where V_1 started with similar behaviour to the current until the ionization reached probe (V_1), then started to decline. As can be seen on the figure, (V_2) exhibits the same shape as the current trace, indicating a linear behaviour (no ionization). At 60kV, the ionization zone has propagated further down to the second probe (V_2) as shown in Fig. 8.

In a similar test, the height of the upper layer was increased to 15cm and the lower layer height was reduced to 15cm, as shown in Fig 6 b. In this case, the threshold voltage to initiate the ionization increased to 62kV instead of 54kV. Thus, the thickness of the upper layer has a major effect on the initiation of the soil ionization phenomenon in two layer soil.

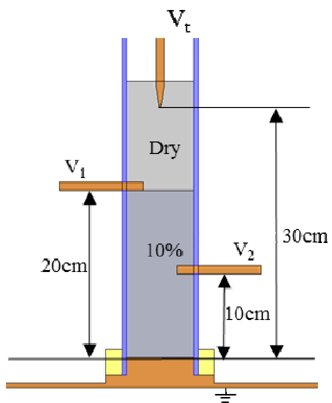

Fig. 4. Sample and voltage probes arrangements for III-B

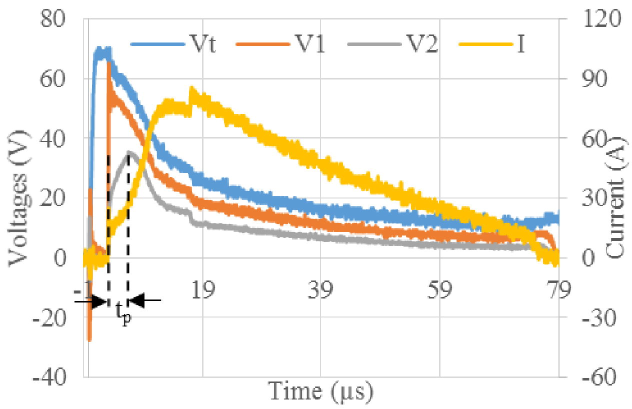

Fig. 5. Voltages and current traces in dry sand (10cm) over wet sand (20cm, 10% wc)

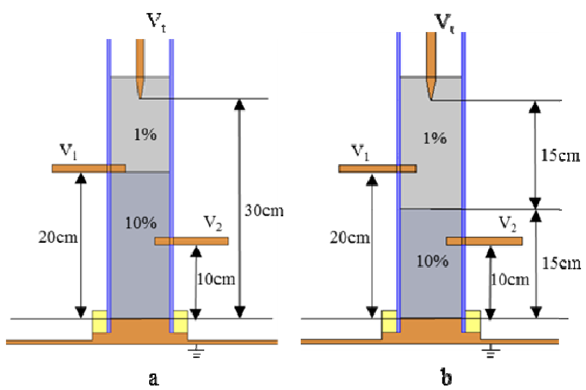

Fig. 6. Sample and voltage probe arrangements for IV-A

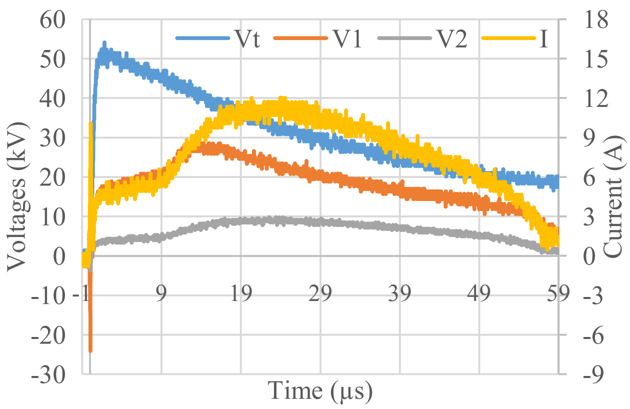

Fig. 7. Voltages and current traces in 1% wet sand (10cm) above 10% wet sand (20cm), propagation only to V_1 probe

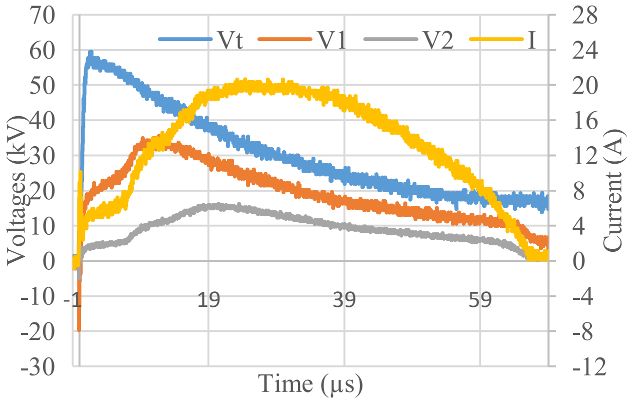

Fig. 8. Voltages and current traces in 1% wet sand (10cm) above 10% wet sand (20cm), propagation up to V_2 probe

Fig. 9 shows the currents waveforms obtained under different voltage levels when both layers had a 15cm thickness. The increase of the second peak is thought to represent the growth of the ionization zone further down in the sand sample as the applied voltage increased. It is also noticeable that the soil ionization initiation time decreases with voltage increase.

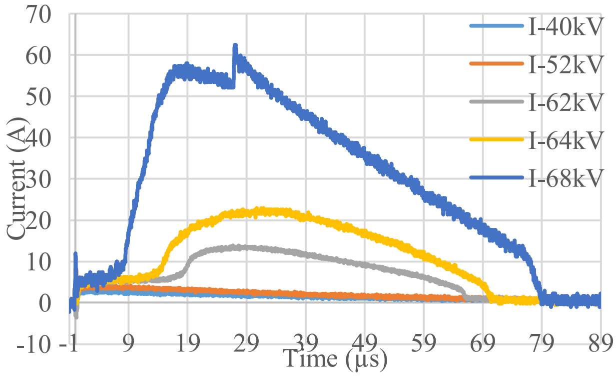

Fig. 9. Current traces for ionization propagation in 1% wet sand (15cm) above 10% wet sand (15cm)

B. *Upper Layer of Higher Water Content*

The configuration of the sample and the probes are shown in Fig. 10. The upper layer has a 10cm column with 10% wc, and the lower layer has 1% wc with 20 cm height. The probe (V_1) is placed at the interface between the two layers, and (V_2) is at the middle of the bottom layer. Fig. 11 shows an example of this discharge, where a voltage impulse of 76kV peak was applied, but no second current peak observed. However, the longer rise time of the current than the applied voltage may indicate that there was a weak ionization has only initiated around the electrode, but it did not propagate far from the electrode and did not cross to the bottom layer.

In a similar test, where the upper and lower layers have the same height (15 cm) as shown in Fig. 10 b. A small second current peak started to emerge at 60kV, as can be seen in Fig. 12. However, soil ionization has initiated and propagated only in the upper layer, and it did not cross to the bottom layer. The second current peaks obtained in this test were lower than those obtained in the previous tests, even at voltage near the breakdown level.

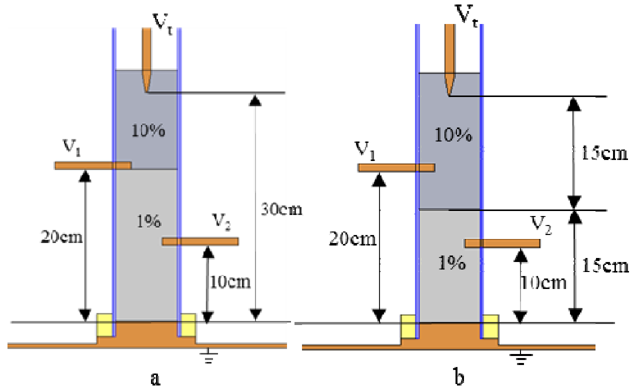

Fig. 10. Sample and voltage probes arrangements for IV-B

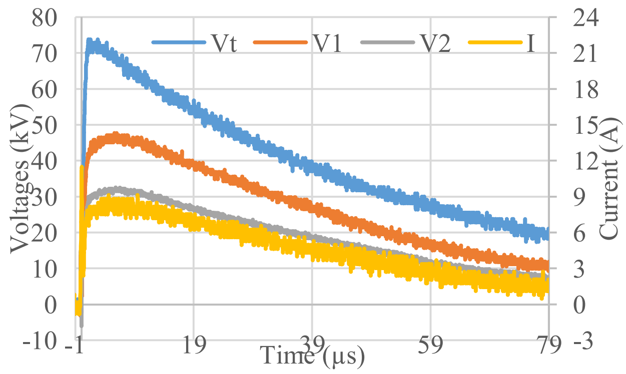

Fig. 11. Voltages and current traces in 10% wet sand (10cm) above 1% wet sand (20cm)

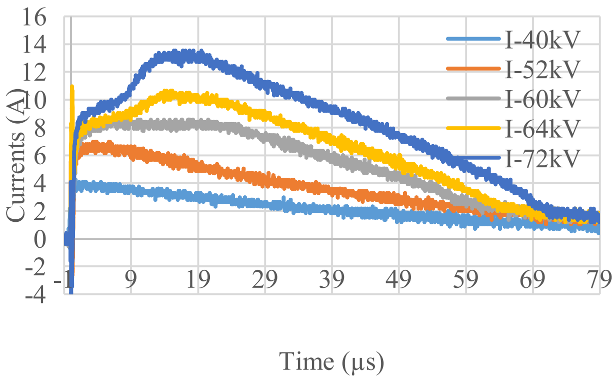

Fig. 12. Current traces for ionization propagation in 10% wet sand (15cm) above 1% wet sand (15cm)

This test may indicate that the higher resistivity layer being at the bottom of a two-layered soil is not desirable for the earthing systems under transient conditions. This scenario gives less resistivity reduction, limited ionisation propagation and lower dissipating currents.

V. CONCLUSION

Investigation of soil ionization initiation and propagation in several two layer sand samples with various moisture contents was conducted. Soil ionization is thought to cause the breakdown of the dry sand after few propagation stages. The propagated ionization discharge in dry soil could initiate the soil ionization in the wet sand placed underneath the dry layer if the wet layer has sufficient moisture content. This means that the electric field at the tip of the discharge after the breakdown of the dry layer can be high enough to initiate the ionization in the wet layer.

The presence of a high resistivity layer on top of a lower resistivity layer offers better resistivity reduction, deeper ionization propagation and higher dissipated current values than the other scenario with the high resistivity layer is at the bottom of the sample. Furthermore, soil ionization does not tend to propagate from the low resistivity to the high resistivity layers, which may be due to the tendency of the current to flow in the less resistivity soil.

Given the findings in this investigation, soil ionization should be considered when designing earthing systems in two-layer soil, where the resistivity and the thickness of each layer should be taken in account.

REFERENCES

[1] C. J. Blattner, "Analysis of Soil Resistivity Test Methods in Two-Layer Earth," *IEEE Transactions on Power Apparatus and Systems,* vol. PAS-104, pp. 3603-3608, 1985.

[2] J. L. del Alamo, "A comparison among eight different techniques to achieve an optimum estimation of electrical grounding parameters in two-layered earth," *IEEE Transactions on Power Delivery,* vol. 8, pp. 1890-1899, 1993.

[3] J. Ma, F. P. Dawalibi, and R. D. Southey, "On the equivalence of uniform and two-layer soils to multilayer soils in the analysis of grounding systems," *IEE Proceedings-Generation, Transmission and Distribution,* vol. 143, pp. 49-55, 1996.

[4] M. Nayel, L. Boyang, T. Yu, and Z. Yingzhen, "Study of Soil Resistivity Measurements in Vertical Two-Layer Soil Model," in *Power and Energy Engineering Conference (APPEEC), 2012 Asia-Pacific*, Shanghai, 2012, pp. 1-5.

[5] "IEEE Guide for Safety in AC Substation Grounding," *ANSI/IEEE Std 80-1986,* 1986.

[6] A. C. Liew and M. Darveniza, "Dynamic model of impulse characteristics of concentrated earths," *Proceedings of the Institution of Electrical Engineers,* vol. 121, pp. 123-135, 1974.

[7] A. M. Mousa, "The soil ionization gradient associated with discharge of high currents into concentrated electrodes," *IEEE Transactions on Power Delivery,* vol. 9, pp. 1669-1677, 1994.

[8] A. Habjanic and M. Trlep, "The simulation of the soil ionization phenomenon around the grounding system by the finite element method," *IEEE Transactions on Magnetics,,* vol. 42, pp. 867-870, 2006.

[9] Y. Liu, N. Theethayi, R. Thottappillil, R. M. Gonzalez, and M. Zitnik, "An improved model for soil ionization around grounding system and its application to stratified soil," *Journal of Electrostatics,* vol. 60, pp. 203-209, 2004.

[10] K. J. Nixon, I. R. Jandrell, and A. J. Phillips, "A simplified model of the lightning performance of a driven rod earth electrode in multi-layer soil that includes the effect of soil ionisation," in *Industry Applications Conference, 2006. 41st IAS Annual Meeting. Conference Record of the 2006 IEEE*, Tampa, FL, 2006, pp. 1821-1825.

[11] "Methods of test for soils for civil engineering purposes Part 1: General requirements and sample preparation," *British standard BS 1377-1,* 1990.