Toward Enhancing Soil Resistivity Measurement and Modelling for Limited Inter-electrode Spacing

O. Kherif, *Member, IEEE,* S. Robson, *Member, IEEE,* S. Mousa, N. Harid, H. Griffiths, D. Thorpe, and A. Manu Haddad, *Member, IEEE*

***Abstract*—This paper explores the influence of the maximum inter-electrode spacing in soil resistivity measurements on the one-dimensional soil modelling process. Soil equivalent models are generated based on actual measurements using a Wenner configuration. The results indicate that soil resistivity models are significantly impacted by the maximum inter-electrode spacing. For short spacings, RMS errors ranging from over 19% to approximately 26% are observed, leading to up to a 5% reduction in upper layer resistivity and a 45% difference in the lower layer resistivity. To address this issue, a practical solution is proposed to improve the measurement and modeling process for sites with limited inter-electrode spacing. The viability and rationale behind this solution are discussed and verified using extensive additional measurements. The verification process yielded positive results, confirming the potential of the proposed method for two-layer soils, as considerable improvement in the soil model was achieved. To cover additional scenarios and simulate measurements at different locations, synthetic data based on theoretical expressions is also considered. The synthetic data provided further evidence of the effectiveness of the proposed solution, but also highlights the need for further investigations to generalize the method for soils with a greater number of layers.**

***Index Terms*—Soil resistivity, modelling and simulations, grounding systems, Wenner measurement array, standardisation.**

I. Introduction

Soil resistivity measurement and modelling are key steps in numerous engineering applications, including lightning protection systems and grounding designs, transmission lines studies, electromagnetic interference studies, corrosion and cathodic protection [1]–[4]. Indeed, effective measurements followed by an accurate modelling process of soil electrical resistivity are crucial to provide an optimal solution, a safe design, and/or effective analysis and studies for all of the associated applications. Usually, soil structure is determined from the potential distribution on earth surface after injecting an electric current into the soil. Different configurations were developed for soil resistivity measurement, and Wenner arrangement, as shown in [5], represents one of the widely used techniques. Even though it is not recommended for power engineering applications [6], soil resistivity can still be measured in the laboratory using different procedures (e.g., [7]).

O. Kherif, S. Robson, S. Mousa, H. Griffiths, and A. Haddad are with the Advanced High Voltage Engineering Research Centre, School of Engineering, Cardiff University, Cardiff CF24 3AA, UK. e-mail: (KherifO@cardiff.ac.uk ; RobsonS1@cardiff.ac.uk ; MousaS@cardiff.ac.uk ; GriffithsH@cardiff.ac.uk and Haddad@cardiff.ac.uk).

N. Harid with the Electrical Engineering and Computer Science Department, Khalifa University, P O Box 127788, Abu Dhabi, UAE. e-mail: (Noureddine.Harid@ku.ac.ae).

D. Thorpe is with Kingsmill Industries (UK) Limited, Pinxton, Derbyshire NG16 6NS, UK. e-mail: (DT@kingsmillearthing.co.uk).

In fact, the direct interpretation or inversion of soil resistivity curves to determine thicknesses and resistivities of soil layers has been the topic of interest of researchers and geophysicists for many years (e.g., [8]–[12]). For multi-layer modelling, the interpretation of vertical electrical sounding curves is usually made by curve-fitting procedures in which a series of theoretical curves are used in conjunction with the measurement in order to select the best one. For instance, authors in [8] presented an expression to approximate soil apparent resistivity for soil with an arbitrary number of layers horizontally stratified. In addition, authors in [10] used optimisation based on Chebyshev polynomials in order to obtain the best possible representation of the apparent resistivity equation. Moreover, soil resistivity frequency dependent is considered (e.g., [13]–[15]). In [13], it was found that thicknesses of soil layers remain constant while resistivities showed slight decreases with frequency. In [14], the authors experimentally studied soil characterizations with both frequency (dispersion) and current density, leading to the proposal of an improved equivalent circuit in [15].

Various configurations and electrode dispositions have been proposed in the literature for improved soil resistivity measurement along with the associated impacts (e.g., [16]–[18]). In [16], a comprehensive review emphasized the often-overlooked impact of local soil variations around ground electrodes. The complexity of effective grounding design and the crucial role of soil resistivity, especially in the context of soil heterogeneity, have been addressed in [17]. Additionally, the work in [18] introduced the use of non-linear electrode arrangements to overcome challenges in confined spaces, combining multiple methodologies and increasing measurement points compared to traditional configurations.

Accurate modelling of soil resistivity relies on effective measurement results, and a single incorrect data point can significantly alter the equivalent model, leading to a deviation from the actual soil properties (i.e., the best representation of soil resistivity as a multi-layer model). Soil resistivity measurements often require reaching deeper soil layers, which is typically achieved by increasing the inter-electrode spacing. However, practical constraints at the testing site may limit the ability to achieve the desired spacing distance. In addition to these practical limitations and assuming that the measurements are accurate, the interpretation process itself can be influenced by the chosen technique and the underlying assumptions (e.g., [19], [20]). For instance, the theoretical curves used in the interpretation are impacted by various parameters, including the number of layers and the initial resistivities of the upper and lower layers, among others [20]. As a result, special attention is necessary in these areas to ensure a clear understanding of the soil resistivity measurements and modelling process.

In this paper, the key aspects of soil resistivity measurements and modeling are presented to discuss the issue of limited maximum inter-electrode spacing. The problem and the proposed solution are outlined in Section II. In Section III, the impact of inter-electrode spacing is quantified using measurement results. The verification process is covered in Sections IV and V, focusing on additional experimental data and synthetic data, respectively. Finally, the main conclusions and future perspectives are presented at the end.

II. Problem and Proposed Solution

Soil resistivity is affected by many factors, such as temperature, soil grain size and distribution, and the concentration of dissolved salts in the contained water [6]. In practice, 1-D soil resistivity measurements for a given test configuration are influenced by the position of the test electrodes, the inter electrode spacing and the surface measurement profile, in addition to the instrument's accuracy. Therefore, the best representation of the soil is obtained by considering a variation of soil resistivity in all directions ($\rho = \rho(x, y, zgm)$). This representation is impractical, and it is common in engineering applications to approximate the soil with an equivalent model to represent the soil conditions, where 1D models (known as multi-layer models), 2D models, and 3D models, can be considered [21]. This paper discusses only the 1D model of soil, which covers uniform and multi-layer soil structures.

A. Soil Resistivity Measurement and Modelling

As per the relevant international standards (e.g., IEEE Std 81 [6], BS 7430 [2]), apparent electrical resistivity of soil can be measured using different techniques. In this paper, a four-point method Wenner configuration is considered. In this method, four probes are driven, all at depth "b", into the soil in a straight line at intervals "a" as represented in Fig. 1.

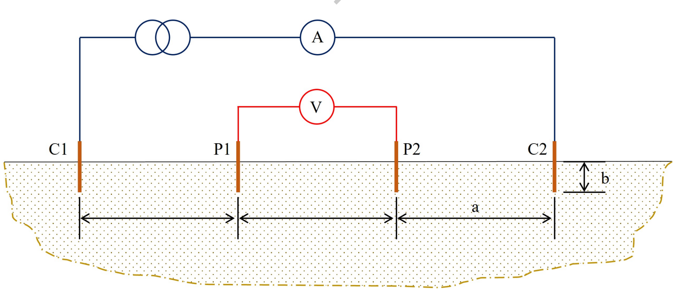


Fig. 1. Wenner configuration for soil resistivity measurements

An electrical current is injected across the outer probes and the potential difference between the inner probes is measured to calculate soil resistivity from the voltage/current ratio and in accordance with the geometrical configuration of the test. From a series of soundings at the same survey central point, one can obtain either soil apparent resistance or apparent resistivity as a function of the distance between the test electrodes. Considering electrode spacing distances greater than the burial depth of the probes ($a \gg b$), soil resistance is measured and converted to apparent resistivity as follows [5]

$$\rho_a = 2\pi a R \tag{1}$$

The same apparent resistivity can also be expressed for a known soil structure as follows [8]

$$\rho_a = \rho_1 \left\{ 1 + 2a \int_0^{\infty} f(\lambda) \left[J_0(\lambda a) - J_0(2\lambda a) \right] d\lambda \right\} \tag{2}$$

in which, $J_0(x)$ is the zero order Bessel's function of the first kind, and $f(\lambda)$ is a function of soil resistivity and depth of each layer.

Starting from a preliminary 1D soil model, soil apparent resistivity at any given electrode spacing distance is calculated according to Equation (2). The calculated results are then compared to the measurements, and the model can be considered as an equivalent representation of the soil resistivity if a good agreement is found between the calculation and measurement. If not, the parameters of the preliminary model should be adjusted, and the process should be repeated until a successful comparison is achieved. A detailed description of this process can be found in several research works (e.g., [18]). In addition, a few works (e.g., [22], [23]) refer to certain practical aspects of model formulation such as interactive model parameter selection and model constraints. However, these aspects are not fully investigated because there is no clear recommendation for the maximum electrode spacing, the impact of short inter-electrode spacing and the requirements to improve measurement techniques and modelling process.

B. Limited Inter-electrode Spacing

A uniform model is the simplest method for representing soil resistivity, assigning a single value across the entire site. While this model may be accurate in rare cases of truly homogeneous soil, it is generally an oversimplification. In such ideal conditions, a single measurement might suffice, but as shown in [24], this uniformity is uncommon, even in water. A more accurate approach is a multi-layer model, where soil resistivity is represented by horizontal layers with isotropic resistivities. In this model, "n" layers are defined by resistivities $\rho_1, \rho_2, \rho_3, \ldots, \rho_n$ and thicknesses $h_1, h_2, h_3, \ldots, h_{(n-1)}$. The i-th layer has resistivity ρ_i and thickness h_i, while the deepest layer extends infinitely. According to IEEE Std 81 [6], a set of readings taken with various probe spacings yields resistivities that, when plotted against spacing, can indicate distinct layers of different soil or rock, providing insight into their respective resistivities and depths. Larger spacings are needed for better representation, particularly for deeper soil layers as represented in the example of Fig. 2.

This example demonstrates the portion of soil assessed using large and small electrode spacings. The larger spacing penetrates deeper soil layers, allowing the third soil layer,

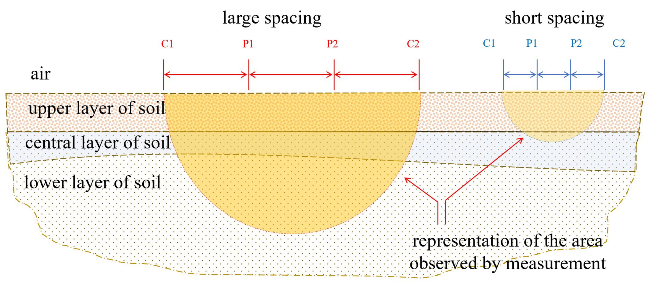


Fig. 2. Representation of large and short spacing in measurements

which is undetected with the short spacing, to become observable.

IEEE Std 81 and similar standards recommend repeating measurements at the same location but rotated 90° from the initial test to ensure consistency in the results. For each test, soil resistivity measurements should be ideally conducted within the area covered by the proposed grounding system, following a profile that closely aligns with the system and avoiding potential sources of error like fences or buried objects (conductive objects). However, practical constraints, such as limited maximum inter-electrode spacing, may prevent obtaining an ideal profile. In such cases, the information about the soil may be incomplete, impacting the accuracy of the equivalent soil resistivity model. Investigating the effects of these limitations and addressing this issue are essential for improving the understanding of soil resistivity modeling, which remains an area needing further clarification.

C. Proposed Solution for Limited Inter-Electrode Spacing

In order to overcome the challenge of restricted maximum inter-electrode spacing, particularly pertinent in urban areas where new substation grounding is needed, a practical solution is proposed. Illustrated in Fig. 3, this approach involves a systematic process.

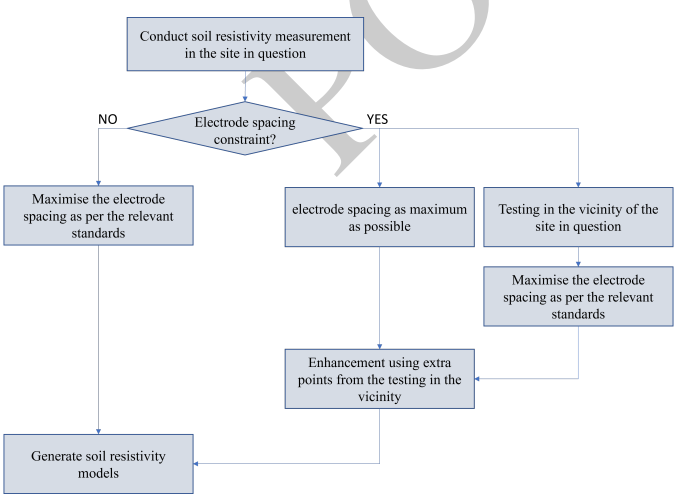


Fig. 3. Proposed methodology

Firstly, data collection is initiated for the site under scrutiny, prioritizing the maximization of inter-electrode spacing. Ideally, the inter-electrode spacing should exceed 50m to ensure accurate measurements and soil structure representation [25]. However, if space constraints are identified, necessitating a reduction in spacing, the proposed solution entails augmenting the collected data. This augmentation is achieved by incorporating additional data points to the measured soil resistivity dataset. It is important to note that these additional data serve to improve the accuracy of the analysis, mitigating the constraints imposed by limited inter-electrode spacing. Therefore, all supplementary data should pertain to the lower part exclusively as the upper part corresponds to the actual soil conditions. Figure 4 provides an example of a site with restricted space, showcasing its surrounding environment.

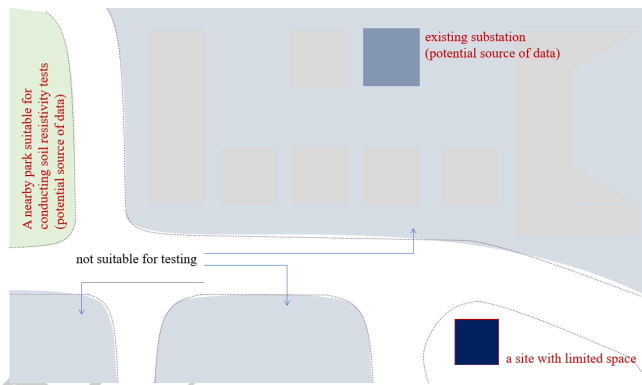


Fig. 4. A typical site with space constraints and potential sources of data

This figure illustrates two prevalent strategies aimed at augmenting data collection in scenarios where space constraints limit the maximum inter-electrode spacing. One strategy involves the incorporation of predetermined soil resistivity values gleaned from nearby substations or comparable projects with conducive soil penetration conditions. Notably, power utilities often possess such pertinent data and can readily provide it, as is the case in the United Kingdom and many other countries. Alternatively, the proposed solution advocates for conducting supplementary testing in proximal areas characterized by larger inter-electrode spacings, such as parks or playing grounds. By strategically sitting test points in these locales, where spatial limitations are less stringent, a more exhaustive dataset can be amassed. This approach enables a more comprehensive analysis of soil resistivity, although its applicability may vary. To ensure its validity, multiple successive measurements should be conducted, and the results should demonstrate stability in the lower part.

It should be noted that the proposed methodology can offer a pragmatic means of addressing the challenges associated with restricted inter-electrode spacing, especially when considering a variety of sources in combination. For instance, additional measurements can be taken in the vicinity and at different sites surrounding the area with space limitations, combining them with those obtained from substations as described previously. In this scenario, one can gain insights into soil heterogeneity (lower layers of soil), and involving an interpreter is recommended. For instance, the interpreter may assess the results based on other factors such as site altitude and subsurface content if known. Figure 5 provides a representation of soil with two layers and two scenarios of measurements. In this figure, the proposed test locations A and B may yield different soil models as the depth of the layer varies from a location to another. For this reason, among others, the interpreter should carefully select the survey location and gather site data while or prior to conducting the test.

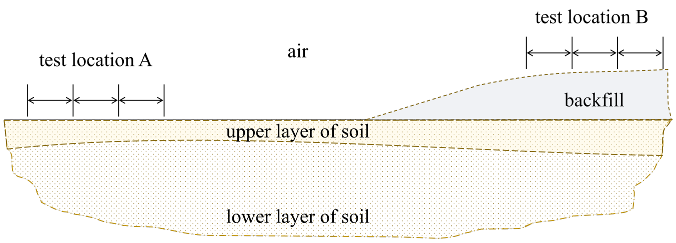


Fig. 5. A typical representation of two site location with different upper layers and sharing the same lower layers

As per the proposed method, it is advised to start measurements on-site despite space limitations. This ensures that soil resistivity measurements accurately represent the actual soil conditions, typically below a depth of a few meters, where the grounding system will be installed. For this testing, it is recommended to follow the guidance of the relevant standards. Integrating measurements from deeper layers enhances the representation of the soil structure at the lower parts and facilitates the development of effective designs, particularly in densely populated urban areas where space is limited. Projects in such areas often require driving long rods to reduce grounding resistance. To validate this assertion, the following sections analyze the stability of both upper and lower soil layers and show the validity of the proposed solution.

III. Soil Resistivity under Space Constraint

A. Soil Resistivity Dataset

To investigate the impact of limited maximum inter-electrode spacing, soil resistivity measurements were conducted at a testing field in Cardiff. The ABEM Terrameter SAS 1000 ground tester coupled with the Lund Imaging System (LIS) was used for the measurements, as illustrated in the experimental set-up shown in Fig. 6.

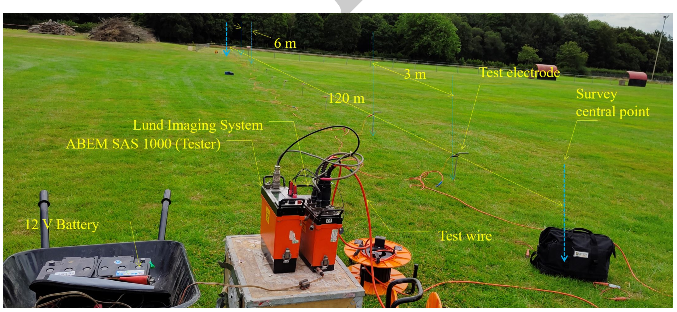


Fig. 6. Experimental setup of a typical soil resistivity test

The system uses an automatic process where the inter-electrode spacing is varied and current is injected between two electrodes and the potential measured between two other electrodes having the same spacing. The measurements taken at a given spacing are averaged to give an apparent resistivity value at that spacing. Additional details about the instruments and test procedure can be found in [26] and [27]. The measured apparent resistivity as a function of inter-electrode spacing is shown in Fig. 7.

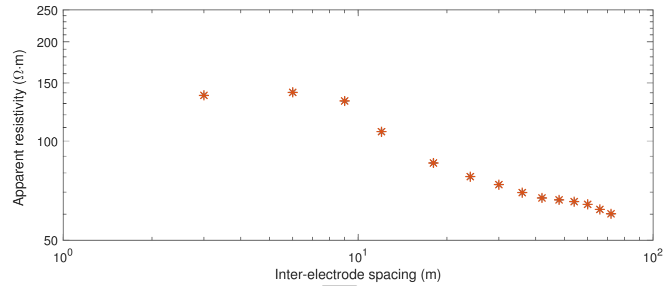


Fig. 7. Soil apparent resistivity measured at different inter-electrode spacings

RESAP module of CDEGS computer tool [28] was utilized for interpreting the results, leading to the derivation of a two-layer soil model. To ensure accuracy, an automatic run of the software was executed, minimizing any potential biases introduced by manual interpretation. This automated process involves RESAP comparing field data with apparent resistivities generated by various soil models, ultimately determining the soil structure that closely matches the observed electric surface response. Table I gives the parameters of the calculated model where an RMS error of 3.37% is obtained.

TABLE I
Two-layer model using RESAP module of CDEGS

LAYER	Resistivity	Thickness
Air	infinite	infinite
Top (upper)	145.08 $\Omega \cdot m$	8.64 m
Bottom (lower)	61.59 $\Omega \cdot m$	infinite

The measurements, along with the calculated model, are utilized in the subsequent sections. It is assumed that the soil model presented in Table I represents the actual soil conditions, and the accuracy of the measurements is confirmed.

B. Impact of Maximum Electrode Spacing

To investigate the influence of the maximum inter-electrode spacing on the calculated soil model, the same dataset is employed, and various scenarios are explored by adjusting the maximum inter-electrode spacings. Table II presents the parameters of the resulting soil model, including the associated RMS error. It is important to emphasize that a two-layer model is specifically considered in this section.

The table clearly illustrates the significant impact of the maximum inter-electrode spacing on the soil resistivity equivalent model. An RMS error below 3.67% is achieved when the inter-electrode spacing is equal to or greater than 42 m. Within this range, the same equivalent model closely aligns with the actual model of the soil. However, for distances below 42 m, the RMS errors range from over 19% to approximately 26% compared to the actual model. In this case, the upper layer resistivity exhibits a maximum reduction of about 5%,

TABLE II
TWO-LAYER MODEL USING RESAP MODULE OF CDEGS FOR DIFFERENT MAXIMUM ELECTRODE SPACINGS

RMS Error (%)	SOIL MODEL Top ($\Omega \cdot m$)	Depth (m)	Bottom ($\Omega \cdot m$)	CONSIDERED DATASET (m) 3	6	9	12	18	24	30	36	42	48	54	60	66	72
3.366	145.08	8.64	61.59	x	x	x	x	x	x	x	x	x	x	x	x	x	x
3.177	146.64	8.28	62.60	x	x	x	x	x	x	x	x	x	x	x	x	x	
3.131	146.00	8.33	62.88	x	x	x	x	x	x	x	x	x	x	x	x		
3.254	146.25	8.26	63.08	x	x	x	x	x	x	x	x	x	x	x			
3.412	146.27	8.26	63.12	x	x	x	x	x	x	x	x	x	x				
3.596	146.39	8.24	63.16	x	x	x	x	x	x	x	x	x					
25.77	138.34	0.20	89.09	x	x	x	x	x	x	x	x						
24.85	138.98	0.20	94.60	x	x	x	x	x	x	x							
23.28	139.27	0.20	101.61	x	x	x	x	x	x								
19.69	143.66	0.21	111.71	x	x	x	x	x									

while the lower layer of the soil experiences a difference of approximately 45%. The relationship between RMS error and inter-electrode spacing is depicted in Fig. 8.

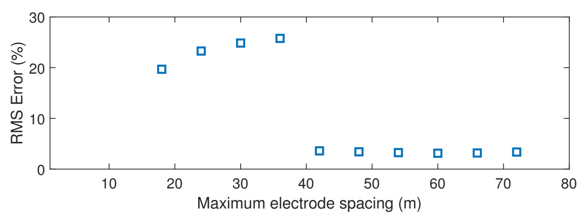


Fig. 8. RMS error evolution as a function of maximum inter-electrode spacing

As can be seen in this figure, a sharp increase in RMS error characterise short inter-electrode spacings, and a stability is observed for larger spacing. A substantial variation is also observed in the other parameters obtained models, and Fig. 9 shows the variation in the model parameters (i.e., upper layer resistivity and depth and lower layer resistivity) for different maximum electrode spacing distances.

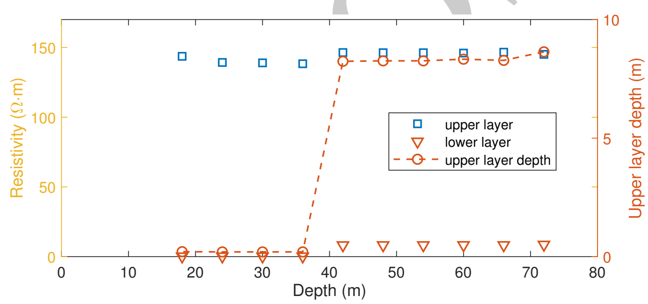


Fig. 9. Model parameters as a function of maximum inter-electrode spacing

The depicted figure clearly shows that the upper layer resistivity remains relatively constant, while the other two parameters exhibit significant variations across different electrode spacing distances. The upper layer depth and lower layer resistivity are highly sensitive to the maximum distance in the Wenner configuration. These variations can have implications for the accuracy of calculated soil resistivity models and, consequently, impact various engineering designs such as grounding systems and transmission line parameters.

IV. PROPOSED SOLUTION EXAMINATION

A. *Verification Stage*

As verification of the proposed technique, a limited maximum electrode spacing of 18 m is considered. The resulting model obtained from the same data exhibits an RMS error of approximately 20%. In such cases, the proposed technique of using extra points can be employed. Two types of tests are conducted as follows: (1) only one single point is considered to enhance the measurements and improve calculated model, and (2) more than one extra point are employed. The results of this approach are summarized in Table III.

As evident from the table, the proposed technique exhibits a significant improvement in the calculated equivalent models of the soil compared to the actual model. For instance, adding only one single point, which is the apparent resistivity of the inter-electrode spacing 72 m, helps reducing the RMS error from 19.69% to 3.99%. Compared to the actual model of 3.37% RMS error, the results are significantly beneficial. Consequently, employing extra points of measured soil resistivity obtained using larger electrode-spacing distances enables a closer approximation to the actual soil model and helps overcome the limitations of a limited maximum electrode spacing. Based on the utilized dataset, enhancement points are often sufficient to improve the equivalent soil model.

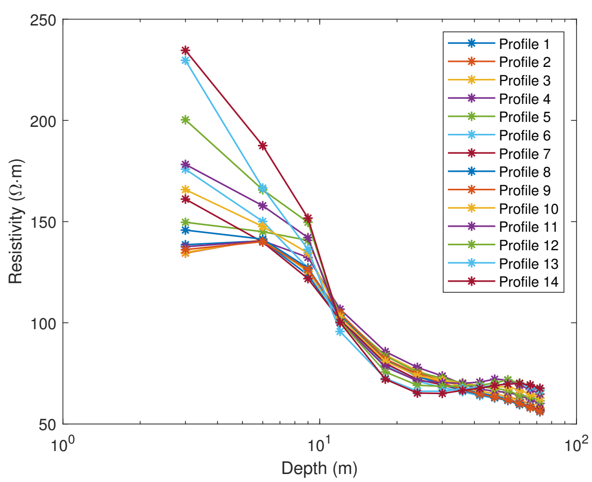
B. *Stability of Soil in Upper and Lower Layers*

It is imperative to acknowledge that the efficacy of the proposed technique hinges upon the consistency of the underlying soil layers, particularly in the lower layers of soil up to 100m [25]. Instances characterized by pronounced heterogeneity in these lower layers may diminish the effectiveness of this technique. Hence, to further elucidate the stability of the site, additional soil resistivity measurements were conducted at the Llanrumney field test site, positioned approximately 50m distant from the initial profile location. In this supplementary investigation, soil resistivity was gauged across fourteen distinct profiles, employing an arbitrary fixed separation of 5m between profile lines (resulting in a total span of 65m between Profiles 1 and 14). Measurements were systematically undertaken along orthogonal lines, as delineated in Fig. 10a. Each profile featured a maximum inter-electrode spacing of 72m. The collective results from these fourteen profiles are graphically depicted in Fig. 10b.

TABLE III
TWO-LAYER MODEL FOR VARIOUS SCENARIOS, WITH AND WITHOUT ENHANCEMENT

RMS Error (%)	SOIL MODEL Top ($\Omega \cdot m$)	Depth (m)	Bottom ($\Omega \cdot m$)	CONSIDERED DATASET (m) 3	6	9	12	18	24	30	36	42	48	54	60	66	72
3.366	145.08	8.64	61.59	x	x	x	x	x	x	x	x	x	x	x	x	x	x
19.69	143.66	0.21	111.71	x	x	x	x	x									
3.985	145.58	8.76	58.15	x	x	x	x	x									x
4.088	146.42	8.53	59.80	x	x	x	x	x								x	
4.224	146.63	8.32	61.58	x	x	x	x	x							x		
4.281	146.54	8.30	62.13	x	x	x	x	x						x			
4.287	146.72	8.24	62.31	x	x	x	x	x					x				
4.264	146.35	8.36	61.78	x	x	x	x	x				x					
3.952	146.53	8.30	62.15	x	x	x	x	x				x			x		
3.987	146.12	8.50	60.80	x	x	x	x	x				x			x		x
3.946	145.82	8.47	61.76	x	x	x	x	x		x				x		x	

(a) test location



(b) test results

Fig. 10. Proposed fourteen profiles for soil resistivity measurements

It is clear that the results reveal significant lateral variations (between 134 and 235Ω.m) in soil resistivity depending on the electrode spacing, particularly for distances below 12m. As the electrode spacing increases, the differences in soil resistivity measurements decrease to around 10Ω.m as the resistivity varies in the range between 56 and 67Ω.m. These variations can be attributed to the relative stability of the lower layers compared to the upper layers. As a function of inter-electrode spacing, Fig. 11 presents a statistical representation of the soil resistivity variation in the vicinity of the site.

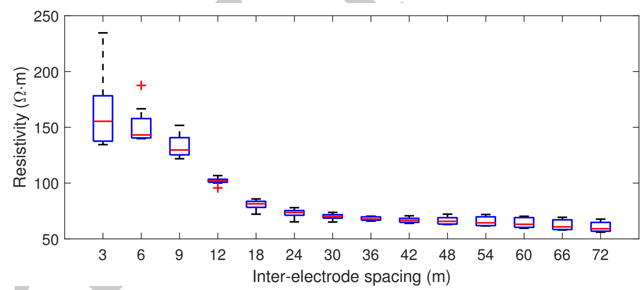


Fig. 11. Boxplot of the measured results from fourteen profiles

The obtained results clearly demonstrate the relative stability of the lower layers of soil up to a distance of 65m. In comparison to the initial measurements taken 50m away, the lower layer results exhibit a similar trend with a relative error of approximately 16%. Therefore, the proposed solution's use of enhancement points may prove effective for distances exceeding 100m (50m + 65m in this test). Given the significant variability in soil resistivity, it is advisable to incorporate additional points from different directions, encompassing the site under consideration (east, west, north, and south of the site). Including one or multiple soil resistivity measurement points from various locations surrounding the site can enhance the equivalent model of soil resistivity and provide more realistic representation of the soil where limited space is identified. Additionally, the proposed technique offers the opportunity to optimize the duration of soil resistivity measurements by reducing the total number of measurements required.

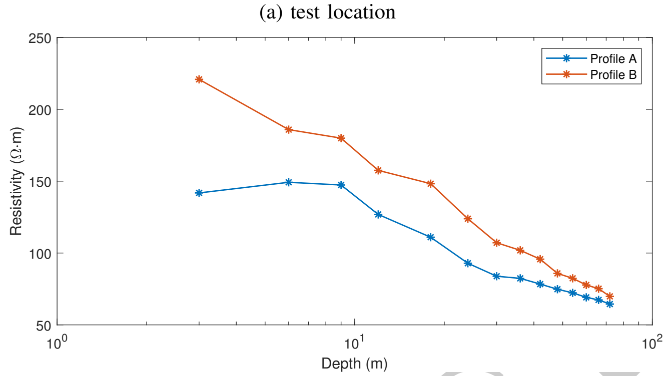
C. Validity of the Proposed Solution

To validate the proposed technique, independent measurements were considered from two profiles, designated as Profile A and Profile B. These profiles were selected for soil resistivity measurements at the Llanrumney field test site, chosen based on the suitability of the test field for the intended tasks. Profile A and Profile B were situated approximately 500m apart from each other. The measured results at these locations were collected and illustrated in Fig. 12, which also indicates the locations of the profiles for reference.

TABLE IV
VALIDATION STAGE USING RESULTS FROM TWO DIFFERENT PROFILES WITH 500M DISTANCE

RMS Error (%)	SOIL MODEL Top ($\Omega \cdot m$)	Depth (m)	Bottom ($\Omega \cdot m$)	CONSIDERED DATASET (m) 3	6	9	12	18	24	30	36	42	48	54	60	66	72
3.378	148.81	12.35	64.42	A	A	A	A	A	A	A	A	A	A	A	A	A	A
19.69	142.99	0.20	131.73	A	A	A	A	A									
3.461	149.01	12.29	66.52	A	A	A	A	A									B
4.088	148.80	11.95	70.18	A	A	A	A	A							B	B	B
5.140	192.30	14.81	68.41	B	B	B	B	B	B	B	B	B	B	B	B	B	B
13.370	222.21	0.20	171.75	B	B	B	B	B									
6.010	199.58	13.16	60.71	B	B	B	B	B									A
5.260	199.30	13.19	61.70	B	B	B	B	B							A	A	A

(a) test location



(b) test results

Fig. 12. Proposed profiles for the validation of the proposed method

From this figure, it is clear that both measurements exhibit a similar trend over the inter-electrode spacing. Profile B demonstrates relatively higher values compared to those obtained from Profile A. The disparity between the results is more pronounced at upper layers, decreasing as the depth increases. These findings align with those presented in the previous section. The measured results are utilized in RESAP under automatic run to generate an equivalent model for each profile. A two-layer model is derived for each profile, as shown in Table IV, and is considered the actual model of the soil for each Profile; A and B. A validation stage is then initiated, which involves two scenarios: the first scenario treats Profile A as the constrained site and supplements it with the data obtained from Profile B, while the second scenario reverses this approach. The corresponding models along with the calculated RMS errors are shown in Table IV.

Compared to the actual model, space limitations may result in an inaccurate representation of the soil structure, particularly affecting the thickness of the upper layer and the resistivity of the lower layer as can be seen from the calculated results in Table IV. However, the upper layer resistivity remains approximately within an acceptable range, with a difference of 3.91% for Profile A and a range of 15.55% for Profile B in comparison with their actual models.

As part of the proposed method implementation, single and multiple points have been included from Profile B to Profile A under space restrictions, and vice versa. For the four considered cases (as shown in lines 3, 4, 7, and 8 of Table IV), the calculated model is significantly enhanced compared to the actual models. Notably, the upper layer resistivity for each profile remains within an acceptable range of variation, indicating that the proposed model does not substantially impact the upper layer, which is primarily influenced by measurements obtained from the site with space limitations. Additionally, a notable improvement is observed in the upper layer thickness and lower layer resistivity. Adding a single or multiple additional points from Profile B to Profile A with restricted spacing to 18m improves the obtained model. For instance, adding a 72m measured resistivity from Profile B to Profile A reduces the RMS error from 19.69 to 3.46% and improve the lower layer resistivity from 131.73 to 66.52 Ω·m, which is closer to the actual value. The upper layer soil resistivity remains in good accordance with that obtained without space restrictions. Similar observations and conclusions are drawn from the second scenario. Overall, model parameters are closer to the actual model with a low RMS error, validating the proposed method under the specified conditions and in similar practical situations.

V. ANALYSIS WITH ARTIFICIALLY GENERATED DATA

The measurements in the previous sections primarily indicate a two-layer model where the soil resistivity of the upper layer is lower than that of the lower layer. In practice, one may encounter different soil structures, such as an upper layer with lower resistivity and a lower layer with higher resistivity. Due to the difficulties in obtaining measurements for various scenarios, artificially generated data is considered in this section, as it was used in similar situation (e.g. [13]). Equation 2 is used to generate results for six known soil structures: LH15, LH10, LH05, HL15, HL10, and HL05. The term ”HL” refers to an upper layer with a relatively high resistivity of 250 Ω·m and a lower layer with a lower resistivity of 50 Ω·m. Conversely, ”LH” corresponds to the opposite configuration, where the number indicates the thickness of the upper layer. Figure 13 illustrates the proposed results.

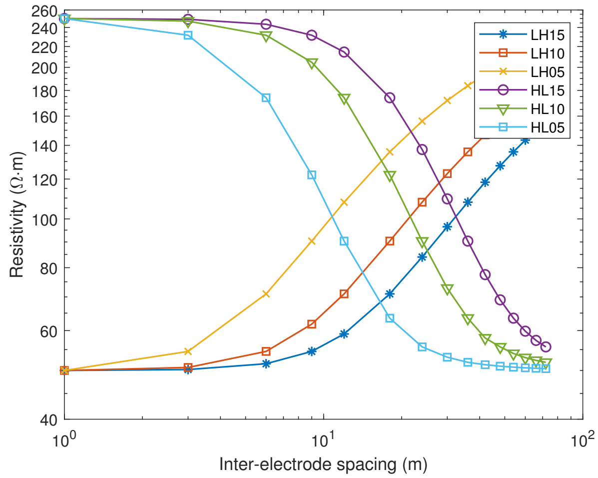


Fig. 13. Artificially generated data for soil resistivity of two-layer structure

To investigate the validity of the proposed solution for limited inter-electrode spacing under different conditions, the soil model is calculated based on the results shown in Fig. 13. The calculations consider a limited space of 18 meters (marked with a single asterisk) and a limited space with an additional single point (marked with a double asterisk). Table V presents the calculated model parameters, with all values rounded to two decimal places.

TABLE V
TWO-LAYER MODEL USING RESAP MODULE OF CDEGS

CASE CASE	Upper layer ($\Omega \cdot m$)	Thickness (m)	Lower layer ($\Omega \cdot m$)	RMSE (%)
LH15	48.68	12.82	212.19	2.37
LH15*	49.03	8.13	90.97	2.49
LH15**	50.00	13.48	210.97	2.41
LH10	47.96	8.61	226.80	2.44
LH10*	50.00	7.79	145.08	2.36
LH10**	49.01	9.03	224.50	2.27
LH05	50.00	4.87	243.33	1.05
LH05*	50.00	4.38	199.59	2.45
LH05**	50.00	5.33	254.61	2.42
HL15	250.00	15.63	48.64	1.74
HL15*	250.00	9.16	134.03	2.48
HL15**	250.00	26.70	48.70	2.20
HL10	250.00	9.72	50.08	1.40
HL10*	250.00	8.55	73.98	2.07
HL10**	250.02	9.58	50.06	2.17
HL05	250.00	5.24	49.38	2.00
HL05*	250.00	4.72	54.63	2.36
HL05**	250.00	5.07	51.16	1.96

The results reveal several interesting conclusions regarding the influencing factors and the most affected model parameters. To facilitate a more thorough discussion, the results are organized into the following sub-sections.

A. Upper-layer Resistivity

As shown in Table V, the upper layer resistivity remains consistent regardless of whether short or large inter-electrode spacings are used in the proposed cases for both low and high resistivity scenarios. The values are close to the actual value of 50 Ω·m. This observation aligns closely with the results previously presented in Tables II, III, and IV, confirming that the upper layer resistivity is not significantly affected by the constraints of limited spacing or by the implementation of the proposed method. This consistency validates the proposed method's ability to preserve accurate information about the upper layer. In other words, the upper layer resistivity remains unaffected by whether the site is limited or not, and measurements taken at the location of the new substation (or grounding system) will yield acceptable readings for the upper layer resistivity. The enhancements made using the proposed method do not substantially alter the upper layer resistivity.

B. Upper-layer Thickness

The results concerning the upper layer thickness highlight a significant consideration that was not evident from the results obtained from measurements. Although the synthetic data (artificial measurements) in this section were derived from a theoretical model, the calculated model exhibits a slight deviation from the known model in terms of upper layer thickness. This deviation has important implications for the accuracy of the extracted model and the validity of the proposed method. Notably, soils with larger upper layer thicknesses are more susceptible to this deviation than those with smaller thicknesses. For instance, when using the complete dataset in LH15 case, the calculated upper layer thickness is 12.82 m, compared to the 15 m thickness of the actual model - resulting in a deviation of 2.18 m, or approximately 14.53%. Similarly, deviations of 1.39 m (13.9%) and 0.13 m (2.6%) were observed for soils with upper layer thicknesses of 10 m and 5 m, respectively. These findings indicate that the calculated model tends to deviate more from the actual model as the upper layer thickness increases.

When considering the measurement limitations - specifically, a maximum inter-electrode spacing of 18 m - the impact on upper layer thickness becomes more pronounced. Soils with thicker upper layers are significantly affected by the shorter inter-electrode spacing, whereas soils with a 5 m upper layer thickness are only slightly affected, showing an increased deviation of 0.62 m (12.4%) compared to the actual model. By applying the proposed method to the LH15, LH10, and LH05 cases, a marked improvement was observed. For LH15, the thickness was corrected to 13.48 m, an improvement from the 8.13 m thickness obtained under the considered measurement limitation, representing a reduction in error by approximately 35.3%. Similar improvements were noted in all three scenarios when compared to the actual known model.

Conversely, when the layers were reversed - where the upper layer has higher resistivity and the lower layer has lower resistivity - similar conclusions were drawn regarding thickness. However, in one instance, the proposed model yielded an incorrect thickness compared to the actual model. In the HL15 case, the actual model's thickness is 15 m, but the limitation to 18 m spacing resulted in a thickness of 9.16 m, a 39% reduction, confirming the significant impact of spacing limitation. However, the proposed method estimated a thickness of 26.70 m, which is 78% higher than the actual model. Although the proposed method generally provides a better estimation of thickness as it was the case for all the cases, this discrepancy suggests that it may not always yield the correct interpretation or parameters of the model in terms of thickness. Further investigation is necessary to address this limitation.

C. Lower-layer Resistivity

The lower layer resistivity is also impacted by the limitation of inter-electrode spacing. Even when a maximum spacing of 72m is considered and the data is derived from the theoretical model, the lower layer resistivity shows a slight difference from the actual model. When considering a maximum spacing of 18 m, the values are significantly affected in the cases marked with an asterisk, and the difference increases with the soil's upper layer thickness. For instance, in the LH15 case, the limitation caused the resistivity to decrease from 250 to 90.97 Ω·m, representing a 63.6% reduction. However, the proposed method corrected the resistivity to 210.97 Ω·m, reducing the error by 46.4%. The difference becomes smaller as the upper layer thickness decreases, indicating that thinner upper layers are less affected by the spacing limitation. The same conclusions apply across the different cases, whether LH or HL. In a specific case, HL15, where the upper layer thickness was incorrectly estimated as shown in Section V-B, the value of the lower layer resistivity was corrected and is close to the actual value of 50 Ω·m. The resistivity was 134 Ω·m under the spacing limitation, a 168% increase, but it was corrected to 48.70 Ω·m using the proposed method, reducing the error by 63.6%. This suggests that the proposed method shows positive potential for accurately estimating lower layer resistivity, even when upper layer thicknesses are misestimated.

D. RMS Error

The RMS error is relatively low across the three scenarios in different soil conditions, whether for short or large spacing. This is expected since the results were derived from a mathematical expression. However, this observation highlights that RMS error alone cannot reliably indicate how closely the model approximates the actual soil model. The RMS error only reflects how closely the measurements align with the proposed model. As shown by experiments, the RMS error can exhibit significant deviations, which may occur when the calculated model deviates from the actual soil model or when the actual model itself is complex.

VI. Conclusion

The study focused on soil resistivity measurement and modeling, with both experimental and theoretical investigations exploring the effects of maximum inter-electrode spacing on the accuracy of computed soil models. These investigations aimed to provide a better understanding of this critical parameter and its impact on soil resistivity modeling. The findings revealed that limited spacing could result in significant errors in the calculated soil model. In response to this challenge, the paper proffered a practical solution where empirical findings distinctly demonstrated a marked enhancement in the fidelity of computed soil models upon the adoption of this proposed technique. Central to the efficacy of this method was the strategic utilization of supplementary points derived from measured or predetermined soil resistivity values, obtained through larger inter-electrode spacing. The findings showed that the proposed approach facilitated a more accurate approximation to the actual soil model without affecting the upper layer resistivity that characterises the site in question.

The proposed method has been tested and successfully verified for two-layer soil, but further investigation is necessary for cases involving three or more layers. Independent verification stage is also recommended in order to confirm these findings. Moreover, the involvement of an experienced interpreter is essential for effectively implementing the proposed solution at sites with limited space.

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References

[1] "IEEE Guide for Safety in AC Substation Grounding," in IEEE Std 80-2013 (Revision of IEEE Std 80-2000/ Incorporates IEEE Std 80-2013/Cor 1-2015) , vol., no., pp.1-226, 15 May 2015.
[2] BS 7430:2011+A1:2015, "Code of practice for protective earthing of electrical installations," 31 Dec 2011
[3] O. Kherif, S. Robson, N. Harid, D. Thorpe and A. Haddad, "Considerations on Earthing Impedance Measurement using Low-magnitude Variable-frequency Currents," 2022 36th International Conference on Lightning Protection (ICLP), 2022, pp. 374-378.
[4] "IEEE Guide for Evaluating AC Interference on Linear Facilities Co-Located Near Transmission Lines," in IEEE Std 2746-2020 , vol., no., pp.1-49, 8 July 2020, doi: 10.1109/IEEESTD.2020.9135009.
[5] F.Wenner, "A method for measuring earth resistivity," J. Washington Acad. Sci., vol. 5, no. 16, pp. 561–563, 1915.
[6] "IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System," in IEEE Std 81-2012 (Revision of IEEE Std 81-1983) , vol., no., pp.1-86, 28 Dec. 2012.
[7] "Standard Test Method for Measurement of Soil Resistivity Using the Wenner Four-Electrode Method", ASTM International, West Conshohocken, PA, USA, ASTM G57-20.
[8] T. Takahashi and T. Kawase, "Analysis of apparent resistivity in a multi-layer earth structure," in IEEE Transactions on Power Delivery, vol. 5, no. 2, pp. 604-612, April 1990.
[9] A. G. Martins-Britto, F. V. Lopes and S. R. M. J. Rondineau, "Multilayer Earth Structure Approximation by a Homogeneous Conductivity Soil for Ground Return Impedance Calculations," in IEEE Transactions on Power Delivery, vol. 35, no. 2, pp. 881-891, April 2020.
[10] R. R. A. Coelho, A. E. C. Pereira and L. M. Neto, "A High-Performance Multilayer Earth Parameter Estimation Rooted in Chebyshev Polynomials," in IEEE Transactions on Power Delivery, vol. 33, no. 3, pp. 1054-1061, June 2018.
[11] W. R. Pereira, M. G. Soares and L. M. Neto, "Horizontal Multilayer Soil Parameter Estimation Through Differential Evolution," in IEEE Transactions on Power Delivery, vol. 31, no. 2, pp. 622-629, April 2016.
[12] Bo Zhang, Xiang Cui, Lin Li and Jinliang He, "Parameter estimation of horizontal multilayer earth by complex image method," in IEEE Transactions on Power Delivery, vol. 20, no. 2, pp. 1394-1401, April 2005.
[13] Z. -X. Li and S. -W. Rao, "The Inversion of One-Dimensional Soil Parameters in the Frequency Domain With Considering Multilayered Earth Based on Simulated Annealing Algorithm," in IEEE Transactions on Electromagnetic Compatibility, vol. 62, no. 2, pp. 425-432, April 2020.

[14] A. D. B. Manjunath et al., ”Investigation Into Variation of Resistivity and Permittivity of Aqueous Solutions and Soils With Frequency and Current Density,” in IEEE Transactions on Electromagnetic Compatibility, vol. 64, no. 2, pp. 443-455, April 2022.

[15] A. D. B. Manjunath et al., ”Equivalent Circuit Models for Soils and Aqueous Solutions Under 2-Terminal Test Configuration,” in IEEE Transactions on Electromagnetic Compatibility, vol. 65, no. 1, pp. 225-234, Feb. 2023.

[16] U. Muhammad, F. Aman and N. M. Nor, ”Effect of Localised Soil on the Measured and Calculated Resistance Values,” 2023 4th International Conference on High Voltage Engineering and Power Systems (ICHVEPS), Denpasar Bali, Indonesia, 2023, pp. 604-608.

[17] O. Kherif et al., ”Impact of Profile Orientation and Position on Soil Resistivity Measurement for Earthing Applications,” 2023 58th International Universities Power Engineering Conference, Ireland, 2023.

[18] O. Ramos-Leaños, F. A. Uribe, L. Valcárcel, A. Hajiaboli, S. Franiatte and F. P. Dawalibi, ”Nonlinear Electrode Arrangements for Multilayer Soil Resistivity Measurements,” in IEEE Transactions on Electromagnetic Compatibility, vol. 62, no. 5, pp. 2148-2155, Oct. 2020.

[19] O. Kherif, S. Robson, N. Harid, D. Thorpe, S. Stivanello and A. Haddad, ”On the Impact of Soil Resistivity Measurement and Modelling on Grounding Performance,” 2022 36th International Conference on Lightning Protection (ICLP), 2022, pp. 379-382.

[20] F. Dawalibi and C. J. Blattner, ”Earth Resistivity Measurement Interpretation Techniques,” in IEEE Transactions on Power Apparatus and Systems, vol. PAS-103, no. 2, pp. 374-382, Feb. 1984.

[21] Loke, M. H. (1999). A Practical Guide to 2D and 3D Surveys. Electrical Imaging Surveys for Environmental and Engineering Studies, 8-10.

[22] W. P. Calixto, L. M. Neto, M. Wu, K. Yamanaka and E. da Paz Moreira, ”Parameters Estimation of a Horizontal Multilayer Soil Using Genetic Algorithm,” in IEEE Transactions on Power Delivery, vol. 25, no. 3, pp. 1250-1257, July 2010.

[23] R. S. Nikjoo, S. H. H. Sadeghi, R. Moini and K. Sheshyekani, ”Determination of multilayer soil parameters using Simulated Annealing algorithm,” 2010 30th International Conference on Lightning Protection (ICLP), Cagliari, Italy, 2010.

[24] D. Guo et *al.*, ”Controlled Large-Scale Tests of Practical Grounding Electrodes—Part I: Test Facility and Measurement of Site Parameters,” in IEEE Transactions on Power Delivery, vol. 29, no. 3, pp. 1231-1239, June 2014, doi: 10.1109/TPWRD.2013.2284261.

[25] ”Earthing of power installations exceeding 1 kV a.c.”, BS EN 50522, Feb. 2023.

[26] Instruction Manual, ”Terrameter SAS 4000 / SAS 1000”, ABEM Product Number 33 0020 26, ABEM Printed Matter GGEO-100049, Aug. 2018.

[27] O. Kherif et *al.*, ”On the High Frequency Performance of Vertical Ground Electrodes and LRM Application,” in IEEE Transactions on Electromagnetic Compatibility, doi: 10.1109/TEMC.2024.3435788.

[28] Current Distribution, Electromagnetic Interference, Grounding and Soil Structure Analysis (CDEGS), Safe engineering services, Canada, 2022. [Online]. https://www.sestech.com/en/Product/Package/CDEGS