PREPRINT

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Considerations of Earth Resistance Reduction Agent Studies

Muhammad Noh Hamzah[1]*, Mohd. Zainal Abidin Ab Kadir[1], Shafreeza Sobri[1], Chandima Gomes[2] and Syahrun Nizam Md. Arshad Hashim[3]

[1]*Department of Electric and Electronics Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia*
[2]*School of Electrical and Information Engineering, University of the Witwatersrand, 1 Jan Smuts Avenue, Braamfontein 2000, Johannesburg, South Africa*
[3]*Centre of Excellence for Renewable Energy, Faculty of Electrical Engineering Technology, Pauh Putra Main Campus, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia*

ABSTRACT

Earth resistance reduction agent (ERRA) studies are done to determine the best-performing material in different orientations and arrangements of earthing systems. Most studies in the past have adopted the installation of a row of earthing systems with ERRAs, using a single reference earthing. This is plausible only if the soil is highly homogeneous in its horizontal breadth and vertical depth soil resistivity attributes, so the comparisons can be made justly and accurately. This paper will demonstrate, using earth soil resistivity and electrode resistance values, that assuming a homogeneous soil in both horizontal and vertical directions can lead to misleading interpretations of the ERRA studies. A combination of earthing electrodes that are untreated and treated with ERRAs is used to demonstrate this issue. Soil resistivity and earthing resistance measurements were done for comparison purposes. Results found that the soil in the tested premises is inherently inhomogeneous. Earth resistance values of untreated soil were found to be 127.90, 45, 46.26, 35.84, 115.11, 51.95, 60.95, and 41.16 Ω, respectively. In comparison, earth resistance values of treated soil were found to be 617.33, 178.91, 163.75, and 148.23 Ω, respectively. Suggestions to effectively improve ERRA studies are then outlined in this paper, too.

ARTICLE INFO

Article history:
Received: 16 September 2024
Accepted: 17 March 2025
Published: 25 September 2025

DOI: https://doi.org/10.47836/pjst.33.6.01

*E-mail address*es:
muhammadnoh.work@gmail.com (Muhammad Noh Hamzah)
mzk@upm.edu.my (Mohd. Zainal Abidin Ab Kadri)
shafreeza@upm.edu.my (Shafreeza Sobri)
chandima.gomes@wits.ac.za (Chandima Gomes)
syahrun@unimap.edu.my (Syahrun Nizam Md. Arshad Hashim)
* Corresponding author

Keywords: Earth resistance, inhomogeneous soil, soil resistivity

INTRODUCTION

Lightning and power systems need efficient earthing systems to return electrical current from the source or earth (Mohamad Nasir et al., 2021). Apart from the electrical integrity

e-ISSN: 2231-8526

(due to damage from corrosion), one of the other requirements of efficient electrical earthing is the earthing electrode dealing with its resistance when encased in its associated soil. The resistance to earth of an earthing electrode responsible for this purpose must be at its lowest according to the requirements of the standards (i.e., 1-10 Ω). Earthing resistance is proportional to soil resistivity and vice versa according to the Institute of Electrical and Electronics Engineers (IEEE) 81-2012, which indicates soil resistivity should be low to lower earthing resistances of earthing systems (Dilushani et al., 2020; IEEE, 2012). Earthing resistance with soil resistivity is an important parameter for engineers in ensuring electrical safety and earthing design (Al-Shawesh et al., 2021; Sinchi-Sinchi et al., 2022). Earth resistance determines the effectiveness of the earthing system that was designed efficiently to dissipate fault currents or lightning to the earth safely. This will reduce the risk of electric shocks, equipment malfunctions, and fire as the voltage build-up in the electrical system is minimal. However, the surroundings of soil and environment associated with a nearby structure that is to be protected by the earthing systems are already predetermined by its soil resistivity. The surrounding soil of earthing systems deployed can be altered in terms of its soil material by soil conditioning, enhancing, or treatment. A practical approach to reducing the ground resistivity of an earthing rod is to use ERRAs (Hamzah et al., 2023; Sinchi-Sinchi et al., 2022). IEEE 81-2012, IEEE 80-2013, and International Electrotechnical Commission (IEC) 62561-7 permit the use of ERRAs for this purpose (IEC, 2011; IEEE, 2012, 2015). In the technical field, ERRAs play a key role in improving the efficiency of earthing systems by lowering the resistance between the earthing and the earth. The ERRA efficiency parameter is given by:

$$\eta = 1 - \frac{R_e}{R_r} \qquad [1]$$

where η represents the efficiency of an earthing electrode, R_e in reference to the earthing electrode, R_r. Higher η values portray higher efficiencies of the applied ERRA to the earthing system and vice versa, which in turn ensures dissipation of current in the case of fault, impulse, and stray currents that are significant in maintaining the safety and reliability of any electrical system (Androvitsaneas et al, 2017). Additionally, the parameter is crucial for engineers to evaluate the suitability of ERRAs in site-specific areas. In the economic sense, higher η values contribute towards cost savings in material and installation, maintenance reduction, space optimization, and infrastructure protection.

ERRAs can accommodate multiple earthing rods, earthing rod depth, and high soil resistivity in space-restricted areas. With increasing urbanization and population density (Patra et al., 2018), land becomes increasingly scarce; thus, a more sustainable approach to electrical earthing is required (Toh & Leong, 2023). This approach alters part of the earth of the surrounding earthing rod by replacing it with ERRAs to enhance its soil resistivity in favor of electrical earthing (IEEE, 2015). This means that the soil resistivity of the enhanced area will be lowered without too much land space being used as opposed to without ERRAs. Consequently, the earthing resistance of the associated earthing rod of a certain area will be lowered as well to a certain amount, depending on the efficiency of the ERRA used and the surrounding soil profile. As a result, a lower number of earthing electrodes is used to reach the low value of earthing resistance (IEEE, 2012). Areas where high resistivity of soil is prevalent are suitable for this kind of solution. One advantage of this method is that when dealing with soils that are hard for the electrodes to penetrate, such as in the study of Sinchi-Sinchi et al. (2022), the soil of the area can be altered with ERRAs that are generally easy for earthing electrodes to be driven in or, in some cases, installed horizontally depending on the soil profile.

Swileam et al. (2019) showed that the soil resistivity is unique to its own place. Various factors affect the soil resistivity at different depths and breadths, making it diverse at every point (Gerscovich & Vipulanandan, 2023). It is essential to recognize that failing to examine the soil profile carefully can lead to inaccuracies in ERRA studies or the design of earthing systems. A lot of assumptions and ambiguity are made this way, which gives a skewed interpretation of the soil profile. The study showed that there is a significant difference between the average and localized soil resistivity at different places, even at distances of 5 meters apart. Waste of potential soil space can also occur when the soil resistivity of an area can be utilized for an earthing system designed to go unnoticed in the area due to poor electrical resistivity surveying (Sinchi-Sinchi et al., 2022). Therefore, it is essential that before earthing systems are driven into the ground, their respective localized soil resistivity is determined so earthing arrangements can be designed as efficiently as possible.

At places where high soil resistivity is measured, alterations of the soil can be done efficiently in terms of cost and management, especially when there is limited space. As the depth of the soil increases, soil resistivity decreases (Lech et al., 2020), although this might not necessarily be the case. This information is critical for ERRA studies, as the alteration of the soil may only require treatment of the topsoil, depending on the soil profile, which is less costly. There has not been any standard procedure or proper methodology to test ERRAs in a soil area. Typical soil resistivity profile surveys are shown in Figure 1, which is a scattered soil resistivity measurement survey compared to a localized one. Figure 1 a) shows soil resistivity measurement to obtain the soil resistivity in several areas of the field. Figure 1 b) shows localized soil resistivity in a particular area. Figure 1 c) shows a soil resistivity survey in several localized areas. Localized soil resistivity surveys are done to see the relevant soil resistivity values across the row of earthing electrodes that are to be tested with the ERRAs. This approach is more effective than a scattered measurement for observing soil homogeneity.

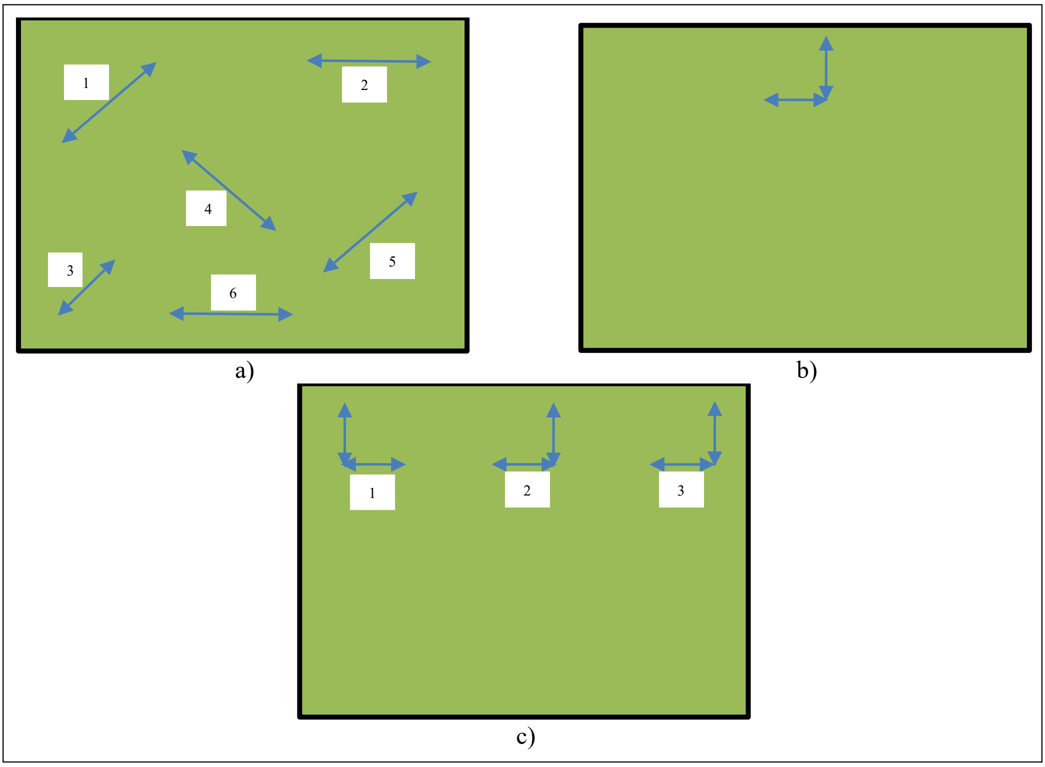

Figure 1. a) Average soil resistivity survey in a larger surface area at several spots of the field; b) Localized soil resistivity measurement in different directions of the field; and c) Localized soil resistivity in several areas of the same vertical plane
Note. The number of measurements in a particular space can vary

A soil resistivity survey is done to search for a high soil resistivity area for ERRA studies based on the horizontal and vertical profiling of the respective soil (Mostafa et al., 2018). Usually, the soil is assumed to be homogeneous across the whole field based on the survey, when this is highly unlikely due to having different soil structures across the soil bed (C. Chen et al., 2024; Zhang et al., 2019). A high soil resistivity field is suitable for this kind of study, as it would test the effectiveness of ERRAs in reducing the earth resistance of an earthing electrode driven into the earth. To see the resistance to earth of an electrode after the soil survey, a rod is usually driven at a place where it is suited to be the reference electrode, usually at a corner or end of a given field, such as in Figure 2. The rest of the earthing electrodes with ERRAs are deployed along the row initiated by the reference electrode. Most ERRA studies in the past have been evaluated based on one or two reference electrodes (Hamzah et al., 2023; S.-D. Chen et al., 2006; Wan Ahmad et al., 2018). An earthing electrode is usually placed at the start or end of a row of earthing with ERRAs, with the rest of the earthing electrodes enhanced with their respective ERRAs, as demonstrated in Figure 2. Most of the ERRA studies in the past have been done this way.

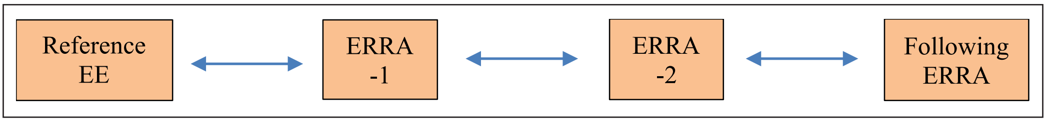

Figure 2. Typical earth resistance reduction agent (ERRA) study of row configuration placement with their respective earthing electrodes (EE)

Soil Inhomogeneity in ERRA Studies

The difference between the reduced earthing resistance of the earthing rod with ERRAs and the reference earthing is the efficiency of the ERRA in reducing earth resistance values. Fluctuation values over time are also a measure of the reliability of the ERRAs. Measurements are taken for an extended period at different frequencies to evaluate their performance in terms of fluctuation and earth resistance decrement. Androvitsaneas et al. (2012) studied the earth resistances of 5 earthing systems with ERRAs and introduced the efficiency factor to evaluate their performances for a period of one year. This is similar to the one used by L.-H. Chen et al. (2009) and S.-D. Chen et al. (2006), as mentioned in Trifunovic (2018). The ERRA efficiency formula is given in Equation 1.

The performances of their earthing systems were found not to be consistent throughout the one-year study but showed a decrease with respect to the reference earthing electrode. Though the efficiency factor proposed by Androvtsaneas et al. (2012) gives some insight into the performance of the earthing systems, the information that is obtained from the efficiency factor can be misleading and would only work for homogeneous soils in their horizontal lengths and vertical depths, which is highly improbable (Lech et al., 2020). This method is viable only if there is a certainty that for every electrode placed in the ground, it has the same or at least the same soil resistivity values, which is difficult to determine even with the aid of measuring the local soil resistivity, which will be demonstrated later. Hence, usually the soil resistivity is sought to determine the average soil resistivity around the area of interest. However, only determining the soil resistivity of a respective area may not suffice to interpret the homogeneity of the adopted soil if done in a scattered manner, as mentioned previously. The placement configuration done by S.-D. Chen et al. (2006) would be a more accurate kind of ERRA study since two earthing electrodes cover the area where the ERRA in their study are being tested. This testing configuration is shown in Figure 3. The earthing resistance values of the reference electrodes differed by a certain value in each periodic measurement, but not significantly.

Most of the studies have tested different ERRAs with their earthing electrode to be tested against the reference earthing. ERRAs can be of bentonite, marconite, and fly ash (Mohd Tadza et al., 2019). This means for every type of ERRA encased to one earthing electrode tested against the reference earthing, there will only be one earthing electrode with one kind of ERRA that is tested. If the soil is inhomogeneous to begin with, an incorrect account of their efficiencies will be displayed. This will be demonstrated in the results section, where three earthing electrodes with the same kind of ERRA are tested against a reference electrode, which was found to be different in efficiency levels.

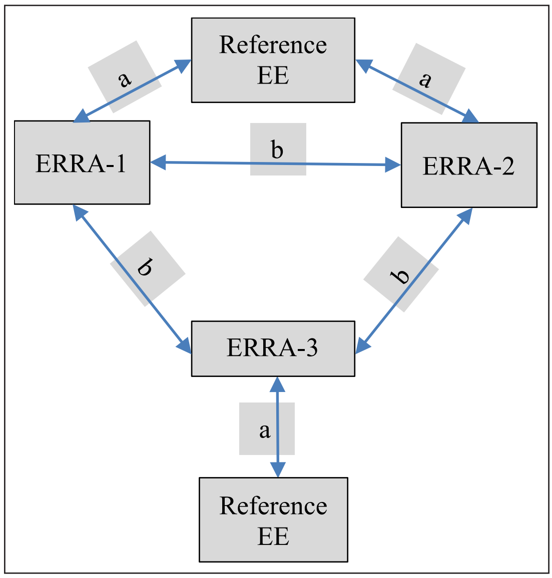

Figure 3. 2 Reference earthing covering the ERRA electrodes in between (Adopted from S.-D. Chen et al., 2006)
Note. EE = Earthing electrode; ERRA = Earth resistance reduction agent; a = Distance between tested reference earthing and tested earthing electrode; b = Distance between tested earthing electrodes

METHODOLOGY

The ERRA studies typically begin by determining the average soil resistivity of an area. High soil resistivity areas are preferable to see the extent of the effectiveness of ERRAs in decreasing earth resistance values. To demonstrate that ERRA studies can be inaccurate without taking proactive measures in inhomogeneous soils, copper-bonded earthing electrodes of dimensions shown in Figure 4 were installed at eight different locations in the same field, as seen in Figures 5 and 6. In Figure 4, the reference earthing is simply the tested earthing conductor with the native soil, while the industrial earthing system is encased with the industrial ERRA.

The distances of 7 m and 9 m in Figure 6 were chosen based on the site-specific limitations due to restricted space in the area, so the earthing electrodes can be spread as far as possible to evaluate the variety of the earthing resistance soil profile of the area using the eight earthing electrodes. The standards also suggest that the distances between electrodes should be at least equal to their length to avoid electrical interference, where the distances are at least 4.7 times their earthing electrode length (IEEE, 2000). The earthing electrodes

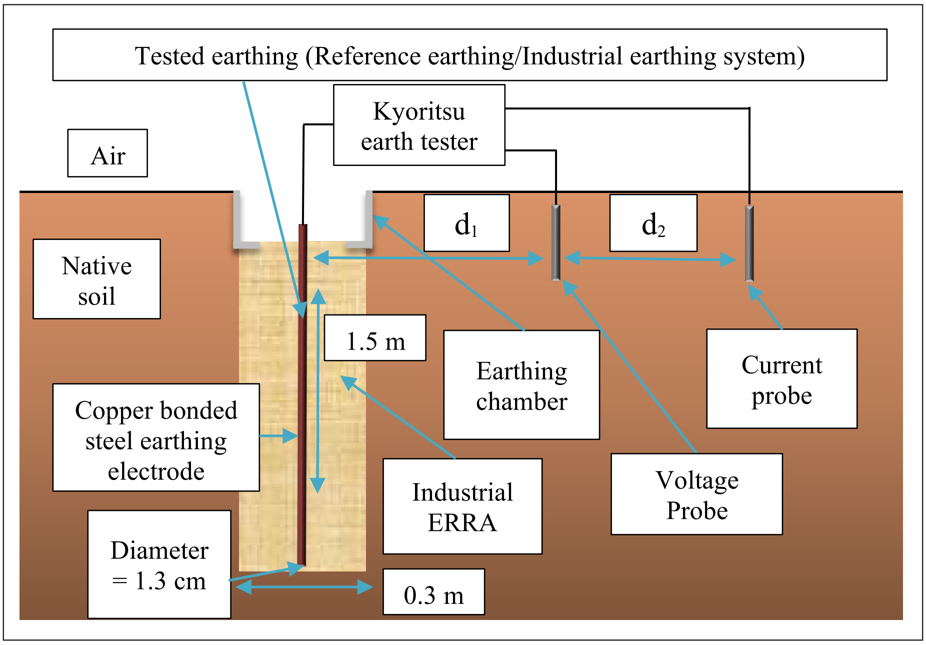

Figure 4. Dimensions of earthing electrodes in the experiment and measuring earthing electrode resistance
Note.
d_1 = The distance from the tested earthing electrode to the voltage probe
d_2 = The distance from the voltage probe to the current probe
ERRA = Earth resistance reduction agent

Figure 5. One of the untreated earthing electrodes (EE-3)

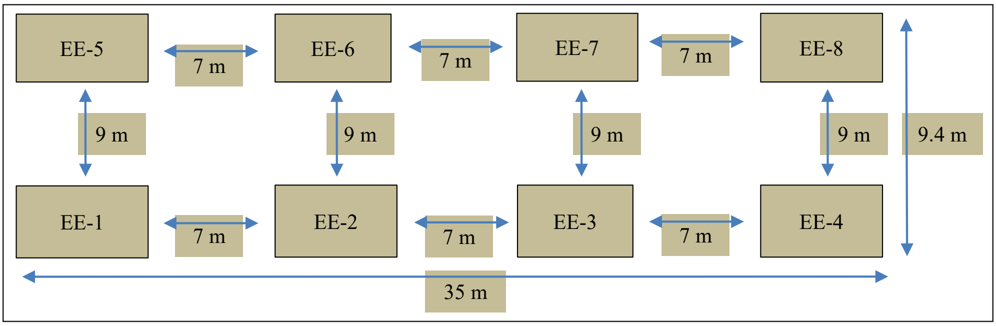

Figure 6. Untreated earthing electrode (EE) placement in the same field (aerial view)

in the field are untreated with any ERRA, which means the earthing resistances are of the native soil. Average soil resistivity values were also measured at a depth of 2 m for a period of a year using the Megger soil resistivity tester (United Kingdom). Earth resistances were measured using the fall-of-potential method for a duration of 19 weeks every other week (second week of every two weeks) using the Kyoritsu earthing measurement tester (Japan) as shown in Figure 4 using the fall-of-potential method. All measurements were taken according to the IEEE 80-2013 and IEEE 81-2012 standards, where Ohm's Law (V = IR) is used to calculate earthing resistance, which is computed in the Kyoritsu earth resistivity tester. The efficiency of ERRAs is computed using Equation 1.

Another earthing system was deployed in a different location within the premises of Universiti Putra Malaysia (UPM), and it will also be considered in this study. They include the industrial earthing systems that were deployed in a high soil resistivity area, which can be seen in Figures 7 and 8. The ERRA that is used in this study is an industrial-grade material named Earth-Enhancing Material (EEM)-10. This separate study tests a reference earth and three earthing electrodes, fully encased with EEM-10. The dimension of the configuration is given in Figure 4. Soil resistivity measurements were also taken in the respective local earthing of 1 meter and 2 meters depth, as given in Table 1, to see the inhomogeneity of the soil.

Table 1
Performance of industrial earth resistance reduction agent (ERRA) in inhomogeneous soil of treated earth

Earthing electrode	**Average (Ω)**	**Fluctuations (Ω)**	**Average drop (%)**	**Respective soil resistivity**	
				1 meter (Ω-m)	**2 meters (Ω-m)**
Reference electrode	617.33	72.65	-	1650.91	907.92
Industrial ERRA-1	178.91	21.93	71.01	1883.38	818.38
Industrial ERRA-2	163.75	19.85	74.47	1690.18	783.83
Industrial ERRA-3	148.23	16.85	75.99	1529.96	753.98

Note. Fluctuation is categorized by standard deviation

Figure 7. An industrial earth resistance reduction agent earthing (treated earthing)

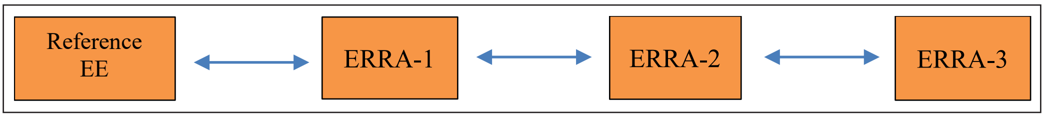

Figure 8. Industrial earth resistance reduction agent (ERRA) configuration (treated earthing electrodes)

RESULTS AND DISCUSSION

Earth Resistance in Inhomogeneous Soil with Untreated Earth

As can be seen in Table 2 in relation to Figure 6, the earthing resistance values are not consistent, given that they are in the same field and untreated with ERRAs. An ideal earth resistance value for ERRA studies should be around the values of EE-1 or EE-5 for reference earthing placed in the field due to their high values compared to the tested electrodes (EE-2, EE-3, EE-4, EE-6, EE-7, and EE-8). The average earthing resistances for Earthing 1 to 8 were found to be 127.90, 45, 46.26, 35.84, 115.11, 51.95, 60.95, and 41.16 Ω, respectively, as can be seen in Figure 9. The results almost imitate an ERRA study, where EE-2, EE-3, EE-4, EE-6, EE-7, and EE-8 are seen to be lowered with respect to EE-1 and EE-5 of their respective rows when none of the EEs are treated with ERRAs. The highest and lowest average earth resistances are found from EE-1 and EE-4, having values of 127.90 and 35.84 Ω, respectively. It is clear from the measurements made that there is a variety of earthing resistance values that indicate soil inhomogeneity. This is as stated in IEEE STD81-2012, where driving earthing electrodes is indicative of the soil resistivity of a particular area along a lateral plane of the soil. Due to the soil texture and structures, various soil resistivity values exist (Gerscovich & Vipulanandan, 2023).

Table 2
Earth resistance and localized equivalent soil resistivity of each earthing electrode

Earthing electrode number	Average (Ω)	Standard deviation (Ω)	Localized equivalent soil resistivity (Ω-m)
1	127.89	12.77	206.85
2	45	4.61	72.78
3	46.26	0.99	74.82
4	35.84	0.9	57.97
5	115.11	6.26	186.18
6	51.95	4.13	84.03
7	60.95	2.48	98.58
8	41.16	1.64	66.57

Using soil resistivity (Equation 2), the localized equivalent soil resistivity for the respective earthing electrode can be deduced as in Table 2 (IEEE 81-2012) to see the soil resistivity variation.

$$\rho_{eq} = \frac{2\pi RL}{\left[\ln\left(\frac{8L}{d}\right) - 1\right]} \qquad [2]$$

where ρ_{eq} represents the equivalent soil resistivity, R is the measured earthing resistance, L is the length of the electrode, and d is the electrode's diameter.

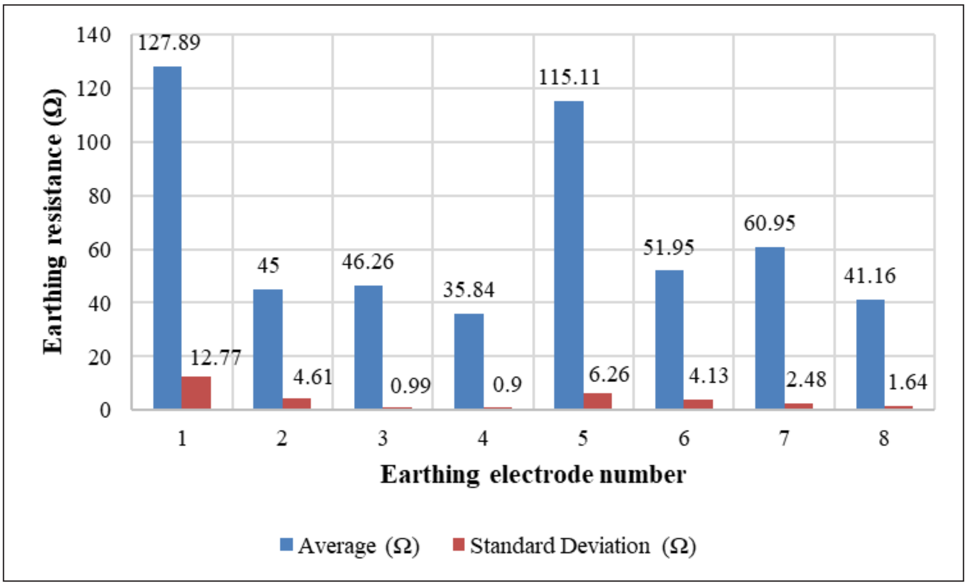

Figure 9. Variation of earthing resistances of untreated earthing electrodes on the same plane

As can be seen in Table 2, the localized soil resistivity varies depending on the area, as depicted in Figure 6, and its respective earth resistance electrodes. Figure 9 shows a comparison of the average earthing resistance, accompanied by its standard deviation, of the earthing electrodes in the field. Less deviation is seen in lower value earthing resistances from Table 2, which indicates that lower soil resistivity values are more likely to fluctuate less in earth resistance value with respect to time. This is highly important because earthing systems should be more stable in terms of fluctuation values. High fluctuation of earthing resistance values over time may indicate underlying problems such as soil moisture variations, corrosion or degradation of the electrodes, or loose connections.

When finding a reference electrode for an ERRA study, if the assumption is made based on the average soil resistivity and EE-1 as the reference, then EE-2, EE-3, and EE-4 would also be assumed to have about the same average earth resistance values as EE-1. The measured earth resistance values of EE-2, EE-3, and EE-4 have proved that this is not the case. The same would be for the case of EE-5 and the rest of its row. In this scenario, if ERRAs were installed in EE-2, EE-3, or EE-4 while having EE-1 as the reference, the percentage drop with the effect of ERRAs would be determined with the aid of the soil surroundings of the respective earthing electrodes. This will pose an inaccurate account of ERRA accuracy regarding the earth resistance drop. Also, if ERRAs were installed in areas where the earthing resistance was already lowered to begin with, it would be a waste of ERRA in practical terms. This is because if a reduction of earthing resistance were to happen to these local earthing electrode areas, there would only be a minor to no reduction. Hence, applying ERRAs in these areas would be an inefficient earthing system design in terms of estimating the efficiency of an ERRA.

The other scenario would be that when EE-4 or EE-8 is sought first as the reference, the earthing electrode value is already lowered due to the soil environment encasing their respective earthing electrode. This poses the problem of needing to remove the earthing electrode, as it is not suitable to be a reference electrode. However, it does provide an indication of whether an ERRA study is viable in the area. This also provides vital information that soil resistivity values are not enough to determine if an area is suitable for an ERRA study. This proves qualitatively that soils in this area of study are inherently inhomogeneous and not suitable for ERRA studies. However, in the case of real earthing applications, only earthing electrodes numbers 1 and 5 need to be treated with ERRAs. Hence, it is proven that inhomogeneous soils are not suitable for ERRA studies, where incorrect assumptions on the soil profile will lead to inaccuracy of the study.

Using information on the soil profile of the area, if the area is needed to be used to install an earthing system, only EE-1 and EE-5 may need ERRAs to reduce their earth resistance. The soil profile indicates that there is a soil inhomogeneity case that the designer of the earthing system can utilize. There is a decrease in soil resistivity value in horizontal and vertical directions, as indicated in Figure 9 (horizontal decrease in the downward direction) and Table 2 (vertical decrease in the right direction). The earthing system can then be installed by connecting all the earthing electrodes present in the area to achieve the earthing resistance desired by the standard of around 1-10 Ω (IEEE, 2015). The area where lower earth resistance values are found may indicate that the area is high in moisture, and vice versa.

Figure 10 shows the 3D surface plot of the earthing resistance across electrode positions. The figure gives a better representation of the variability of earthing resistance across the plane. Using the coefficient of variability (*CV*) formula:

$$CV = \frac{\sigma}{\mu} \times 100\% \qquad [3]$$

where σ and μ are the standard deviation and mean values of the untreated earthing resistance. The *CV* was found to be 54.18%, indicating that there is high variability of

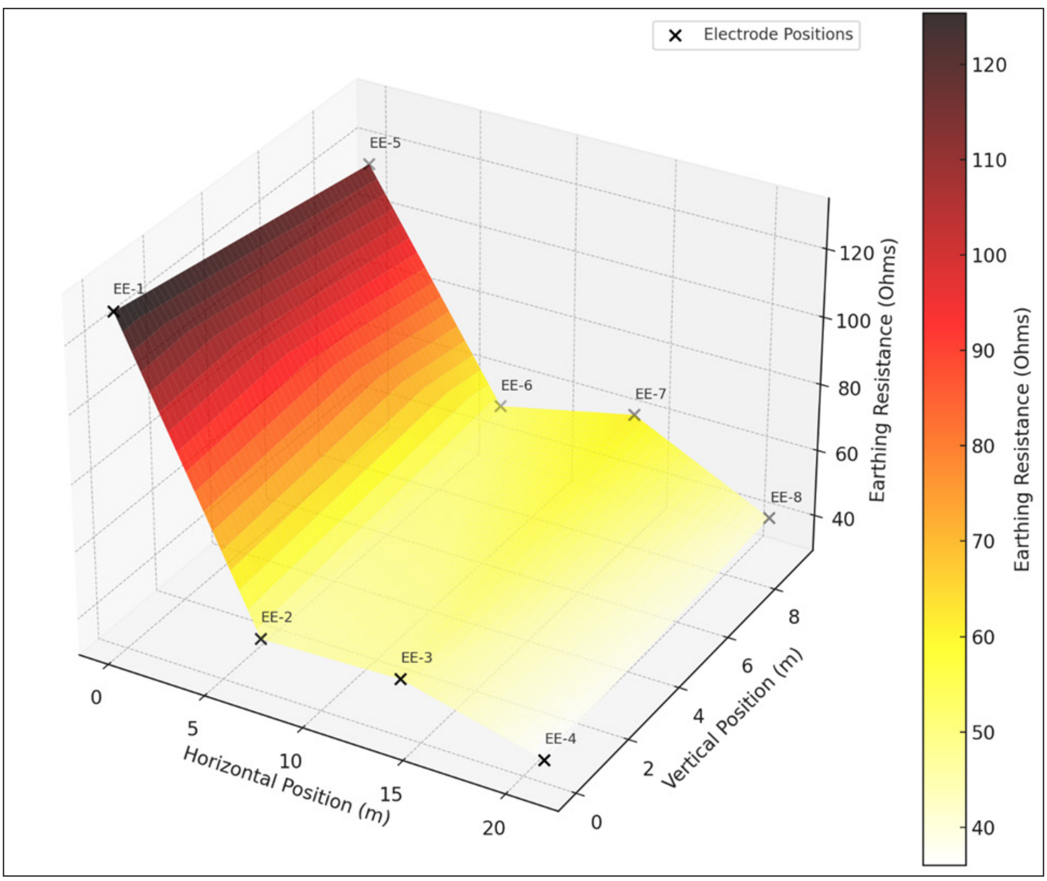

Figure 10. The 3D plot of untreated earthing electrodes (EE)

earthing resistance in the soil. From the figure, there is a very noticeable difference in soil variability, which reflects the inhomogeneity of the soil profile in the area. The darker regions (e.g., EE-1 and EE-5), where earthing resistance is higher, could indicate that there is lower moisture and salinity. However, brighter regions (e.g., EE-2, 3, 4 and EE-6, 7, 8) of the 3D plot show less variety with lower earthing resistance values, indicating higher levels of moisture and salinity. These variations of earthing resistance show that if ERRAs are to be tested in this region, the underlying resistivity variations may appear distorted than their actual value.

Earth Resistance in Inhomogeneous Soil of Treated Earth

In a separate study to see the earth resistance of industrial ERRA in a slightly inhomogeneous soil, the *CV* was found to be 9.38% using Equation 3. The variability calculation only included industrial earthing 1, 2, and 3, as they are the only ones treated with ERRAs. Table 1 and Figure 11 show the performance of the industrial ERRA done in a separate field. An ideal ERRA study would have a significant percentage drop regarding the reference electrode, as demonstrated in Figure 11. The ERRA efficiency is computed using Equation 1. The average earth resistances for the reference electrode, Industrial ERRA-1, Industrial ERRA-2, and Industrial ERRA-3 are 617.33, 178.91, 163.75, and 148.23 Ω, respectively. The average percentage drop of Industrial ERRA-1, Industrial ERRA-2, and Industrial ERRA-3 based on the reference drop is 71.01, 74.47, and 75.99%, respectively. Although the ERRAs installed at the respective electrodes are of the same type and similar amount, there is a slight percentage difference in the average drop.

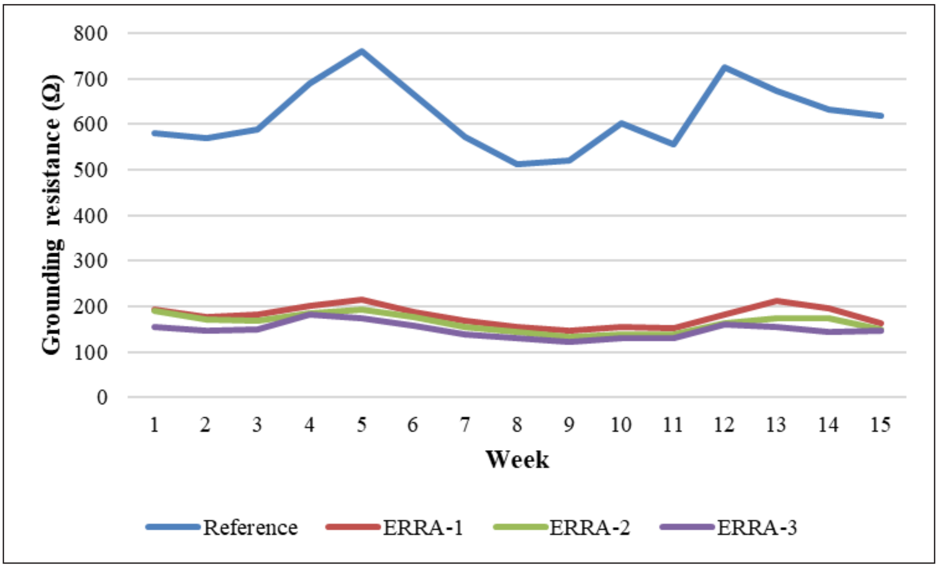

Figure 11. Performance of industrial earth resistance reduction agents (ERRAs)

This section of the study suggests that a perfectly homogeneous soil is impossible to achieve when the localized soil resistivity values slightly differ from one point to another. The reference, Industrial ERRA-1, Industrial ERRA-2, Industrial ERRA-3, and Industrial ERRA-4 soil resistivity measurements show the values of 1650.91, 1883.38, 1690.18, and 1529.96 Ω-m for 1 meter depth, and 907.92, 818.38, 783.83, and 753.98 Ω-m, respectively. This shows that the localized soil resistivity of each earthing electrode varies slightly from one another, which will result in different performances of the industrial ERRA with respect to their localized soil. This part of the study demonstrates that there is a variation in earthing resistance value, although the same ERRA was deployed to the three tested earthing electrodes. The surrounding soil resistivity plays a role in determining the final value of the earthing electrode displayed in Table 1.

Recommendations for Improved Accuracy of ERRA Studies

As shown in the results and discussion section, it is evident that ERRA studies may lead to inaccurate results if proper inspection is not done beforehand**.** It is evident from the results and literature that soils are inhomogeneous across the soil bed (Zhang et al., 2019). As a result, the earth resistance of earthing electrodes will vary depending on the surrounding soil that it is encased in. Thus, soil resistivity measurements should be taken accurately across the soil bed to reduce the inaccuracies of the ERRA studies. Depending on the soil profile, different configurations can be adopted for the ERRA study if precise and sufficient measurements are made. The row configuration, which is the conventional way, can be used if the soil resistivity survey shows a good sign. The experimental study or real-world applications of electrical earthing are site-specific and may require different approaches for optimal outcomes. Since it is almost impossible to attain a perfectly homogeneous soil, the ERRA studies will have to depend on the information obtained from the soil profile data.

It is recommended that the soil resistivity measurement be done specifically where the earthing electrode is going to be driven. This will give more confidence in deploying the earthing electrodes that are to be tested with their respective ERRA. While it may be more challenging, the expected outcome is going to be more precise and accurate. Regular monitoring is crucial to observe the fluctuations in values represented by the standard deviation value over time. An increase in standard deviation values over time may indicate that the integrity of the installed earthing electrode or system has been compromised. Thus, it is important that an effective earthing system has a low earthing resistance value according to the standard and can maintain this value for long periods of time.

Practical and Environmental Implications of Installing Earthing Systems

As there are practical implications of soil homogeneity in designing the electrical earthing system, the engineer must do an extensive soil resistivity survey and analysis to minimize the time and effort required to install the earthing system. There are various considerations to be made that will provide the engineer with information to ease the process of designing and installing the earthing system. The engineer must be able to determine if the earthing system electrodes should be installed vertically, horizontally, or a combination of both, depending on the soil profile (IEC, 2002). Thus, engineers must also have environmental and geotechnical insights into the surrounding environment. This is highly important, especially when the cost of excavation of the soil is high. The soil profile does not consist only of the soil resistivity value, but also other signs of the nature of the surrounding soil. For instance, a high resistivity value measured at a depth of meters may indicate the presence of bedrock (Ward et al., 2014). Hence, it may not be viable to install the earthing system vertically in that area. Installing the earthing system horizontally may be a better option depending on the allowable space. However, in certain cases where the area is restricted, soil modifications (ERRAs) are needed to lower the soil resistivity.

Soil resistivity can also indicate if there is underground water at the bottom. Soils that are saturated with water have low soil resistivity as the soil is more conductive. Sudden changes to very low resistivity after certain depths indicate that groundwater is available (X. Chen et al., 2022). Thus, the electrical earthing engineering installation team may use this to their advantage. Longer earthing rods or conductors can be driven relatively more easily into the soil area, due to the low resistivity and softness of the soil compared to dry soils.

Soil resistivity can provide many indicators of the soil. Electrical engineers can use these markers to their advantage to save costs when designing earthing systems, as mentioned above. However, regarding the testing of ERRAs, the person in charge of the study must find a location that can accommodate these tests, as this will be vital to assess the performance of the ERRA. Hence, careful investigation of the soil profile must be done before accommodating for a slight difference in soil resistivity values of the tested earthing electrodes.

Another consideration that engineers may overlook is the electrical contact that the driven electrode has with the soil. There have been reports that electrodes encased with bentonite can shrink due to dry conditions (Mohd Tadza et al., 2019). This, in turn, results in decreased electrical contact with the associated electrode to the bentonite aggregate, which results in higher earth resistance. Soil erosion may occur in areas where the soil is sandy and high in water displacement. This can also result in reduced electrical contact of the earthing electrode with the associated soil, which increases the earthing resistance of the overall earthing system. Hence, it is appropriate that regular earth resistance measurement is made to maintain the integrity of the earthing system and make proper adjustments.

CONCLUSION AND RECOMMENDATIONS

The soil resistivity variability in inhomogeneous soil is impactful in determining the ERRA experiments. The nature of soil is different in terms of environmental conditions, soil composition, moisture content, and other factors. This can result in inaccurate assessments, which may lead to inefficient earthing systems being developed and increase safety risks.

This paper has demonstrated that an ERRA study can be misleading due to the wrong estimation of the soil resistivity profile around the soil bed that is being tested. Soil resistivity values can also give misleading interpretations of the earth resistance that an earthing rod can have after being driven into an earth area due to wrong assumptions. The information obtained in this study can be used as a guide to develop earthing systems with greater efficiency in terms of soil resistivity. This measure will save costs on electrode and land usage, which is another problem that arises.

It is proposed that ERRA studies deploy more than 1 reference earthing (of about 4-5) to each zone related to the tested earthing electrode with ERRA, if it is done using the row configuration at the allowable distance according to the standards. This is especially when there are a lot of ERRAs to be studied for their performances as depicted in Figure 3. More than 1 reference earthing allows for more accuracy of the baseline reference earthing value. This will allow for diverse soil conditions (a variety of earth resistance or soil resistivity values) to be standardized, ensuring that reference earthing results are generalized and consistent in baseline readings. Multiple reference earthing can capture the earth resistance variability of the soil profile of concern wherever it is deployed. Hence, a controlled environment consisting of multiple earthing reference electrodes should be considered for better accuracy in determining the efficiency of ERRAs.

ACKNOWLEDGEMENTS

We would like to extend our deepest gratitude to Prof. Ir. Dr. Ts. Mohd Zainal Abidin Ab Kadir and Dr. Shafreeza Sobri for their invaluable knowledge and guidance throughout this research. Their insights have significantly contributed to the successful completion of this paper. Our sincere thanks also go to Prof. Dr. Chandima Gomes for both his extensive knowledge and generous financial support. His contributions have been crucial to the advancement of this research. Lastly, we are grateful to Assoc. Prof. Dr. Syahrun Nizam Md Arshad Hashim for his meticulous review and constructive feedback on the manuscript, ensuring the rigor and clarity of our work.

REFERENCES

Al-Shawesh, Y., Lim, S. C., & Nujaim, M. (2021). Analysis of the design calculations for electrical earthing systems. *International Review of Electrical Engineering*, *16*(2), 104–117. https://doi.org/10.15866/iree.v16i2.16839

Androvitsaneas, V. P., Gonos, I. F., & Stathopulos, I. A. (2012). Performance of ground enhancing compounds during the year. In *International Conference on Lightning Protection* (pp. 1–5). IEEE. https://doi.org/10.1109/iclp.2012.6344356

Androvitsaneas, V. P., Gonos, I. F., & Stathopulos, I. A. (2017). Research and applications of ground enhancing compounds in grounding systems. *IET Generation, Transmission and Distribution*, *11*(13), 3195–3437. https://doi.org/10.1049/iet-gtd.2017.0233

Chen, C., Yang, Z., Deng, Y., Ma, H., & Qian, J. (2024). Experimental investigation of thawing behavior of saline soils using resistivity method. *Journal of Geophysics and Engineering*, *21*(3), 854-867. https://doi.org/10.1093/jge/gxae037

Chen, L.-H., Chen, J.-F., Liang, T.-J., & Wang, W.-I. (2009). A research on used quantity of ground resistance reduction agent for ground systems. *European Transactions on Electrical Power*, *20*(4), 408–421. https://doi.org/10.1002/etep.322

Chen, S.-D., Chen, L.-H., Cheng, C.-K., & Chen, J.-F. (2006). An experimental study on the electrical properties of fly ash in the grounding system. *International Journal of Emerging Electric Power Systems*, *7*(2). https://doi.org/10.2202/1553-779x.1284

Chen, X., Guo, Z., Liu, C., Liu, J., & Wu, Q. (2022). Groundwater detection using the pseudo-3D resistivity method: A history of case studies. *Applied Sciences*, *12*(13), 6788. https://doi.org/10.3390/app12136788

Dilushani, P. D. R., Nawodani, W. R. N., Bambaravanage, T., & Udayakumar, K. A. C. (2020). Soil resistivity analysis and earth electrode resistance determination. *IOSR Journal of Electrical and Electronics Engineering*, *15*(2), 26–35.

Gerscovich, D. M. S., & Vipulanandan, C. (2023). Data analyses to correlate the soil properties to the electrical resistivity. *Geotechnical and Geological Engineering*, *41*, 4507–4528. https://doi.org/10.1007/s10706-023-02529-y

Hamzah, M. N., Gomes, C., Afiq, M., & Ab Kadir, M. Z. A. (2023). Performance of active electrical earthing systems: Results and discussion. In *12th Asia-Pacific International Conference on Lightning* (pp. 12–15). IEEE. https://doi.org/10.1109/APL57308.2023.10182183

Institute of Electrical and Electronics Engineers. (2000). *IEEE guide for safety in AC substation grounding*. IEEE. https://doi.org/10.1109/IEEESTD.2000.91902

Institute of Electrical and Electronics Engineers. (2012). *IEEE guide for measuring earth resistivity, ground impedance, and earth surface potentials of a grounding system*. IEEE. https://doi.org/10.1109/IEEESTD.2012.6392181

Institute of Electrical and Electronics Engineers. (2015). *IEEE guide for safety in AC substation grounding*. IEEE. https://doi.org/10.1109/IEEESTD.2015.7109078

International Electrotechnical Commission. (2002). *IEC 60364-5-54: Electrical installations of buildings – Part 5-54: Selection and erection of electrical equipment – Earthing arrangements, protective conductors and protective bonding conductors*. IEC.

International Electrotechnical Commission. (2011). *IEC 62561-7: Lightning protection – Part 7: Requirements for earthing installations and measures for protection against electrical shock* (3rd ed.). IEC.

Lech, M., Skutnik, Z., Bajda, M., & Markowska-Lech, K. (2020). Applications of electrical resistivity surveys in solving selected geotechnical and environmental problems. *Applied Sciences*, *10*(7), 2263. https://doi.org/10.3390/app10072263

Mohamad Nasir, N. A. F., Ab Kadir, M. Z. A., Osman, M., Abd Rahman, M. S., Ungku Amirulddin, U. A., Mohd Nasir, M. S., Zaini, N. H., & Nik Ali, N. H. (2021). Influence of lightning current parameters and earthing system designs on tower footing impedance of 500 kV lines. *Energies*, *14*(16), 4736. https://doi.org/10.3390/en14164736

Mohd Tadza, M. Y., Mohamad, D., Tripathy, S., Rahman, R. A., & Ismail, M. A. M. (2019). Bentonite and marconite for electrical grounding applications from geotechnical engineering perspective. In *AIP Conference Proceedings* (Vol. 2129, No. 1, p. 020078). AIP Publishing. https://doi.org/10.1063/1.5118086

Mostafa, M., Anwar, M. B., & Radwan, A. (2018). Application of electrical resistivity measurement as quality control test for calcareous soil. *HBRC Journal*, *14*(3), 379–384. https://doi.org/10.1016/j.hbrcj.2017.07.001

Patra, S., Sahoo, S., Mishra, P., & Mahapatra, S. C. (2018). Impacts of urbanization on land use/cover changes and its probable implications on local climate and groundwater level. *Journal of Urban Management*, *7*(2), 70–84. https://doi.org/10.1016/j.jum.2018.04.006

Sinchi-Sinchi, F., Coronel-Naranjo, C., Barragán-Escandón, A., & Quizhpi-Palomeque, F. (2022). Soil treatment to reduce grounding resistance by applying low-resistivity material (LRM) implemented in different grounding systems configurations and in soils with different resistivities. *Applied Sciences*, *12*(9), 4788. https://doi.org/10.3390/app12094788

Swileam, G. S., Shahin, R. R., Nasr, H. M., & Essa, K. S. (2019). Spatial variability assessment of Nile alluvial soils using electrical resistivity technique. *Eurasian Journal of Soil Science*, *8*(2), 110–117. https://doi.org/10.18393/ejss.528851

Toh, L. S., & Leong, K. W. (2023). Foundation earthing system – Its application and electrical safety considerations. *IEM Journal*, *83*(1). https://doi.org/10.54552/v83i1.172

Trifunovic, J. (2018). A mathematical method for determining optimal quantity of backfill materials used for grounding resistance reduction. *Mathematical Problems in Engineering*, *2018*, 4863702. https://doi.org/10.1155/2018/4863702

Wan Ahmad, W. F. H., Lai, W. L., Jasni, J., & Ab-Kadir, M. Z. A. (2018). Variations of soil resistivity values due to grounding system installations with natural enhancement material mixtures. In *34th International Conference on Lightning Protection* (pp. 1-5). IEEE. https://doi.org/10.1109/iclp.2018.8503373

Ward, W. O. C., Wilkinson, P. B., Chambers, J. E., Oxby, L. S., & Bai, L. (2014). Distribution-based fuzzy clustering of electrical resistivity tomography images for interface detection. *Geophysical Journal International*, *197*(1), 310–321. https://doi.org/10.1093/gji/ggu006

Zhang, Z., Dan, Y., Zou, J., Liu, G., Gao, C., & Li, Y. (2019). Research on discharging current distribution of grounding electrodes. *IEEE Access*, *7*, 59287–59298. https://doi.org/10.1109/access.2019.2914058