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Comparing horizontal versus vertical arrangement on the ground resistance values

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ABSTRACT

It is important to compare the horizontal electrodes versus vertical ground electrodes particularly when there is limited area to extend the horizontal ground electrode and hard soil at the deeper soil in order to install the vertical rod electrode. Although all of these can be assessed by computational work, much work has shown that computed resistance values are different than measured resistance values and these computational softwares are not always available to the users. For these reasons, the aim of this paper is to address this shortfall by considering two sites with two-layer soil resistivity model where site 1 with upper layer higher than the lower layer and vice versa for site 2. For the same size of ground electrodes, vertical arrangement is found to have lower ground resistance values, despite higher soil resistivity at the lower layer soil. Soil compaction after backfilling the trench during the installation of horizontal electrode has been identified as the main factor that contributes to differences between the measured and computed resistance values.

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1. INTRODUCTION

A grounding system prevents severe damage to power system equipment and injury to persons by providing a path of low resistance for the fault current to effectively discharge into the ground. A low ground resistance value can be obtained by having a low soil resistivity and by increasing the cross sectional area of the ground electrodes. As mentioned in IEEE Standard 80 [1], field data which includes the soil resistivity measurements and determination of the soil resistivity profile is the first step that needs to be assessed in the design of ground grid. As the soil is inhomogeneous in nature, and the soil resistivity varies laterally and longitudally, a few soil resistivity models have been proposed whereby a uniform soil model is suggested for a little variation in apparent resistivity, while a 2-layer and multi-layer soil models can be considered in large variation of apparent soil resistivity and more complex soil profiles. As the uniform soil is normally represented as an average of the soil resistivity values measured along lateral distances [1], several computational softwares and analytical methods can be found in literature [2]–[8] to represent the soil profile into 2-layer and multi-layer soil models to provide close approximation of the actual soil. In this work, 2-layer soil model is interpreted with current distribution, electromagnetic fields, grounding and soil structure analysis (CDEGS) is used.

Another important parameter that needs to be considered in the design of a ground grid is the ground electrode's size and configurations whereby various formulas have been suggested in literature and standards [1], [9]–[13] on the use of different ground electrode's size and configurations. In general, the larger the cross sectional area, the lower is the ground resistance value. However, for the same size of ground electrodes, it is not clear whether the vertical or horizontal electrode's arrangement is the contributing factor towards lower ground resistance value, particularly in two-soil layers. By general rule of thumb, for two-layer soil model, if the larger part of the electrode installed in the soil layer that has low resistivity, lower resistance value would be expected, since more contact area with the low resistivity results. The results in this present study are found to be in a contrary for horizontal rod electrodes; despite a large part of horizontal ground electrode installed in low resisitivy soil, R_{DC} of horizontal electrode is found to be higher than that of vertical electrode which has large contact area in high resistivity soil. The percentage of resistance reduction when vertical and horizontal electrodes used are also found to be different. Although a study has been carried out in [14] on the effectiveness of ground electrodes in 2-layer soil model, the work is performed only by computational approach, whereby the soil resistivity of two layers has an extreme difference by 100%. They [14] found that percentage reduction as the number of electrodes is increased is higher in vertical than the horizontal electrodes. As the work in comparing the horizontal and vertical rod electrodes by measurement method is found to be limited as well as to provide some considerations for power engineers to consider electrodes would provide a good design, this current paper presents the results of the resistance values of these two types of electrodes; horizontal and vertical ground electrodes.

In the design procedure of grounding systems [1], the resistance value of the ground electrode, R_{DC} is computed, whereby this parameter is then used to calculate other important parameters, i.e., touch and step voltages. It is therefore important to obtain close results between the computed and measured R_{DC} values, so that other parameters are correctly represented. Several reasons have been identified in [1] on the expected differences between the measured and computed result, among which are limitations in the equations, soil interpretation which may not be accurate and presence of metallic structure buried at the vicinity to the grounding systems. Despite these reasons, no specific study has been carried out on these differences, particularly looking at the soil properties and the way the ground electrodes are installed. In this paper, CDEGS is utilised to compute the R_{DC} values, whereby these computed R_{DC} values are then compared to the measured R_{DC} values. Differences between the measured and computed R_{DC} values are noted, whereby higher percentage differences between the measured and computed are seen in horizontal ground electrode than the vertical ground electrode for the two sites. This shows that a more careful consideration in the design of grounding systems, particularly for the horizontal ground electrode and high soil resistivity needs to be given as the computed results may vary significantly than the measured ground resistance value, hence appreciably give inaccurate design that would lead to high potentials at and around the vicinity of the ground electrodes.

In summary, this paper is aimed to identify the best installation (whether horizontal or vertical) for the same size of ground electrode that gives a low resistance value of grounding systems and to determine the percentage difference between the measured and computed resistance values, as the percentage differences are found to be dependent on the types of installation and the soil resistivity. This study would be useful to power engineers in deciding whether the horizontal or vertical installation shall be adopted for different soil resistivity. In this work, vertical arrangement is found to have lower ground resistance than the horizontal arrangement, regardless of the soil resistivity. On the other hand, the percentage difference between the measured and calculated R_{DC} values are found to be dependent on the types of installation and soil resistivity; larger percentage differences between measured and calculated R_{DC} in horizontal electrodes installed at site of high soil resistivity. This paper is subsectioned into experimental arrangement which includes the ground electrodes configurations and installation, soil resistivity and ground resistance measurements and test results and computer simulation part in which the interpretation of soil resisitivity of two sites are presented. Finally, the result analysis is discussed in the conclusions section.

2. EXPERIMENTAL ARRANGEMENT

2.1. Field sites

Two sites are selected to perform field measurement tests. The chosen sites are located in the university's area, as shown in Figures 1(a) and (b), respectively for site (a) and (b). Soil resistivity tests are performed at both sites by the Wenner method [1], whereby several traverses, as shown in the figures are laid around the site. Averaged soil resistivity data obtained from these several traverses are keyed into RESAP module of CDEGS. The soil resistivity data consists of the soil resistivity values for different spacing of the probes used during the measurements. In this model, the soil resistivity profile is interpreted into a 2-layer soil models, defining the soil resistivity of upper layer, ρ_1 and soil resistivity of lower layer, ρ_2, and the height of the upper layer, h_1 with the height of the lower layer, h_2 is an infinite. These sites are selected to provide variation in the soil resistivity profile, whereby one site is having higher soil resistivity at the upper soil layer, ρ_1 than the lower layer, ρ_2 meanwhile another site is having higher soil resistivity at the lower layer, ρ_2 than the upper layer, ρ_1.

(a)

(b)

Figure 1. Images of the selected sites obtained from the google map; (a) site (a) and (b) site (b)

2.2. Ground electrodes

In order to provide a fair comparison between the vertical and horizontal electrodes installed, the same ground electrodes, each one having a diameter of 16 mm and a length of 1.5 m are used. Figures 2(a) to (d) show the vertical rod arrangement, whereby the same electrodes are arranged horizontally for the horizontal arrangement. The ground electrodes are defined as V1, V2, V3, and V4 respectively for single, two, three and four rod electrodes arranged vertically, and H1, H2, H3, and H4 respectively for single, two, three and four rod electrodes arranged horizontally. Examples of its installation at site are shown respectively in Figures 3(a) and (b) for vertical and horizontal electrodes, in which the trench is formed for the installation of horizontal electrodes and the vertical rod electrodes are driven into the soil by hammering. A coupler is used to extend the electrodes to a longer length. All of these electrodes are installed below 300 mm under the ground's surface. Fall-of-potential method, is utilised to measure the ground resistance value for each configuration, with the results are presented in the next section.

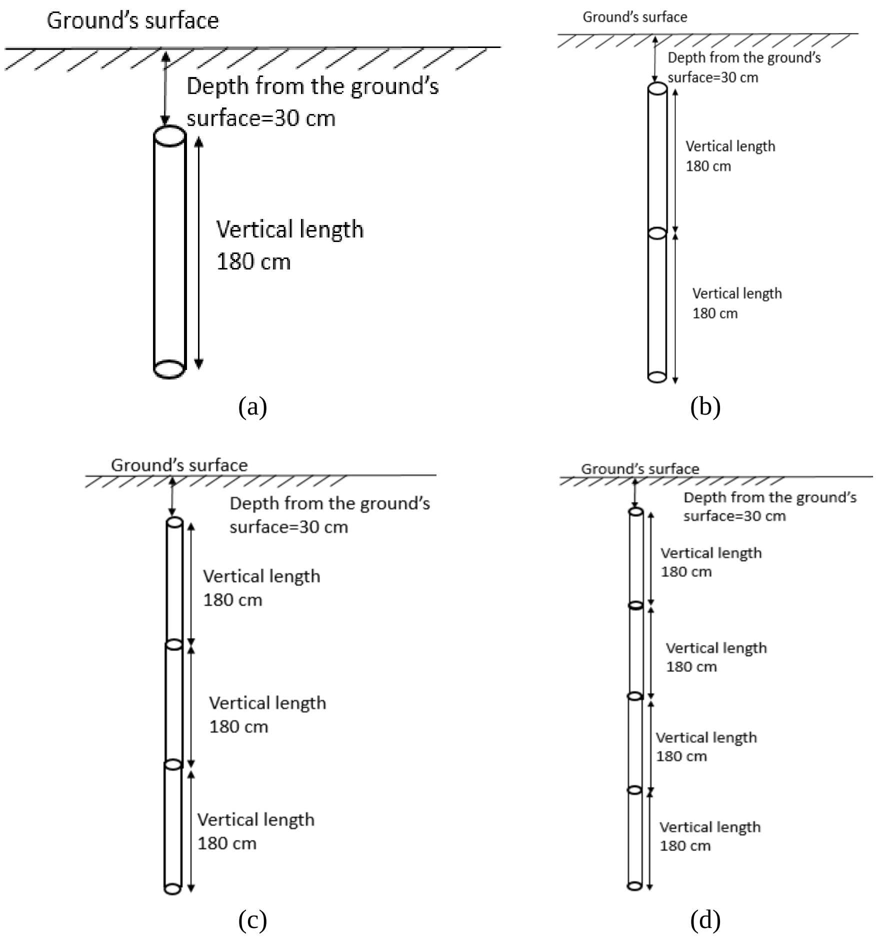

Figure 2. Ground electrodes used; (a) configuration V1, (b) configuration V2, (c) configuration V3, and (d) configuration V4

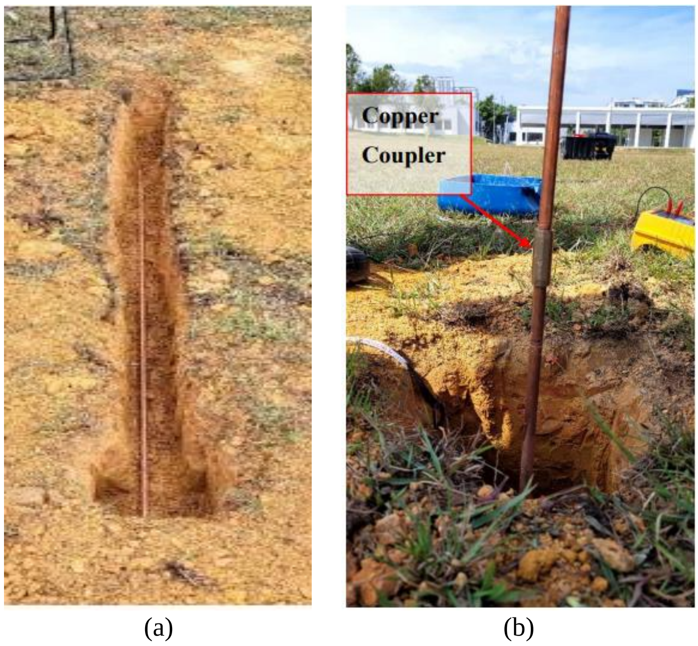

Figure 3. Installation of the electrodes; (a) horizontal and (b) vertical

3. EXPERIMENTAL RESULTS

3.1. Soil resistivity profile

Table 1 summarises the soil resistivity profles for both sites 1 and 2. As can be seen in the table, site 1 has lower soil resistivity at the upper layer than the lower layer, and vice versa for site 2. For the electrodes installed horizontally, they are installed below 30 cm from the ground's surface, hence from Table 1, these horizontal electrodes are installed in the upper layer only, while for the vertical rod electrodes, the rod electrodes in contact with both upper and layer soil layers. The height of the upper layer for site 1 is high, hence majority parts of the electrodes are installed at upper layer, while for site 2, the electrodes are mostly installed at upper layer for V1 and all horizontal electrodes (H1-H4), while other electrodes (V2-V4) having their parts mostly installed at lower layer, since the height of the upper layer is only at 1.24 m.

Table 1. Soil resistivity profiles for two sites

Site	Soil resistivity profile			
	ρ_1 (Ωm)	ρ_2 (Ωm)	h_1 (m)	h_2 (m)
1	71.5	208.9	4.06	Infinite
2	726.6	213.8	1.24	Infinite

3.2. Measured ground resistance value, R_{DC}

Table 2 presents the R_{DC} values for the eight electrodes installed at sites 1 and 2. As can be seen in the table, for both sites, and as expected, the more the number of electrodes, the lower the R_{DC} values are. For the same configurations, higher R_{DC} values are found for ground electrodes arranged horizontally than vertically for both sites. This is thought to be caused by a better and firm contact between the electrodes and the soil when the electrodes arranged vertically, by hammering the rod in comparison to the electrodes arranged horizontally in which the trench is first made, and the heaped soil is then poured and compacted or pressed into the trench. The loosening of the soil for the electrodes arranged horizontally reduces the interconnection passages in the soil, hence high R_{DC} in comparison to the electrodes arranged vertically.

Table 2. Measured R_{DC} values for all configurations at two sites

Configuration	R_{DCmeas} at Site 1	R_{DCmeas} at Site 2
V1	33.3	79.6
V2	16.4	28.8
V3	14	25.4
V4	13.8	22.2
H1	79.6	679
H2	28.8	616
H3	25.4	509
H4	22.2	407

Figures 4 and 5 show the measured R_{DC} values between the horizontal and vertical electrodes, respectively for sites 1 and 2. It can be seen that for the same number of electrodes, larger differences between the horizontal and vertical electrodes installed at site 2 than site 1. It is noted that the percentage differences between horizontal and vertical electrodes for site 2 are found to be more than 88%, while for site 1, the percentage differences are below 60%. Higher R_{DC} values in horizontal electrode than the vertical ground electrode could be caused by the soil is disturbed in which the excavation is carried out during the trench making for the installation of horizontal electrode, and though the soil is pressed during the backfilling, it may not be as compacted as before the excavation. During soil excavation, loss in soil cohesion, or the ability of soil to stick together can be expected as discussed in [15]–[19]. Due to loss in cohesion, more air voids within the soil can be expected, which would reduce the interconnection passages in soil and relatively increase its ground resistance values. Another procedure involved in the installation of horizontal ground electrode is backfilling the soil into the trench and pressing the soil firmly. However, the pressing may not be as firmly as the natural or original soil condition, creating more air voids hence again give lesser interconnection passages than that original soil condition (before the excavation), higher R_{DC} values than the vertical ground electrodes can be expected. It is found that the soil around the pile during the piling would experience compaction [20]–[25]. In relation to this present work, the soil compaction around the electrode that may occur during the vertical ground electrode installation is thought to be the reason for the lower R_{DC} values than the horizontal ground electrode. Vertical rod installation involves of driving the rod electrode into the ground, without much disturbance to the soil, which has improved the compaction in soil surrounds the ground electrode for vertical ground electrode's arrangement.

Another important observation is that horizontal electrodes give higher R_{DC} values than the vertical rod electrodes despite horizontal electrodes are only installed in upper layer which has lower soil resistivity than the lower layer in site 1. This could be caused by the degree of cohesiveness that can be dependent on the soil properties, whereby the gravelly soil, normally with larger particles tends to have lower cohesion than that the fine or smaller particles, as found in several studies [15]–[19]. As site 2 has higher soil resistivity, presumably has more air voids and lower cohesion than that of site 1, which would lose cohesiveness easily than that at site 2 when the soil is disturbed during excavation. Installation of vertical rod installation improved the R_{DC} while the horizontal rod electrodes causing more air voids in soil are also observed from the comparisons between the measured and computed results obtained from CDEGS are presented in the next section.

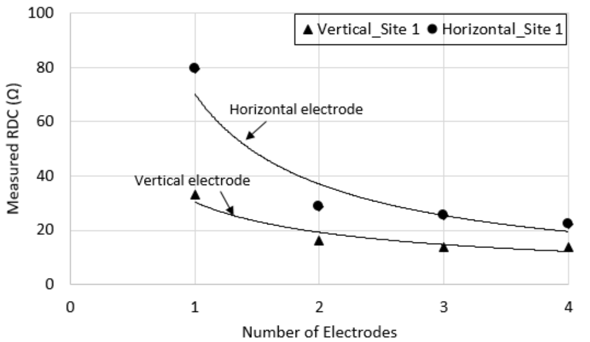

Figure 4. Measured R_{DC} values for horizontal and vertical electrodes installed at site 1

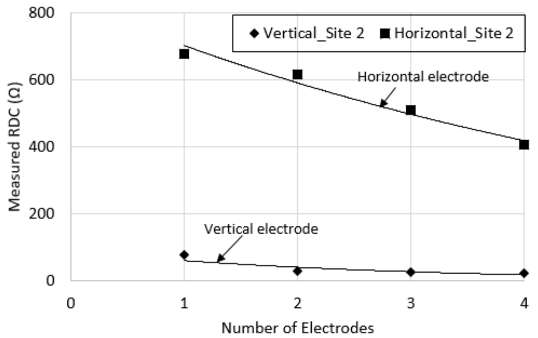

Figure 5. Measured R_{DC} values for horizontal and vertical electrodes installed at site 2

3.3. Computed ground resistance value, R_{DC}

The ground resistance values, R_{DC} are also computed by CDEGS, whereby the computed and measured R_{DC} results and percentage differences between measured and computed are plotted in Figures 6 and 7, respectively for sites 1 and 2. It can be seen that larger differences between the measured and computed R_{DC} in horizontal than the vertical ground electrodes for both sites. As the trench is needed to install the horizontal ground electrode, much part of the upper soil layer is disturbed due to the excavation, hence the upper soil layer profile would vary more significantly than the resistivity values used in the calculation, which used the data from the original soil profile, presented in Table 1. This also explains the reason why higher measured R_{DC} value than the calculated R_{DC} value for horizontal electrodes installed at both sites, whereby during the trench making, mixtures of soil of different shapes and sizes of air gaps are formed, and the pressing on heaped soil to backfill the trench may not have been the same as original compacted soil, during the installation, loosening the soil, enlarging the air voids within the heaped soil, hence reduce the interconnection passages within the soil, in which increased the measured R_{DC} value. On the other hand, measured R_{DC} values are found to be lower than the computed R_{DC} values for all vertical ground electrodes installed at both sites. This could be caused by the compaction of the soil around the electrode as the electrode is driven into the ground. When the soil around the electrode is compacted, the soil pressed together which enclosed air voids, providing continuity of water paths within the soil, hence a better interconnection passages in soil. For the calculated R_{DC} value, the soil resistivity data from Table 1 is utilised, in which the computational method applied does not consider the effect of soil compaction that may take place when the ground electrode is driven into the ground.

On another signifant observation is that percentage differences between the computed and measured R_{DC} values for vertical ground electrodes installed at site 2 is more than 40% higher than the vertical electrodes installed at site 1. As the soil resistivity at site 2 is higher, more air voids can be expected to be present for soil at site 2. When the vertical rod electrode is driven into the ground, again the soil compaction becomes the factor. The computed R_{DC} values use the soil resistivity profile, whereby the soil has more air voids and compared to the compacted soil, significant difference can be expected between measured and calculated R_{DC} values. On the other hand, for site 1, having a lower soil resistivity value, whereby the soil may have lesser air voids, in which when compacted, less effect can be expected between the measured and calculated. It is also noticed that larger differences between measured and calculated R_{DC} in horizontal electrodes installed at site 2 in comparison to site 1. This can be explained by higher soil resistivity at site 2, whereby higher porosity and air gaps within the soil than that at site 1 is expected, hence soil at site 2 loosen more easily than the soil at site 1 during excavation, causing lesser interconnection passages in heaped soil, which gives larger percentage differences between the measured and computed, whereby the original and rather more compacted soil is considered for the computational analysis. This work demonstrates that the heaped soil used to backfill the trench for the installation of horizontal ground electrode must be firmly tapped or pressed to provide better interconnection passages in soil, hence reduce the ground resistance value.

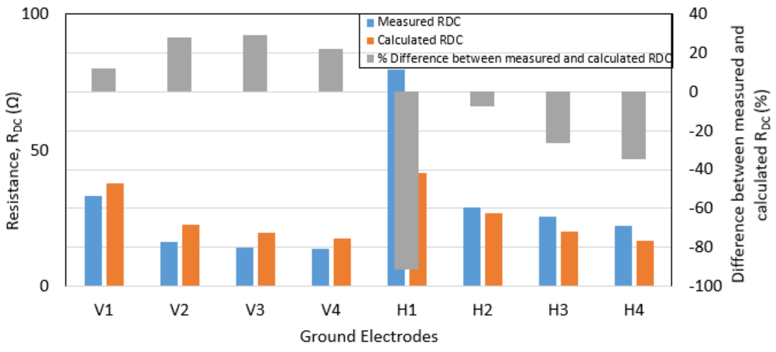

Figure 6. Measured RDC values for horizontal and vertical electrodes installed at site 1

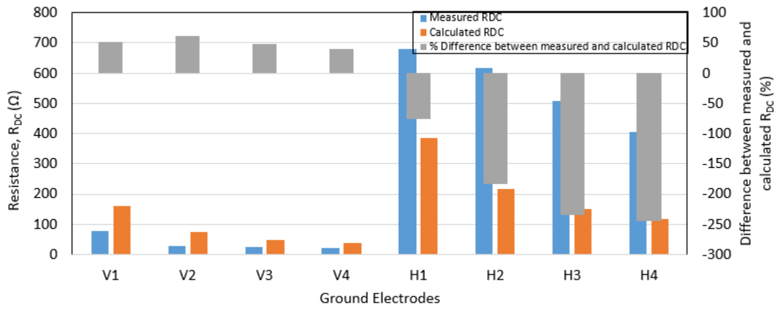

Figure 7. Measured RDC values for horizontal and vertical electrodes installed at site 2

4. CONCLUSION

In this paper, eight ground electrodes, arranged horizontally and vertically installed at two sites are assessed on its ground resistance values by measurement and computational approaches. Two sites are distinguished by having lower soil resistivity at the upper layer, ρ_1 than the lower layer, ρ_2 for site 1 ($\rho_1 < \rho_2$), and vice versa for site 2, having higher resistivity at the upper layer than lower layer ($\rho_1 > \rho_2$). The following can be made on the measurement method: i) for the same ground electrodes, lower ground resistance for vertical arrangement than the horizontal arrangement for both sites, indicating that the arrangement of ground electrode is not influenced by the soil layers, but mostly by the method of installation; soil excavation for the horizontal electrode and soil compaction during the installation of vertical rod; ii) the percentage difference between the horizontal and vertical arrangements of the ground electrodes are found to be very significant for site 2, which could be caused by larger differences between the upper and lower layer soil resistivities than that for site 1; and iii) when the measured R_{DC} are compared to the calculated R_{DC} values, the soil excavation during the installation of horizontal electrode and soil compaction during the installation of vertical electrode is also thought to influence the results. Nonetheless, it can be concluded that vertical rod electrode is preferred as the soil is compacted during the installation, hence reducing the R_{DC}.

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