COMPUTATION STABILITY OF GROUNDING SYSTEMS IN SOILS CONTAINING HETEROGENEOUS VOLUMES

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Abstract

This paper studies the performance of grounding systems in soil structures containing heterogeneous soil volumes. This type of soil is crucial for the investigation of a range of practical problems that cannot be approximated by a layered soil structure. This type of problems involves grounding systems that are either close to, partially or totally immersed in one or several finite volumes of soil materials that have resistivity values quite different from that of the bulk volume of surrounding soil (native soil). This paper focuses on the stability of the algorithm used to compute the response of grounding grids for different scenarios. It also describes and discusses the computed results that pertain to a number of typical grounding scenarios, comparing them to some known limiting case solutions.

Keywords

Grounding; Earthing, Soil Volumes, and Power System Planning

1. Introduction

A successful grounding analysis should be based on a soil structure model that is as close as possible to the real soil at the site of interest. In many cases, a horizontally layered soil provides a very good approximation. The study of grounding systems in various types of layered soils has been the subject of considerable attention by several researchers in the past decades [1-6]. However, there is a class of grounding problems that is crucial for the investigation of a range of practical problems that cannot be approximated by a layered soil structure. This type of problems involve grounding systems that are either close to, partially immersed in or totally immersed in one or several finite volumes of soil materials that have resistivity values that are quite different from that of the bulk volume of surrounding soil (native soil). Analysis of grounding systems buried in soils containing a number of finite volumes of soil with arbitrary resistivity values has been carried out quite recently [7-10]. The analytical model is described in [7], while typical examples and validation are provided in [8-10].

The analysis of grounding systems located near or within finite soil volume heterogeneities can be carried out only using numerical methods when the shape of the volume is arbitrary. In many cases of practical interest, the computation results depend critically on the manner in which the surface of the soil volume is broken into elements (*patches*). The main difficulties are encountered in cases where the grounding system is located near a soil volume interface, or inside (or close to) thin soil volumes. In such cases, it may be impossible to obtain reliable results even when using all available computer resources. In this paper we discuss a computation technique which helps to overcome these difficulties.

2. Analyses

2.1 Summary of the Theoretical Model

The electric field generated by a grounding system located in a soil with finite heterogeneities is caused by charges located on the finite volume interface with the soil and on the surface of the ground conductors. The method employed in the analysis is the so-called boundary element method. The surface of each rectangular volume is subdivided into small elements (patches). Each of the patches is assumed to have a uniform charge distribution. Each ground conductor is subdivided into small conductor segments. Each conductor segment is assumed to have a uniform surface charge distribution. The method of images is applied for all interface patches and all conductor segments, taking into account the presence of the earth surface. The charge distribution in the system is determined by numerically solving integral equations expressing the boundary conditions on each surface element of the finite volume interfaces and on the conductor segments. Finally, the earth potentials anywhere can be computed by considering the contributions from all the charges on the conductor segments and on the finite volumes soil

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interfaces. See Reference [7] for detailed analytical derivations.

2.2 Cubic Soil Volume

As mentioned in Section 2.1, a numerical method is used to carry out the analysis of the finite volume soil heterogeneity. In this numerical approach, every surface of the soil volume is subdivided into hundreds of small surface elements or patches having a uniform charge distribution. The distribution and size of the patches is the most important factor affecting the accuracy of the computation results.

As a rule, the patch distribution needed to achieve a specific computation accuracy depends on the resistivity ratio between the soil volume and the surrounding soil and on the proximity of conductors (and other soil volumes) to the soil volume interface.

Let us first analyze the number of patches needed to obtain reliable and stable results for resistive and conductive soil volumes when conductor is located far enough from the volume faces. The simple scenario shown in Figure 1 is used.

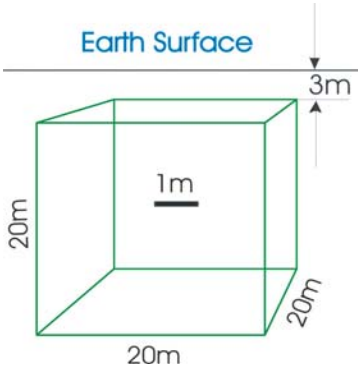

Figure 1. Conductor Segment Is Located at the Center of a 20m x 20m x 20m Cubic Soil Volume

Table 1. Resistivities of Soil Volume and Resistivity Ratios

ρ_{Volume} (Ω·m)	$\nu = \rho_{Volume} / \rho_{Native}$
0.1	0.001
1	0.01
10	0.1
1000	10
10000	100

Table 2. Patch Distributions

Patch Distribution per Volume Face (Same for All Faces)	Total Number of Patches per Volume
5 x 5	150
10 x 10	600
15 x15	1350
20 x 20	2400
25 x 25	3750

The grounding system consists of a 1m long conductor, immersed in the center of 20m x 20m x 20m cubic soil volume of resistivity ρ_{Volume}. The soil volume, in turn, is immersed in the surrounding soil of resistivity $\rho_{Native.}$ The top volume face is located 3m below the earth surface.
In all our examples, we assume that a current of 1000 Amps is injected into the grounding system and that the resistivity of the native soil ($\rho_{Native)}$ is 100 Ohm-m.

A series of tests is conducted for the resistivity ratios ($\nu = \rho_{Volume} / \rho_{Native}$) shown in Table 1 and the patch distributions shown in Table 2. Every volume face has an identical uniform patch distribution N x N, where N is the number of patches per volume edge. The relative error (in percent) for the grounding system resistance (R) is computed with respect to the case with the maximum number of patches (i.e. 25 x 25 patches per volume face or 3750 patches per volume):

$$\text{Error}(\%) = (R_{N \times N} - R_{25x25}) / R_{25x25} * 100\%.$$

The profiles showing the error as a function of the resistivity ratios (ν) are shown in Figure 2. This figure gives some indication of the number of patches required for conductive ($\nu < 1$) or resistive ($\nu > 1$) soil volumes in order to get adequate results. The lower the resistivity ratio ν (i.e. conductive soil volume), the larger the number of patches required to reach the best possible result. However, for $\nu > 0.1$ the error is very small and the results are stable. This means that, for example, for $\nu \sim 10$ (or higher) there is no need to use a large number of patches per face; the results are very accurate even if the total number of patches per volume does not exceed 1000.

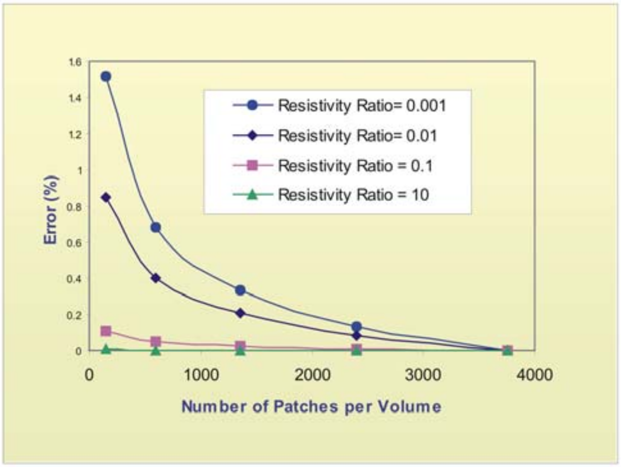

Figure 2. Percentage of Error for Grounding System Resistance Computation versus Number of Patches per Soil Volume

Note that the above conclusion pertains to the cases where conductors are located far enough from the volume interface.

The current density distribution for a resistivity ratio $\nu = 0.1$ and a uniform patch distribution with 25x25 patches

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on every face of the volume is shown in Figure 3. The current density distribution is illustrated by unfolding the volume surfaces as one would unfold the hollow cube, in order to see all faces at once. The top face of the cube (the face closest to the earth surface) is centered with respect to the cube sides. The bottom of the cube is to the right side of the cube.

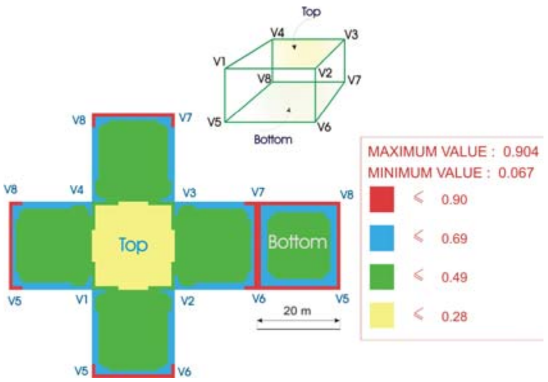

Figure 3. Current Density Distribution over the Soil Volume Interface for ν= 0.1 and 25 x 25 Patch Uniform Distribution per Soil Volume Face

From Figure 3 we can see that the current densities are practically constant in the central areas of the volume faces and gradually increase towards the volume edges.

Now let us consider the volume subdivision when the conductor is located close to the bottom face as shown in Figure 4. The conductor is located at a distance of 1m from the bottom face.

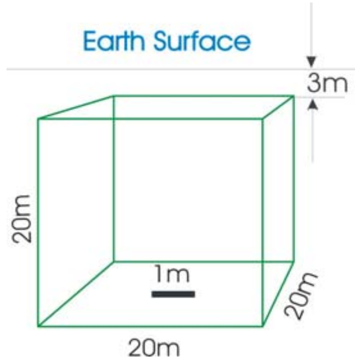

Figure 4. Conductor in the Proximity to the Bottom Face of a 20m x 20m x 20m Cubic Soil Volume

Table 3. Grounding System Resistance (ν = 0.1)

Scenario	Patch Distribution per Volume Face	Grounding System Resistance, Ω
1	All Faces 5 x 5 (Total 150)	8.46
2	All Faces 15 x15 (Total 1350)	8.00
3	All Faces 25 x 25 (Total 3750)	7.99
4	5x5 & Adaptive Subdivision (Total 750)	7.99

The grounding system resistance for four different patch distribution patterns is computed in Table 3 for a resistivity ratio of ν = 0.1 (i.e., volume resistivity is 10 Ω-m). In the first three scenarios, the subdivision is uniform and identical for all volume faces. We can see from the table that the results become stable starting at the 15x15 subdivision pattern. Scenario 4 in Table 3 uses an adaptive patch subdivision technique. This technique adjusts the size and the density of the patches in the vicinity of conductors; the closer the volume interface is to a conductor, the smaller and denser the patches become. The pattern of this subdivision technique is shown in Figure 5. All soil volume faces are initially subdivided into 5x5 patches. Adaptive subdivision is applied to the bottom volume face to reflect the proximity of the conductor. A total of 750 patches are generated for this scenario.

This adaptive subdivision approach is based on the fact that the charges on the volume interface are much larger and vary very fast in the proximity of the conductor segment(s). As a result, when the conductor is located close to one of the volume faces, the patch distribution for this face should be more refined than for the faces which are at larger distances from the conductor.

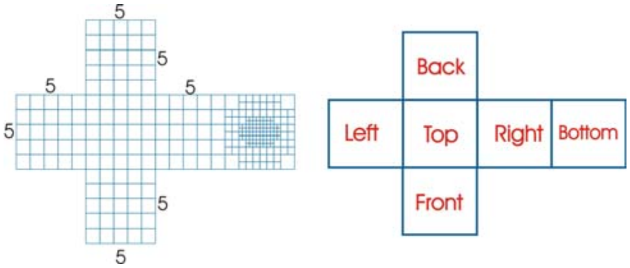

Figure 5. All Faces Are Initially Subdivided Into 5x5 Patches. Adaptive Patch Subdivision Is Applied to the Bottom Face

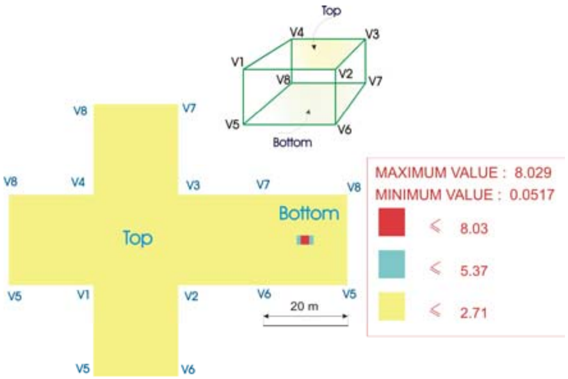

Figure 6. Current Density Distribution over the Soil Volume Interface for ν = 0.1. Adaptive Patch Subdivision Applied for the Bottom Face

Figure 6 shows the current density distribution on the volume interfaces for the adaptive patch subdivision scenario (Scenario 4). We can see that the largest current densities are concentrated in the proximity of the

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conductor on the bottom face. This is why the adaptive subdivision is more efficient in this case; though we can obtain the same results using the maximum number of patches (see scenarios 2 and 3 in Table 3), when using the adaptive approach, the total number of patches required is greatly reduced.

2.3 Thin Rectangular Soil Volume

In this section we consider the scenarios where the grounding grid is immersed or located nearby a thin finite layer of soil material with a resistivity different from that of the surrounding soil. First let us consider the case (Figure 7a) when the grid is embedded in the thin rectangular soil volume (100m x 100m x 1m) of resistivity ρ_1. The soil volume, it turn, is surrounded by a uniform soil of resistivity ρ_2. The top face of the volume coincides with the earth surface. A 4-mesh, 80m x 80m grid is buried at a depth of 0.5m, and symmetrically positioned inside the soil volume.

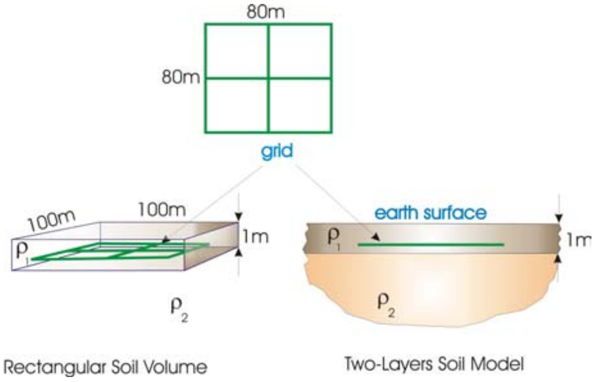

Figure 7. Rectangular (a) and Horizontal Two-Layer (b) Soil Models. Grid is Inside the Soil Volume

Such cases are very common in practice. For example, this scenario could correspond to the case where the grid is embedded in a concrete slab or in backfill material. The corresponding horizontal two-layer limiting case scenario is shown in Figure 7b.

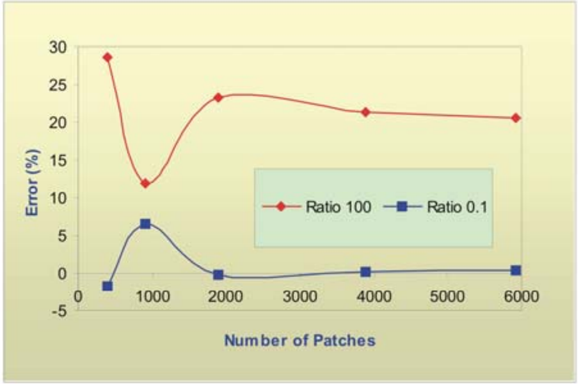

Figure 8. Percentage of Error for Grounding System Resistance Computation verus Number of Patches (Uniform Patch Distribution)

Figure 8 shows the percentage of error on the ground system resistance as a function of the number of patches (uniform patch distribution and size). The error for a conductive soil volume (ratio=0.1) become negligible starting at 2000 patches per volume, while for a resistive volume (ratio=100) the error remains close to 20% even for 6000 patches per volume. This error can be reduced to negligible values by using adaptive patch technique as explained hereafter.

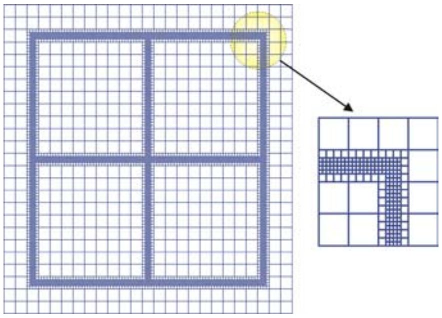

Figure 9. Pattern of Patch Distribution for the Bottom Surface of the Soil Volume

Since the distance from the soil volume bottom face to the grid is only 50 cm, the adaptive patch subdivision technique has been used. The patch distribution for the bottom face is shown in Figure 9. For scenarios of this kind, the computation process is extremely sensitive to the patch distribution. To obtain stable and reliable results, the patches in the proximity of the grid conductors should have a size of about 50 cm or even less. If this condition is not observed, the results can be unpredictable. Using an extremely dense patch configuration in the proximity of grid conductors (see Figure 9) which looks like the imprint of the grid, we were able to obtain stable results. The number of patches needed for the computations is about 4000. Figure 10 shows the current density distribution over the bottom face of the soil volume for the case ρ_1=10000 Ω·m and ρ_2=100 Ω·m (i.e. ν = 100). We can see that the current distribution pattern mirrors exactly the location of the grid.

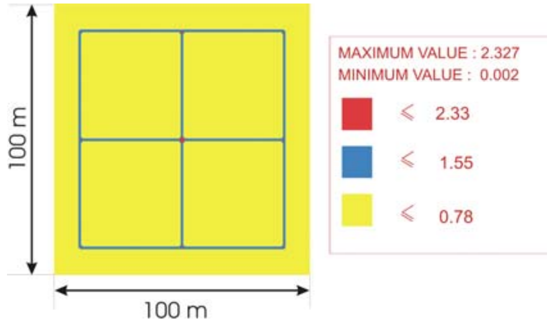

Figure 10. Current Density Distribution over the Bottom Face of the Soil Volume: resistivity ratio ν =100. Grid Is inside the Soil Volume

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The grounding system resistance and touch voltage to a point located above the center of the grid were computed for multiple resistivity ratios both for the rectangular soil volume and the horizontal two-layer soil models. The results are shown in Figures 11 and 12. The results for a uniform 100 Ohm-m soil are also shown for comparison.

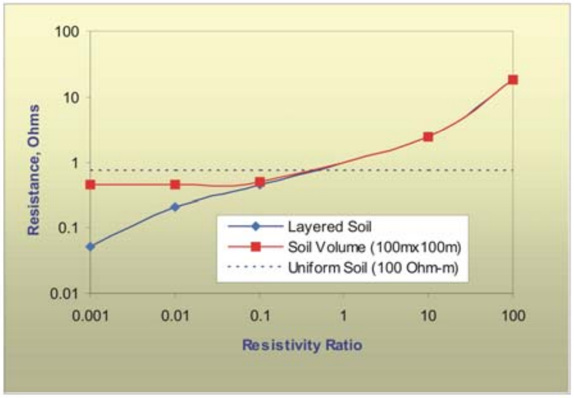

Figure 11. Grounding System Resistance versus Resistivity Ratio. Grid Is inside the Soil Volume

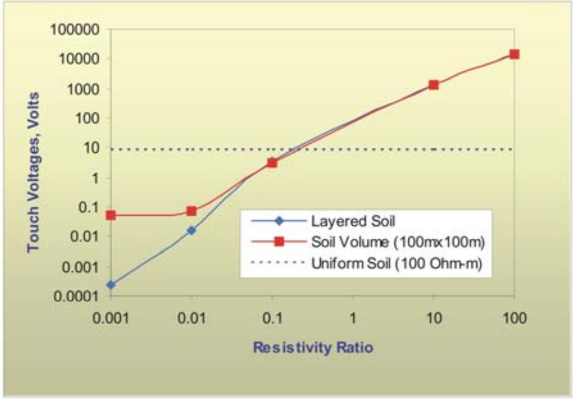

Figure 12. Touch Voltages versus Resistivity Ratio. Rectangular Soil Grid Is Inside the Soil Volume

We also considered a scenario when the grounding grid is located outside the thin soil volume. Figure 13 shows a case where the grid is located just beneath a thin soil volume. In practice, for example, the presence of grass over a substation area creates a thin low resistivity layer just above the grid, while the presence of any kind of soil covering materials (gravel, crashed rock, asphalt, etc.) creates a thin, high resistivity soil layer above the grid.

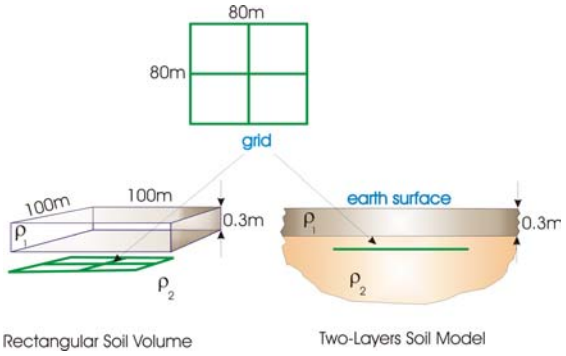

Figure 13. Rectangular (a) and Horizontal Two-Layer (b) Soil Models. Grid is Outside the Soil Volume

In this scenario the position and the size of the grid are kept the same as for the previous case; only the thickness of the soil volume is decreased to 0.3 m. The corresponding two-layer soil model, which we will use for comparisons, is shown in Figure 13b.

Figure 14 shows the current density distribution over the bottom face of the soil volume for the case ρ_1=10000 Ω·m and ρ_2=100 Ω·m (i.e. ν = 100). The plots showing the dependence of the grounding system resistance and touch voltages on the resistivity ratios are shown in Figures 15 and 16, respectively.

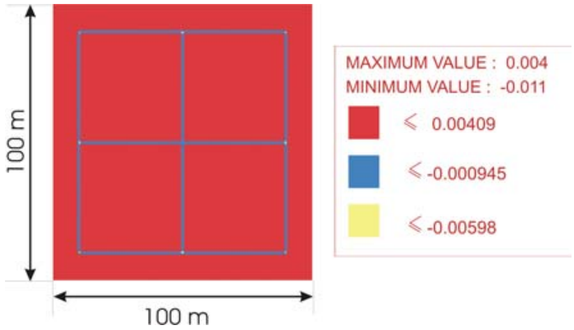

Figure 14 Current Density Distribution over the Bottom Face of the Soil Volume: ρ_{Volume}=10000sΩ·m and ρ_{Native}=100sΩ·m

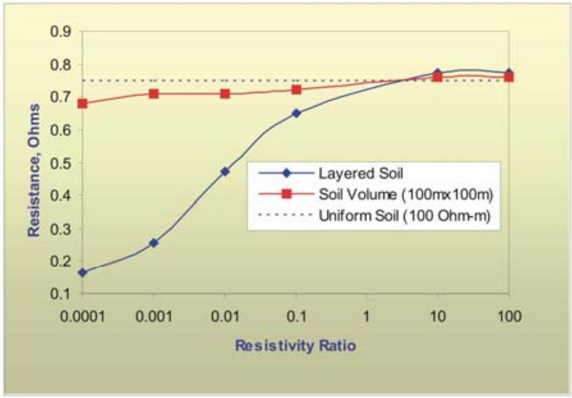

Figure 15. Grounding System Resistance versus Resistivity Ratio. Grid Is Outside the Soil Volume

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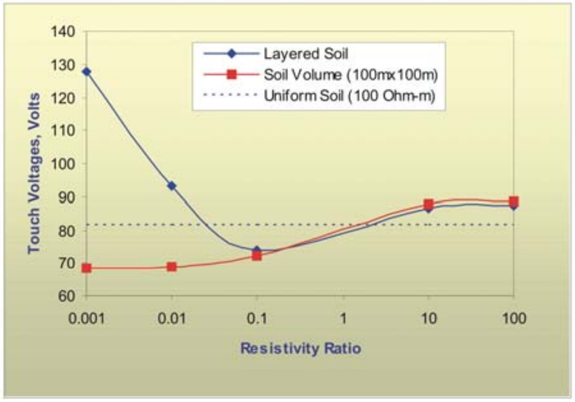

Figure 16. Touch Voltages versus Resistivity Ratio. Rectangular Soil Grid Is Outside the Soil Volume

We can see that in both cases (grid inside the soil volume and grid outside the soil volume) the computation results (resistances and touch voltages) for the rectangular soil volume and the two-layer soil become very close when the resistivity ratio ν >1.0, i.e. for resistive volumes, which is expected. The distinction between the two soil models becomes essential for ratios ν < 0.1, i.e. for conductive soil volumes.

3. Conclusions

Grounding systems that are either close, partially immersed or totally immersed in one or several finite volumes of soil materials that have resistivity values quite different from that of the bulk volume of soil surrounding (native soil) constitute an important class of practical grounding problems.

This work shows that a greater number of patches is required to achieve accurate results for conductive soil volumes compared to resistive ones when conductors are located far enough from the volume interface. In the case when the grid is immersed or located near the thin soil volume it is easy to achieve accurate results for conductive soil volumes using smaller number of patches compared to resistive ones. The study also shows that the adaptive subdivision technique minimizes the number of patches required to obtain reliable and stable results. It is especially important for the cases when the grid is close to the volume interface.

Using adaptive subdivision techniques leads to efficient and economical patch distribution on each volume face particularly for very thin soil volumes. Computed results are compared to some known limiting case solutions (horizontal 2-layer and uniform soil models). The results show very good agreements with the reference limiting cases. More complex soil volume scenarios will be examined in future research work.

4. Acknowledgments

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