Soil Model Seasonal Analysis for Grounding Systems

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Abstract – **A grounding system's behavior is significantly affected by the soil's electrical resistivity in the low frequency range of 50 and 60 Hz. In general, the soil resistivity can be rigorously defined with a 3D map but simulations for engineering applications can use a simplified model. The multilayer soil model is often suitable for most grounding system analysis. The soil model parameters usually are calculated starting from soil resistivity measurement provided using the classic Wenner or Schlumberger methods. These measurements are provided in a short time period, usually in a few hours or a few days. As a consequence, the measured values are tied to a specific date and climatic history.**

Moisture content, chemical content, and temperature are known to affect soil resistivity. Both moisture and chemical content can be challenging to predict, as they depend on rainy or drought periods or on human activity and these are not within the scope of this paper. In contrast, the current and future temperature of soil can be accurately predicted.

This paper considers the effects of soil temperature related to the seasonal variation and is based on a model implemented in a commercial simulation environment (XGSLab®). This will show how seasonal variation can accurately predict a grounding system behavior throughout the year, comparing real world measurements, and also highlight the hazardous impact that seasonal variation may develop for a grounding system's performance. As will be evident, the possibility to manage an arbitrary number of soil layers is crucial to rigorously evaluate the seasonal effects of the soil temperature.

Index Terms-- **Grounding Systems, Earthing Systems, Multilayer Soil Models, Temperature Dependence of Soil Resistivity, Seasonal Effects on Grounding System**

I. INTRODUCTION

The seasonal effects on grounding system behavior are often ignored despite their actual relevance. It is known that soil parameters significantly affect grounding system's resistance to earth and the resulting touch and step voltages. Soil measurements, specifically the shallow superficial depths, depend on the measurements period, the season, and on the climatic conditions the days, weeks, or months before the measurements. This is a critical aspect in the grounding system analysis because a grounding system that is safe today could be unsafe in a week or a month.

The grounding system behavior depends on the soil resistivity and the soil resistivity depends on many factors and in particular on moisture, chemical contents, and temperature.

The effects of moisture and chemical contents are out of the scope of the paper and moreover, at least for the moisture (a parameter dependent on rainy or drought periods), are often unpredictable.

Regarding moisture content, it is also useful to remember that the amount of water in a soil strongly influences resistivity only up to a water content of about 14 - 18% [1]. After this water content, the rate of decrease of the soil resistivity becomes much less. Inversely, a reduction in water content can strongly increase the soil resistivity. Though not the focus of this paper, a simple and effective technique to consider the effects of moisture content will be mentioned.

The effects of soil temperature on the soil resistivity is known above and below the freezing point. Moreover, the soil temperature can be predicted with adequate precision. This is the reason why in the following, the seasonal dependence of the soil model will be evaluated with reference to the seasonal temperature variations.

There is not a standardized approach on how to model the seasonal effects on the soil regarding grounding system analysis, but this paper outlines the methods to accurately predict seasonal variation.

Section II of the paper describes the theoretical approach used in the prediction of the ground temperature starting from the climatic conditions.

Section III of the paper describes the soil temperature resistivity dependence in both cases, below and above the freezing point.

Section IV of the paper describes a method for the adjusting a soil model to account for the seasonal temperature variations and corresponding resistivity variations.

Section V of the paper provides a comparison of calculated electrode impedance to measured values from summer to spring in the State of New York.

Section VI of the paper describes an application of the above method to a real case using a commercial simulation environment.

Unless otherwise noted all quantities are in SI units.

II. Ground Temperature

Climatic conditions affect the ground temperature in the superficial layers of the earth. These effects are usually limited up to a few meters or tens of meters depending on the ground thermal diffusivity.

Moreover, the ground temperature increases about 1 °C per 50 m due to geothermal heat flow from the center of the earth to the surface. This additional effect does not significantly affect the temperature of the superficial layers and thus is excluded in this paper.

The ground temperature can be calculated using the classic heat conduction theory. The general heat conduction equation is represented by the following equation:

$$\frac{\partial T_g}{\partial t} = \frac{k}{pc}\nabla^2 T_g + \frac{h}{pc} \quad (1)$$

where T_g is the ground temperature, t the calculation time, k is the ground thermal conductivity, p is the ground density, c is the ground specific heat capacity, and h is the heat source power intensity.

The heat conduction equation in the absence of heat sources in the propagation medium is represented by the following Fourier's equation [5], [6]:

$$\frac{\partial T_g}{\partial t} = \frac{k}{pc}\nabla^2 T_g \quad (2)$$

Equation (2) indicates that the rate of change of temperature is proportional to the divergence of the heat flow expressed and gradient of the temperature.

The three ground parameters p, c and k in (1) and (2), in general can vary with temperature, moisture, and depth. Ground anisotropy gives rise to the thermal conductivity tensor k. Real life is very complex and includes many effects simultaneously like soil heterogeneity, anisotropy, phase changing, vegetation, microclimatic differences, and more. In such conditions (1) and (2) can be solved only using finite element method.

The analytical approach is possible only introducing some suitable simplifications. For instance, (2) can be solved with an analytical approach with uniform soil and if all ground parameters are constant and scalar. The assumption of uniform ground is rarely met in nature but can be adopted for engineering to derive the analytical solution of (2) with results useful for practical applications.

In the following, the ground will be assumed as a uniform half-space, and climatic conditions above the soil surface will be considered uniform. With such assumptions, (2) can be reduced to the following one-dimensional partial differential equation:

$$\frac{\partial T_g}{\partial t} = a\frac{\partial^2 T_g}{\partial z^2} \quad (3)$$

where z is a vertical coordinate (positive downwards) and a is the thermal diffusivity of the ground:

$$a = \frac{k}{pc} \quad (4)$$

Equation (3) can be subject to the following initial boundary condition at the soil surface where the temperature is supposed to be known:

$$T_g\left(0,t\right) = T_{gs}\left(t\right) \quad (5)$$

where T_{gs} is the ground surface temperature.

The ground surface temperature can be approximated as equal to the air temperature. The air temperature fluctuates with cycles of thousands of years, centuries, one year, and one day. For engineering purposes, cycles one year and one day are considered. The air temperature annual fluctuation can be described with the following equation based on a simple harmonic function:

$$T_a = T_{maa} + A\sin\frac{2\pi\left(t-t_s\right)}{Y} \quad (6)$$

where T_a is the air temperature, T_{maa} is the mean annual air temperature, A is the amplitude of the yearly fluctuation of the air temperature, t_s is the time of the early spring with mean daily air temperature $T_{maa,}$ and Y is the time for a complete cycle of an year.

The mean annual ground temperature T_{mag} is usually a few °C more than the mean annual air temperature T_{maa}. The additional temperature of the ground in relation to the air T_{add} is about 1 °C in normal conditions and may be 5 °C in cases of deep snow for a long duration or asphalt [2]. Snow is an insulator if compared to soil and protect the ground surface from heat loss in winter. Without soil covering layers, the T_{add} also depends on the average wind speed [6].

It follows:

$$T_{mag} = T_{add} + T_{maa} \quad (7)$$

The mean daily ground surface temperature can be then expressed with the following equation:

$$T_{gs} = T_{mag} + A\sin\frac{2\pi\left(t-t_s\right)}{Y} \quad (8)$$

Equations (6) and (8) ignore the diurnal fluctuations of the air temperature and consider only the annual fluctuation around the mean annual air temperature. This approximation is in general acceptable taking into account that diurnal fluctuations usually affect the ground temperature only at a depth of much less than a meter.

The ground surface temperature taking into account the diurnal fluctuations can be expressed with the following equation:

$$T_{gs} = T_{mag} + A\sin\frac{2\pi\left(t-t_s\right)}{Y} + B\sin\frac{2\pi\left(t-t_d\right)}{D} \quad (9)$$

where in addition to (8), B is the amplitude of the diurnal fluctuation of the air temperature, t_d is the time in the morning with mean daily air temperature, and D is the time for a complete cycle of a day (1 day = 86400 s).

Unlike the annual fluctuation, the diurnal fluctuation of the air and ground surface temperature often cannot be represented using a simple harmonic function. As known by the Fourier transforms, a periodic function can be expressed as a composition of harmonic function. However, in the following, diurnal fluctuation of temperature will be not considered.

Equation (3) can be also subject to the following initial condition at the infinite depth where the ground temperature is constant and equal to the average ground temperature:

$$T_g\left(\infty, t\right) = T_{mag}, \quad (10)$$

The analytical solution of (3) taking into account the boundary conditions (8) and (10) provides the following equation:

$$T_g = T_{mag} + Ae^{-z\sqrt{\frac{\pi}{aY}}}\sin\left(\frac{2\pi\left(t-t_s\right)}{Y} - z\sqrt{\frac{\pi}{aY}}\right) \quad (11)$$

or with the boundary conditions (9) and (10):

$$\begin{aligned} T_g = T_{mag} &+ Ae^{-z\sqrt{\frac{\pi}{aY}}}\sin\left(\frac{2\pi\left(t-t_s\right)}{Y} - z\sqrt{\frac{\pi}{aY}}\right) \\ &+ Be^{-z\sqrt{\frac{\pi}{aD}}}\sin\left(\frac{2\pi\left(t-t_d\right)}{D} - z\sqrt{\frac{\pi}{aD}}\right) \end{aligned} \quad (12)$$

In the following, time will be expressed in days and not in seconds. Moreover, the complete cycle of a year will be approximated to 365 days. Of course, the equation (3) is valid again, and the only shrewdness is to consider the right unit "m^2/d" for the thermal diffusivity of the ground (sometimes in documentation this parameter is expressed in cm^2/s or m^2/s).

Some values for thermal diffusivity:

- Snow, peat: 0.010 m^2/d
- Sandy soil: 0.055 m^2/d
- Rock: 0.110 m^2/d

Equations (11) and (12) incorporate the following important concepts:

1) The ground temperature at the surface corresponds to T_{gs} (boundary condition (8) or (9)).
2) At infinite depth the ground temperature is equal to T_{mag} (boundary condition (10)). This because the geothermal heat flow from the center of the earth has been ignored.
3) The ground temperature variation is again harmonic, with amplitude related to the air temperature fluctuations that decreases exponentially with the depth.

   The effects of the annual fluctuations are negligible when the variation is less than 1 % of the amplitude at the soil surface A, then the depth z is:

   $$z > -\ln 0.01\sqrt{\frac{aY}{\pi}} = 49.64\sqrt{a}$$

   Usually, the amplitude is negligible at depths of 5–6 m in soils or 15–20 m in rock.

   For instance, z = 4.96 m if a = 0.010 m^2/d, and z = 16.5 m if a = 0.110 m^2/d.

   The effects of the diurnal fluctuations are negligible when the variation is less than 1 % of the amplitude at the soil surface B, then the depth z is:

   $$z > -\ln 0.01\sqrt{\frac{aD}{\pi}} = 2.598\sqrt{a}$$

   For instance, z = 0.26 m if a = 0.010 m^2/d and z = 0.86 m if a = 0.110 m^2/d,
4) Close to the soil surface, the ground temperature remains in phase with the air temperature while below the soil surface there is phase lag that increases with depth.

   Due to the high thermal inertia of ground, the maximum ground temperature at a depth of a few meters occurs about 6 months later than the maximum air temperature, and the minimum ground temperature occurs about 6 months later than the minimum air temperature.

   For the diurnal fluctuations, at a depth of a few decimeters, the maximum ground temperature occurs about 12 hours later than the maximum air temperature, and the minimum ground temperature occurs about 12 hours later than the minimum air temperature.

Of course, the diurnal fluctuations of the air temperature cannot be predicted with precision and in the long-term. Anyway, as anticipated, the ground temperature variation related to the diurnal fluctuations of the air temperature is limited to a thin layer.

For these reasons, in the following, only the effects of the systematic yearly fluctuation of the air temperature are considered and the reference equation for the ground temperature will be (11).

Fig. 2.1 represents the temperature distribution during a whole cycle of one year in the air and in the ground at depths 1, 2, 5 and 10 m with T_{maa} = 2 °C, T_{add} = 1 °C, A = 14 °C, t_s = 120 d and a = 0.025 m^2/d.

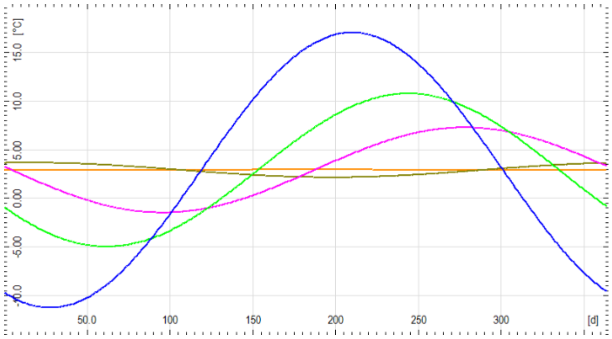

Fig. 2.1. Yearly fluctuation of air and ground temperature

The used values T_{maa}, T_{add} and A are related to a location at about the 50th parallel north and is dependent on the specific site. The value t_s is similar to all the northern hemisphere and is shifted about 6 months in the southern hemisphere, where t_s is about 300 d.

Fig. 2.2 represents the ground temperature distribution in the same conditions as described for Fig. 2.1, during days 120 and 120+365/2, which equals about 302 (day 1 indicates the 1st of January). In these two specific days, the air and soil surface temperature are the same but as evident, the ground temperature in depth is completely different and the corresponding grounding system behavior will be different.

Day 120 is in the early spring and the ground is partially frozen, whereas day 302 is in the late summer and the ground temperature is well above 0 °C at all depths.

The ground temperature distribution depends on the temperature in the days before with an increasing memory effect with depth; therefore, use of only air and soil surface temperature information is not representative of the real-world effects.

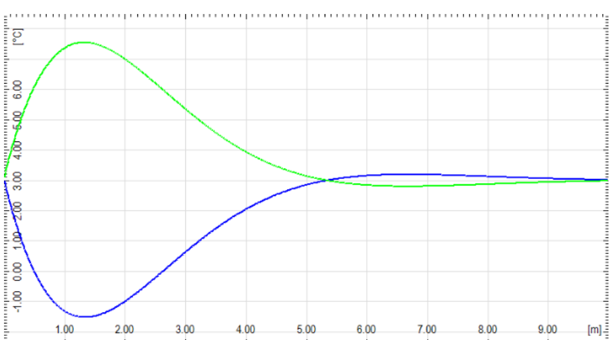

Fig. 2.2. Ground temperature as function of depth in days 120 (blue) and 302 (green)

III. Soil Resistivity Temperature Dependence

The flow of electricity in the soil is largely electrolytic, and determined by the transport of ions dissolved in moisture.

Reducing temperature reduces electrolytic activity, and hence conductivity. Upon freezing, conductivity of water becomes that of ice, which is very low. For this reason, the soil resistivity temperature dependence is usually divided in two distinct parts: above and below the freezing point.

Below the soil freezing point, the resistivity dependence is almost an exponential function of the temperature. The soil freezing point is not exactly 0 °C but is usually in the range between -0.5 and -0.7 °C. For practical purposes, the soil resistivity temperature dependence below the freezing point up to temperatures -15 °C, then in the range of interest, can be expressed with the following equation:

$$\rho = f \rho_{0+} e^{-\alpha(T-T_0)} \tag{13}$$

$$f = \frac{\rho_{0-}}{\rho_{0+}} \tag{14}$$

where ρ_{0+} is the soil resistivity immediately above the freezing point, f indicates the eventual discontinuity in resistivity across the freezing point, α is the coefficient of resistivity temperature dependence below the freezing point, and T_0 indicates the soil freezing point.

Above the freezing point and up to about t = 40 °C, then in the range of interest, the dependence of the soil resistivity with the temperature is quite linear and can be expressed with the following equation:

$$\rho = \rho_{0+} \frac{1+\beta(T_0-25)}{1+\beta(T-25)} \tag{15}$$

where ρ_{0+} is the soil resistivity immediately above the freezing point, β is the coefficient of resistivity temperature dependence above the freezing point, and T_0 indicates the soil freezing point.

Fig. 3.1, shows some examples of soil resistivity temperature dependence [3], [4].

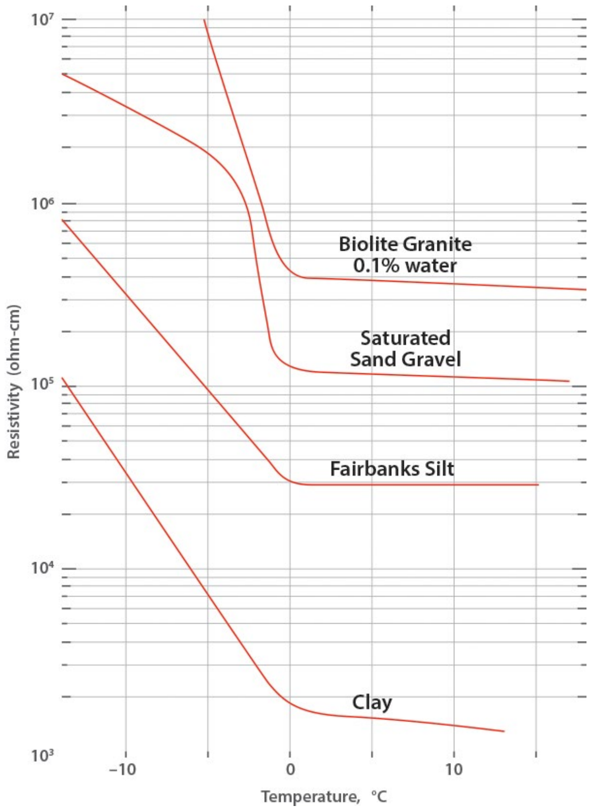

Fig. 3.1. Soil resistivity temperature dependence

Using (13) and (15) and settings the parameters ρ_{0+}, f, α, and β, *it* is possible to fit the curves of soil resistivity temperature dependence in documentation in the range of -15 to 40 °C with accuracy sufficient for all engineering applications.

Fig. 3.2 shows an example related to clay normalized to ρ_{0+}.

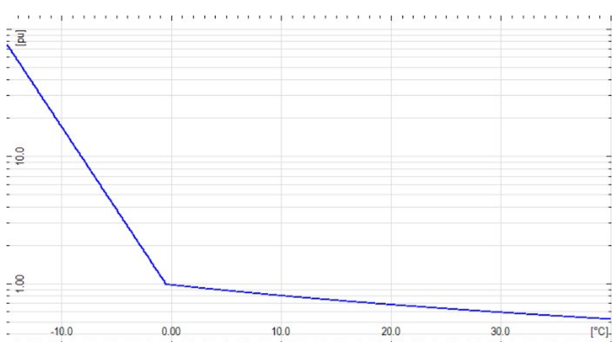
Fig. 3.2. Normalized soil resistivity temperature dependence of clay

The soil resistivity temperature dependence below the ground freezing point is very strong and at -10 °C the resistivity can be 10 times the value ρ_{0+}. The coefficient α is usually in the range 0.10–0.25.

The soil resistivity temperature dependence above the ground freezing point is not so strong, but is not negligible either. A difference of +20 °C in temperature above the freezing point can correspond to a halving of the soil resistivity. The coefficient β is usually in the range 0.0020–0.025.

In general, both conditions about temperature below and above the freezing point should be considered during the design of a grounding system. High soil temperature usually results in a reduction in moisture and other collateral effects that are not addressed in this paper.

In this paper, the soil resistivity temperature dependence is evaluated taking into account a constant water content. In a similar way, it is possible to consider the soil resistivity water content dependence with a constant temperature.

Finally, it is possible to combine temperature and water content effects considering the soil resistivity temperature dependence with different water contents.

Once the ground temperature has been evaluated, it is possible to analyze the effect of the water content simply by changing the soil resistivity temperature dependence curve to a different resistivity temperature curve corresponding to the water content difference.

Of course, one can argue that the water content affects the thermal diffusivity and then ground temperature distribution. This is important to note, but also consider the change of water content is usually related to the rain that affects a superficial layer of the soil with a thickness usually well below 1 m. That premised, the ground temperature can be calculated using the reference thermal diffusivity and the rain effects can be considered simply by changing the curve of soil resistivity temperature dependence using the curve related to a different water content.

In this way, effects of temperature and water content can be superimposed, and it is possible to include the effects of a few rainy days in the soil model.

IV. Soil Model Seasonal Variation

In the following, the soil modeling refers to the multilayer model, which is one of the most suitable models for grounding system analysis. A multilayer soil model consists of many horizontal layers with a given resistivity and thickness. As the bottom layer represents the edge of the pertinent soil, this bottom layer thickness is infinite.

The previous sections of the paper have described the models for the calculation of ground temperature as a function of depth and the temperature dependence of the soil resistivity. It should be evident that a system in a “uniform soil model” in the case of seasonal temperature variation should be considered as a multilayer model if the ground temperature is taken into account.

The soil model is usually calculated starting from soil resistivity measurement provided using the classic Wenner or Schlumberger methods. These measurements are carried out in a short period; usually in a few hours or a few days and then the model is referred to a specific date and climatic condition history.

If the yearly fluctuation of air temperature and thermal properties of the ground are known, it is possible to have a good knowledge of the ground temperature during the measurement period and of future temperatures.

Using the following method, starting from the soil model and the related ground temperature, it is possible to predict the soil model in each day of the year.

Using equations (13) and (15) it is possible to calculate the following correction factors from resistivities in the measurement day and the calculation day:

$$k_m = \frac{\rho_{0+}}{\rho_{Tm}}$$

$$if\ T_m > T_0 \quad k_m = \frac{1+\beta\left(T_m - 25\right)}{1+\beta\left(T_0 - 25\right)} \tag{16}$$

$$if\ T_m < T_0 \quad k_m = \frac{1}{fe^{-\alpha\left(T_m - T_0\right)}}$$

$$k_c = \frac{\rho_{Tc}}{\rho_{0+}}$$

$$if\ T_c > T_0 \quad k_c = \frac{1+\beta\left(T_0 - 25\right)}{1+\beta\left(T_c - 25\right)} \tag{17}$$

$$if\ T_c < T_0 \quad k_c = fe^{-\alpha\left(T_c - T_0\right)}$$

where T_m and T_c indicate the temperatures at the measurement and calculation day respectively.

The correction factor in general is a function of depth and can be calculated by multiplying (16) and (17):

$$k = \frac{\rho_{Tc}}{\rho_{Tm}} = k_m k_c \tag{18}$$

The application of the correction factor (18) to the resistivity at the measurement day gives the resistivity at the calculation day. This can be done for any depth. The resulting model can be approximated with a new multilayer soil model with a suitable number of layers. The possibility to consider a large number of layers is fundamental to represent the resistivity changing as a function of depth with accuracy.

The criteria for the evaluation of the thicknesses of the resulting model should consider the following practical rules:

1) Initial layers will be considered and divided in sublayers.

2) The thickness of sublayers will follow a geometrical sequence to increase with depth. The minimum thickness of sublayers will be not lower than a given limit. For instance, 0.2 m may be a reasonable value.

3) The resistivity of each sublayer will be equal to the average resistivity after the application of the correction factor.

4) The process can be applied with some constraints to avoid an excessive number of sublayers. For instance, using a tolerance 2%, only original layers with depth up to the following limit will be treated:

$$z < -\ln 0.02 \sqrt{\frac{aY}{\pi}}$$

5) To avoid adjacent layers with too similar properties, a final compaction cycle can be added.

The whole process has been implemented in the SA (Seasonal Analysis) module of the XGSLab® simulation environment and is described step-by-step in the following:

STEP 1: Set the yearly fluctuation of the air temperature and the thermal properties of the ground, and then calculate the ground temperature distribution during the measurements and calculation days.

STEP 2: Calculation of the resistivities in the measurement and calculation days, and then calculation of the related correction factor.

STEP 3: Application of the correction factor to the original soil model developed from the day of measurements and approximation of the modified soil model using many sublayers. The resulting modified soil model can be significantly different in the presence of frozen soil.

V. COMPARISON OF CALCULATIONS TO FIELD MEASUREMENTS

Results presented in the following two sections were obtained with the SRA (Soil Resistivity Analysis) and SA (Seasonal Analysis) modules implemented in the XGSLab® simulation environment.

The National Fire Protection Agency (NFPA) investigated the longevity of various conductors in ten locations in the USA. The National Electric Grounding Research Project included electrode resistance measurements, soil resistivity measurements, soil moisture, and soil temperature on a monthly basis for the duration of the multi-year project. In the state of New York, six electrodes, three vertical ground rods to a depth of approximately 2.5 m (8 feet), and three horizontally trenched rods at a depth of approximately 1 meter (3 feet), were installed. Though testing was incomplete at this site, continuous measurements from 2000 to 2001 showed a strong trend with the seasonal variation in soil temperature.

Both the horizontal and vertical electrode configurations were modeled to generate a computer calculated resistance for comparison to the measured values in New York. The blue lines in the Fig. 5.1 show the measured electrode impedance for the horizontally placed ground rods, with the equivalent calculated impedance from XGSLab shown in red.

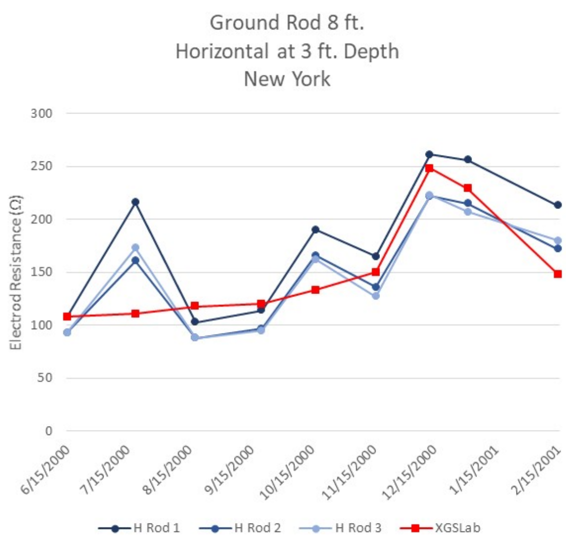

Fig. 5.1. Measured and calculated horizontal rod resistance

The measured electrode resistance shows an increasing resistance when entering the colder months of December and January. The nominal summer resistance increased up to 2.5 times for the measured values. This trend and the increasing resistance are seen in the calculated model. Note that the measured electrodes show a single dramatic resistance increase in July, which may be correlated to a drop in the soil moisture recorded in the same time period.

The blue lines in the Fig. 5.2 show the measured electrode impedance for vertically installed ground rods, with the equivalent calculated impedance in XGSLab shown in red.

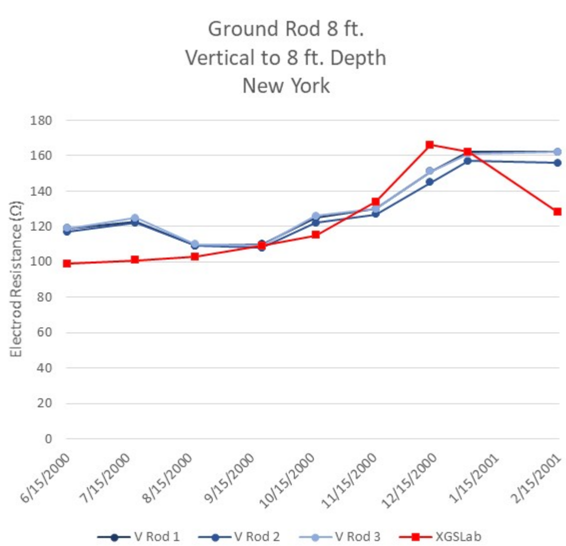

Fig. 5.2. Measured and calculated vertical rod resistance

The vertically installed rods show an increase in measured and calculated resistance, but this trend is not as dramatic as seen in the horizontally placed electrodes. This is due to the rods' depth extending to soil layers that are not significantly affected by the seasonal variation.

The trend and magnitude of resistance increase are similar for the calculated and measured values in periods of significant freezing. The calculated resistance compares well to the measured values for both electrode configurations.

VI. A Case Study of Safety with Seasonal Variation

Understanding that the soil resistivity will change, the varying behavior of a grounding system may result in hazardous conditions during some periods of the year. This section provides a case study for a grounding system that considers seasonal variation.

Suppose an original four-layer soil model with the following parameters calculated using SRA:

- Soil resistivity of the upper layer = 92.86 Ωm
- Soil resistivity of the second layer = 22.00 Ωm
- Soil resistivity of the third layer = 84.53 Ωm
- Soil resistivity of the bottom layer = 164.6 Ωm
- Upper layer thickness = 1.26 m
- Second layer thickness = 3.71 m
- Third layer thickness = 11.67 m

Suppose the site is related to a location in a cold region with the following climatic conditions:

- T_{maa} = 2 °C
- T_{add} = 1 °C
- A = 14 °C
- t_s = 120 d

Suppose the following average thermal properties of the soil and the average thermal diffusivity calculated using equation (4):

- k = 0.5 W/(m K)
- p = 2000 kg/m^3
- c = 864 J/(kg K)
- a = 0.025 m^2/d

Fig. 2.1 represents the temperature in the air and in the earth at some depth distributions during a whole cycle of one year.

Suppose also:

- t_m = 260 d
- t_c = 70 d

Fig. 6.1 represents the ground temperature distribution during measurement and calculation days as a function of the depth.

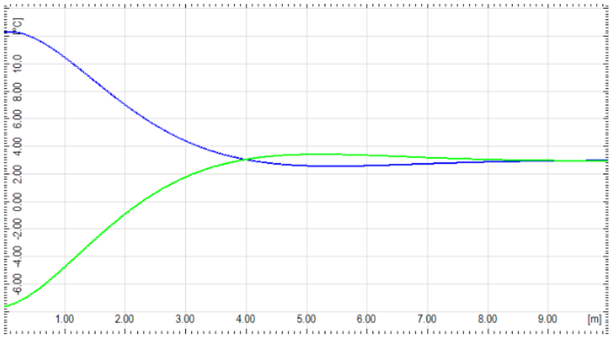

Fig. 6.1. Ground temperature distributions during measurement (blue) and calculation (green) days

Suppose finally that soil type = clay. Fig. 6.2 represents the correction factor distributions from resistivities in measurement and calculation days as a function of depth.

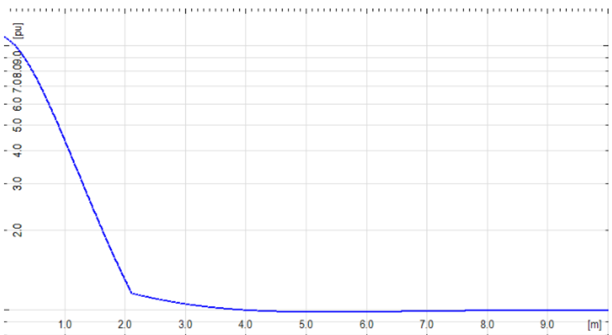

Fig. 6.2. Correction factor distributions from resistivities in measurement and calculation days

Fig. 6.3 represents the original and modified soil model after the application of the correction factor as a function of depth.

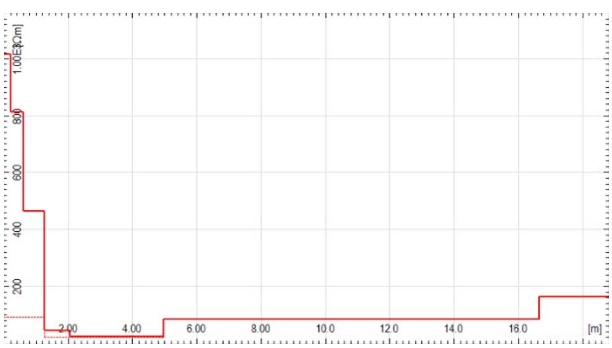

Fig. 6.3. Original (dashed line) and modified (solid line) soil models (t_c = 70 d)

The modified model shown in Fig. 6.3 clearly indicates that the number of layers significantly increases, but is required to properly align with the application of the correction factor. In this specific case the layer numbers are 4 and 7 for original and modified soil model, respectively.

It is also interesting to see how the modified soil model changes during seasons. The following figures show modified models in four days (seasons):

- Winter: day 29
- Spring: day 120
- Summer: day 211
- Fall: day 302

As expected, the seasonal effects are relevant, especially in the winter. During the spring, the seasonal effects are related to a frozen layer at an intermediate depth. Seasonal effects are less significant during the summer and fall for this case study, showing matching or slightly different results compared to the original soil model.

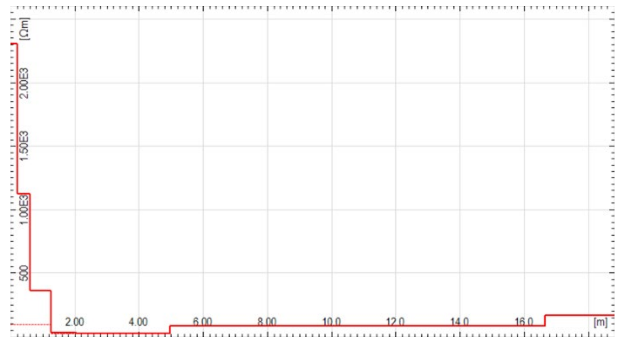

Fig. 6.4. Original (dashed line) and modified (solid line) soil models (t_c = 29 d)

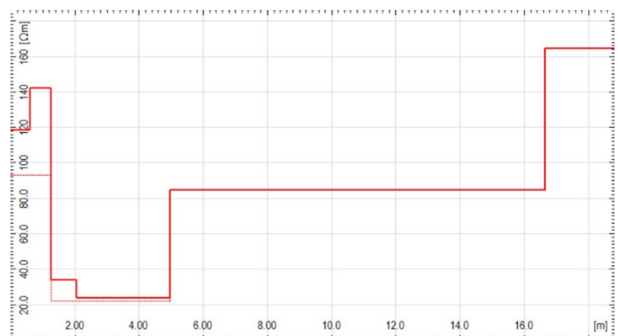

Fig. 6.5. Original (dashed line) and modified (solid line) soil models (t_c = 120 d)

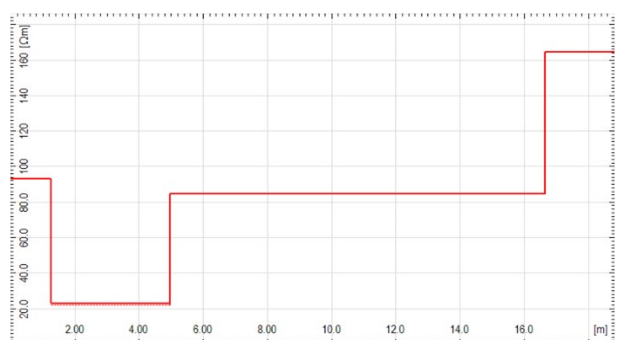

Fig. 6.6. Original (dashed line) and modified (solid line) soil models (t_c = 211 d)

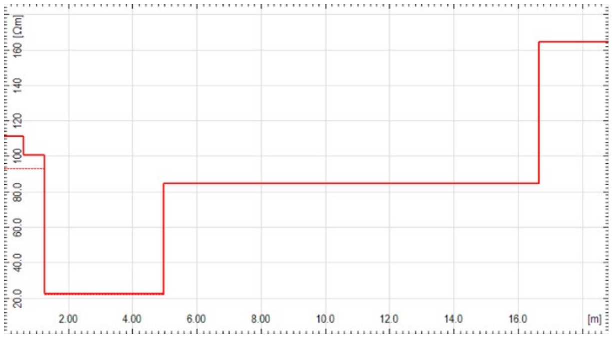

Fig. 6.7. Original (dashed line) and modified (solid line) soil models (t_c = 302 d)

After this preliminary analysis about how the soil model changes during seasons, it is interesting to analyze how the modified soil model affects the grounding system behavior.

Suppose a small substation with the following data:

- Current to earth: $I_e = 8$ kA
- Clearance time: $t_f = 0.5$ s
- Grid depth: $h = 0.7$ m
- Soil covering layer thickness: $h_s = 0.1$ m
- Soil covering layer resistivity: $\rho_s = 5000$ Ωm

The safety conditions are evaluated with reference to the IEEE Std 80-2013 and a body weight of 70 kg.

The calculation has been performed using the equipotential assumption. This is acceptable because the electrical size of the system (the ratio between the physical size and the wavelength) is much smaller than one. In general, voltage drop should also be considered along the grounding conductors.

The resistance to earth in the four seasons calculated using the corresponding modified soil models are as follows:

- Winter: 1.162 Ω
- Spring: 0.9115 Ω
- Summer: 0.8324 Ω
- Fall: 0.8363 Ω

As expected, the resistance to earth in winter is higher than the correspondent value during other seasons. This is because the grid depth is limited to 0.7 m and is encompassed by the cold season's frost depth.

The following figures show the safe areas during the four seasons. In green areas, the touch voltages are below permissible values, but yellow areas indicate touch voltage that exceed the permissible value.

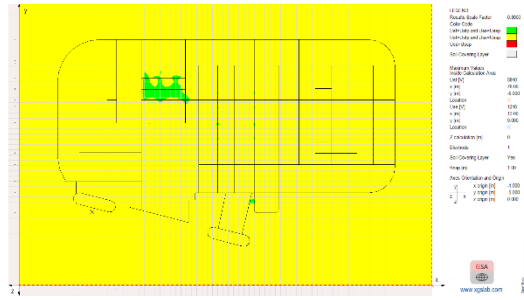
Fig. 6.8. Safe areas in winter (t_c = 29 d)

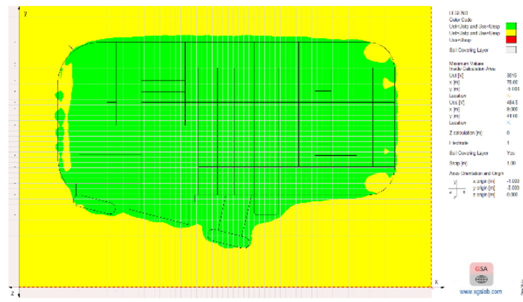
Fig. 6.9. Safe areas in spring (t_c = 120 d)

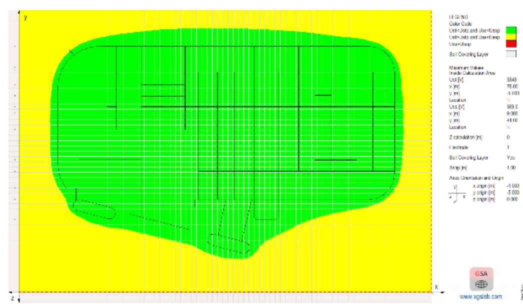
Fig. 6.10. Safe areas in summer (t_c = 211 d)

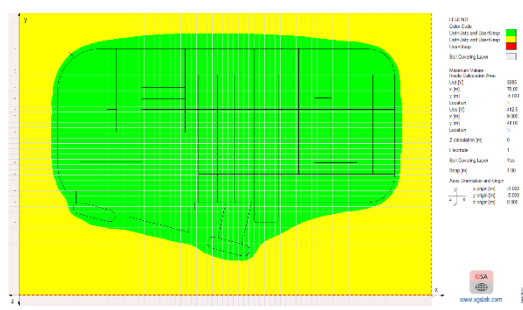
Fig. 6.11. Safe areas in fall (t_c = 302 d)

In winter, the grid shows hazardous conditions for touch voltages, but other seasons are generally within safety limit. In the specific conditions, a bigger grid depth or the use of long rods can prevent dangerous conditions during the cold season.

CONCLUSION

It is evident from the discussion above that the effects of the ground temperature are too relevant on soil models and in the grounding system behavior to be ignored.

The seasonal variation air temperature affects the temperature of the superficial layers of the soil. As a consequence, the resistance to earth and the touch and step voltages vary, possibly reducing safety. These changes are relevant in both winter and summer conditions because the temperature dependence of the soil resistivity is relevant in both cases. In cold regions where soil can freeze, special attention is required for the winter conditions.

Taking into account the seasonal dependence of grounding behavior it is not surprising to recognize that measurements on grounding systems can significantly change with the seasons and that a safe system today can be unsafe another day.

This conclusion is alarming but the knowledge of the phenomenon can help to reach safety levels that consider the seasonal effects. Certainly, the use of modern tools and suitable methods as the method described in this paper and implemented in the SA module of the XGSLab® simulation environment can be useful.

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