EARTH SURFACE POTENTIAL FOR SCALED VERTICAL ROD INTO TWO LAYER SOIL MODEL

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Abstract: This paper presents an experimental work using scale model for vertical rod to measure the Earth Surface Potential (ESP). Scale model is based on the similarity theory. It reveals that one replaces the investigation of a phenomenon in nature by the investigation of an analogous phenomenon in a model of smaller or larger scale under special laboratory conditions. The scale factor of the system is taken as 300. The AC voltage is applied on the scaled vertical rods with different configurations as well as the DC voltage. The two layer model soil is simulated using two glass tanks that have a conducting connection between different water resistivities via copper rods. The effect of the depth, length and radius of the vertical rod as well as the water resistivities on the ESP is studied. The effect of the temperature rise on ESP can be investigated. The results obtained from the scale model are compared with those given by computer simulation, which is based on Current Simulation Method.

1 INTRODUCTION

Typically, the lightning stroke is associated with potential rise, potential difference and transient energy transfer between grounding systems and the surrounding environment. Great damages may occur to the equipments and humans if the grounding system is not properly designed.

As the number and complexity of AC substations increase, the need of accurate design procedures for grounding systems becomes highly important and should consider safety and cost issues. Analytical techniques in some cases are so complex and therefore, studying the phenomenon using scale model is greatly convenient. For grounding system design, the goal of the experimental work that is based on scale model is to analyze the grounding system behavior during faults with different rod structures.

Tracking the potential distribution of complicated ground electrode arrangements cannot be easily performed by analytical based methods, since the difficulty degree increases with the increase of grounding system rod combinations and configurations. For mesh type electrode arrangements with irregular depth of burial, which is the way used with potential control purposes for other complicated structures, it is common to use models [1, 2]. For this purpose such model measurements using an electrolytic tank were undertaken [3-5]. Some attempts to measure the Earth Surface Potential (ESP) with the scale model for some different grid configurations were implemented [3-9].

In this paper, measurement of earth surface potential by injecting DC and AC current into a scale model vertical rods and some other configurations for uniform and non-uniform soil. Some parameters affect the surface potential on the water surface, such as burial depth, length and radius of the vertical rods as well as the resistivity of the water in the tank. The effect of temperature in top and bottom layers on the surface potential is studied. The ESP for real case is calculated using Current Simulation Method (CSM), presented in [10]. The results from this simulation is compared with the scale model results.

2 EXPERIMENTAL SETUP

2.1 One layer model soil

The purpose of the scale model experiments is to investigate the effect of the vertical rods and other grounding configurations on both of water grounding resistance and the ESP when discharging currents are flowing into it. The components of the experimental setup are; an electrolytic tank that simulates the homogenous earth soil with dimensions of 75cm length, 75cm width, and 50cm height as illustrated in Figure 1, Power supply (AC or DC), voltmeter and ammeter devices. Different rod configurations are given in Figure 2. The scale factor between the reality and scale model is 300:1. Distilled water with salted tap water is used as an electrolyte, which serves as an adequately conducting medium, representing the homogeneous earth. Change in the salinity causes a change in the liquid resistivity. A voltmeter and ammeter are respectively connected in parallel and series with the test tube, as described in Figure 3. Based on Ohm’s law, the water resistance can be estimated from the voltmeter and ammeter readings. Hence, the resistivity of the water that emulates the soil resistivity ρ can be calculated using Eqn 1.

$$\rho = \frac{RA}{L} \qquad (1)$$

where, ρ = Water resistivity (Ω.m)
L=Length of the tube (m)
A= Cross-section of the tube in (m^2)

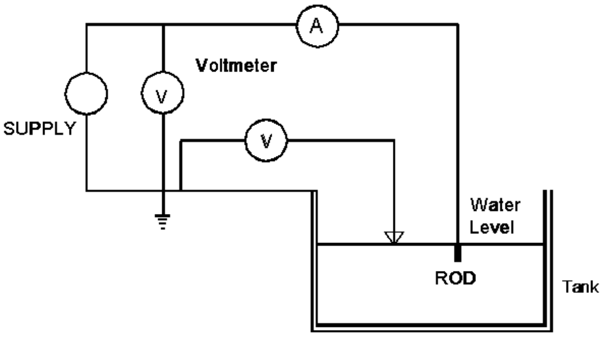

Figure 1: Experimental Setup for homogenous soil

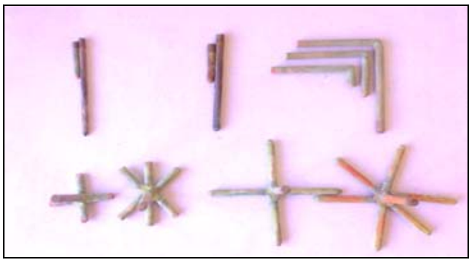

Figure 2: Configuration of rods used as scale model

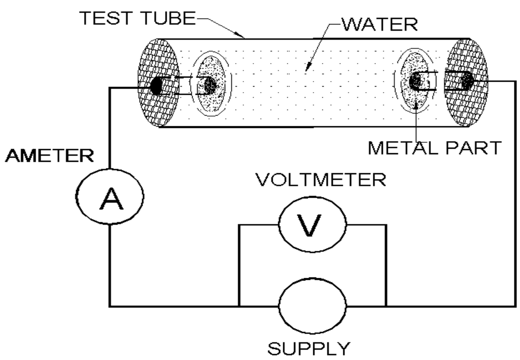

Figure 3: Measurement of the water resistivity

2.2 Two layer soil model

The experimental setup for a two-layer soil model is presented in Figure 4. The current is injected into the scaled electrode and a digital voltmeter measures the voltage on the water surface. The electrolytic tank that simulates the bottom layer has dimensions of 75cm length, 75cm width, and 50cm height and the top layer tank has dimensions of 65cm length, 65cm width, and 25cm height. The scale factor between the reality and scale model is taken as 300:1. In this section, the effect of some parameters on ESP, V_t, V_s and R_g will be studied.

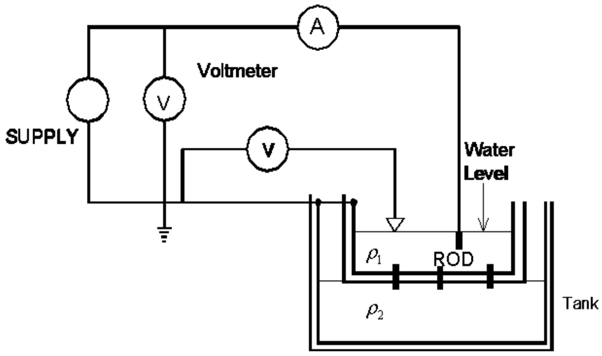

Figure 4: Experimental Setup for two layer model soil.

3 EXPERIMENTAL RESULTS FOR ONE LAYER MODEL SOIL

The effect of the depth, length and radius of the vertical rods and other rod configurations, rod burial depth and water resistivities on the ESP is investigated.

3. 1 Effect of rod length.

Based on experimental measurements conducted with vertical rods shown in Figure 5, the relationship between the distance from the rod in cm and the ESP in V is presented in Figure 6, and Table 1. The ESP and the Ground Potential Rise (GPR) decrease with the increase of the rod length. This result can be interpreted based on Eqn 2, which states that the grounding resistance (R_g) reduces with the increase of rod length. Further, the touch voltage, V_t (Eqn 3) and the maximum step voltage, V_S, given in Eqn 4, decrease since the reduction rate of the GPR is greater than the reduction rate of the ESP.

$$R_g = \frac{GPR}{I_g} \qquad (2)$$

wher, Rg= Grounding resistance (Ω.m)
GPR =Ground Potential Rise
Ig= Grounding current (A)

$$V_{touch}\,\% = \left(\frac{GPR - V_1}{V_1}\right) \times 100 \qquad (3)$$

wher, V_1 = Surface potential at distance 1 cm from the rod.

$$V_{step}\,\% = \left(\frac{V_1 - V_2}{V_1}\right) \times 100 \qquad (4)$$

where: V_1 and V_2 are the surface potential at points 1 and 2 on the surface potential profile. The distance between the two points is 1 cm.

Figure 5: Configuration of vertical rods used in the scale model (different length and diameter)

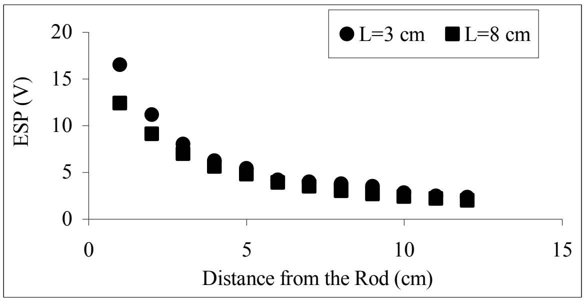

Figure 6: Effect of rod length (L) on the ESP (Diameter of Rod (D)= 3mm, Depth of Rod(H) = 0, Resistivity of water (ρ) =7.63Ω.m and DC Voltage)

Table 1: R_g, V_T and V_S for different vertical rod length

Test	L cm	D mm	H cm	ρ Ω.m	N	RL cm	R_g Ω	V_t %	V_s %
1	3	3	0	7.63	0	0	42.5	61.2	29.69
2	8	3	0	7.63	0	0	21	41	26.6

Another configuration to study the effect of vertical rod length is presented in Figure 7. The radial rod length is kept constant while the vertical rod length is varied. As shown in Figure 8 and Table 2, the increase in vertical rod length results in a reduction in ESP and R_g.

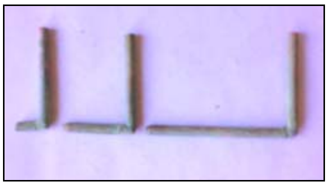

Figure 7: Configuration of rods used as scale model for the effect of rod length with radial length constant (RL)=5cm

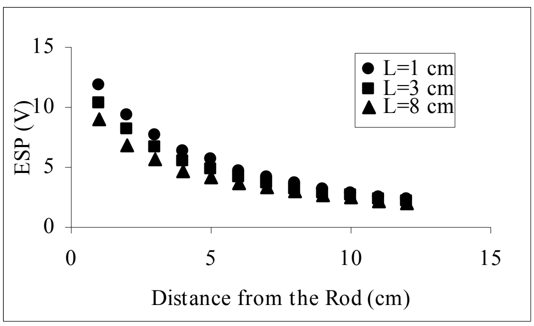

Figure 8: Effect of rod length on the ESP(D= 5mm, H = 0, ρ =7.63Ω.m, Radial Length (RL)=5cm , Number of Radial(N)=1 and DC Voltage)

Table 2: R_g, V_T and V_S for different vertical rod length

Test	L cm	D mm	H cm	ρ Ω.m	N	RL cm	R_g Ω	V_t %	V_s %
1	1	5	0	7.63	1	5	22	46.3	21.2
2	3	5	0	7.63	1	5	19.8	42.4	22.11
3	8	5	0	7.63	1	5	15.7	42	23.33

3.2 Effect of rod diameter

As depicted in Figure 9 and Table 3, the effect of rod diameter on the ESP is not significant, since the variation of the vertical rods diameter causes a small change on ESP and the GPR. Hence, the effect of vertical rod diameter can be neglected.

3.3 Effect of rod depth

Based on Figure 10, the ESP and the GPR decrease with the increase of the rod depth (taken from the water surface). The ESP reduction is caused by the reduction of the grounding resistance (R_g). The calculated step and touch voltages are arranged in Table 4. It can be seen that the increase of rod depth results in a reduction in step and touch voltages. When the rod depth is 3 cm under water, the step voltage decreases by 3%, but touch voltage is reduced by 20%.

3.4 Effect of water resistivity

Figure 11 illustrates the variation of water resistivity with ESP. A significant change in ESP is noticed with the variation of water resistivity.

The ESP and GPR decrease with the decrease in water resistivity (ρ) as the grounding resistance is reduced. A decrease in water resistivity will cause a decrease in step voltage (V_S), as well as touch voltage (V_t), as presented in Table 5.

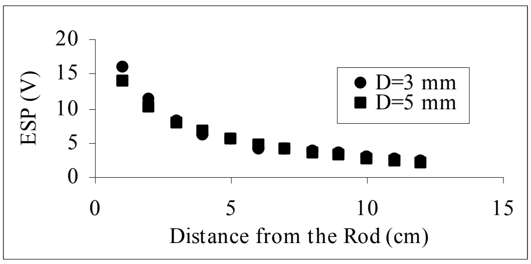

Figure 9: Effect of rod diameter (D) on the ESP (L= 3cm,H = 0,ρ =7.63Ω.m and DC Voltage)

Table 3: R_g, V_T and V_S for different vertical rod diameter

Test	L cm	D mm	H cm	ρ Ω.m	N	RL cm	R_g Ω	V_t %	V_s %
1	3	3	0	7.63	0	0	42.5	61.2	29.69
2	3	5	0	7.63	0	0	42.5	61.1	27.14

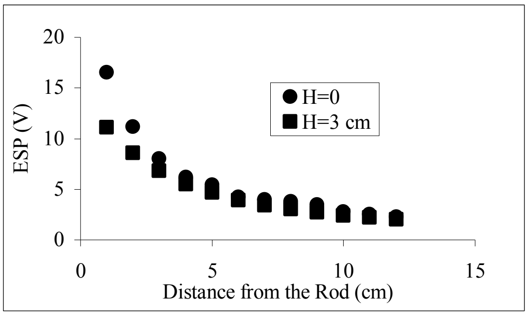

Figure 10: Effect of rod depth (H) on the ESP (L= 3cm, D = 3mm, ρ =7.63Ω.m and DC Voltage)

Table 4: R_g, V_T and V_S for different vertical rod depth

Test	L cm	D mm	H cm	ρ Ω.m	N	RL cm	R_g Ω	V_t %	V_s %
1	3	3	0	7.63	0	0	42.5	61.2	29.69
2	3	3	3	7.63	0	0	25	41	26.6

3.5 Effect of Number of Radial Rods

Figure 12 shows some of rod configurations with different number of radials. As seen in Figure 13, the increase of the number of radial rods that connected to the vertical rod plays an important part to reduce the ESP and R_g. Further, when the number of radial rods is increased, the step and touch voltages will decrease, as seen in Table 6.

3.6 Effect of Applied Voltage Type

As seen in Figure 14, the type of the power supply (AC or DC) affects the ESP values. The AC power supply gives reduced values of ESP and R_g. Further, the Step and touch voltages will decrease, as seen in Table 7.

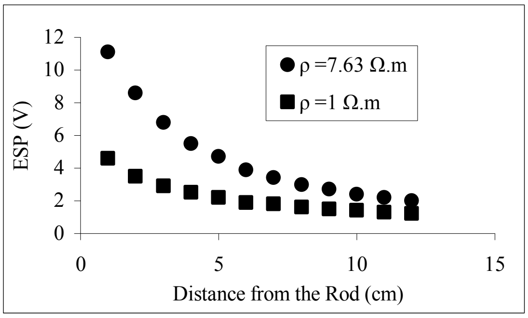

Figure 11: Effect of water resistivity (ρ) on the ESP (L= 3cm, D = 3mm, H =3 and DC Voltage)

Table 5: R_g, V_T and V_S for different water resistivity

Test	L cm	D mm	H cm	ρ Ω.m	N	RL cm	R_g Ω	V_t %	V_s %
1	3	3	0	7.63	0	0	42.5	61.2	29.69
2	3	3	0	1	0	0	26.1	65.9	28.3

Figure 12: Configuration of rods used as scale model for the effect of Number of Rod Radial (N) and Radial Length (RL)

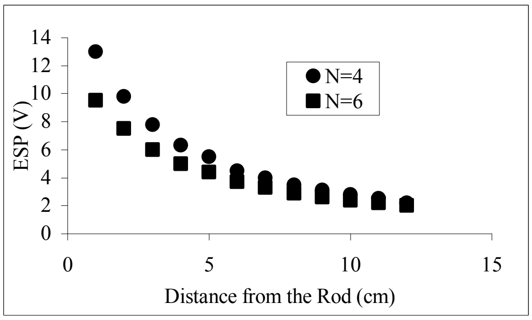

Figure 13: Effect of Number of Rod Radial (N) on the ESP (L= 5cm, D = 5mm, ρ=7.63Ω.m , H = 0, Radial Lenght(RL)= 2cm and DC Voltage)

Table 6: R_g, V_T and V_S for different number of radials

Test	L cm	D mm	H cm	ρ Ω.m	N	RL cm	R_g Ω	V_t %	V_s %
1	5	5	0	7.63	4	2	21	40	24.6
2	5	5	0	7.63	6	2	15	38.1	21

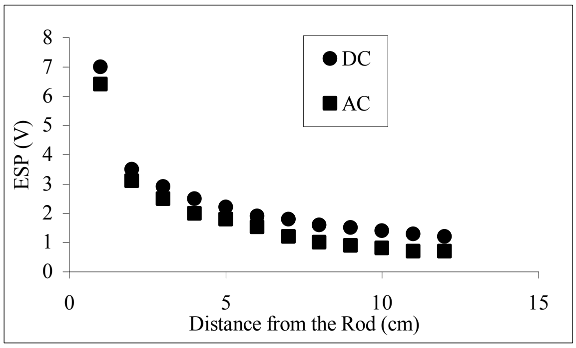

Figure 14: Effect of Supply Voltage on the ESP (L= 3cm,D = 3mm,ρ =1Ω.m and H =3)

Table 7: R_g, V_T and V_S for different supply type

Test	L cm	D mm	H cm	ρ Ω.m	N	RL cm	R_g Ω	V_t %	V_s %
1	3	3	0	1	0	0	26	26	65.9
2	3	3	0	1	0	0	17	17	50.6

4 EXPERIMENTAL RESULTS FOR TWO LAYER MODEL SOIL

4.1 Effect of rod length.

The relationship between the distance from the rod in cm and the ESP in V at different rod lengths is presented in Figure 15. The ESP and GPR decrease with the increase of the rod length.

4.2 Effect of rod depth

As shown in Figure 16, the ESP and the ground potential rise (GPR) decrease with the increase in rod depth due to the reduction of the grounding resistance (R_g).

4.3 Effect of Bottom Layer Resistivity

The effect of the bottom layer resistivity is not significant since the rod is located in the upper layer, as shown in Figure 17. The effect of the bottom layer becomes more active when the rod penetrates down in the bottom layer.

4.4 Effect of Top Layer Thickness

As seen in Figure 18, An increase of the TLT causes a higher of ESP and R_g. Further, when the TLT is increased, the step and touch voltages will increase.

4.5 Effect of Applied Voltage Type

ESP values resulted from different applied voltage types are presented in Figure 19, Slightly reduced values of ESP are given with AC voltage supply. Moreover, step and touch voltages will decrease with AC voltage type.

4.6 Effect of temperature

Figure 20 illustrates that the electrolyte temperature has a significant impact on decreasing the resistivity and hence the resistance of the water.

It is shown in Figure 20 that when the top layer temperature is greater than that of bottom layer, the ESP and GPR is decreased. Since the rod is located in the upper layer only, the resistivity of the top layer has a great effect on the ESP and GPR.

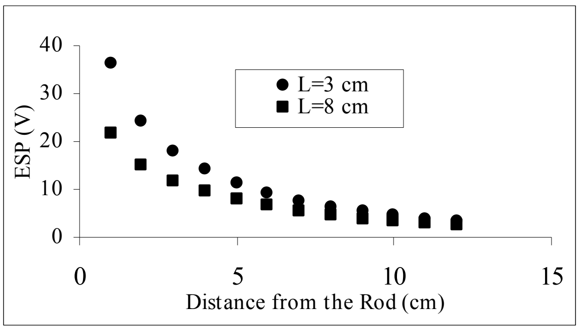

Figure 15: Effect of rod length on the ESP ($D= 5mm$, $H = 3cm$, $\rho_1=7.63\Omega.m$, $\rho_2 =3\Omega.m$,TLT =15cm and DC Voltage)

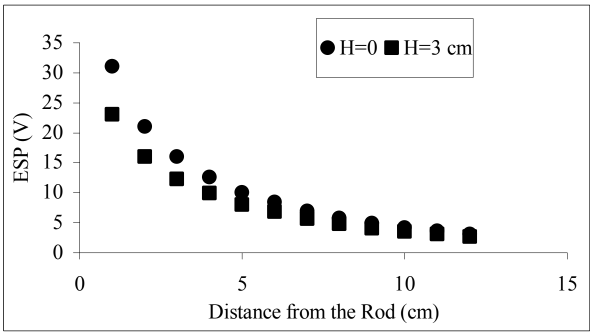

Figure 16: Effect of rod depth on the ESP (L= 8cm, D = 3mm, $\rho_1=7.63\Omega.m$, $\rho_2 =3\Omega.m$, TLT =15cm and DC Voltage)

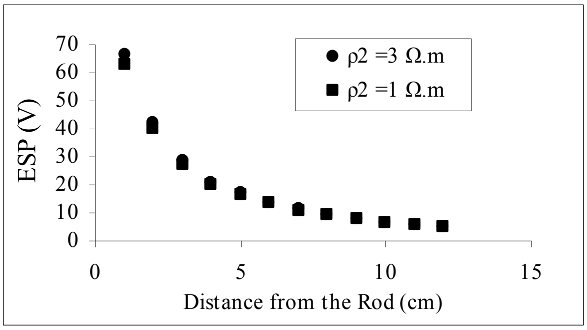

Figure 17: Effect of Bottom Layer Resistivity (ρ_2) ontheESP.
(L=3cm,D=3mm, H=0, $\rho_1=7.63\Omega.m$,TLT=25cm and DC Voltage)

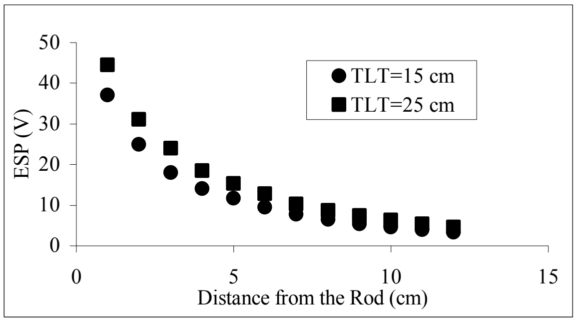

Figure 18: Effect of Top Layer Thickness (TLT) on the ESP
(L=3cm,D=3mm,H=3cm,$\rho_1=7.63\Omega.m$, $\rho_2=3\Omega.m$ and DC Voltage)

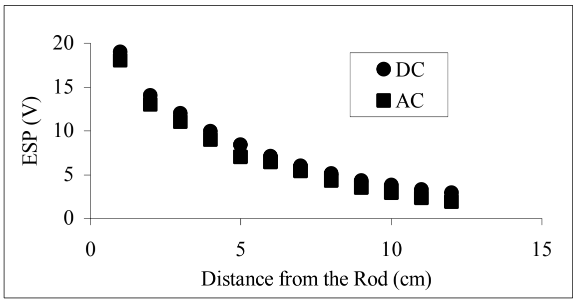

Figure 19: Effect of power supply on the ESP (L=3, D=5mm, H=3cm, $\rho_1=7.63\Omega.m$, $\rho_2=3\Omega.m$,N=6, RL=4cm and TLT =15cm)

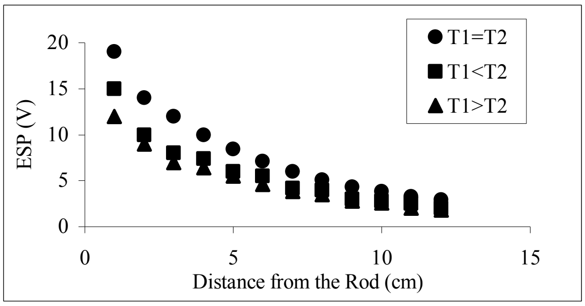

Figure 20: Effect of soil temperature on the ESP (L=5, D=5mm, H=0, ρ_1=7.63Ω.m, ρ_2=3Ω.m, N=6, RL=4cm, TLT =15cm and DC voltage)

5 VALIDATION OF THE SIMULATION

A simulation program based on the current simulation method [10] is used to calculate the ESP on the earth for real cases. To compare between the simulation and the experimental work, the scale factor is taken as 300:1, i.e the 3 cm in the experimental setup is equivalent to 9 m in the simulation code. Figure 21 presents a comparison between simulation results and experimental setup results. The performance of the two curves is almost the same, and therefore, the simulation code is a valid method for ESP calculation.

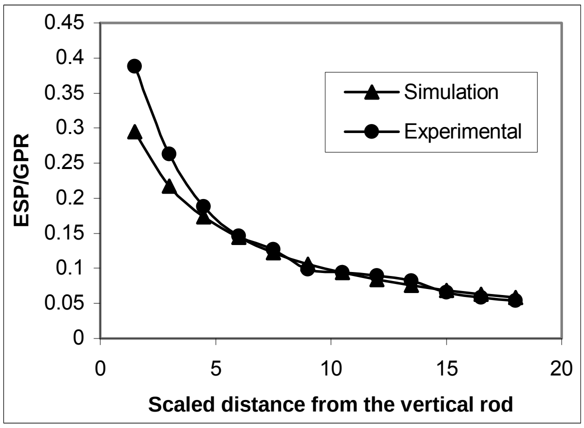

Figure 21: ESP/GPR at scaled distance from the rod for one layer soil. (L= 3cm,H = 0,ρ =7.63Ω.m and DC Voltage).

6 CONCLUSIONS

The objective of this paper is to measure the Earth Surface Potential (ESP) resulted from discharging current flow into grounding vertical rods and other different configurations using a scale model immersed in an electrolytic tank. If all dimensions of the rods and other parameters such as water resistivity are reduced by the same factor, the results given with such model can be used as guidelines for safe design of grounding systems. The water resistivity and the ESP are decreased with the increase of water temperature. The experimental work results agree with the simulation results given by the CSM. This agreement proves the validity of the simulation code.

7 REFERENCES

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