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Distribution of Electric Field InElectro Osmotic Consolidation of Soil

Yaju Sayami
Dept of Civil Engineering
Wuhan University
Wuhan, China
ysayami@gmail.com

***Abstract*-In earlier times, Electro-osmosis of soil was used to extract minerals like gold, iron etc from the soil but in recent days, electro-osmosis has been used for consolidation of soil. Electro-osmosis of soil has been a great boon in the field of geotechnical engineering. Many improvements have been brought to this field like replacing electrodes as Electro-Kinetic Geosynthetics(EKG), which has greatly reduced electric consumption. However, it still has many problems like the soil around the electrodes are found to be more consolidated and dry. In this paper, we will be discussing the different causes and solutions on how to eliminate or reduce this problem by studying the distribution of the electric field in the soil. This is a simulation-based experiment, two models with different dimension and positioning of EKG will be compared, in which distribution of the electric field will be obtained as results. By analyzing the results, the effective positioning of EKG is determined.**

***Keywords*- Electro-osmosis, Electro-Kinetic Geosynthetics, Consolidation.**

I. INTRODUCTION

Soft and saturated soil has high water content, which leads to uneven settlement when a structure is constructed over it. There are different methods to strengthen soils such as preloading, dewatering using sand drains, vacuum consolidation, chemical addition, etc.Preloading is a good technique, but it may take many years to complete this process.

The same problem occurs with additives as it requires a lot of time for the cementing phases to form and gain strength. The main disadvantage associated with sand drains is the smear zone, and also the outer surface of sand drains will be blocked by the surrounding clay particles and thus its effect gets reduced as it depends greatly on the coefficient of hydraulic permeability.

And, a sand drain also takesa couple of months to complete its action. In another hand, we have Electrokinetic dewatering using similar energy consumption as that of vacuum consolidation but with as relatively much lesser time. This method can be much more cost effective and time effective as compared to other methods.Electrokinetics and electro-osmosis are methods used for manipulating pore pressure and plasticity indices of soils.

These are one of the important methods for soil reinforcement and geosynthetics are anodes and cathodes introduced in soil structure. Applying current to the soil to induce water flow is the basic concept of electrokinetics. This technique can be used in environmental remediation wherein contaminants are recovered or removed from the soil by causing groundwater to flow to a collection point.

II. THEORY

The Helmholtz-Smoluchowski theory is one of the most used models to describe electroosmotic processes [3-4]. The Helmholtz-Smoluchowski theory basic idea is that the movement of pore water is under the balance of electric field and viscosity (Figure 1). According to Helmholtz-Smoluchowski for determining the electro-osmotic flow zeta potential(ζ) and the charge distribution in the fluid plays an important role.

Themovement of colloidal particles in the soil-liquid interface is due to electric potential(ζ)at the intersection betweenthe fixed and mobile parts of the electrical double layer. The ζ is less than the surface potential of a particle [5-6].The magnitude and sign of the ζ are dependent on the interfacial chemistry of both liquid and solid phase. His potential is additionally affectedion exchange capacity, size of ion radius, and the thickness of the double layer [8-9].

The fluid flux per unit area of the soil per unit electric gradient i.e, the electro-osmotic permeability of the soil(k_e) controllers the rate of electro-osmotic flow. The value of k_e is a function of the ζ, the viscosity of the pore fluid, the soil porosity, and the soil electrical permittivity.

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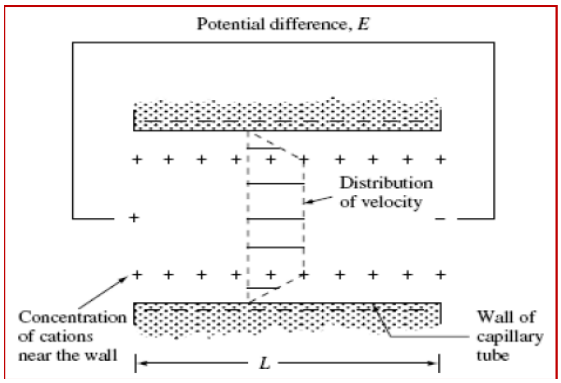

Figure.1 Helmholtz-Smoluchowski Theory for Electro osmosis.

The coefficient of electro-osmotic permeability is given by Equation (1):

$$q=\frac{\varepsilon\zeta}{V_t}n\frac{E}{L}A \qquad (1)$$

Where:
ζ = Zeta potential
Vt = Viscosity of the pore fluid
n = Soil porosity
ε = Soil electrical permittivity
A = Gross cross-sectional area perpendicular to water flow
L = Length
q = Flow rate

The Smoluchowski's equation, the most elementary expression for ζ gives a direct relation between zeta potential and electrophoretic mobility, which is (Equation (2)):

$$A=\pi r^2$$

$$\zeta=4\pi V_t\frac{EM}{D_t} \qquad (2)$$

Where:
ζ = Zeta potential
EM = Electrophoretic mobility at actual temperature
V_t= Viscosity of the suspending liquid
D_t= dielectric constant

The ζ of clay is usually negative, but the magnitude and sign of the ζ are dependent on the interfacial chemistry of both liquid and solid phase [2-7]. The ζ is directly proportional to a thickness of the double layer. As the ζ increases, the thickness of the double layer increases [5-6].
Positive ζ causes the processor of electroosmosis to happen from cathode to anode and negative ζ causes the process of electro-osmosis to happen for the anode to the cathode [2]. According to some scholars variation of ζ in clays due to pH of the clay but there was no variation of ζ was found in organic soils due to pH.So according to studies as the magnitude of ζ reduces as the acidity of soil increased. The electro-osmotic flow can almost be eliminated at ζ of zero [10-16].

The Helmholtz-Smoluchowski theory assumes the pore radii are relatively large compared to the thickness of the diffuse double layer and all of the mobile ions are concentrated near the soil-water interface. These assumptions are valid as long as soils with large pores are saturated with water. For small capillaries or unsaturated soils, the Helmholtz-Smoluchowski equation is less applicable.

Das [1] reported that Schmid in 1951 proposed a theory in contrast to the Helmholtz- Smoluchowski theory. It was assumed that the capillary tubes formed by the pores between clay particles are small in diameter and results in the excess cations would be uniformly distributed across the pore cross-sectional area (Figure 2). Based on this theory (Equation 4):

$$q=n\frac{r^2A_oF}{8V_t}\frac{E}{L}A \qquad (4)$$

Where:
r = Pore radius
A_o= Volume charge density
F = Faraday constant
n = Porosity
A = Gross cross-sectional area perpendicular to water flow
L = Length
V_t= Viscosity
q = Flow rate

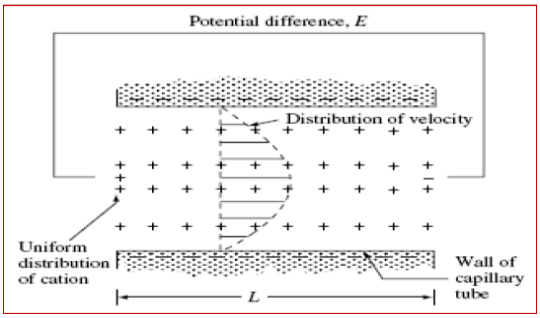

Figure.2 Schmid Theory for Electro-osmosis.

However, the most widely used electro-osmotic flow equation for the soil system is proposed by Casagrande [19] (Equation (5)):

$$q=k_e i_e A \qquad (5)$$

Where:
A = Gross cross-sectional area perpendicular to water flow
i_e= Applied electrical gradient
k_e= Coefficient of electro-osmotic permeability
q = Flow rate

Application of direct current through electrodes causes electrolysis reactions at the electrodes [10-14,17]. Oxidation of water at the anode generates an acid front and reductions at the cathode generate a base front. Electrolysis reactions are described by the Equations (6) and (7).

$$2H_2O - 4e^- \rightarrow O2 \uparrow + 4H^+ \quad \text{(anode)} \qquad (6)$$

$$4H_2O - 4e^- \rightarrow 2H_2 \uparrow + 4OH^- \quad \text{(cathode)} \qquad (7)$$

Within the first few days of electrokinetic processing, electrolysis reactions gradually decrease the pH in the surrounding of the anode and increase the pH in the surrounding of the cathode. Total applied current is directly dependent to there'scharges[11-14].

Due to electroosmosis process and ionic migration, the acid produced at the anode movies through the soil towards the cathode. And also due to diffusion and ionic migration, base produced at the cathode initially moves towards the anode. However, the counterflow becausethe electroosmosis makes slower the back-diffusion and migration of the base front.

The movement of the base front is slower than the movement of the acid front because of (i) the counteracting electro-osmotic flow and (ii) the ionic mobility of H^+ is higher than OH^-[11-16, 18]. Geotechnical reactions in the soil pore significantly impact electrokinetic phenomena and can enhance or make slower the electrokinetic process. Geomechanical reactions including precipitation, dissolution, sorption, and complexation reactions are highly dependent on the pH conditions [11-16, 18, 20-22].

III. NUMERICAL MODEL OF ELECTRO-OSMOTIC CONSOLIDATION IN CLAY

In order to find voltage distribution produced by DC current supplied to EKG material, two solid models were prepared. One will be acting as soil and other will be acting as EKG material. For modeling, SolidWorks 2013 has been used. As our experiment is comparison based experiment two different models are created.

1. Model 1

As mentioned above all the models are prepared in SolidWorks 2013. Our first model consists of two major parts. A 2m×3m×5m solid cuboids which will be our model for soil and the second one is 10cm×4mm×5m cuboids' which will be our model for EKG and Nonconductive material inserted into soil model.

2D and the 3D figure for the above-mentioned models are shown in Fig.3 and Fig. 4 Fig.3 is the 2D figure for the first model. Here dimension of two components of model andpositioning of EKG material in the soil is shown. As you can see in Figure3 soil model is 3m×2m and two EKG models of 10cm×4mm have been placed 1m apart from each other and also 1m from two sides of soil. Fig.4 is a 3D diagram of the first model. First 3D model of soil is shown in the Fig.4 As you can see in Fig.4 soil model of 2m×3m×5m two 10cm×4mm is extruded throughout the soil model.

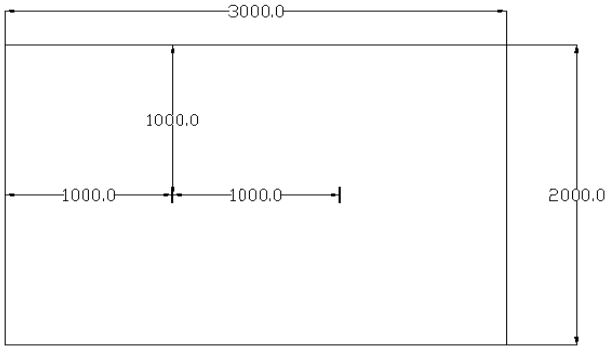

Figure.3 (2D figure for Model1).

Another figure is of EKG and nonconductive material of 10cm×4mm×1m, five of these componentsare assembled to form a single strip of 10cm×4mm×5m as shown in Fig.4 So the second model is composed of five components where the top, middle and the bottom layer is assigned as EKG material and two components in-between EKG materials are assigned as Nonconductive (NC) materials. So finally this two stripis inserted into the first soil model andour final model is formed.

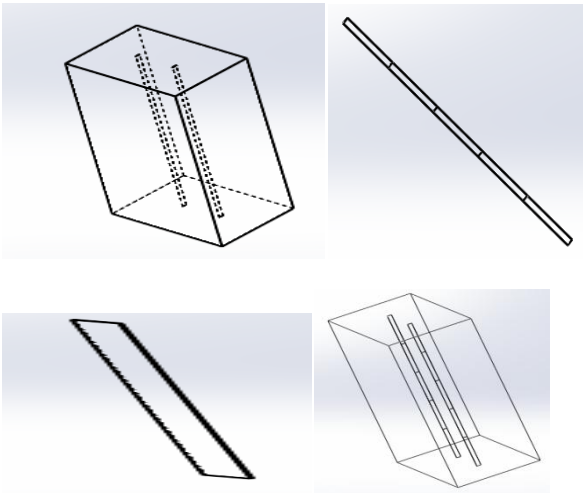

Figure.4 (3D figure for Model1)

2. Model 2

As mentioned above all the models are prepared in SolidWorks 2013. Our second model also consists of two major parts. A 4m×7m×5m solid cuboid which will be our model for soil and the second one is

10cm×4mm×5m cuboid which will be our model for EKG and Nonconductive material.

2D and the 3D figure for the above-mentioned models are shown in Fig.5 and Fig.6. Fig.5 is the 2D figure for the second model. Here the dimension of the model and the positioning of two EKG materials in the soil is shown. As you can see in Figure2.1 soil model is 4m×7m and two EKG models of 10cm×4mm have placed 2m apart from each other and also 2m from two sides of soil.

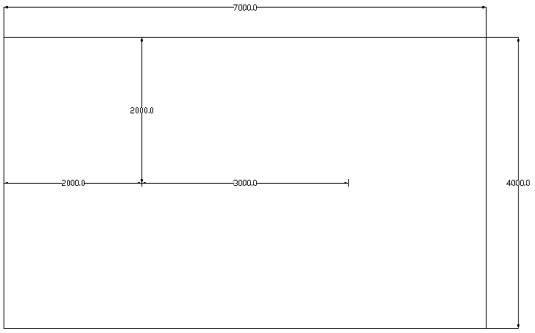

Figure.5 (2D figure for Model2).

Figure6 is a 3D diagram of the second model. First 3D model of soil is shown in the Figure6. As you can see in Figure6 of soil model of 4m×7m×5m two 10cm×4mm is extruded throughout the soil model. Another figure is of EKG and nonconductive material of 10cm×4mm×1m, five of these models are assembled to form a single strip of 10cm×4mm×5m as shown in Figure6. So the second model is composed of five components where the top, middle and the bottom layer is assigned as EKG material and two components in-between EKG materials are assigned as Nonconductive (NC) materials. So finally this two stripis inserted into the first soil model and our final model is formed.

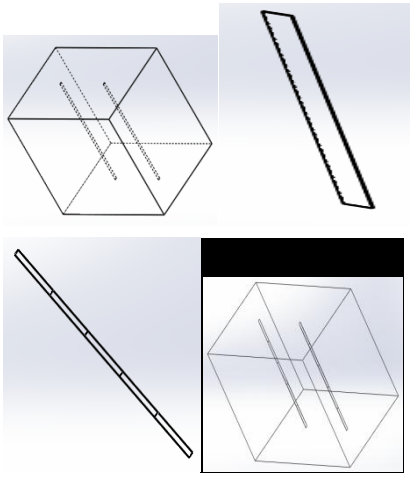

Figure.6 (3D figure for Model2).

IV. ASSIGNING BOUNDARY CONDITION AND THE PROPERTIES OF MATERIALS

In this experiment basically, three physical properties of the material are assigned. Those three physical properties are Density (kg/m^3), Isotropic Elasticity and Isotropic Resistivity (ohm m). So, values of these properties of soil, EKG and nonconductive materials are listed in the table below. Properties of material were assigned to the respective materials.

Table 1 physical properties are Density.

Material/Properties	Density(kg/m^3)	Isotropic Elasticity		Isotropic Resistivity(ohm m)
		Young's Modulus(Pa)	Poisson's Ratio	
Soil	1600	5000	0.45	30
EKG	1600	5000	0.45	10×10^{-3}
Non-Conductor	1600	5000	0.45	10×10^{10}

V.BOUNDARY CONDITION

Before carrying out simulation it is important to set boundary parameters. Here boundary condition is related to potential difference or voltage. So, the periphery of the soil material is at zero potential and EKG is supplied to a different voltage in different layers. As we have seen in Figure4 and Figure6 EKG strip consist of five layers among which there are EKG material and rest two are Non-conductor. EKG at top, middle and bottom layer is applied with 0V, 40V, and 80V respectively. Non-Conductor placed in-betweenof EKG isn't applied with any kind of voltage as they are acting as an insulator between two EKG materials.

VI.RESULT

1.Construction prior to obtaining results

Before caring out simulation for obtaining theresult, certainconstructionsare made in the ANSYS. For the first model having a dimensionof 2m×3m×5m, five surfaces (say it as a plane) are constructed along Z-Y Axis and at every 0.5m along X-Axis as shown in Figure7. Naming these planes as Plane1, Plane2, Plane3, Plane4 and Plane5 at 0.5m, 1m, 1.5m, 2m and 2.5m along X-Axis respectively.

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Further constructing 11 lines along these planes from bottom to top of the model. Each line is constructed at every 0.2m interval of the plane as shown in Figure8. Also constructing 3 planes along X-Z Axis at ever 0.5m along Y-Axis Figure9.Naming these planes as Plane6, Plane7 and Plane8 Further constructing 16 lines along these planes from bottom to top. Each line is constructed at every 0.2m interval of the plane as shown in Figure10.

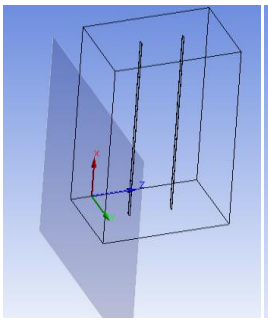

Figure 7

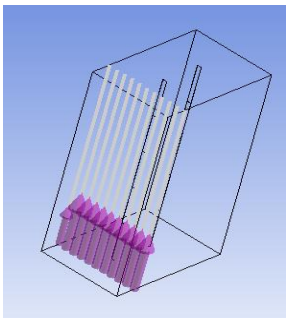

Figure 8

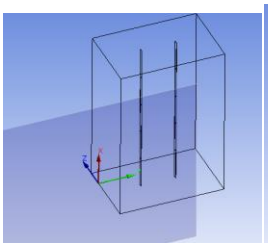

Figure 9

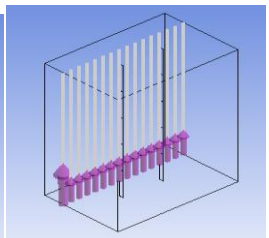

Figure 10

Similarly, certain construction was made for the second model. Six surfaces (say it as a plane) are constructed along Z-Y Axis and at every 1m along X-Axis as shown in Figure11.Naming these planes as Plane9, Plane10, Plane11, Plane12, Plane13 and Plane14 at 1m, 2m, 3m, 4m, 5m and 6m along X-Axis respectively.Further constructing 11 lines along these planes from bottom to top of the model. Each line is constructed at every 0.4m interval of the plane as shown in Figure12. Also constructing 3 planes along X-Z Axis at ever 1m along Y-Axis Figure13.Naming these planes as Plane15, Plane16 and Plane17 Further constructing 11 lines along these planes from bottom to top. Each line is constructed at every 0.7m interval of the plane as shown in Figure14.

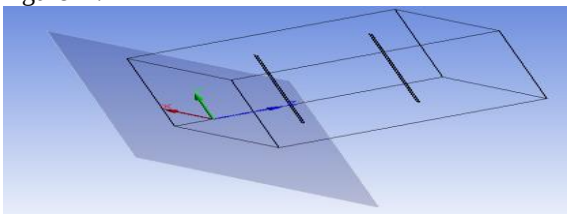

Figure11

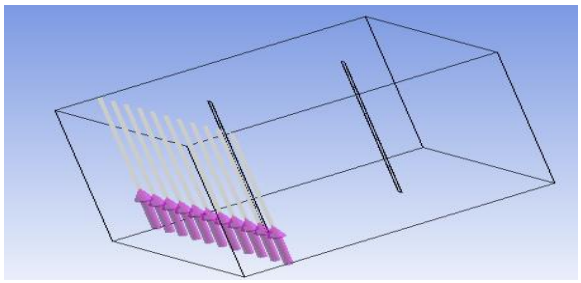

Figure12

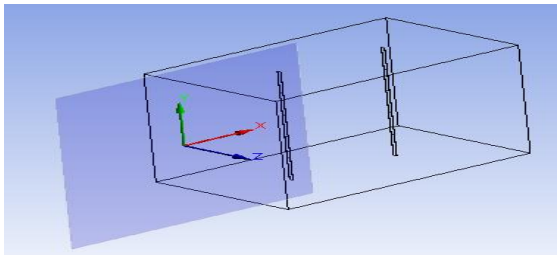

Figure13

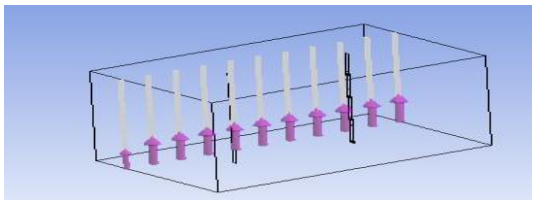

Figure14

VII.ELECTRIC VOLTAGE DISTRIBUTION

As mention above all the boundary conditions are applied and simulation is carried out. As a result of applying different voltage along EKG material voltage have been distributed throughout the model. Voltage along line constructed along the plane was exported to excel and with these voltages contour for voltage were plotted in Auto CAD.

1. Model 1

Figure obtained from ANSYS and Auto CAD drawing for voltage distribution along plane 1,2,3,4,5,6,7 and 8 is shown below. The first figure is obtained from ANSYS which show the distribution of voltage in along actual plane while simulation.

Here you can see maximum and minimum values of voltage on the left side and on the right side different colors indicating the voltage on the plane. The second figure is also showing the distribution of voltage but here a detail view of voltage distribution could be seen. In second figure counter line for voltage are drawn which is drawn in the interval of every 1V.

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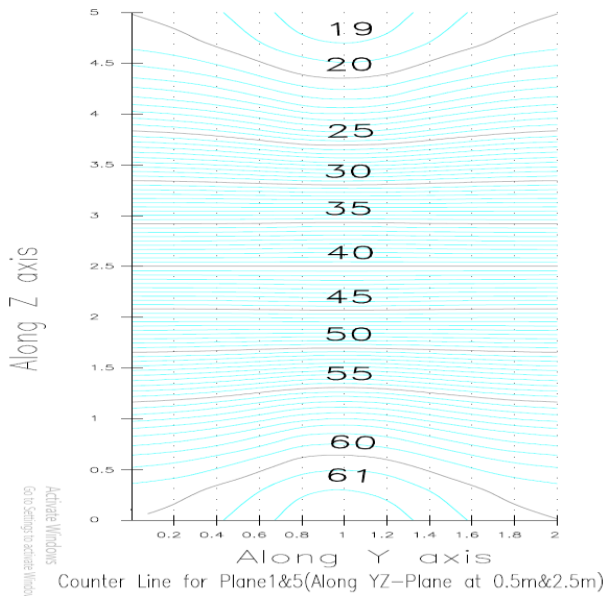

Figure15. (The figure for Voltage Distribution From Auto CAD For Plane 1 and 5.).

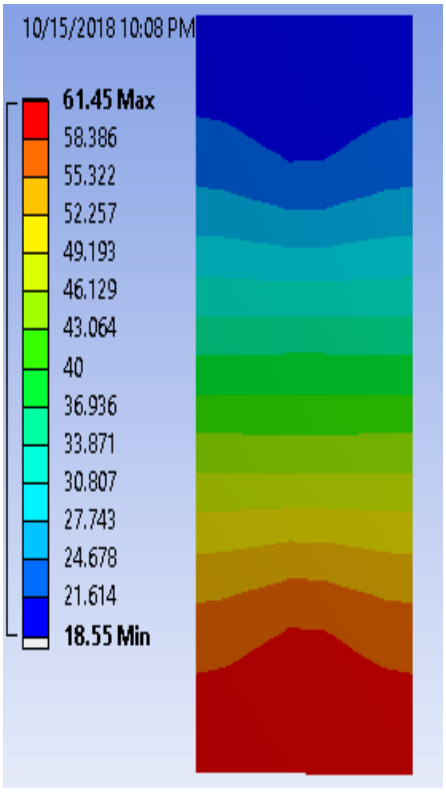

Figure16. (The figure for Voltage Distribution From Ansys For Plane 1 and 5.)

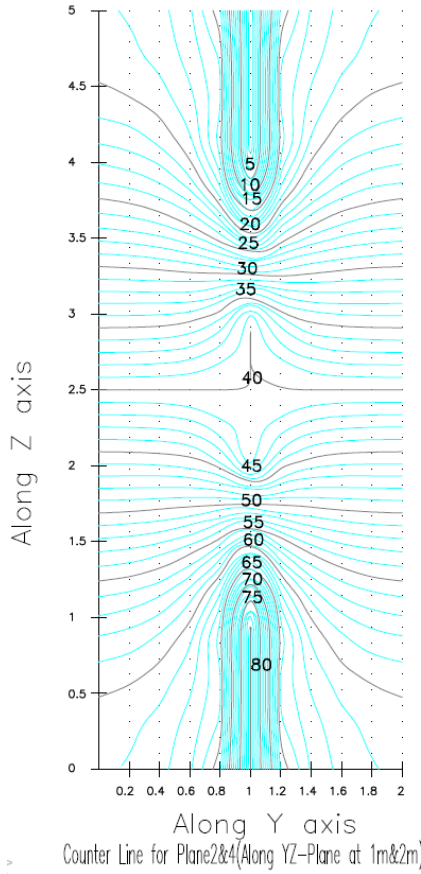

Figure17. (The figure for Voltage Distribution From Auto CAD For Plane 2 and 4.)

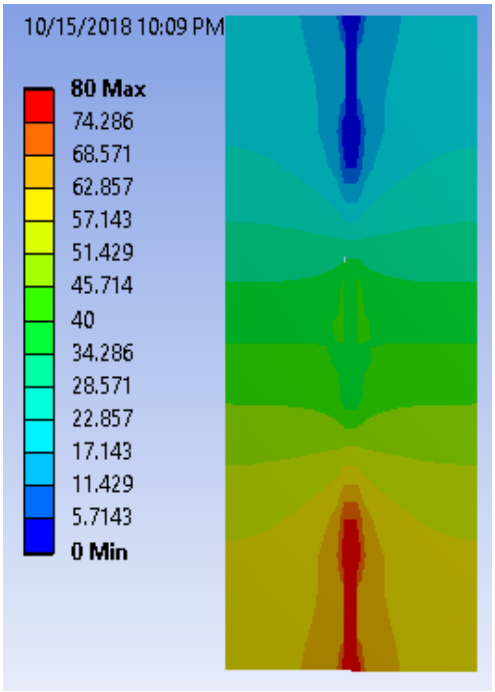

Figure18. (The figure for Voltage Distribution From Ansys For Plane 2 and 4.)

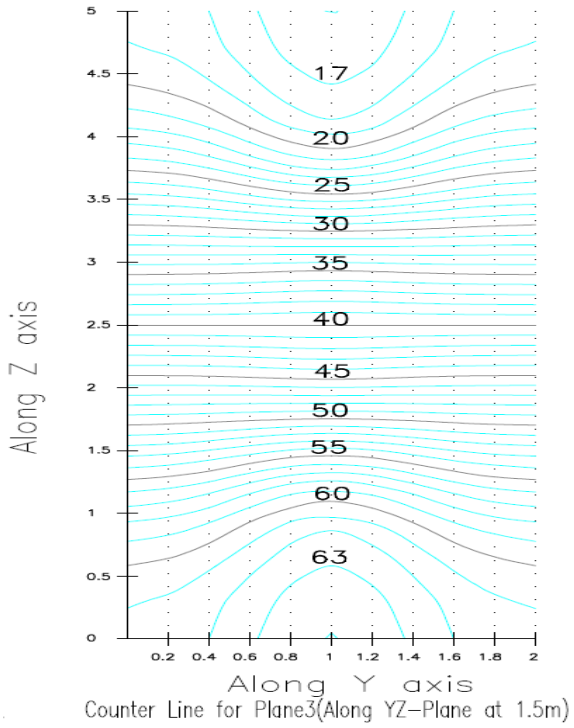

Figure19. (The figure for Voltage Distribution from Auto CAD for Plane 3.)

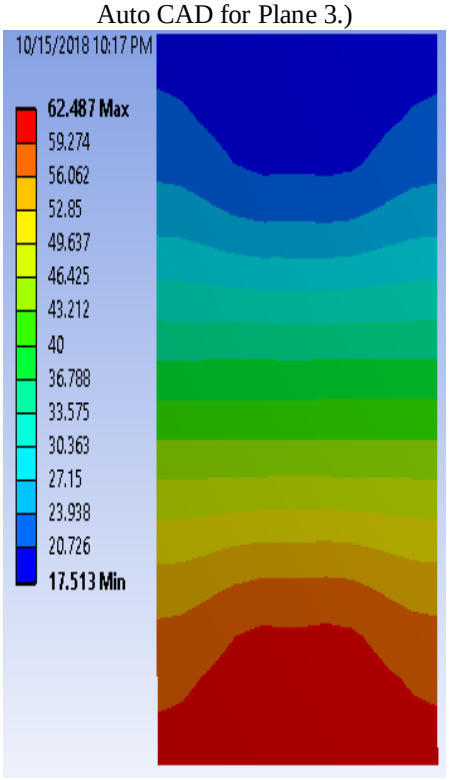

Figure20. (The figure for Voltage Distribution From Ansys For Plane 3)

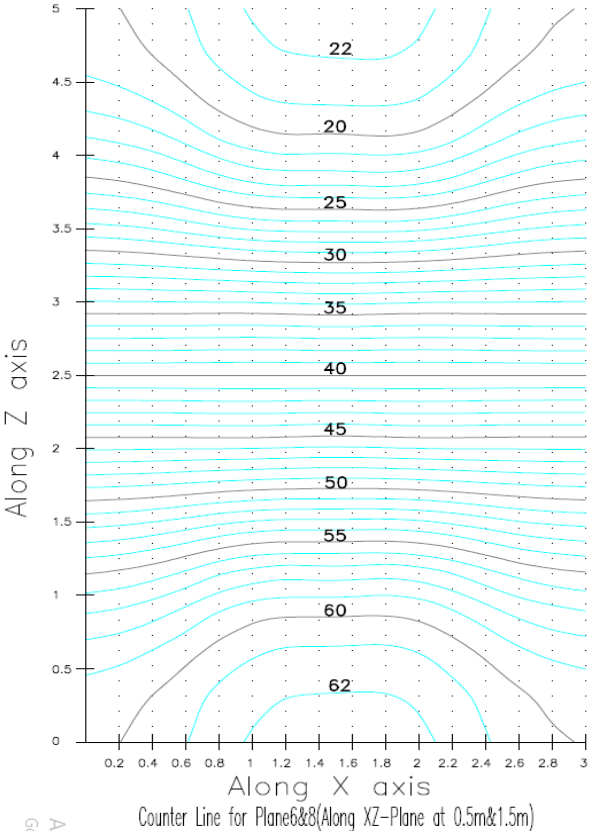

Figure21. (The figure for Voltage Distribution From Auto CAD For Plane 6 and 8.)

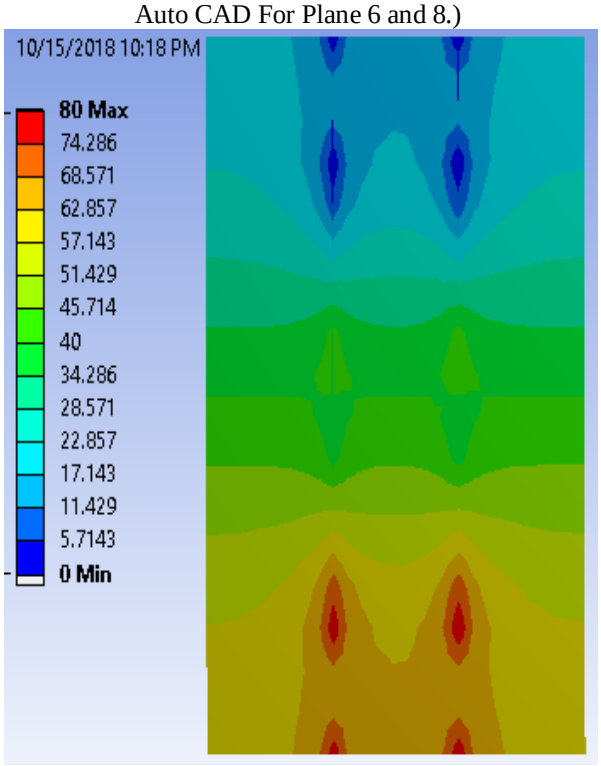

Figure22. (The figure for Voltage Distribution From Ansys For Plane 6 and 8.)

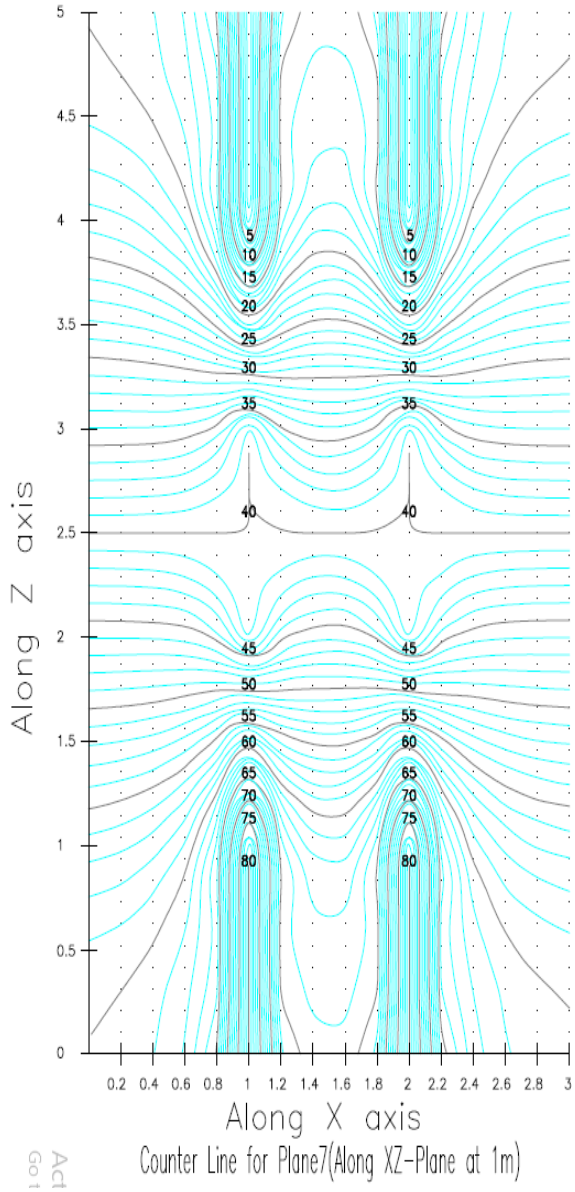

Figure23. (The figure for Voltage Distribution From Auto CAD For Plane 7.)

2. Model 2

Figure obtained from ANSYS and AutoCAD drawing for voltage distribution along plane 9, 10,11,12,13,14,15,16 and 17 is shown below. The first figure is obtained from ANSYS which show the distribution of voltage in along actual plane while simulation. Here you can see maximum and minimum values of voltage on the left side and on the right side different colors indicating the voltage on the plane.

The second figure is also showing the distribution of voltage but here a detail view of voltage distribution could be seen. In second figure counter line for voltage are drawn which is drawn in the interval of every 1V.

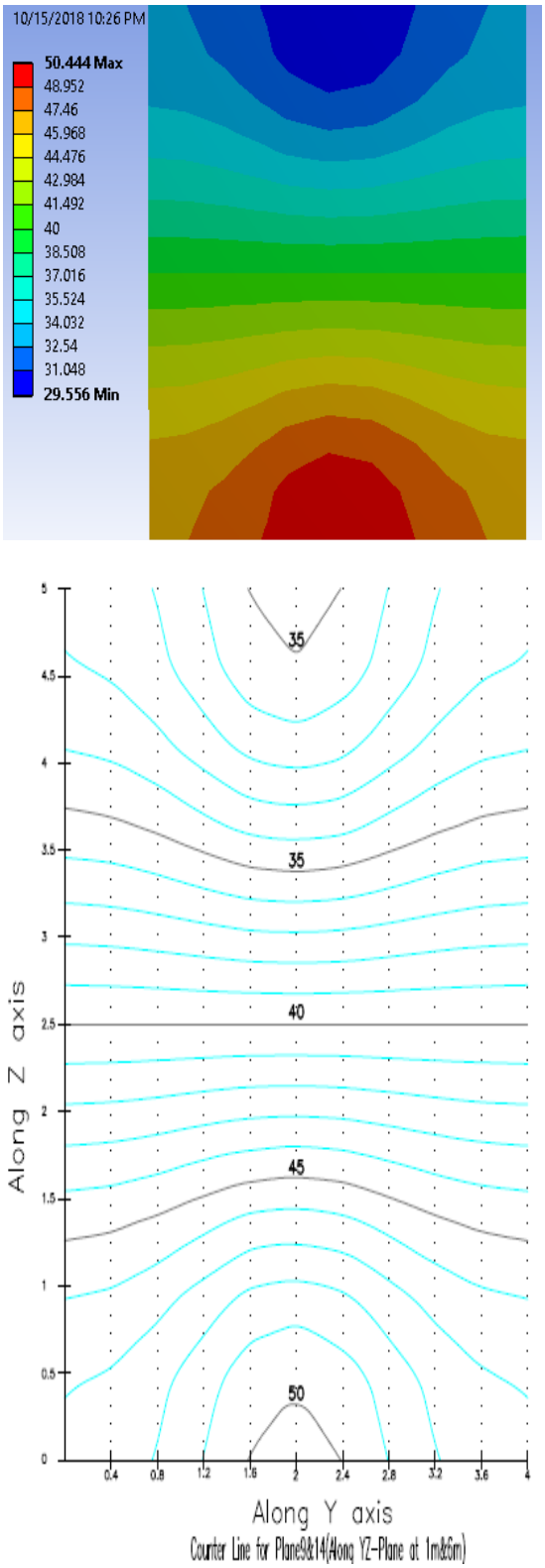

Figure24. (The figure for Voltage Distribution From Ansys and Auto CAD For Plane 9 and Plane14.)

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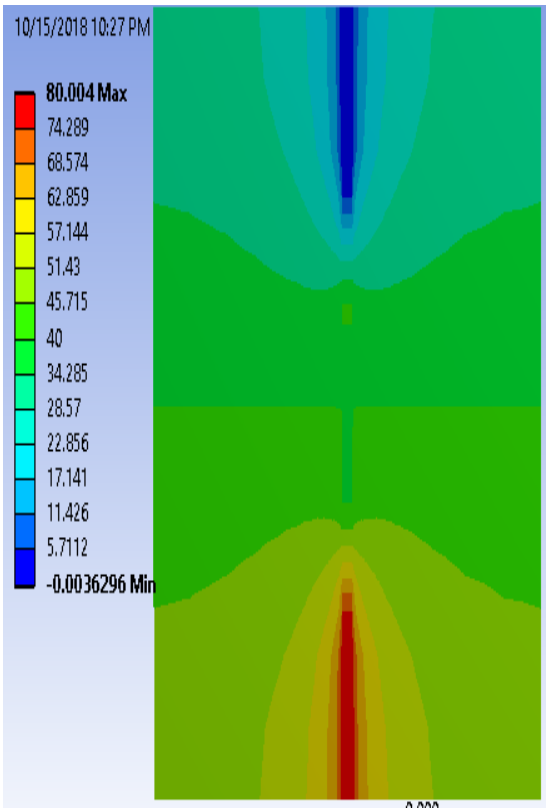

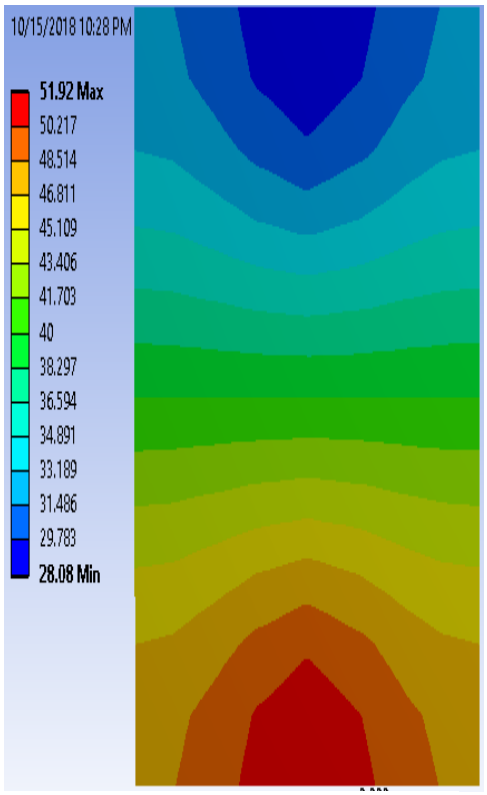

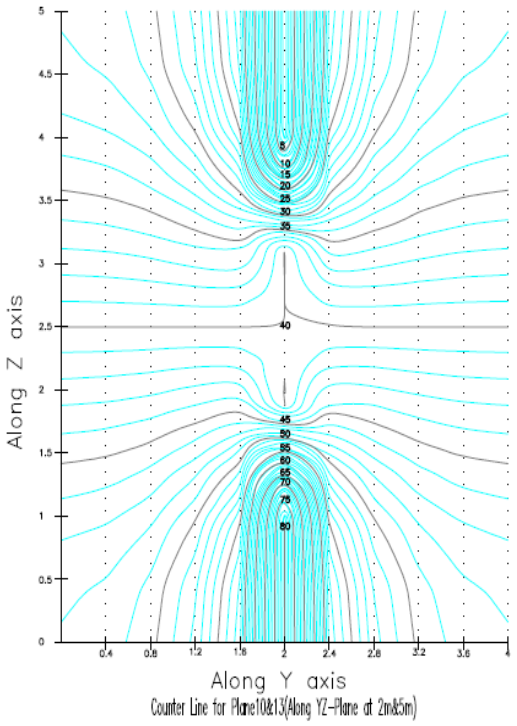

Figure25. (The figure for Voltage Distribution From Ansys and Auto CAD For Plane 10 and Plane13.)

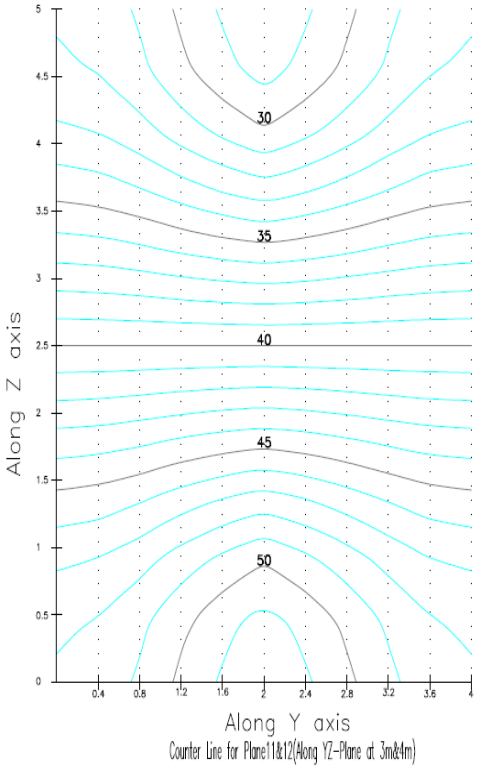

Figure26. (The figure for Voltage Distribution From Ansys and Auto CAD For Plane 11 and Plane12.)

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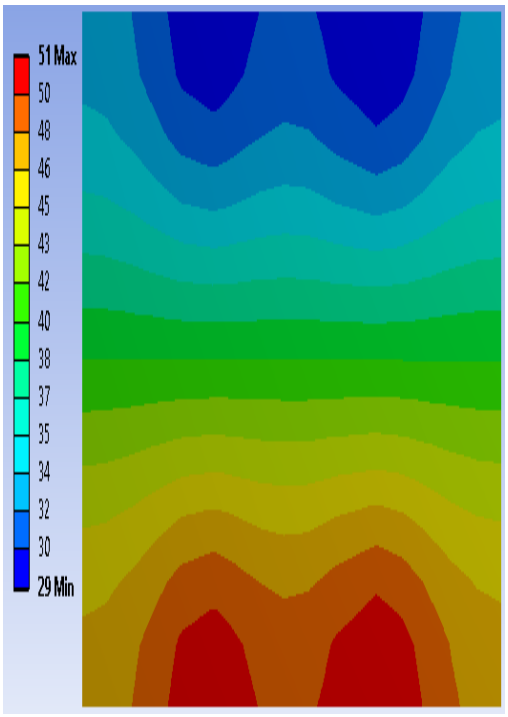

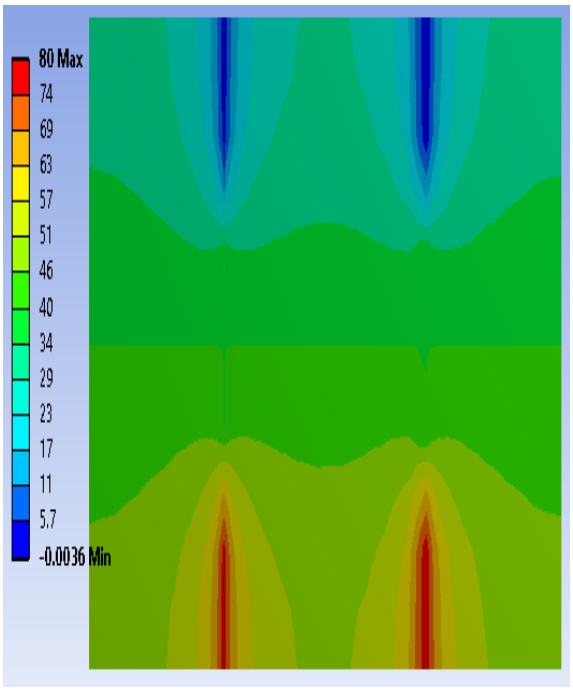

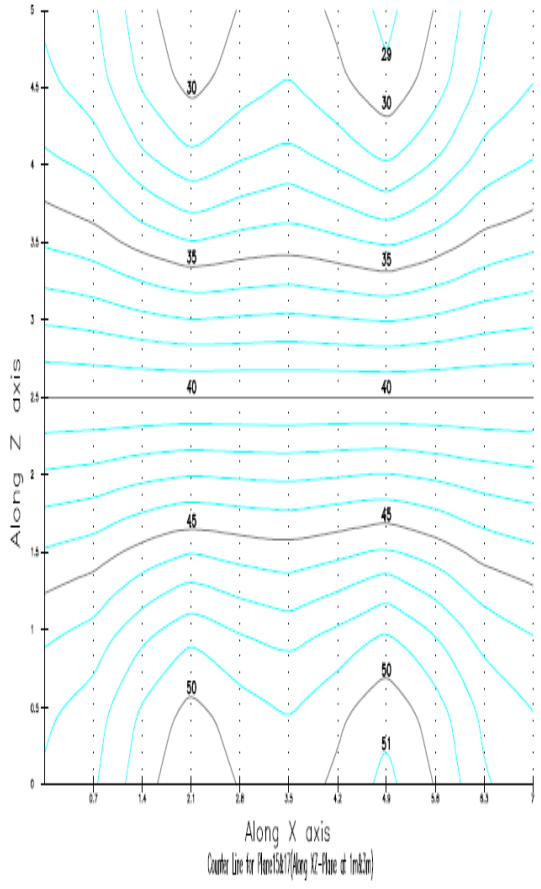

Figure27. (The figure for Voltage Distribution From Ansys and Auto CAD For Plane 15 and Plane17.)

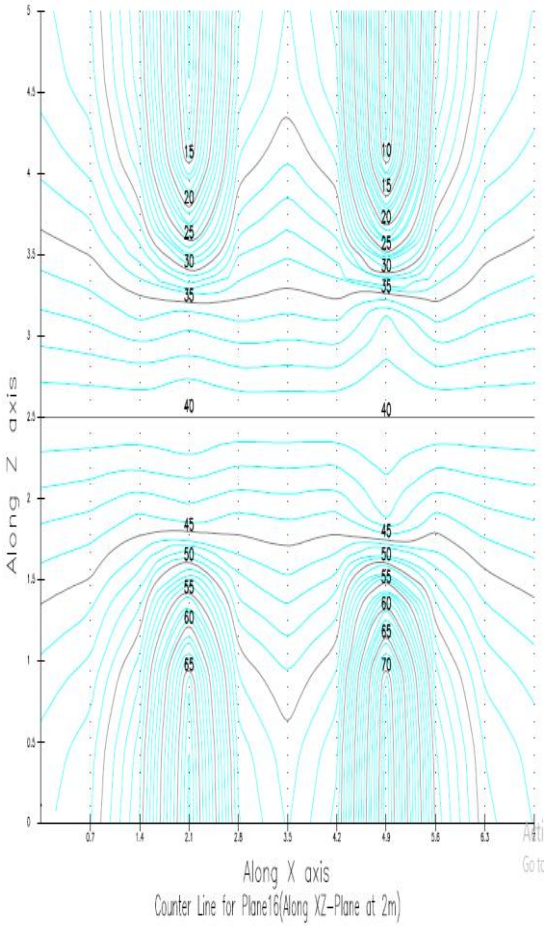

Figure28. (The figure for Voltage Distribution From Ansys and Auto CAD For Plane 16.)

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VIII. CONCLUSION

As you can see in the results above. In model 1 intensity of voltage is concentrated at the positions of the electrodes. Voltage is densely concentrated for 0.8-1.2m which is 0.4m of densely concentrated voltage. Also in model 2 voltages are densely concentrated along positions of electrodes but the densely concentrated voltage ranges from 1.6-2.4m which is 0.8m of densely concentrated voltage which is a double area that from model 1.Also, distribution of voltage in model 2 is much more uniformly distributed as compared to model 1. By observing above results it can be concluded the soil near electrodes are more consolidated as the voltage is densely concentrated at the position of electrodes. Also, model 2 i.e in placing electrodes 3m apart has more coverage of the area of voltage, whereas in model 1 most of the voltage is concentrated at electrodes which are the wastage of current. So, from the aboveresults, it can be clearly seen that placing electrodes 3m apart is much more effective than placing electrodes 1m apart. This way the total no of electrode need is reduced and also the effectiveness of the electro-osmosis is also increased as the distribution of voltage seen much more uniform in the model 2.

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