A NEW APPROACH FOR ANALYSIS OF NONCONVENTIONAL GROUNDING INSTALLATIONS BY MEANS OF FEM

G. Ts. Velev[1*], A. Weinläder[2], S. Tenbohlen[2], P. K. Petrov[1]
[1]Technical University of Gabrovo,4 Hadji Dimitar str., 5300 Gabrovo, Bulgaria
[2]University of Stuttgart, 47 Pfaffenwaldring, 70569 Stuttgart, Germany
*Email: g_velev@tugab.bg; g.velev@gmail.com

Abstract: Grounding installations with electrodes encased in current-conductive medium (in most of the cases concrete with current-conductive ingredients inside) are more and more often met for application in high voltage electrical power facilities, such as power substations and power plants, where the soil resistivity has inadmissibly high values or there is an increased risk of electrochemical electrode corrosion. Since the conventional grounding installations analysis and design are performed easily by analytical calculations or via specialized commercial software products, the same is not valid for grounding installations with conductive medium incased electrodes. In such cases the FEM implementation is an excellent approach for modeling and design of this nonconventional type of grounding installations regardless of the engaged electrodes type, their configuration and geometry. Furthermore, using FEM it is easy to investigate the respective grounding installation behavior in fault situations e.g. calculation and graphical interpretation of earth surface voltage distribution, maximum step- and touch-voltages calculations in case of short circuits etc. The procedures and studies presented inhere are performed for single conductive concrete encased electrodes but the same approach is suitable for design of overall grounding installations involving conductive concrete encased electrodes.

1 INTRODUCTION

Numeric methods such as “Finite elements” are suitable for modeling of conductive concrete encased grounding electrodes and overall grounding installations, using their geometrical dimensions and the respective predefined soil model.

In the scientific society there are numbers of authors who have performed FEM modeling and analysis of conventional grounding grids and single electrodes [1-6]. However, regarding grounding installations with electrodes encased in conductive concrete, there are almost no available analytical and practical methods for their design and analysis.

The paper presented inhere discusses a simple approach for FEM modeling and analysis of single conductive concrete encased grounding electrodes, which is applicable for entire grounding grids regardless of their shape and configuration in uniform, two-layer or multilayer soils. Furthermore the approach proposed in that paper allows easy calculation of the most important grounding grid parameters regarding the electrical safety - grounding resistance, earth surface voltage distribution, step and touch voltages.

2 FEM MODELS DESCRIPTION AND THEIR APPLICATION

2.1 Background

The most important step in determining the size and the layout of an AC substation grounding installation is to estimate its resistance to ground. The commercial software product ANSYS® is used for FEM modeling. In order to calculate grounding resistance by simulations, one of the following methods have to be involved [2, 3, 7]

A. Electrostatics Analysis - The electrostatics analysis requires the ANSYS calculation of the stored energy from the electric field into the Earth

$$W = \frac{1}{2} C \cdot U^2 \tag{1}$$

Having in mind that the soil medium capacitance for arbitrary configuration is:

$$C = \frac{\varepsilon}{\sigma \cdot R} \tag{2}$$

The following equation (3) in agreement with (1) and (2) allows us to determine the resistance to ground, once the stored energy from the electric field into the Earth is calculated by ANSYS.

$$R = \frac{\varepsilon \cdot U^2}{2 \cdot \sigma \cdot W} \tag{3}$$

Normally the soil model for AC grounding installations is characterized only by its resistivity ρ_S, $\Omega.\mathrm{m}$. In such cases the absolute soil permittivity ε is neglected (for low system frequencies - 50 HZ) and therefore the electrostatics approach is not the most suitable one.

B. Current flow analysis - The pure electrical conduction effects in soil when electrical current is flowing into the earth through a metal electrode could be modeled easily using FEM. Grounding resistance in that case is determined from the voltage *U* and the power *P* dissipated in soil:

$$R = \frac{U^2}{P} \tag{4}$$

The dissipated power is defined by:

$$P = \int_V E \cdot J dV = \int_V \sigma \cdot E^2 dV = \int_V \frac{E^2}{\rho_S} dV \tag{5}$$

where: J = current density (A/m^2);
ρ_S = soil resistivity (Ω.m);
σ = soil conductivity (S/m);

2.2 Conductive concrete encased electrodes FEM models description

Using the current flow analysis approach and its implementation in ANSYS it is very easy to take into consideration the characteristics of the soil, its stratification, the conductive concrete encasement resistivity etc. Grounding installations with arbitrary geometry and electrodes shape could be modeled and examined. The presumptions that are to be made are as follow:

- ✓ All metal parts of the grounding installation have the same potential. Normally that potential is applied as boundary condition and its value could be arbitrary set;
- ✓ The soil volume surrounding the respective grounding electrode/s is presented as hemisphere with appropriate dimension;
- ✓ Soil is assumed to be isotropic and uniform;
- ✓ The hemispherical volume of soil that represents the appropriate soil model is assumed to have a radius of 20 m (When a fault current is injected into the earth, the soil surface voltage distribution changes following a hyperbolic law. The surface potential is higher in proximity of the place where the current is injected and it decreases when the distance form the place of injection is increased. At infinite distance the earth surface potential becomes $\varphi = 0$ V. Practically, the earth surface potential becomes 0 V independent on the current intensity for distances exceeding 15 - 20 m away from the current injection point);
- ✓ The electrical field caused by the fault current flowing through the grounding electrode and the soil is represented in FEM using the electrical scalar potential φ by Poisson's equation (6) and boundary condition (7):

$$-\nabla\left(\sigma \cdot \nabla\varphi\right) = 0 \tag{6}$$

$$\varphi = 0 \; (x \to \infty), \text{ where } \frac{\partial\varphi}{\partial n} = 0 \tag{7}$$

where: σ = electric conductivity (S/m);
φ = electric scalar potential (V).

A. Vertical grounding electrodes - The vertical electrodes modeled with ANSYS and their actual dimensions and parameters are illustrated in Fig.1.

As soon as the problem has axial symmetry, it is solved using 2D FEM axi-symmetrical modeling.

In 2D that hemispherical soil volume projection over the x-y plane is a semi-circle. Because of the axial symmetry only one half of the model is considered.

The materials' electromagnetic properties (for the electrode, soil, conductive concrete etc.) are represented only by the respective resistivities. That assumption returns absolutely accurate results because the problem is pure electrical conduction and the electromagnetic field has only an electrical component.

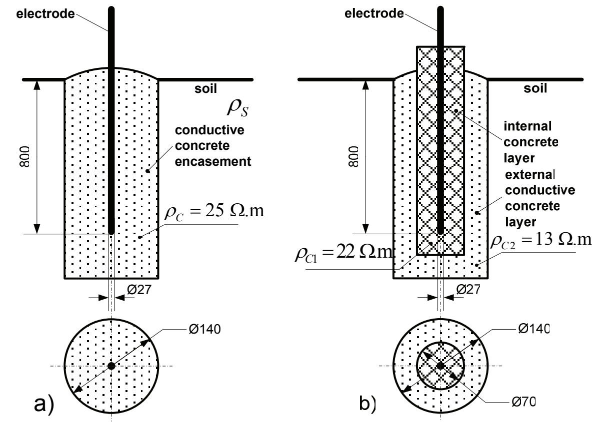

Figure 1: Vertical electrodes modeled by ANSYS: a) conductive concrete encased vertical electrode; b) vertical electrode encased in two different concentric layers of conductive concrete.

The magnetic component is neglected because the grounding electrodes' parameters are calculated for system and near system frequencies, where the soil permittivity and electrode inductance are negligible and therefore they are not taken into consideration.

In order to enhance the numerical calculation accuracy a couple of mesh refinements are performed. The mesh size is chosen to be very fine at near proximity to the electrode where the current density is the highest and respectively coarser in proximity to the boundary, where the potential gradient gets small.

The electrode material resistivity for zinc-plated steel is set to $1,611.10^{-7}\ \Omega.\text{m}$. The soil resistivity value is 52,6 $\Omega.\text{m}$ according to the predefined uniform soil model.

The applied voltage on the electrode could be arbitrary and it is chosen to be 10 kV for all simulations.

The setup with the meshed geometry and the respective boundary conditions is illustrated in Fig.2.

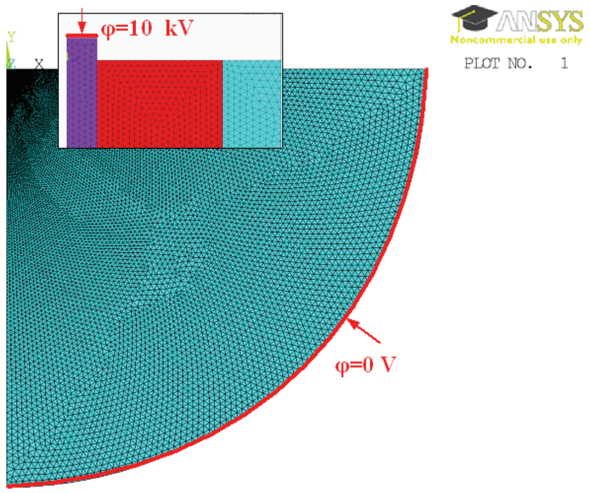

Figure 2: Vertical concrete encased electrode modeled by ANSYS – generated mesh and set boundary conditions.

- **Defining and calculating the resistance to ground in 2D geometry by ANSYS**

Per definition the resistance to ground R_G is equal to the voltage of the grounding grid during a fault over the flowing current through it.

$$R_G = \frac{U_G}{I_G},\ \Omega \tag{8}$$

As the Voltage of the grounding electrode $U_G = 10\ \mathrm{kV}$ is applied to it as a FEM model boundary condition, the only unknown quantity is the current I_G flowing through the electrode. That current is obtained using the ANSYS post processing module using the calculated by the program results for the current density $\vec{J}$. The governing integral dependence for the current then is as follow:

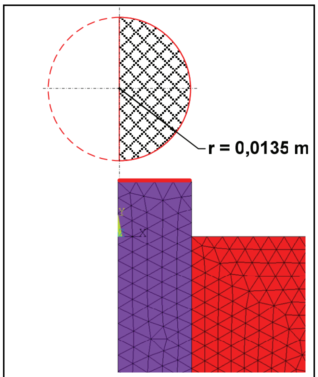

Figure 3: FEM setup for calculation of the current, flowing through the electrode.

$$I = \oint \vec{J}_N\ dP = 2\pi \cdot \int_0^r r \cdot \vec{J}_N\ dr \tag{9}$$

where: $\vec{J}_N$ = component of the current density, normal to the face area of the electrode, where the boundary voltage is applied (A/m^2);

P = electrode cross-section area (m^2).

The results obtained from ANSYS for the current distribution across the electrode cross-section area are displayed in Fig. 4.

The current flowing through the electrode then is taken from Fig. 4 for the actual value of the rod radius – 0.0135 m. The calculated current is $I = 221{,}792\ \mathrm{A}$.

The resistance to ground then is:

$$R_G = \frac{U_G}{I_G} = \frac{10000}{221{,}792} = 45{,}09\ \Omega\,.$$

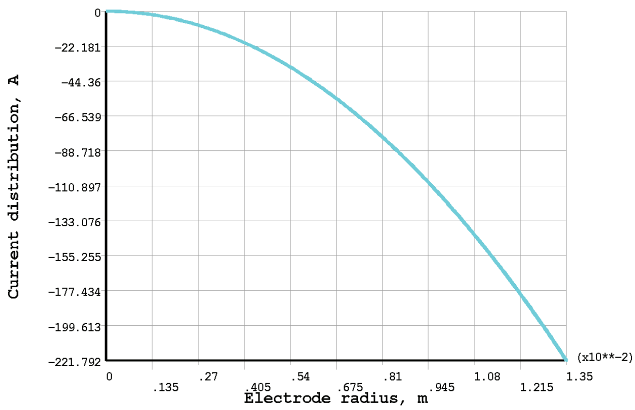

Figure 4: Current distribution in direction normal to the cross-section area of the electrode.

B. Horizontal grounding electrodes **-** The application of FEM for modelling of single horizontal grounding electrodes and overall grounding grids requires implementation of three dimensional (3D) problem formulation. The reason is that in such cases there is no axial symmetry regarding the modelled geometry and the two dimensional assumption is not applicable.

A horizontal bar type conductive concrete encased electrode modeled with ANSYS and its actual dimensions and parameters are illustrated in Fig. 5.

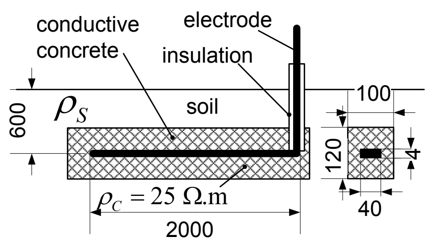

Figure 5: Conductive concrete encased horizontal bar-type electrode modeled by ANSYS.

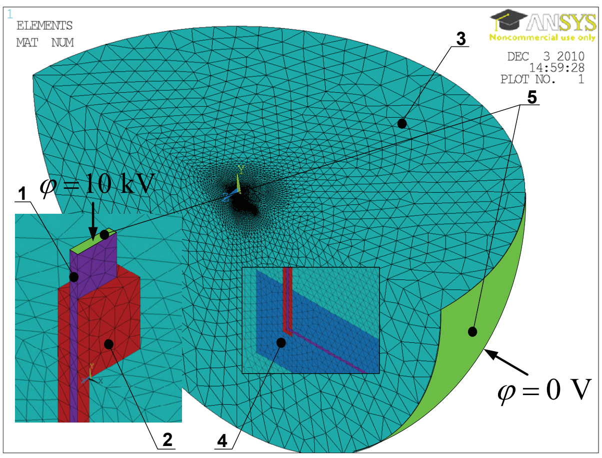

Figure 6: 3D model geometry meshing and set boundary conditions for conductive concrete encased horizontal bar-type electrode, where: 1- bar type electrode, 2 - insulation, 3 - soil medium, 4

- conductive concrete encasement, 5 - areas where boundary conditions are set.

The soil environment surrounding the horizontal electrode in the 3D ANSYS model is represented by a hemisphere with a radius of 22 meters. One half of the geometry has been modeled in 3D, since in that case there is symmetry regarding the x-y plane.

In order to take into consideration only the influence of the encased horizontal bar type electrode, the vertical part of the interconnecting steel bar going up to the surface has been insulated externally according to Fig. 5 and Fig. 6 regarding the ANSYS 3D FEM model. The insulation material resistivity implemented in the FEM model is chosen to be $\rho_{INS} = 1.10^{50}\ \Omega.\mathrm{m}$ (ideal insulation).

- **Defining and calculating the resistance to ground in 3D geometry by ANSYS**

The applied voltage on the grounding electrode is the same $U_G = 10\ \mathrm{kV}$ and the current flowing through the electrode I_G is calculated by ANSYS integrating the current density component $\vec{J}_N$, normal to the electrode's cross-section over the electrode cross-section area.

The current density distribution in direction normal to the electrode cross-section area is calculated using ANSYS by means of slicing the geometry with the ANSYS working plane.

The governing integral dependence for the current then is as follow:

$$I_G = \oiint_S \vec{J}_N \ dS \tag{10}$$

Since one half of the electrode has been modeled, the current value obtained via the surface current density integration has to be doubled. The calculated current then is $I = 2 \times 222,65 = 445,3\ \mathrm{A}$. The resistance to ground is : $R_G = \dfrac{U_G}{I_G} = \dfrac{10000}{445,3} = 22,46\ \Omega$

2.3 Defining Earth surface voltage distribution around concrete encased electrodes by ANSYS

Step- and touch-voltage calculations are essential in the grounding grids design process as they are directly related with the reliable operation and personnel's safety precautions of any high-voltage facility. Step- and touch-voltages are dependent directly on the earth surface voltage distribution in the territory of the substation in a case of fault situations (short circuits, insulation failures etc.).

If short-circuit calculations are available for an arbitrary substation, it is a better assumption to apply current injected to the grounding grid ANSYS model instead of applying potential as an initial boundary condition. However only for grounding resistance calculations both assumptions are applicable.

Earth surface voltage distribution calculated by ANSYS in 2D for the vertical concrete encased electrode from Fig.1a) is presented graphically in Fig. 7 and for conductive concrete encased horizontal bar-type electrode in 3D in Fig.8.

In the case where an overall grounding installation is modeled with FEM, earth surface potential profiles are examined and respective spots violating the electrical safety step- and touch-voltage norm regulated values are determined following the same procedure.

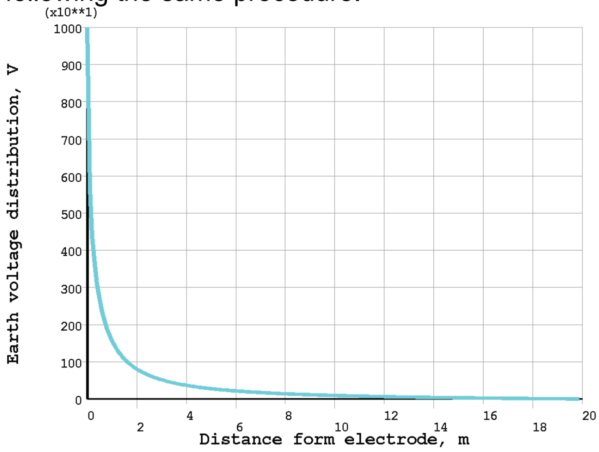

Figure 7: 2D earth surface voltage profile around single vertical conductive concrete encased electrode.

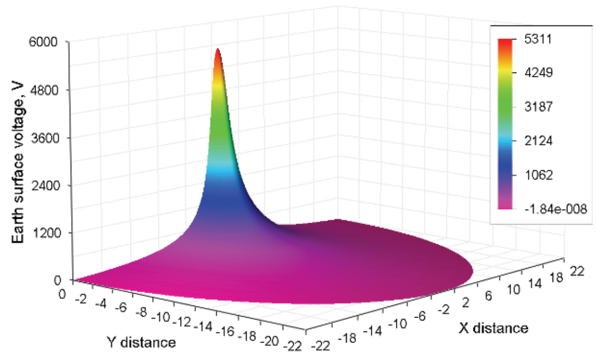

Figure 8: 3D earth surface voltage profile around single conductive concrete encased horizontal bar-type electrode.

3 DEFINING THE EFFICIENCY OF CONDUCTIVE CONCRETE ENCASED ELECTRODES BY FEM SIMULATIONS

In that study case the resistance to ground is calculated by ANSYS for all conductive concrete encased grounding electrodes according to Fig. 1 and Fig. 5. FEM simulations are performed alternatively for conventional vertical and horizontal electrodes, having the same dimensions and soil conditions as the concrete encased ones.

Grounding resistance for each conductive concrete encased electrode then is compared with the value calculated for conventional electrode with the same geometry (see Table 1).

Table 1

Type of electrode	ANSYS Results	
	Grounding resistance	Relative resistance reduction
	Ω	%
Vertical conventional	64,16	-
Vertical encased (Fig. 1a)	47,06	26,7
Vertical encased in two layers (Fig. 1b)	33,67	47,5
Horizontal conventional	24,32	-
Horizontal encased (Fig. 5)	18,79	22,7

Conclusions are made regarding the relative resistance reduction in percents achieved by encasing grounding electrodes in conductive concrete:

- ✓ When grounding electrodes are encased in conductive concrete their resistance decreases between 22,7 and 47,5 % depending on the conductive concrete conductivity and the encasement volume. If that measure is applied for real substation grounding grids the effect will be in the same range;
- ✓ It is obvious that it is more efficient to encase vertical grounding electrodes, where the resistance reduction is higher, than horizontal ones;
- ✓ However horizontal electrodes could be encased not only for reducing their resistance to ground but in order to increase their corrosion protection in fields with aggressive electro-chemical soil conditions as stated and discussed in details according to [8];
- ✓ If conductive concrete with resistivity $\rho_{C2} = 13\ \Omega.\mathrm{m}$ is used to encase grounding installation electrodes, the resistance reduction reaches stable (45 – 50) % in dependence on the respective geometry (the developed conductive concretes' properties are discussed in [9]).

4 CONCLUSIONS

- ✓ The FEM approach described inhere is a suitable tool for modeling and analysis of single conductive concrete encased electrodes and overall grounding installations involving this new type of electrodes;
- ✓ It could be successfully applied by engineers for grounding grids design, as it is easy to be handled with;
- ✓ The involved FEM simulations allow fast determination and localization of step- and touch-voltages with maximal intensity in the respective substation territory on the basis of earth surface potential profile analysis in fault situations;
- ✓ Calculation of grounding resistance is easy for grounding installations with arbitrary shape and dimensions;
- ✓ Grounding grid design and analysis could be performed assuming uniform soil model or two- and multi-layer soil structure, so the real anisotropic behavior of soil could be taken into consideration;
- ✓ Important advantage is the opportunity to choose between applying voltage or injecting simulated fault currents on the modeled grounding grid (or a single electrode) in dependence on the objectives followed;
- ✓ It has been verified that applying conductive concrete encasement on grounding electrodes, their resistance decreases in the range (25-50) % in dependence on the respective geometry and the conductive concrete's resistivity.
- ✓ FEM modeling and analysis could be successfully applied in validating of new analytic methods for calculation of the resistance to ground and design of nonconventional grounding installations involving conductive concrete encased grounding electrodes.

5 ACKNOWLEDGMENTS

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7 APPENDICES

Some intermediate simulations and their graphical interpretations regarding the potential, electrical field and current density distributions in soil of conductive concrete encased electrodes are illustrated in the figures below.
*The gray zones in the figures below correspond to areas where the predefined set range is exceeded.

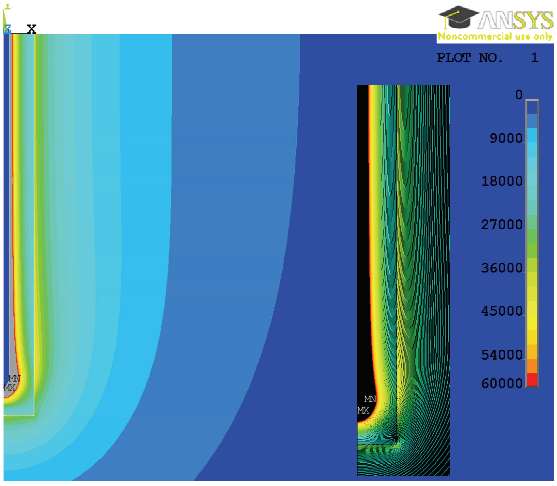

Figure 9: Electric field distribution in soil around a vertical grounding electrode encased in one layer of conductive concrete.

As could be seen from the following Fig. 10 the electrical field magnitude has a local decrease at the area defined by the second conductive concrete layer, because of its very low resistivity. Furthermore that external for the electrode concrete layer will create an effective short-circuit path for the DC stray currents into the earth. In that way the metal electrode will be galvanically protected against excessive electrical corrosion.

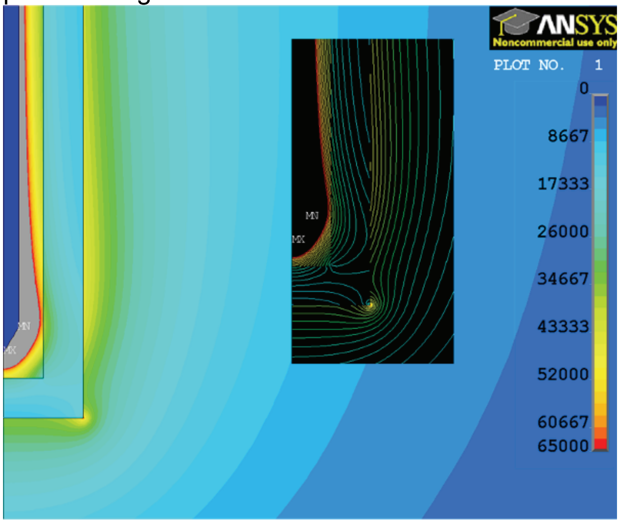

Figure 10: Electric field distribution in soil around vertical grounding electrode encased in conductive concrete in two different layers.

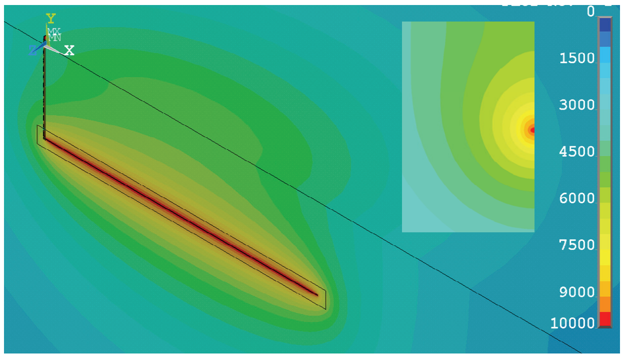

Figure 11: Voltage distribution in soil around horizontal bar-type grounding electrode encased in conductive concrete.

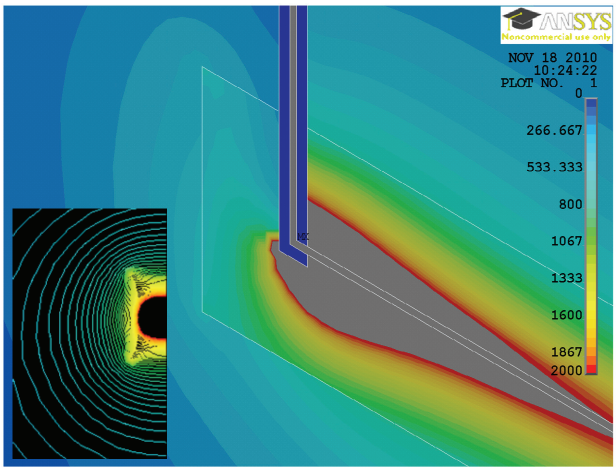

Figure 12: Current density distribution in soil around a horizontal bar-type grounding electrode encased in conductive concrete.