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Numerical Simulation of Cathodic Protection Systems for Transmission Towers with Grillage-Type Foundations

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ABSTRACT

Underground corrosion of structures in electric power transmission and distribution (T&D) lines is the primary cause of in-service equipment degradation. Each year, utility companies spend increasing amounts of their revenue on inspection and refurbishment of corroded structures, and maintenance of a large population of aging structures has become a serious engineering and economic problem. Accordingly, effective and economically feasible corrosion mitigation techniques, specifically designed for transmission infrastructure, are highly on demand.

Cathodic protection is proved to be an efficient cost-effective method to mitigate on-going corrosion in buried components of steel structures. Conventional cathodic protection design methods, which still are widely used in practice, are mostly based on empirical formulas and engineer/technician experience. Such design methods, although very useful, are not optimized and cost-effective since they fail to incorporate geometrical factors and transient design parameters, thus require the use of relatively large safety factors. In this study, a physics-based approach with modeling and experimental aspects is proposed to establish an in-depth understanding of cathodic protection system design for transmission towers with grillage-type foundations/anchors. The focus of this study is development of an electrochemical simulation tool for designing an optimum cathodic protection systems for carbon steel and galvanized steel transmission structures. Lack of precise numerical analyses on this important issue is apparent in the literature.

Keywords: cathodic protection, galvanic anodes, electrochemical simulations, underground corrosion, transmission structures

INTRODUCTION

Electrical transmission structures are composed of two sections; the aboveground section which supports the overhead conductor, and the underground section, i.e., structure foundation, that supports the aboveground section. Both aboveground and underground portions of transmission structures are subject to aging as a result of environmental and mechanical stresses; nonetheless, it is well known that the risk of material degradation is much higher at the foundation due to underground corrosion. Nowadays, electric power companies are faced with a large aging population of transmission structures, and underground corrosion has become a serious engineering and economic problem. Each year, utilities spend increasing amounts of their maintenance budget on inspection and refurbishment of corroded structures. Accordingly, effective and economically feasible corrosion mitigation techniques specifically designed for transmission infrastructure are highly on demand.

Cathodic protection is proved to be an efficient and reliable method to mitigate underground corrosion at buried members of steel structures. Cathodic protection of underground steel structures is a relatively mature subject for structures with simple geometries, such as piping systems; however, there is a lack of guidelines on design of cathodic protection systems for underground components in transmission structures. This shortcoming is mainly related to the wide range of foundation designs and the associated geometrical complexities, whereas more difficulties arise in design and optimization of cathodic protection systems for aging structures due to variations in metal-soil interfacial conditions.

It is important to mention that cathodic protection for transmission structures is a geometry-related matter; therefore, unlike pipelines, it is not possible to extend an anode bed design for a specific foundation to other types of foundations. Accordingly, in this study, a knowledge-based approach is proposed to design and optimize cathodic protection systems for buried components of transmission structures. Emphasis has been put on galvanic systems; nonetheless, the presented approach can be easily extended to impressed current systems with minimum modifications.

As shown in Figure 1, H-frame towers with guy wires are the selected structures for this study. The structures have grillage-type foundation at the footing of two tower masts and grillage-plates with two shafts at the footing of two anchors, see Figure 2 and Figure 3. Grillage foundations are selected because, firstly, they are common in transmission structures with spread footings, and secondly, due to their geometrical irregularities (edges, holes, bends and joints) design of cathodic protection system for this type of foundations is proved to be a challenge. The authors plan is to study cathodic protection systems for other types of foundation in future publications.

The proposed design process includes the following steps:

a) Three-dimensional geometry modeling or the buried structure,
b) Field survey and data collection,
c) System selection and primary calculations,
d) Finite element electrochemical modeling,
e) Optimization of anode bed design.

At the proceeding sections each of the above-mentioned design steps are discussed in more details.

Figure 1: Sample photos of guyed transmission towers

Figure 2: Tower leg footing

Figure 3: Anchor footing

CATHODIC PROTECTION SYSTEM DESIGN

The primary goal in the proposed modeling approach is to find detailed distributions of potential and current density on the buried surfaces of the structure. Such information allows to examine the performance of the cathodic protection system and modify the anode bed design in order to sufficiently polarize the structure in order to meet the NACE criteria for cathodic protection.[1]

Three-dimensional Geometry Modeling

Three-dimensional CAD models of tower foundation at mast and anchor footings are show in Figure 4 and Figure 5. The original structural drawings of the tower are used to generate these detailed geometry models. Such detailed geometry models enable precise calculation of the total surface area and evaluation of projected surface areas in different directions. Calculated surface area of buried structures are listed Table 1.

Table 1: Surface area of the grillage foundations at tower footings

Footing	Total Surface Area		Buried Surface Area		Buried Section
	ft^2	m^2	ft^2	m^2	%
Mast	143	13.3	136	12.6	95
Anchor	176	16.3	172	16.0	98

A hemisphere of soil with the radius of 3 m is selected as the electrolyte (soil) domain for electrochemical simulations. Furthermore, an infinite element domain is considered around the main domain to take account for the effects of infinite soil environment. In Figure 6, the computational domain at a mast footings is depicted. The infinite element domain forms a shell around the main domain. The physical thickness of the infinite element domain is selected to be 0.5 m; however, the equations are scaled in this domain to present an approximately 1000 times larger radius.

After selecting the size of the anodes for cathodic protection, CAD models for anodes must be included in the computational domain as well.

Figure 4: Three dimensional CAD model of mast foundation

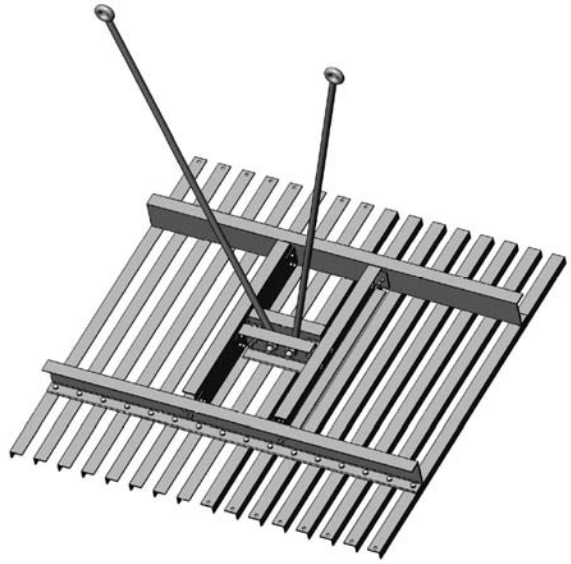

Figure 5: Three dimensional CAD model of anchor foundation

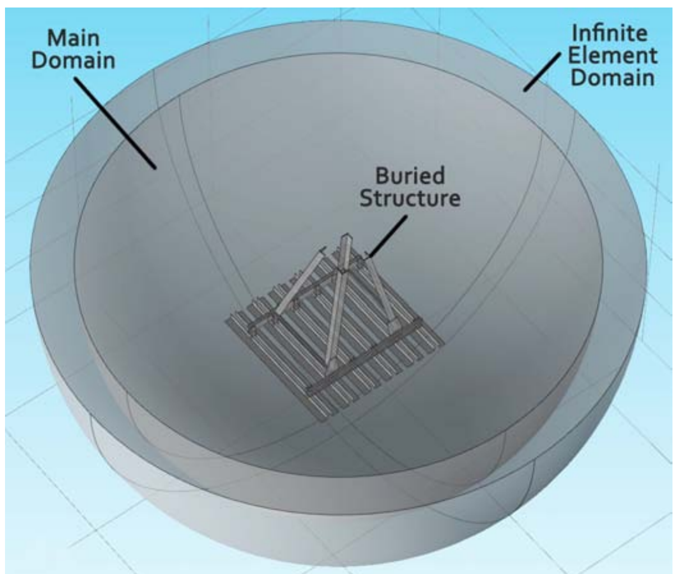

Figure 6: Configuration of the computational domain at mast footing. The aboveground portion of the footing is subtracted from the geometry

Field Survey and Data Collection

Due to variations in soil characteristics, the design of cathodic protection systems varies from one structure to another, even for structures with identical geometries. Nonetheless, it is not economically feasible to collects field data for all corroding structures along a power line and design individual cathodic protection systems for each structure. Instead, a desk study must be performed to select a few structures that represent the condition of all similar structures in the line and perform field survey on these representative structures.

For the sake of modeling accuracy, certain tests must be performed on site to collect relevant data, and to characterize the soil service environment. The required measurements include:

a) Soil resistivity measurements,
b) Soil-to-structure potential,
c) Cathodic protection current requirement test.

It is recommended to perform soil resistivity tests using Wenner four-pin method, as per ASTM G57 standard.[2] Wenner four-pin method with different pin spacing allows to evaluate resistivity of different soil layers, i.e., Barnes layer analysis, and implement it in the model. Since the distribution of protection current strongly depends on the soil resistivity value, modeling of cathodic protection systems with different soil horizons can make a big difference in simulation results, and thus, it is a very important feature. For this study, the above-mentioned measurements where performed at the footings of four structures, labeled A to D, in a Nova Scotia Power transmission line. The collected data are summarized in Table 2 to Table 4.

Table 2: Soil-to-structure potential values (V_{CSE})

Structure	Structure-to-soil Potential	
	Most Electropositive	Most Electronegative
A	-0.567	-0.753
B	-0.482	-0.757
C	-0.649	-0.753
D	-0.523	-0.717

Table 3: Soil resistivity values (ohm-cm)

Structure	Soil Layer Depth				
	0-2 ft 0-0.6 m	2-4 ft 0.6-1.2 m	4-6 ft 1.2-1.8 m	6-8 ft 1.8-2.4 m	8-10 ft 2.4-3.0 m
A	20,032	41,236	12,033	7,036	7,776
B	43,933	271,010	94,043	20,612	24,676
C	40,792	181,995	107,410	95,191	598,570
D	37,689	11,562	5,627	4,753	3,564

Labels B1, B2 in Table 4 correspond to the towers base at mast foundations, whereas A1 and A2 represent the anchor footings.

The required current to cathodically protect the structure foundations were measured by current interruption technique using two temporary drive-in magnesium anodes and a portable DC power supply. The distance between the anodes and the structure footing (at grade level) was around 3-4 feet.

Table 4: Required current values (mA) for cathodic protection

Structure	Footing			
	Base B1	Base B2	Anchor A1	Anchor A2
A	NA	70	60	NA
B	60	NA	110	NA
C	20	NA	NA	60
D	NA	40	83	NA

System Selection and Primary Calculations

High-potential magnesium alloy anodes (Type M1, per ASTM B843-13)[3] are selected to cathodically protect the structures, and a minimum life of 20 years is considered for the cathodic protection systems. Specification of the anode material are presented in Table 5.

Table 5: Specification of high-potential magnesium anodes (M1 Type)

Nominal potential	-1.75 V_{CSE} (with backfill material)
Current efficiency	50%
Utilization factor	85%
Theoretical capacity	0.251 (A-yr/kg); 0.114 (A-yr/lb)
Theoretical consumption rate	3.98 (kg/A-yr); 8.76 (lb/A-yr)

The required capacity of the cathodic protection system can be calculated from the following formula:

$$Q_{cp} = I_{prot} \times \text{Life} \quad (1)$$

where Q_{cp} is the capacity of cathodic protection system (A-yr), I_{prot} is the required protection current (A), and the expected life is in year. As listed in Table 4, different protection currents are measured at base and anchor footings. Here, we consider maximum current values at base and anchor footings to calculate the maximum capacity. Accordingly, the capacity of cathodic protection system for base and anchor footings are 2.2 A-yr and 1.4 A-yr, respectively.

Once the capacity of cathodic protection system is determined, minimum mass of the anode for the system can be calculated from the following equation:

$$m_{mg} = \frac{Q_{cp}}{Q_{mg} \times E \times U} \quad (2)$$

where m_{mg} is the minimum mass of magnesium anode (kg), Q_{mg} is the theoretical capacity of anode material, which is 0.251 A-yr/kg for selected magnesium anodes as given in Table 5, E is current efficiency of the selected anodes (50%), and U is utilization factor (85%) for anodes. From the above equation, the required mass of anode for cathodic protection of mast and anchor footings can be calculated as 13.1 kg (29 lb) and 20.6 kg (45.5 lb), respectively. These simple calculations to find the required mass of anodes does not include the effects of polarization and passivation of anodes due to formation of oxide films on the anode surface. In practice, a safety factor ranging from 1.5 to 4 may be used to correct the mass of anodes and take account for the transient effects. In this study a polarization factor of 1.8 is considered. Thus the required mass of anode for cathodic protection of mast and anchor footings are corrected as 23.6 kg (52.1 lb) and 37.1 kg (81.8 lb), respectively.

Magnesium anodes are commercially available as 9 lb, 17 lb, 20 lb and 32 lb anodes packaged with backfill material, and they can be custom-ordered in larger sizes as well. Now the question is how to distribute the calculated mass of anode around the buried structures in order to have an effective cathodic protection system. In general, for structures with irregular geometries such as grillage–type foundations, cathodic protection systems with distrusted anodes around the structure provide a better protection level; but the cost for excavation and installation can be a limiting factor. The objective of numerical simulations in the next section is to investigate different anode bed design and find an optimum design with minimum number of anodes in order to effectively protect the selected structures.

Finite Element Electrochemical Modeling

The governing equation for mathematical description of ionic current is the mass balance equation in the electrolyte domain, e.g., soil environment, which describes the transport of species (ions) between anode and cathode sites through the electrolyte. For each dissolved species in the electrolyte, the mass flux between the anode and cathode is given by Nernst-Planck equation:[4]

$$\mathbf{N}_i = -z_i u_i F c_i \nabla\varphi - D_i \nabla c_i + c_i \mathbf{v} \tag{3}$$

where $\mathbf{N}_i$ is the mass flux vector (mol/cm^2 s) of species i, z_i is charge number of species i, u_i is the mobility coefficient (mol cm^2/J s) for species i, F is Faraday's constant (96487 C/mol), c_i is the concentration (mol/cm^3) of species i, φ is the electric potential (V), D_i is the diffusion coefficient (cm^2/s) of species i, and $\mathbf{v}$ is the bulk electrolyte velocity (m/s) vector.

The first term on the right-hand side of Eq. (3) takes account for migration of ions due to electric field, the second term describes the diffusion contribution into the mass flux due to concentration effects, and the last term is the convection term due to bulk velocity of the electrolyte. Note that Eq. (3) includes two transport properties, u_i and D_i.

The mass balance equation for species i reads:

$$\frac{\partial c_i}{\partial t} + \nabla \cdot \mathbf{N}_i = R_i \tag{4}$$

where t is time (s) and R_i is the rate of production or depletion of specie i in unit volume (mol/cm^3). The term R_i describes the effects of homogeneous chemical reactions in the bulk of the electrolyte, but not the reactions at soil-structure and soil-anode interfaces.

The current density vector $\mathbf{i}$ (A/cm^2) in the electrolyte can be obtained from Eq. (3) as:

$$\mathbf{i} = F \sum_i z_i \mathbf{N}_i \tag{5}$$

By multiplying Eq. (4) with $z_i F$ and taking summation over all species, the following equation can be obtained:

$$\frac{\partial}{\partial t}\left[F \sum_i z_i c_i\right] + \nabla \cdot F \sum_i z_i \mathbf{N}_i = F \sum_i z_i R_i \tag{6}$$

The first term on the left-hand side of Eq. (6) with the units of (C/s cm^3) describes the rate of change in charge density, while the second term is the divergence of current density $\mathbf{i}$. The right-hand side of Eq. (6) vanishes as long as there are no homogeneous reactions in the bulk electrolyte, or if all the homogeneous reactions giving rise to the R_i are electrically balanced. Accordingly, from the electrical point of view, Eq. (6) can be observed as the balance equation for charge—current continuity equation.

If one assumes electroneutrality in the electrolyte, i.e.:

$$\sum_i z_i c_i = 0 \tag{7}$$

then Eq. (6) reduces to:

$$\nabla \cdot F \sum_i z_i \mathbf{N}_i = \nabla \cdot \mathbf{i} = 0 \tag{8}$$

By substituting $\mathbf{N}_i$ from Eq. (3) into Eq. (8), the following equation can be obtained:

$$-F^2\,\nabla\cdot\nabla\varphi\sum_i z_i^2 u_i c_i\; -F\,\nabla\cdot\sum_i z_i D_i \nabla c_i + F\,\nabla\cdot\mathbf{v}\sum_i z_i c_i = 0 \tag{9}$$

The last term in Eq. (9) is zero due to the electroneutrality assumption, which is equivalent to saying that bulk motion of the electrolyte contributes nothing to the current density.

The second term Eq. (9) describes the diffusion effects due to concentration gradient. If we assume that electrolyte is well mixed, then no concentration gradient exists in the electrolyte, $\nabla c_i = 0$; and the second term vanished from the ion-transport equation. Thus the above equation simplifies to:

$$-F^2\,\nabla\cdot\nabla\varphi\sum_i z_i^2 u_i c_i\; = 0 \tag{10}$$

Equation (10) can be recast into the well-known Laplace equation for electric potential:

$$-\sigma\nabla^2\varphi = 0 \tag{11}$$

with:

$$\sigma = -F^2\sum_i z_i^2 u_i c_i \tag{12}$$

where σ with the unit of S/cm is the electrical conductivity of the electrolyte.

Boundary Conditions

Equation (11) must be solved over the electrolyte domain, subject to relevant boundary conditions at the surfaces of anode and cathode. In this study, anodic and cathodic Tafel equations are used for relating the current density at electrode-electrolyte interface to electrode and electrolyte potentials. Tafel expressions in the following form are used:[4]

$$i_\mathrm{a}(\varphi) = i_{0,\,\mathrm{a}} \times 10^{\frac{\eta_\mathrm{a}(\varphi)}{A_\mathrm{a}}} \quad \text{and} \quad i_\mathrm{c}(\varphi) = i_{0,\,\mathrm{c}} \times 10^{\frac{\eta_\mathrm{c}(\varphi)}{A_\mathrm{c}}} \tag{13}$$

where i_0 is the exchange current density (A/m^2), A is the Tafel slope (V), and η is the overpotential (V):

$$\eta_\mathrm{a} = \varphi_\mathrm{a} - \varphi_\mathrm{e} - E_{\mathrm{eq,\,a}} \quad \text{and} \quad \eta_\mathrm{c} = \varphi_\mathrm{c} - \varphi_\mathrm{e} - E_{\mathrm{eq,\,c}} \tag{14}$$

The subscript ‘a’ and ‘c’ correspond to anode and cathode. Here, φ_a, φ_c, and φ_e denote the potential of anode, cathode, and the electrolyte at electrode-electrolyte interface. The equilibrium potential of electrodes is E_eq.

The parameters in Eqs. (13) and (14) define the kinetic of electrochemical processes at the surface of anode and cathode and their values depend on electrode material and electrolyte properties. In soil applications, Tafel parameters vary with soil conductivity, soil pH level, oxygen concentration (soil aeration level), metal ion concentration, surface area of electrodes, temperature, organic matter content, chloride contamination, and some other factors. Accordingly, electrochemical characterization, i.e., voltammetry tests, are required to obtain polarization curves for corrosion cells with different electrolytes and electrode materials.[5] Laboratory evaluation of Tafel parameters for soil samples collected at the footing of each structure is a tedious task; moreover, electrochemical simulations of cathodic protection system for each structures with different Tafel parameters is not practical. It is common in practice to characterize a few soil samples and perform electrochemical simulations for the most corrosive service environment.

For this study, values of Tafel parameters are listed in Table 6. The listed coefficients are just indicative values to demonstrate the capability of the proposed modeling approach. The equilibrium potential for different structures are listed in Table 2, which are structure-to-soil potentials measured during field survey. In simulations, an average equilibrium potential of -0.6 V_{CSE} is assumed for the structures. Equilibrium potential of anodes in their backfill material is almost constant and around -1.75 V_{CSE}; see Table 5.

Table 6: Tafel parameters used in electrochemical simulations

A_a	0.050 V
A_c	-0.160 V
$i_{0,\,a}$	0.1 A/m^2
$i_{0,\,c}$	0.001 A/m^2
$E_{eq,\,a}$	-1.750 V_{CSE}
$E_{eq,\,c}$	-0.600 V_{CSE}

RESULTS AND DISCUSSION

The governing equations for electrochemical simulation of cathodic protection systems form a nonlinear system and must be solved numerically. A finite element PDE solver, COMSOL MULTIPHYSICS (Version 5.2), is used to solve the governing equations and obtain three-dimensional distributions of potential and the corresponding ionic current in the computational domain.

As mentioned above, for grillage-type foundation, highly distributed anode beds (more anodes with smaller sizes) provide a better current distribution/protection, and thus are preferred if cost is not a limiting factor. In this section, for the sake of simulations, 32 lb cylindrical anodes with 5.5 inch diameter and 19.5 inch length are considered for anode bed design. The backfill material for the packaged anodes are assumed to be a part of soil domain. Anodes with different sizes and shapes, for example, anodes with "D" shape cross section, can be considered and easily implemented in the model. However, is important to mention that detailed geometry models that feature holes, bolts, and curved surfaces, such as fillets on steel beams, require mesh refinement and thus increase the computational time. Accordingly, for the sake of faster electrochemical simulations some geometry details (holes and bolts) are disables in the CAD models. Our tests confirm that the effects of these geometry simplifications are negligible on the final results.

Vertical installation of anodes around the grillage plates are considered, where anodes holes can be bored using an auger—a fast and cost effective method for underground anode installation. Horizontal installation of anodes may be preferred with slightly more expensive excavations.

The depth for anode holes varies between 5 to 6 ft and their maximum distance from the center of grillage plates is considered to be 5 feet. It should be noted that due to possible difficulties that might be encountered during excavation operation (e.g., presence of rocks and boulders) these dimensions are subject to change in practice. Nonetheless, distance between the anodes and the structure should not exceed 6 ft., because due to high soil resistivities at some sites, the IR drop will reduce the polarization strength at the surface of buried structures.

In Figure 7, Figure 8, and Figure 9, streamlines corresponding to cathodic protection current in soil are shown for different anode arrangements at the tower mast footing. Three different anode bed designs are considered; one with a single horizontal anode located above the grillage plate at its center (Figure

7), and other anode beds with two (Figure 8) and four (Figure 9) vertical anodes located around the buried foundation. The simulation results show how anode arrangements can affect the pattern of ionic current in the surrounding soil.

To evaluate the efficiency of each anode bed design, polarization of the structure must be investigated. In Figure 10, Figure 11, and Figure 12, potential distributions at the surface of mast foundations are depicted. According to the NACE criteria for cathodic protection, surfaces with more electronegative potential that -850 mV_{CSE} are cathodically protected. The results, show that the level of protection directly depend on location and the number of anodes. Figure 10 shows that in a single horizontal anode arrangement, only vertical members of the structure are properly polarized, and only a small portion of the polarized surfaces are completely protected (meet the NACE criteria). When several anodes are located around the structure, polarization is more uniform depending on the number of anodes and their distance from the structure; see Figure 11 and Figure 12. By increasing the distance between the nodes and the structure, polarization tends to be more uniform; however, IR drop in soil reduced the magnitude/level of polarization/protection.

For the anode bed with four vertical anodes, the streamlines in Figure 9 show that higher rates of current density exist at the edges of the structure, while there is lack of sufficient current at the center of the grillage plate, as the result of anodes interference. The result of this non-uniform current distribution is apparent in Figure 12, i.e., excessive polarization at the ends of grillage plate angles and low polarization at the middle of the grillage plate. In order to resolve this issue, installation of another anode between four vertical members of the foundation is recommended; however, manual excavation may be considered for this task.

Similar electrochemical simulations are performed for cathodic protection of the grillage plate and anchor shafts at anchor footings of the structure. Protection current streamlines for anode beds with single horizontal anode and two vertical anodes are shown in Figure 13 and Figure 14, respectively.

To study the level of polarization for each anode arrangement, potential distribution at the surface of anchor grillage and anchor shafts are shown in Figure 15 and Figure 16. The results in Figure 15 show that maximum potential on the surface of the buried structure is -800 mV_{CSE}; accordingly, one anode is unable to properly polarize the structure.

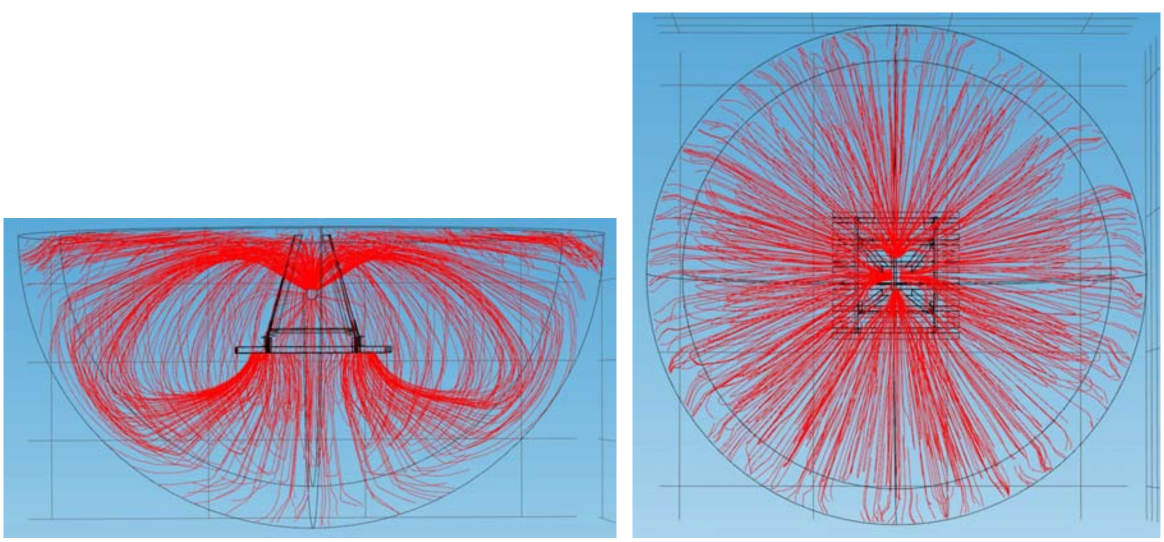

Figure 7: Streamlines of cathodic protection current in soil (single horizontal anode)

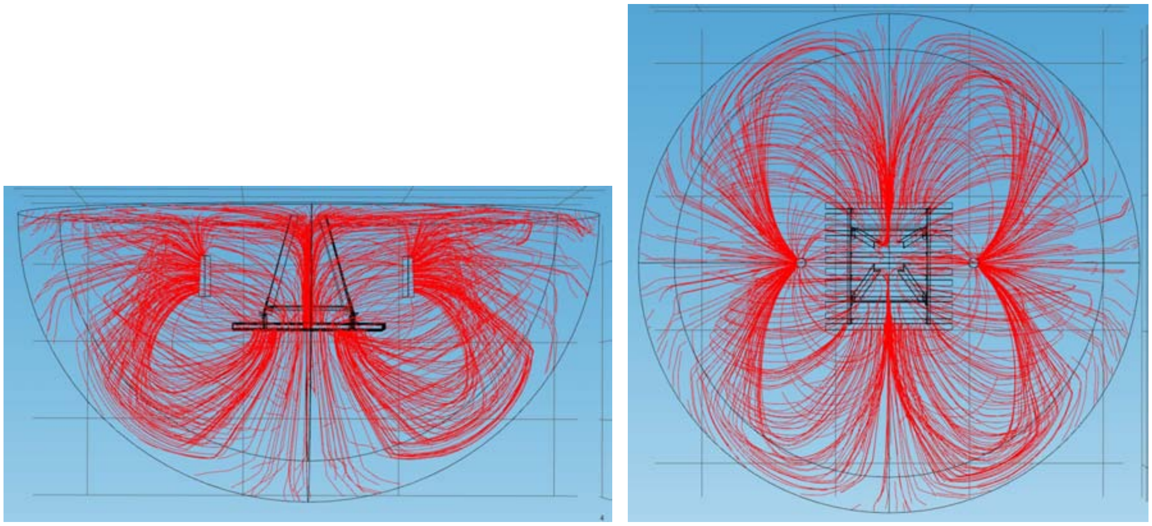

Figure 8: Streamlines of cathodic protection current in soil (two vertical anodes)

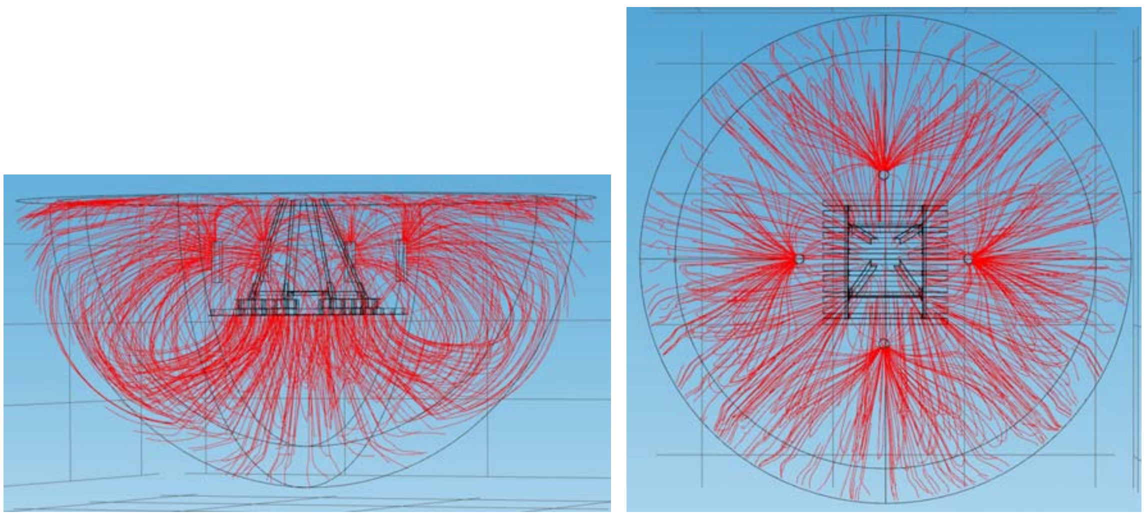

Figure 9: Streamlines of cathodic protection current in soil (four vertical anodes)

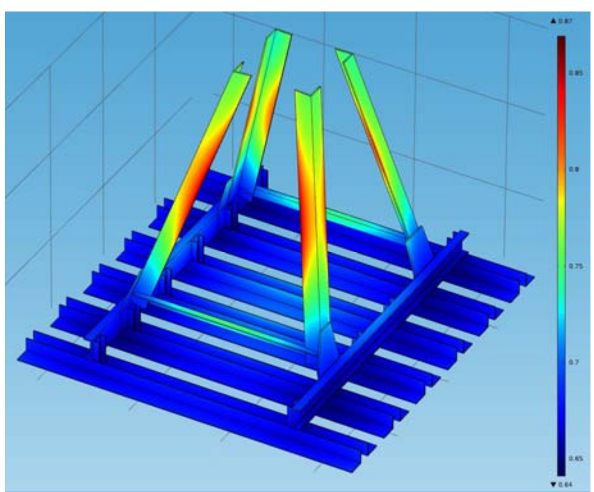

Figure 10: Potential distribution (V_{CSE}) at the surface of buried structure (single horizontal anode).

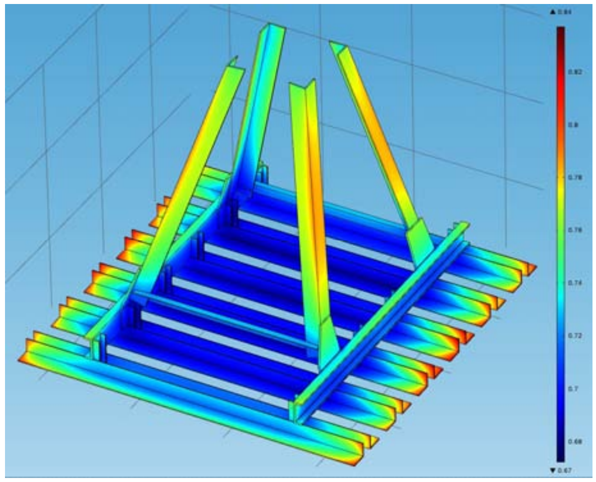

Figure 11: Potential distribution (V_{CSE}) at the surface of buried structure (two vertical anodes)

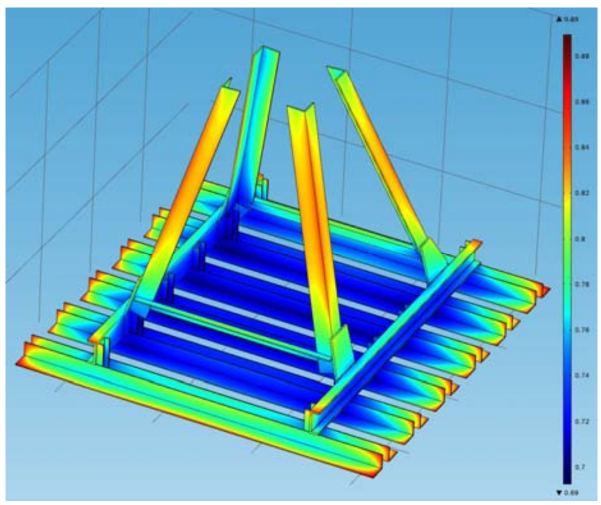

Figure 12: Potential distribution (VCSE) at the surface of buried structure (four horizontal anodes)

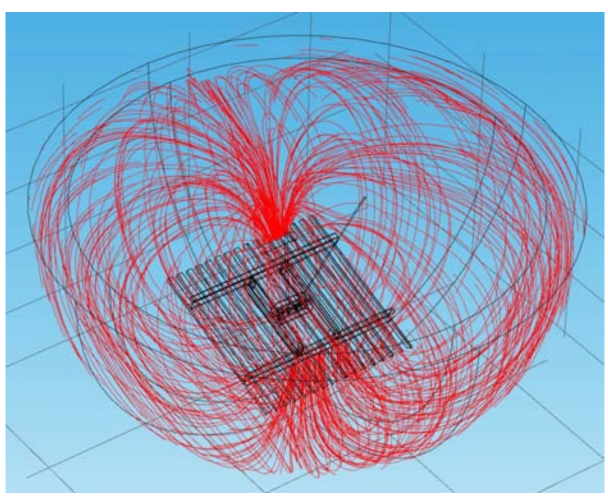

Figure 13: Streamlines of cathodic protection current in soil (single horizontal anode)

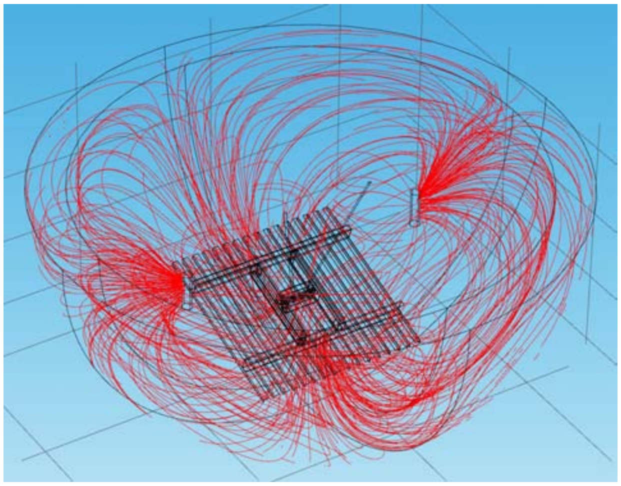

Figure 14: Streamlines of cathodic protection current in soil (two vertical anodes)

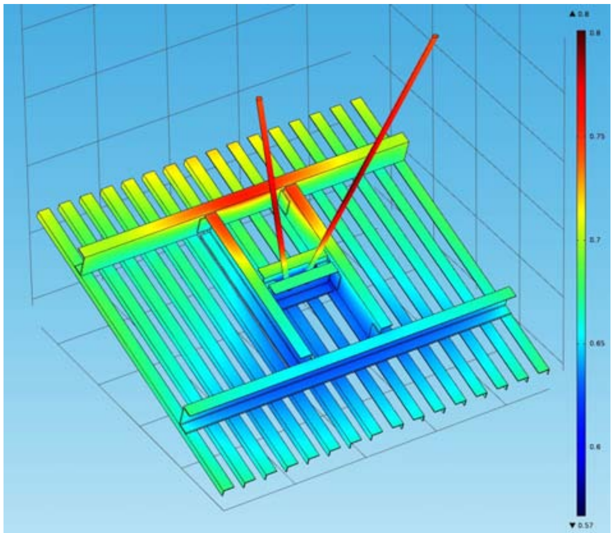

Figure 15: Potential distribution (VCSE) at the surface of anchor (single horizontal anode)

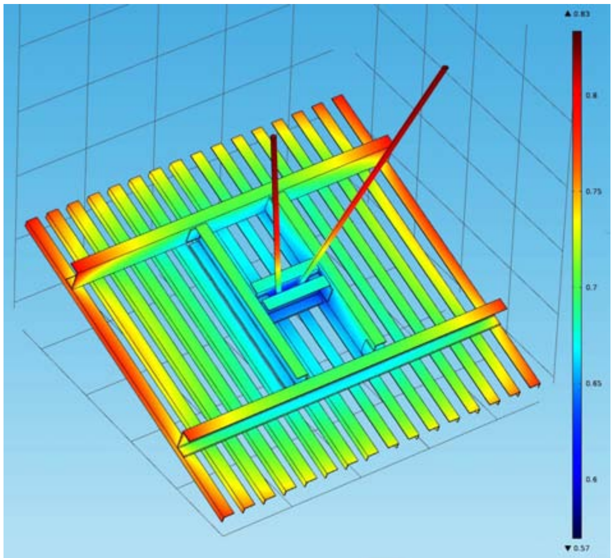

Figure 16: Potential distribution (VCSE) at the surface of anchor (two vertical anodes)

CONCLUSION

A high-resolution numerical approach is presented to design cathodic protection systems for buried structures with complex geometries. The capability of the approach is demonstrated by designing a galvanic cathodic protections system for grillage-type foundations of transmission towers, where three-dimensional calculations allow precise prediction of current and potential distribution at the surface of the buried component of the structure.

The required time for numerical simulation directly depends on the quality of the numerical mesh. On a PC with a 16 GB RAM and Xeon† 2.40 GHz (quad core) CPU, the required computational time for the presented simulations was between 10 min to 35 min depending on the resolution of curves surfaces in the geometry.

In order to further extend the accuracy of the method and simulate more realistic cases, the authors are planning to add the following features to the model:

- Soil environment with different soil layers/resistivities,
- Considering coated surfaces to study the coating effects on the performance of cathodic protection system,
- Presence of concrete backfill around the buried structure,
- Adding surface deformation feature to study anode depletion and its effects of the performance of cathodic protections system.

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† Trade name.