

# Cathodic Protection Modeling of Steels in Corrosive Chemical Environments Using COMSOL Multiphysics

Julieta Daniela Chelaru  
Babeş-Bolyai University, Cluj-Napoca, Romania  
julieta.chelaru@ubbcluj.ro

**Abstract:** This study investigates the electrochemical performance of Sacrificial Anode Cathodic Protection (SACP) systems for offshore steel structures using Finite Element Analysis (FEA). Two structural substrates, S235JR carbon steel and S550QL high-strength steel, were modelled in a 3 wt.% NaCl electrolyte. A comparative analysis was performed between two sacrificial anode materials: a conventional Al-5Mg alloy and a quaternary Al-6Zn-0.2In-1Mg-0.03Ti alloy. The simulations evaluate the influence of anode placement errors by comparing an ideal symmetric distribution (90°) with a clustered configuration (10°). The results show that geometric clustering significantly alters the potential distribution along the structure. For S235JR steel, the clustered configuration produces localized underprotection with potentials reaching  $-0.78$  V (vs. Ag/AgCl). In contrast, for S550QL steel, the same configuration results in localized over-polarization ( $\approx -0.96$  V), thereby increasing the risk of hydrogen-induced stress cracking (HISC). The study demonstrates that improper anode placement may compromise cathodic protection efficiency even when high-performance anode alloys are used. These findings highlight the importance of accurate anode distribution and support the use of numerical simulations in digital twin approaches for offshore corrosion management.

**Keywords:** SACRIFICIAL ANODES, DIGITAL TWIN, CATHODIC PROTECTION, COMSOL MULTIPHYSICS

## 1. Introduction

Corrosion remains a persistent and costly challenge in offshore industrial environments, particularly in aggressive maritime conditions. If left unmonitored, electrochemical degradation can lead to catastrophic structural failures and significant economic losses [1]. To mitigate these risks, Cathodic Protection (CP) using sacrificial anodes is the most widely adopted method for preserving submerged offshore assets [1,2].

The effectiveness of CP systems depends on electrochemical thresholds that vary with substrate metallurgy. According to EN ISO 15589-2, standard carbon steels such as S235JR require a polarized potential maintained between  $-0.85$  V and  $-1.05$  V (vs. Ag/AgCl) for full corrosion immunity [1]. High-strength steels such as S550QL introduce a narrow operational window: while they require cathodic polarization to prevent mass loss, they are highly susceptible to Hydrogen-Induced Stress Cracking (HISC) if the potential drops below  $-1.10$  V (vs. Ag/AgCl) [2, 3]. Achieving a uniform potential distribution is therefore a structural necessity.

Although theoretical designs assume perfect anode symmetry, industrial constraints and installation errors often result in asymmetric or clustered arrangements [4–6]. Such non-ideal configurations reduce the system's "throwing power," creating localized "shadowing effects" that leave areas vulnerable to accelerated corrosion or hydrogen-induced damage. Under Industry 4.0, Digital Twins allow engineers to simulate these non-ideal scenarios and predict structural behavior before failure occurs [1, 5, 7].

This study utilizes COMSOL Multiphysics® [8] to quantify the electrochemical impact of geometric clustering errors, specifically where anodes are placed at  $10^\circ$  intervals instead of the ideal  $90^\circ$  symmetry. Two sacrificial anode chemistries—the binary Al-5Mg alloy and the quaternary Al-6Zn-0.2In-1Mg-0.03Ti alloy—are compared across S235JR carbon steel and S550QL high-yield steel substrates. This analysis provides critical data for predictive maintenance strategies, supporting the transition toward Corrosion 4.0 [9].

## 2. Methodology

The numerical investigation was conducted using the Corrosion Module of COMSOL Multiphysics® [8], whether Secondary or Tertiary Current Distribution interface was used, and which kinetic boundary conditions were applied.

### Model Geometry and Environmental Conditions

The computational domain consists of a cylindrical cathode (15 m height) representing a submerged structural pile. Two thermal scenarios were evaluated:  $20^\circ\text{C}$  for the S235JR substrate and  $15^\circ\text{C}$

for the S550QL substrate, as temperature significantly influences electrolyte resistivity and oxygen solubility. While an isothermal comparison would isolate electrochemical kinetics, this study intentionally differentiates the thermal profiles ( $15^\circ\text{C}$  for S550QL vs.  $20^\circ\text{C}$  for S235JR) to reflect the distinct operational depths and geographic deployments of these structural steels. This dual-variable approach (geometry + temperature) provides a more robust 'stress-test' for the Digital Twin's predictive

Anode Materials: Two distinct sacrificial alloys were defined. The traditional Al-5Mg alloy and the quaternary Al-6Zn-0.2In-1Mg-0.03Ti alloy. The latter is characterized by the addition of Indium (0.2%), which acts as an activator to ensure continuous activation and prevent the formation of a passive alumina film [3, 7]

Boundary Conditions: The anodes were modeled with an equilibrium potential  $E_{eq}$  relative to the Ag/AgCl reference electrode, following DNV-RP-B401 guidelines [7].

Simulation Scenarios: To quantify the impact of installation non-conformities, two geometric configurations were compared:

- Standard Configuration (Control): 4 anodes distributed with perfect  $90^\circ$  radial symmetry.

- Clustered Configuration (Error): A deliberate error where a group of anodes is positioned at a  $10^\circ$  interval (5 anodes), simulating spatial constraints or human error in the process industry [4].

The electrolyte was modeled as a substitute ocean water with a constant salinity of 3 wt.% NaCl (conductivity ( $\sigma$ ) of 4.78 S/m). This concentration was chosen to simulate a standard aggressive marine environment, providing a baseline for analyzing the impact of temperature on ionic mobility. At this salinity, the transition from  $20^\circ\text{C}$  to  $15^\circ\text{C}$  induces a non-linear increase in kinematic viscosity and a corresponding decrease in the diffusion coefficient of dissolved oxygen, which are critical factors for the cathodic reaction kinetics [10, 11]. The study adopts a context-specific thermal mapping, simulating each alloy under its most frequent operational environment.

## 3. Results and Discussion

The surface potential analysis of the pile (Fig. 1) highlights the system's sensitivity to both geometric configuration and anode composition. According to DNV-RP-B401 [7], the optimal protection criteria for steel in seawater requires a potential between  $-0.80$  V and  $-1.05$  V (vs. Ag/AgCl). Results indicate that the Al-6Zn-0.2In-1Mg-0.03Ti alloy achieves a deeper polarization (approaching  $-1.08$  V in adjacent zones) compared to the Al-5Mg alloy, which maintains a more conservative potential. This performance gap is attributed to the presence of Indium, which prevents anode surface passivation. However, in the  $10^\circ$  clustering error scenario, both materials fail to protect the distal ends of the pile (reaching  $-0.78$  V), confirming that the superior chemical activation of the quaternary alloy cannot overcome the ionic

shielding induced by asymmetric distribution [12, 13]. For the S235JR carbon steel substrate, this error leads to localized underprotection, posing a direct risk of generalized corrosion. In contrast, for the S550QL high-strength steel, the same geometric error drives the potential near the cluster toward -1.10 V. While this represents over-polarization, for high-strength steels, such levels are hazardous as they promote hydrogen evolution and subsequent absorption into the metal lattice, triggering Hydrogen-Induced Stress Cracking (HISC) [14].

This delicate balance is easily disrupted by the 10° anode positioning error.

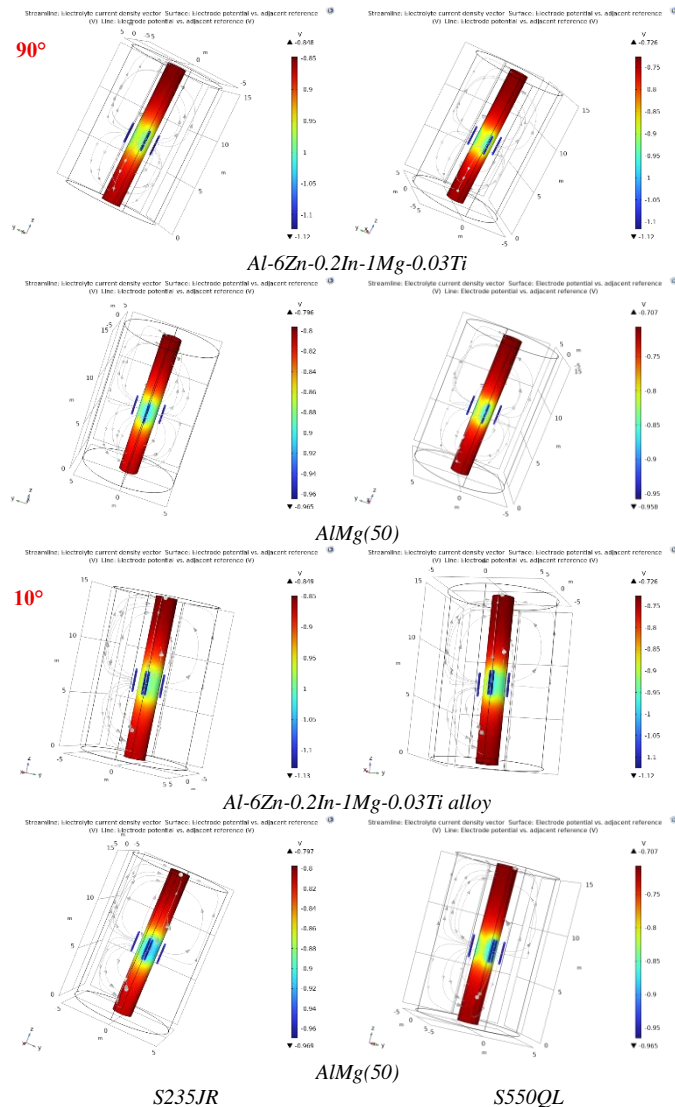


Fig. 1. Surface electrode potential distribution on S235JR and S550QL piles protected by Al-Zn-In-Mg-Ti and Al-Mg sacrificial anodes under symmetric (90°) and clustered (10°) configurations.

The multislice electrolyte potential plots (Fig. 2) reveal the physical mechanisms behind underprotection: the 'potential shadow' effect and the ohmic IR drop. The quaternary alloy generates a more extensive potential field in the electrolyte due to its higher electrochemical activity. However, on the S550QL substrate, this drives the potential toward the critical -1.10 V threshold. Conversely, the Al-5Mg alloy offers a higher safety margin against hydrogen embrittlement but demonstrates significantly lower 'throwing power'. The IR drop is most pronounced in the 10° clustering case, where the density of equipotential lines indicates a massive ohmic resistance that isolates the leeward side of the pile, a well-documented phenomenon by Peabody [15]. The S550QL high-strength steel shows a higher vulnerability to the IR drop generated by clustering. The 'potential shadow' effect is more critical for this substrate because its electrochemical safety window is significantly narrower: it must be polarized below -0.80 V to ensure corrosion protection but maintained above -1.10 V to avoid hydrogen damage.

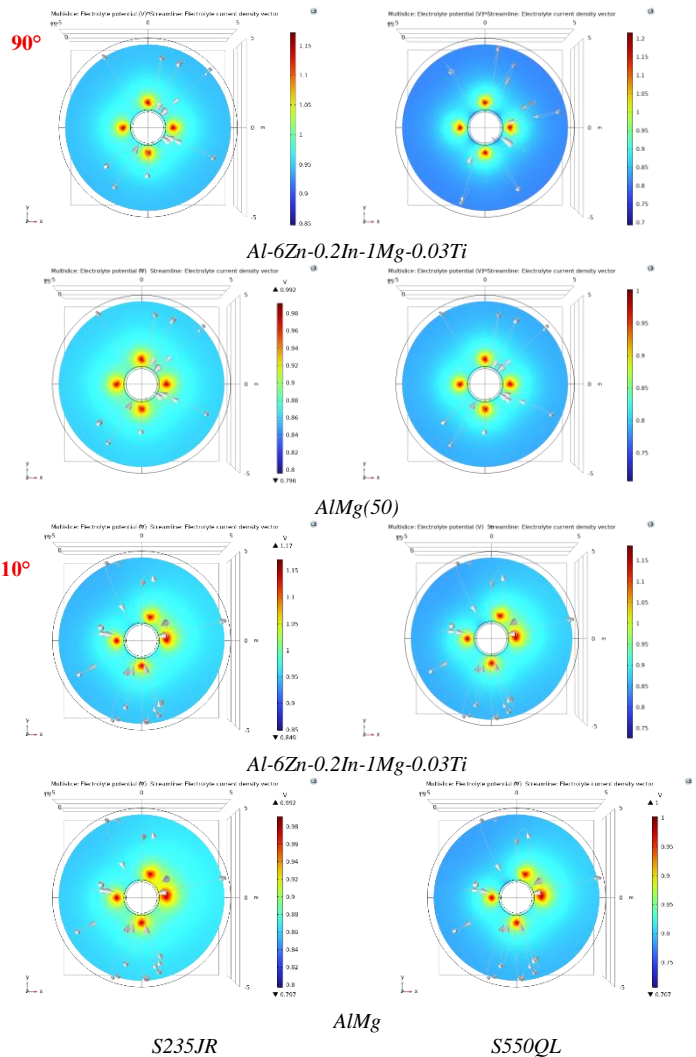
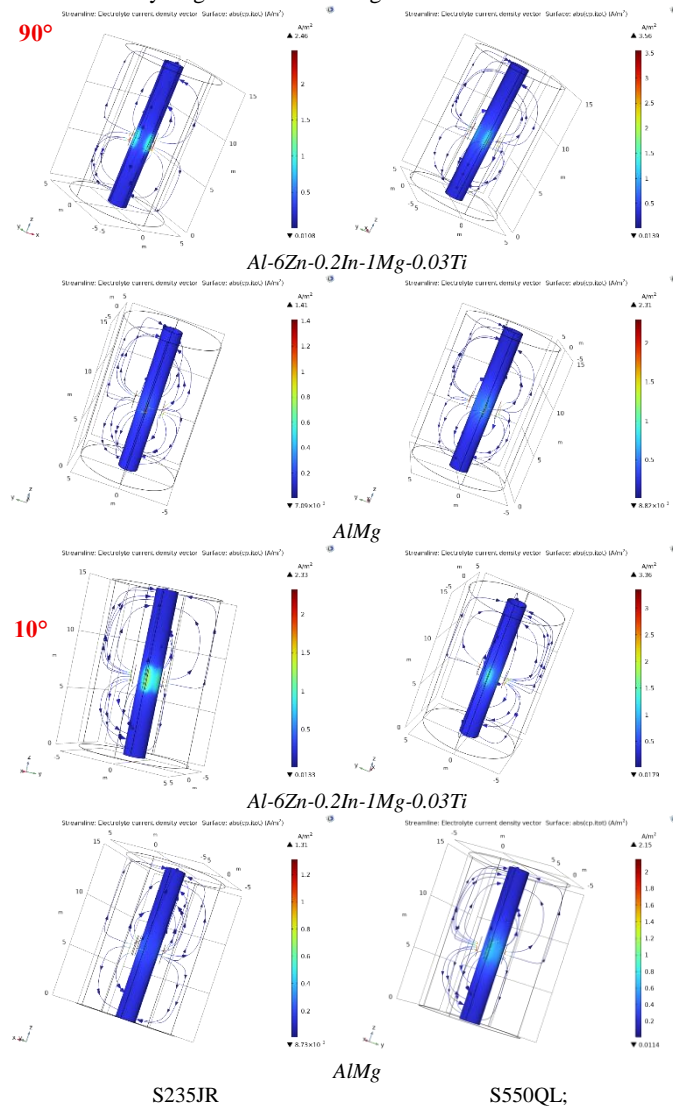


Fig. 2. Multislice electrolyte potential ( $\phi$ ) and current streamline distribution for S235JR and S550QL substrates: (a) clustered anode configuration (10°); (b) symmetric configuration (90°).

The visualization of current streamlines (Fig. 3) emphasizes the 'current crowding' effect and the overall current conversion efficiency of the system. The Al-6Zn-0.2In-1Mg-0.03Ti alloy delivers a significantly higher local current density, which is particularly advantageous in colder waters (15 °C) where electrolyte resistivity increases according to Sharqawy's correlations [11]. In contrast, the Al-5Mg alloy tends to passivate more rapidly under these thermal conditions, restricting the flux lines and failing to reach critical zones of the structure. In the 10° clustering scenario, negative interference is observed as adjacent anodes 'compete' for the same ionic pathways, leading to an inefficient distribution of protective current. This demonstrated inefficiency underscores the value of a Digital Twin framework [16, 17] in detecting 'hidden' current hotspots that could lead to premature anode consumption without ensuring total structural protection. The simulation quantifies a 'divergent failure mode': the 10° error leads to material loss (corrosion) in S235JR steel and structural embrittlement (HISC) in S550QL steel. While the quaternary alloy's high current output is beneficial for polarizing the S235JR pile in resistive environments, it becomes a liability for the S550QL substrate by creating localized zones of high current density that exceed the safe hydrogen evolution limits defined by DNV-RP-B401 [3].

In conclusion, the results highlight that cathodic protection design must consider the operational potential window of the protected steel. While conventional structural steels such as S235JR

require sufficient polarization to avoid corrosion, high-strength steels such as S550QL exhibit a narrower safe potential range due to the risk of hydrogen-induced damage.



**Fig. 3** Electrolyte current density and streamline distribution illustrating current flow for S235JR and S550QL substrates with Al-Zn-In-Mg-Ti and Al-Mg sacrificial anodes under symmetric (90°) and clustered (10°) configurations.

### 3. Conclusions

The numerical investigation into the cathodic protection of offshore structural piles under geometric and environmental stress yields the following key findings:

**Impact of Geometric Non-Conformity:** The simulations indicate that anode placement is the primary determinant of system integrity. A 10° clustering error creates a "potential shadow" effect, leaving structural extremities at potentials more positive than -0.80 V (vs. Ag/AgCl). Consequently, localized corrosion may occur despite the use of high-performance sacrificial alloys, as the configuration fails to meet ISO 15589-2 protection standards.

**Divergent Failure Modes:** Identical geometric faults produce distinct risks depending on the steel grade. For S235JR carbon steel, localized underprotection leads to material loss through oxidation. For S550QL high-strength steel, the clustering of quaternary anodes drives local potentials to be more negative than -1.10 V, introducing a critical risk of Hydrogen-Induced Stress Cracking (HISC) due to excessive cathodic polarization.

**Anode Chemistry and Environmental Sensitivity:** The quaternary Al-6Zn-0.2In-1Mg-0.03Ti alloy exhibits superior "throwing power" in colder, more resistive electrolytes (15 °C) compared to the binary

Al-5Mg alloy. However, its higher electrochemical activity requires precise spatial distribution to prevent the formation of localized over-polarization "hotspots" on the substrate.

**Predictive Modeling and Industry 4.0:** The correlation between electrolyte potential ( $\phi_i$ ) and current streamline dynamics confirms that multi-physics modeling can identify shielded regions not detectable by traditional surface-only measurements. This underlines the necessity of integrating Digital Twin frameworks into predictive maintenance strategies within the Corrosion 4.0 paradigm.

### 3. References

1. J. Zhang, X. Wang, Digital Twins for Corrosion Management in Offshore Structures, *Journal of Marine Science and Engineering*, 10 (2022) 456.
2. P.R. Roberge, *Handbook of Corrosion Engineering*, 3rd ed., McGraw-Hill Education, New York, 2019.
3. DNV-RP-B401, *Cathodic Protection Design*, Det Norske Veritas (DNV), 2021.
4. E. Bardal, *Corrosion and Protection*, Springer Science & Business Media, Trondheim, 2004.
5. R. Javaherdashti, *Corrosion Management in the Chemical Process Industries*, CRC Press, 2015.
6. L. Wright, S. Davidson, *How to Tell the Difference Between a Model and a Digital Twin*, *Advanced Modeling and Simulation in Engineering Sciences*, 7 (2020) 13.
7. M. Sacco, A. Gualtieri, *Industry 4.0 and the Digital Twin in Subsea Engineering*, *Ocean Engineering*, 218 (2021) 108214.
8. COMSOL Multiphysics® v. 6.2, *Corrosion Module User's Guide*, COMSOL AB, Stockholm, Sweden, 2024.
9. EN ISO 15589-2:2014, *Petroleum, petrochemical and natural gas industries — Cathodic protection of pipeline systems — Part 2: Offshore pipelines*, International Organization for Standardization.
10. ASTM D1141-98, *Standard Practice for the Preparation of Substitute Ocean Water*, ASTM International, West Conshohocken, PA, 2021.
11. M.H. Sharqawy, J.H. Lienhard V, S.M. Zubair, *The thermophysical properties of seawater: A review of existing correlations and data*, *Desalination and Water Treatment*, 16 (2010) 354-380.
12. J. Zhang, Z. Zhang, and W. Wu, "Effects of Anode Proximity and Geometric Clustering on CP Interference in Offshore Structures," *Ocean Engineering*, vol. 245, p. 110482, 2022.
13. ISO 15589-2:2024, "Petroleum, petrochemical and natural gas industries — Cathodic protection of pipeline systems — Part 2: Offshore pipelines," International Organization for Standardization.
14. W. H. Hartt and N. K. Lin, "Hydrogen Induced Stress Cracking of Steels with CP in Marine Environments," *Corrosion*, vol. 63, no. 1, pp. 58–69, 2007.
15. A. W. Peabody, *Peabody's Control of Pipeline Corrosion*, 2nd Edition, NACE International, 2001.
16. L. Wang, R. G. Buchheit, "Digital Twins for Corrosion: A Review of the State of the Art and Future Perspectives," *Corrosion Science*, vol. 189, p. 109591, 2021.
17. S. Rossi and M. Fedel, "Smart Coatings and Cathodic Protection: Towards Industry 4.0 Digital Twins," *Coatings*, vol. 10, no. 7, p. 642, 2020.