



RESEARCH ARTICLE

COMPARATIVE TIME-DEPENDENT STUDY OF CORROSION IN REINFORCED CONCRETE AND TUBULAR STEEL PILES UNDER CATHODIC PROTECTION

Yannick Muvunyi*, Kabir Sadeghi

Civil Engineering Department, Near East University, Mersin 10, Turkey
Corresponding Author Email: 20245314@std.neu.edu.tr

This is an open access article distributed under the Creative Commons Attribution License CC BY 4.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

ARTICLE DETAILS

Article History:

Received 20 September 2025
Accepted 23 October 2025
Revised 27 November 2025
Available online 04 December 2025

ABSTRACT

This study presents a long-term comparative assessment of corrosion in reinforced concrete (RC) piles and tubular steel piles exposed to seawater, protected with zinc sacrificial anodes, over a 30-year service life. Since marine foundations are prone to severe corrosion, selecting the most durable pile type is critical for structural safety and serviceability. The research focused on comparing the overall total current requirements of RC and steel piles under identical cathodic protection (CP) conditions to evaluate their relative durability. Using COMSOL Multiphysics 6.3, time-dependent simulations were carried out to capture electrochemical interactions and environmental variations. Results showed that RC piles maintained effective CP throughout the 30 years, whereas tubular steel piles eventually lost adequate protection despite identical anode configurations. These outcomes highlight the distinct corrosion resistance of the two materials and suggest that RC piles deliver better long-term performance under zinc anode CP systems. The findings offer practical insights for engineers designing marine structures, emphasizing strategies to improve resilience and reduce maintenance costs in aggressive coastal environments.

KEYWORDS

Zinc Anode, COMSOL Multi-physics, Faraday's law, Marine Structures.

1. INTRODUCTION

Pile foundations are essential for sustaining offshore platforms, ports, and coastal infrastructure. However, these structures are constantly exposed to one of the harshest natural environments. Seawater contains high levels of chlorides, oxygen, and moisture, while tidal fluctuations cause repeated wetting and drying, which accelerates corrosion. In RC piles, chloride ions gradually penetrate the concrete cover and break down the passive layer around reinforcement, initiating localized corrosion that can lead to cracking and spalling. In tubular steel piles, direct contact with seawater results in rapid electrochemical degradation if no protection system is in place (Melchers, 2020). Such deterioration not only weakens structural capacity but also increases repair costs, threatening long-term safety.

Cathodic protection (CP) is among the most widely adopted methods to combat corrosion in marine piles. By lowering the electrochemical potential of steel, CP significantly reduces corrosion rates. Protection is typically achieved either through impressed current systems or sacrificial anodes made of materials such as zinc or aluminum alloys. Zinc, in particular, is commonly used because of its favorable electrochemical properties, cost-effectiveness, and compatibility with marine conditions (Guo et al., 2024).

Although numerous studies have investigated CP in RC and steel piles, most examine them separately. In RC piles, CP performance depends on chloride transport, carbonation of the cover concrete, and moisture availability (Ghods et al., 2009). Experiments have shown that zinc anodes embedded in concrete exposed to marine conditions can provide long-term polarization as long as the concrete remains conductive (Anand et al., 2013; Tang et al., 2015). Field studies on RC bridges and wharves also report effective CP for 20–30 years, though current demand typically

decreases as corrosion products accumulate (Whitmore and Miltenberger, 2019).

For steel piles, the governing factors differ. Without concrete cover, polarization behavior is largely influenced by seawater chemistry, biofouling, and calcareous deposit formation. That bare steel piles corrode rapidly without CP, while zinc anodes markedly slowed degradation (Escalante et al., 1977). More recent findings suggest that biofouling morphology significantly alters CP current demand over time (Parmeh et al., 2020). These results indicate that CP is effective for both RC and steel piles, but the controlling mechanisms and durability outcomes are not the same.

Despite the extensive body of work, comparative studies of RC and steel piles under identical CP conditions remain scarce. Engineers often rely on general guidelines such as ISO 12696 or NACE standards, which are usually based on independent tests on either steel or concrete. Such standards may not adequately capture the differences in current demand or polarization when both materials are subjected to the same environment. This lack of comparative knowledge creates uncertainty in material selection for marine foundations.

Numerical modeling has emerged as a powerful complement to experimental research. Multi-physics simulations allow the coupling of electrochemical reactions, ion transport, and material changes over long periods. COMSOL Multiphysics has been widely applied in this field, providing insights into potential distribution, current densities, and corrosion evolution under varying boundary conditions (COMSOL AB, 2023a, 2023b). More advanced approaches even integrate phase-field and chemo-mechanical models to simulate crack growth, rust expansion, and feedback between mechanical damage and corrosion kinetics (Korec et al.,

Quick Response Code



Access this article online

Website:
www.macej.com.my

DOI:
10.26480/macem.01.2025.01.06

2023). Such methods highlight the importance of considering time-dependent material changes in evaluating CP performance.

Empirical and modeling studies have yielded valuable insights. For example, real-world deployments show how current demand decreases as anodes degrade and chloride ingress advances (Whitmore and Miltenberger, 2019). Similarly, steel pile simulations demonstrate that CP effectiveness depends heavily on maintaining adequate anode-to-cathode ratios and accounting for biofouling growth (Xu et al., 2021). Collectively, these findings confirm CP as a viable approach but also reveal that RC and steel behave differently in the long term.

However, most research still treats RC and steel piles as separate systems, with limited direct comparison under standardized conditions. Few works have investigated both materials side-by-side using identical zinc anodes across extended service lives. This gap is critical since many marine foundations are designed for lifespans exceeding 30 years. While RC benefits from alkalinity and lower oxygen diffusion, steel piles may offer higher initial polarization but become more vulnerable if anode performance declines.

This study addresses this knowledge gap by directly comparing RC and tubular steel piles subjected to the same zinc CP system over 30 years. Using COMSOL Multiphysics 6.3, the simulations evaluate corrosion progression, polarization behavior, and current demand under identical boundary conditions. The results show that RC piles achieve stable long-term protection, while steel piles experience reduced protection capacity over time. These insights can help engineers optimize pile selection and CP system design, ultimately improving the durability and cost-efficiency of marine structures.

2. EXPERIMENTAL

A computational comparative study was conducted to assess the corrosion behavior of reinforced concrete (RC) and tubular steel piles under zinc galvanic cathodic protection (Zn CP) over a 30-year service life. COMSOL Multi-physics® 6.3 (COMSOL AB, 2023) was employed to model and compare the total current (cd.itot) for each pile type under identical Zn CP conditions.

The modelling process involved two stages. First, the RC pile was represented as a solid cylinder with a length of 6 m and a radius of 0.40 m, incorporating embedded steel reinforcement bars with a radius of 0.00635 m. Total current requirements (cd.itot) were determined in accordance with ISO 12696:2022 (International Organization for Standardization, 2022) for reinforced concrete structures and NACE SP0169:2022 (NACE International, 2022) for steel structures, for a 30-year service period. The corresponding protective current demand was calculated by multiplying the design current density by the external surface area of the pile.

The number of zinc anodes required was determined using Faraday's law of electrolysis, which relates the total charge needed for protection to the mass of sacrificial anode material consumed (Bard, Faulkner, and White, 2022):

$$m = \frac{I \cdot t \cdot M}{n \cdot F} \quad (1)$$

Where m is the mass of zinc consumed (g), I is the protection current (A), t is the service time (s), M is the molar mass of zinc (65.38 g/mol), n is the number of electrons exchanged per zinc atom (2), and F is Faraday's constant (96,485 C/mol). The electrochemical capacity of zinc (≈ 819.9 Ah/kg), its density (7135 kg/m³), and an 80% utilization factor were incorporated to convert the required charge into a practical anode mass (Jones, 2018).

For the RC pile, it was sufficient to meet the protection demand; the calculated demand required for the RC pile is one zinc anode to ensure full protection over the 30-year service life.

In the second stage, the tubular steel pile was modelled as a hollow cylinder of the same dimensions. The zinc anode quantity obtained from the RC pile analysis was applied to the steel pile model. The total current (cd.itot) after 30 years was computed for the tubular steel pile under identical Zn CP conditions.

Boundary conditions included the electrochemical conductivity of seawater and its temperature, with an electrolyte conductivity of 5 S/m at 10 °C. Mesh resolution was set to "fine" to ensure accuracy. Time stepping was defined to start at 365 days, with steps of 365 days, and to stop at

10,950 days (30 years). Material properties and geometry were defined according to the actual dimensions of the piles and anodes.

Hydrogen evolution was ignored for the tubular steel pile, as oxygen reduction reaction was assumed to dominate, given the full seawater exposure. For the RC pile, hydrogen evolution was considered in the cathodic protection analysis. Comparative assessment of the two pile types was performed using total current distribution graphs (cd.itot) generated in COMSOL, enabling direct evaluation of their corrosion protection performance.

3. RESULTS AND DISCUSSION

In this section, the outcomes of the computational analysis are presented for both reinforced concrete (RC) and tubular steel piles subjected to zinc galvanic cathodic protection over a 30-year service life. The results are derived from the COMSOL Multi-physics 6.3 simulations, incorporating time-dependent boundary conditions, pore saturation-dependent conductivity, and oxygen diffusion. Key performance indicators, including electrode current density distributions and zinc anode consumption, are reported. Comparative evaluation between RC and steel piles highlights the influence of material properties and exposure conditions on long-term cathodic protection performance.

3.1 Reinforced Concrete (RC) Pile Findings

In our reinforced concrete pile model, we defined Interpolation σ and Interpolation D02 to enhance the realism and precision of the simulation by capturing the natural variability of environmental conditions. Instead of relying on a single fixed value, Interpolation σ allows us to dynamically adjust the electrolyte conductivity of the system across different locations and conditions, and Interpolation D02, which describes diffusion of oxygen in concrete, reflecting real-world variations in seawater and concrete properties. This approach ensures that the model more accurately represents the true behavior of the reinforced concrete pile under varying environmental influences. COMSOL AB. (2023a).

Figure 1 shows the relationship between effective conductivity and water-filled porosity. As the amount of water in the pores increases, the conductivity rises because water provides a continuous path for ion movement. At low porosity levels, the pathways are limited, so conductivity stays low. But once the pores fill with more water, the connections between them improve, leading to a noticeable jump in conductivity. This behavior underlines how strongly conductivity depends on pore moisture, which is a key factor when assessing durability and corrosion risk in concrete and similar materials.

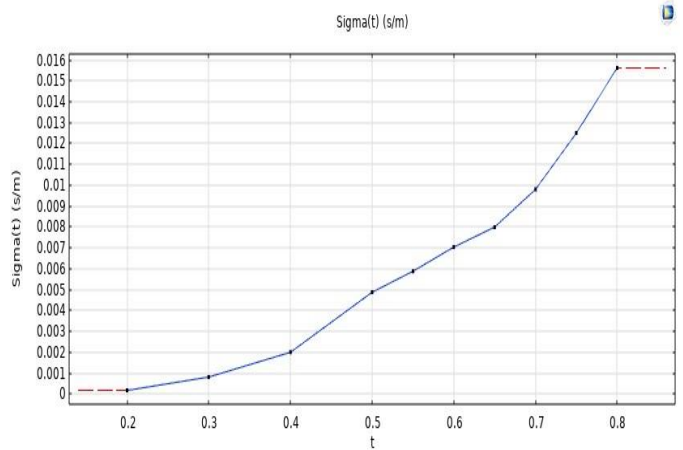


Figure 1: Effective conductivity versus water-filled porosity

Figure 2 shows how oxygen diffusivity changes with pore saturation. As the pores become more saturated, oxygen moves less easily because water blocks the air pathways. When the saturation is low, oxygen can pass through the connected pores more freely, but at higher saturation levels, the pathways are cut off, causing a sharp drop in diffusivity. This pattern makes it clear that oxygen transport strongly depends on pore saturation, which plays an important role in corrosion of reinforced concrete and other porous materials.

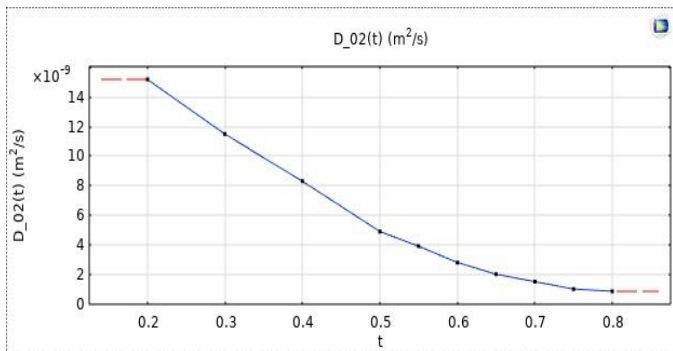


Figure 2: The diffusion of oxygen versus water-filled porosity

The reinforced concrete (RC) pile was idealized as a cylindrical structure with a length of 6 m and an external radius of 0.40 m, reflecting typical marine foundation dimensions. To realistically capture the internal reinforcement, a steel rebar of 6.35 mm radius was embedded within the concrete matrix. This geometric configuration ensured that both the bulk concrete response and the steel reinforcement interactions could be

faithfully represented, providing a balanced and structurally consistent model.

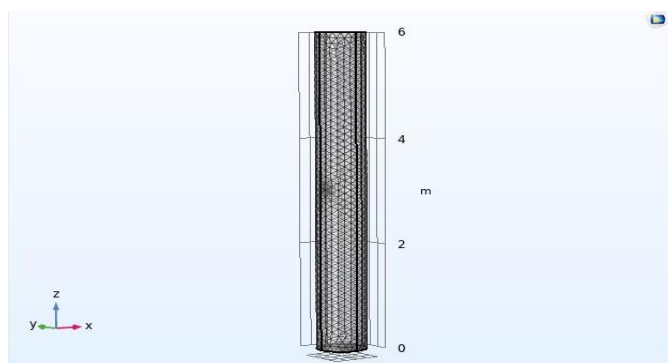


Figure 3: RC pile geometry showing reinforcement details.

The following table summarizes the key electrode surface parameters that are critical for evaluating the cathodic protection performance of the RC pile.

| Table 1: Surface parameters inputs | | | | | | |
|------------------------------------|-------------------------------|------------------|-------|--------|--------|----------|
| No | Parameters | Unit | Zinc | Oxygen | Iron | Hydrogen |
| 1 | Equilibrium potential (Eeq) | V | -0.68 | 0.189 | -0.76 | -1.03 |
| 2 | Exchange current density (i0) | A/m ² | - | 7.7E-7 | 7.1E-5 | 1.1E-2 |
| 3 | Tafel slope (A) | V/decade | - | -0.18 | 0.41 | -0.15 |

Then, the following electrolyte parameters were used in the model to define the cathodic protection performance, based on relevant environmental and material conditions.

| Table 2: Electrolyte Surface Parameters | | | |
|---|--------------------------|--------|--------|
| No | Parameters | Unit | Value |
| 1 | Electrolyte conductivity | S/m | 5 |
| 2 | Temperature | Kelvin | 283.16 |

At the beginning of service life, the system exhibited a slightly high total current density during the first year (up to 365 days). This is expected, as freshly installed cathodic protection systems typically demand a stronger initial current to polarize the steel surface and overcome early resistive effects in the electrolyte. However, as polarization stabilized and the steel surface became better protected, the total current density gradually decreased. By the end of the second year (730 days), the system reached a steady state, where the current demand balanced with the protection needs of the reinforcement. From that point onward, the total current density remained essentially constant throughout the remaining service life, up to the 30th year. This trend reflects a well-designed and sustainable protection system, ensuring long-term durability with optimized current demand.

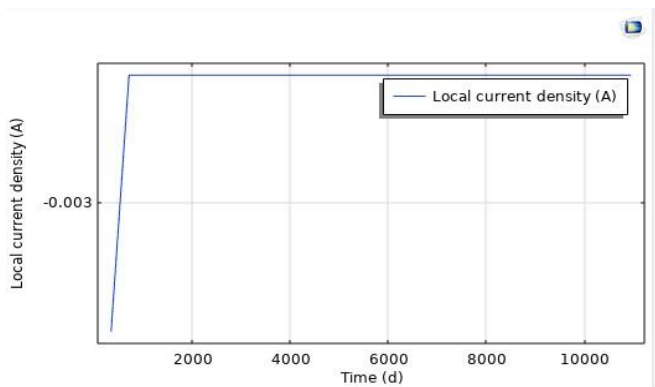


Figure 4: Rebar current (A) vs Time (d)

In cathodic protection modeling, the negative sign (-) of the rebar current indicates that the current is flowing into the steel surface, which means it is well cathodically protected.

| Table 3: Local current (A) vs Time (d) | |
|--|-------------------|
| Time (days) | Local Current (A) |
| 365 | -0.003007 |
| 730 | -0.003007 |
| 1095 | -0.003007 |
| 1460 | -0.003007 |
| 1825 | -0.003007 |
| 2190 | -0.003007 |
| 2555 | -0.003007 |
| 2920 | -0.003007 |
| 3285 | -0.003007 |
| 3650 | -0.003007 |
| 4015 | -0.003007 |
| 4380 | -0.003007 |
| 4745 | -0.003007 |
| 5110 | -0.003007 |
| 5475 | -0.003007 |
| 5840 | -0.003007 |
| 6205 | -0.003007 |
| 6570 | -0.003007 |
| 6935 | -0.003007 |
| 7300 | -0.003007 |
| 7665 | -0.003007 |
| 8030 | -0.003007 |
| 8395 | -0.003007 |
| 8760 | -0.003007 |
| 9125 | -0.003007 |
| 9490 | -0.003007 |
| 9855 | -0.003007 |
| 10220 | -0.003007 |
| 10585 | -0.003007 |
| 10950 | -0.003007 |

This table illustrates clearly and in detail the evolution of total current over the service life of the system, showing an initially high demand in the first year, a gradual reduction by the second year, and a stable

performance maintained up to 30 years.

Electrode potential vs Ag/AgCl means the potential difference between the electrode surface and a nearby reference electrode placed in close proximity in the same electrolyte.

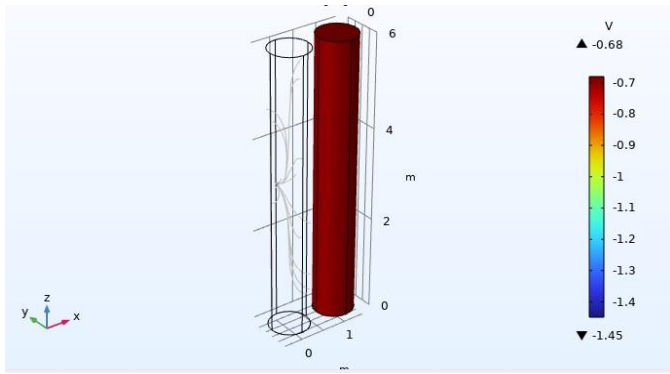


Figure 5: Electrolyte current density vectors (Streamline) & Electrode potential vs Ag/AgCl (Surface)

According to EN 1992 1 1 (Euro-code 2), the minimum longitudinal reinforcement ratio for bored piles is typically 0.5% of the pile cross-sectional area, which for a pile of radius 0.4 m corresponds to 0.002513 m² of reinforcement area (European Committee for Standardization, 2004). The proposed design uses 20 rebars of radius 0.00635 m, providing a total reinforcement area of 0.002534 m², thus satisfying Euro-code 2 requirements. Additionally, BS EN 1536 mandates a minimum of four bars of 12 mm diameter for bored piles (British Standards Institution, 1999), a condition which is also satisfied by the proposed arrangement. Therefore, the reinforcement design complies with both the structural design rules and the execution requirements of the relevant European standards.

In this case, for the safety factor, we used 20 rebars.

- First of all, we calculated the cross-sectional area of the RC pile:

$$r, (\text{pile}) = 0.4\text{m}$$

$$A, (\text{Pile}) = \pi r^2 \quad (2)$$

$$A, (\text{Pile}) = \pi * (0.4)^2 = 0.50265\text{m}^2$$

- Minimum reinforcement requirement:

Minimum longitudinal reinforcement ratio ρ_{min} is 0.5% of the cross-section area,

$$A, (\text{Reinforcement}) = 0.005 * A (\text{Pile}) \quad (3)$$

$$A, (\text{Reinforcement}) = 0.002513\text{m}^2$$

- Cross-sectional area of 1 Rebar:

$$A, (\text{Rebar}) = \pi r^2 \quad (4)$$

$$A, (\text{Rebar}) = \pi * (0.00635)^2 = 0.0001267\text{m}^2$$

- Number of rebars:

$$N, (\text{rebars}) = \frac{0.002513\text{m}^2}{0.0001267\text{m}^2} \quad (5)$$

$$= 19.83, \text{round-off to 20 re-bars.}$$

- Total surface area of rebars for 1 m height:

$$A, (1\text{-rebar}) = 2\pi r h \quad (6)$$

$$A, (1\text{-rebar}) = 2 * \pi * (0.00635) * (1) = 0.0399\text{m}^2$$

$$\text{And for 20 re-bars } 20 * 0.0399\text{m}^2$$

$$A, (20\text{-rebar}) = 0.798\text{m}^2$$

- Average current density:

$$j, (\text{average}) = \frac{I_{(\text{total})}}{A_{(\text{total})}} \quad (7)$$

$$j, (\text{average}) = \frac{-0.003007}{0.798} = -3.768\text{E-}3\text{ A/m}^2 \text{ (For rebars inside the RC pile).}$$

The obtained final current density of $-3.768 \times 10^{-3}\text{ A/m}^2$ ($\approx 3.77\text{ mA/m}^2$) after 30 years falls well within the internationally accepted range for cathodic protection of steel in reinforced concrete structures. According to EN 12696:2022 and NACE SP0169:2013, long-term protective current densities typically lie between 2 and 20 mA/m², depending on concrete resistivity, chloride content, and environmental exposure conditions. This confirms that the modeled value is both realistic and compliant with established standards (European Committee for Standardization, 2022; NACE International, 2013).

To determine the zinc mass required for 30 years of cathodic protection, Faraday's law of electrolysis was applied (Bard et al., 2022). Faraday's law relates the amount of metal consumed to the total electric charge transferred during the cathodic protection period. This allows calculation of the theoretical zinc mass needed to supply the required protective current over the design life of the structure.

In practice, however, not all of the anode's zinc mass can be used effectively. Factors such as uneven dissolution, anode shape changes, passivation, mechanical damage, and loss of electrical contact limit the usable mass of the anode. Based on corrosion engineering practice (Jones, 2018), a conservative utilization factor is applied to ensure reliable long-term protection. For zinc anodes in reinforced concrete structures, an 80% utilization factor is widely accepted. This means only 80% of the anode mass is considered available for electrochemical consumption over its design life, and the remaining 20% is left unused to account for practical losses and to ensure the anode does not degrade below functional limits before the end of the service life.

- Time in seconds:

$$t = T * 365.25 * 24 * 3600 \quad (8)$$

$$t = 30 * 365.25 * 24 * 3600 = 946,728,000\text{ s}$$

- Total charge delivered over 30 years:

$$Q = I * t \quad (9)$$

$$Q = 0.003007\text{ A} * 946,728,000\text{ s}$$

$$Q = 2,846,811.096\text{ C}$$

- And the Mass of Zn electrochemically consumed

$$m, \text{consumed} (M * Q) / (Z * F) \quad (10)$$

$$= \frac{65.38 * 2846811.096}{2 * 96485.33} = 0.9645\text{Kg}$$

- Mass of one cylindrical Zn anode (radius = 0.05 m, length = 1.0 m)

Volume:

$$V = \pi r^2 L \quad (11)$$

$$= \pi * (0.05\text{ m})^2 * (1.0\text{ m}) = 0.007853981633974483\text{ m}^3$$

Mass:

$$m \text{ anode} = V * \rho_{\text{Zn}} \quad (12)$$

$$= 0.007853981633974483\text{ m}^3 * 7135\text{ kg/m}^3 = 56.03815895840794\text{ kg}$$

Usable mass at 80%,

$$m (\text{usable}) = U * m (\text{anode}) \quad (13)$$

$$= 0.80 * 56.03815895840794 = 44.83052716672635\text{ kg}$$

- Installed Zn mass required (accounting for utilization)

$$m, \text{ (installed, req)} = \frac{m_{\text{consumed}}}{u} \tag{14}$$

$$= \frac{0.9645}{0.8} = 1.2056529050613185 \text{ Kg}$$

- Number of Anodes

$$\frac{m_{\text{installed req}}}{m_{\text{anode}}} \tag{15}$$

$$= \frac{1.2056529050613185 \text{ kg}}{56.03815895840794 \text{ kg}} = 0.021.$$

(For practical implementation, the calculated anodic demand corresponded to approximately 0.021. Since fractional anodes are not technically feasible, the design was rationalized to employ a single zinc anode.

3.2 Tubular Steel Pile Findings

A tubular steel pile is a structural element made of steel, shaped as a hollow cylinder (tube) and driven or drilled into the ground or seabed to support loads from a structure above. The hollow shape reduces weight while maintaining strength, making them ideal for deep foundations. Tubular steel pile of 6m height and 0.4 m radius, Zn anode of 1m height and 0.05 radius.

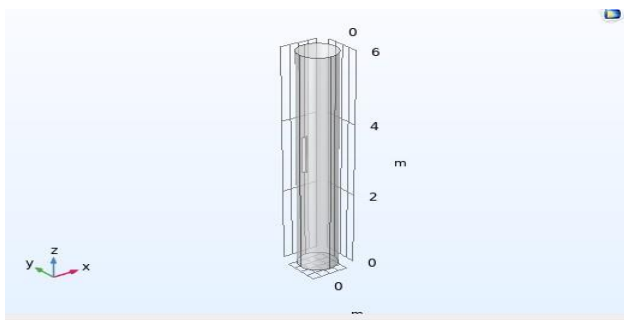


Figure 6: Tubular steel pile protected with zinc rod sacrificial anodes (Zn rod CP system).

The table below summarizes the key electrode surface parameters that are critical for evaluating the cathodic protection performance of the tubular steel pile.

| Table 4: Surface parameters inputs | | | | | |
|------------------------------------|-------------------------------|------------------|----------|--------|-------|
| No | Parameters | Unit | Zinc | Oxygen | Iron |
| 1 | Equilibrium potential (Eeq) | V | -0.95282 | 1.1176 | - |
| 2 | Exchange current density (i0) | A/m ² | 1 | 1E-9 | 0.001 |
| 3 | Tafel slope (A) | V/decade | 0.045384 | -0.1 | 0.1 |

The electrolyte surface parameters used in this analysis were the same as those applied for the reinforced concrete (RC) pile case. This ensures consistency in modeling and allows direct comparison of results between different structural configurations. By using identical electrolyte conductivity, resistivity, and interface properties, the influence of the cathodic protection system can be attributed solely to differences in geometry and current demand, rather than variations in environmental conditions.

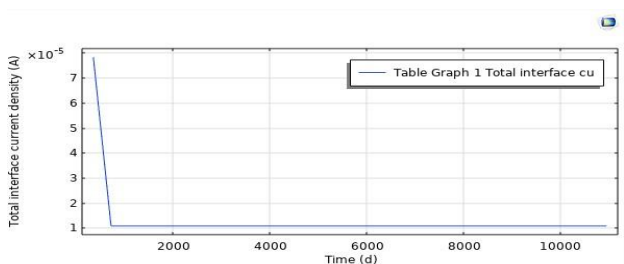


Figure 7: Total interface current (A) vs Time (d)

As observed from this graph, the positive sign of the total interface current density indicates that corrosion protection was not fully achieved. This suggests that from the first year up to the thirtieth year, there was insufficient zinc anode capacity to maintain complete cathodic protection of the tubular steel pile.

| Table 5: Total interface current (A) vs Time (days) | |
|---|-----------------------------|
| Time (days) | Total Interface Current (A) |
| 365 | 7.8387E-5 |
| 730 | 1.0895E-5 |
| 1095 | 1.0895E-5 |
| 1460 | 1.0895E-5 |
| 1825 | 1.0895E-5 |
| 2190 | 1.0895E-5 |
| 2555 | 1.0895E-5 |
| 2920 | 1.0895E-5 |
| 3285 | 1.0895E-5 |
| 3650 | 1.0895E-5 |
| 4015 | 1.0895E-5 |
| 4380 | 1.0895E-5 |
| 4745 | 1.0895E-5 |
| 5110 | 1.0895E-5 |
| 5475 | 1.0895E-5 |
| 5840 | 1.0895E-5 |
| 6205 | 1.0895E-5 |
| 6570 | 1.0895E-5 |
| 6935 | 1.0895E-5 |
| 7300 | 1.0895E-5 |
| 7665 | 1.0895E-5 |
| 8030 | 1.0895E-5 |
| 8395 | 1.0895E-5 |
| 8760 | 1.0895E-5 |
| 9125 | 1.0895E-5 |
| 9490 | 1.0895E-5 |
| 9855 | 1.0895E-5 |
| 10220 | 1.0895E-5 |
| 10585 | 1.0895E-5 |
| 10950 | 1.0895E-5 |

This table presents in detail the progression of total current throughout the system's service life, highlighting a high demand during the first year, followed by a gradual decline in the second year, and a relatively steady state thereafter up to 30 years. Nevertheless, it demonstrates that the zinc anode's current density was inadequate to fully protect the tubular steel pile, in contrast to its sufficient performance for the reinforced concrete pile.

As shown in the electrode potential versus Ag/AgCl plot, corrosion activity was most pronounced in the vicinity of the zinc anode. This indicates that while the anode was supplying protective current, the magnitude was insufficient to fully satisfy the cathodic protection requirements, leaving localized areas exposed to corrosion despite the presence of the anode.

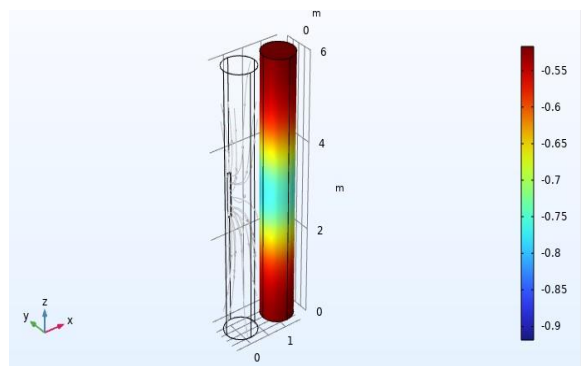


Figure 8: Electrolyte current density vectors (Streamline) & Electrode potential vs Ag/AgCl (Surface)

Furthermore, the total electrode thickness change provides a clear indication of the extent of corrosion affecting the tubular steel pile, showing variations from approximately 1.0×10^{-2} m to 3.5×10^{-2} m from the first year to the thirtieth year. This quantifies the material loss and underscores the impact of inadequate cathodic protection on the long-term durability of the structure.

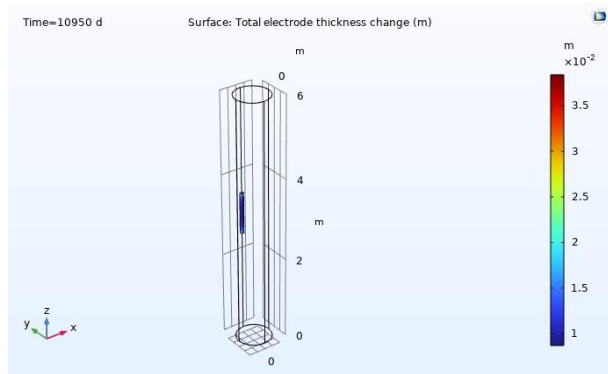


Figure 9: Tubular steel pile thickness change (m)

In this study, we observed that reinforced concrete (RC) piles maintained effective cathodic protection when utilizing zinc anodes of the same dimensions as those employed for tubular steel piles under identical electrolyte conditions. However, the tubular steel piles did not achieve sustained cathodic protection. This discrepancy may be attributed to several factors inherent to the materials and environmental interactions.

RC structures, due to their alkaline environment, facilitate the formation of a passive oxide layer on the steel reinforcement, enhancing the efficacy of cathodic protection systems (Byrne, 2015). Conversely, tubular steel piles, especially those exposed to marine environments, are susceptible to more aggressive corrosion mechanisms, including microbiologically influenced corrosion and localized pitting, which can compromise the performance of sacrificial anodes (Feng, 2020).

Additionally, the geometry and surface area of tubular steel piles may lead to uneven current distribution, reducing the overall effectiveness of the cathodic protection system (Wang et al., 2020). In contrast, the more uniform surface of RC piles allows for a more consistent protective current.

These findings underscore the necessity for tailored cathodic protection strategies that consider the specific material properties and environmental conditions of the structure to ensure long-term durability and performance.

4. CONCLUSIONS

The reinforced concrete (RC) piles maintain effective cathodic protection under marine conditions with zinc anodes of a given size, whereas tubular steel piles under identical conditions fail to sustain protection over time. This discrepancy is attributed to material-specific factors, including differences in corrosion mechanisms, passive layer formation, and current distribution. To enhance the long-term performance of tubular steel piles, it is recommended to increase the size or capacity of sacrificial zinc anodes relative to those used for RC piles. A larger anode would supply a greater protective current, mitigating the more aggressive corrosion experienced by tubular steel structures. Such optimization would improve durability, reduce maintenance requirements, and extend service life. Future research should determine optimal anode sizing under variable environmental conditions to develop robust cathodic protection design guidelines.

REFERENCES

Melchers, R. E. 2020. Long-term durability of marine reinforced concrete structures. *Journal of Marine Science and Engineering*, 8(4), 290.

Guo, Z., Wang, Y., Zhou, X., and Li, H. 2024. Review of cathodic protection technology for steel and reinforcement in concrete structures. *Applied Sciences*, 14(19), 9062. <https://doi.org/10.3390/app14199062>

Ghods, P., Isgor, O. B., McRae, G. A., and Miller, T. 2009. Modeling the chloride-induced corrosion initiation of steel reinforcement in concrete using the finite element method. *Computers and Structures*, 87(3-4), Pp. 196-207.

Anand, K. B., Krishnamoorthy, T. S., and Ganesh, B. 2013. Performance of zinc sacrificial anode in reinforced cement concrete members under chloride intrusion and marine environment exposure. *Revista Matéria*, 18(4), Pp. 1506-1515. <https://doi.org/10.1590/S1517->

70762013000400015

Tang, J., Zhang, Y., and Li, X. 2015. Cathodic protection effect of reinforced concrete beam specimens with zinc sacrificial anode in a marine environment. *Applied Mechanics and Materials*, 1125, Pp. 345-350.

Whitmore, D., and Miltenberger, M. 2019. Galvanic cathodic protection of corroded reinforced concrete structures. *Materials Performance*, 58(2), Pp. 52-57. <https://content.ampp.org/materials-performance/magazine-article/2482/Galvanic-Cathodic-Protection-of-Corroded>

Escalante, E., Hurley, J. A., and Bond, J. A. 1977. Corrosion and protection of steel piles in a natural seawater environment (Report No. 77-165). U.S. Army Construction Engineering Research Laboratory. <https://www.osti.gov/biblio/6903762>

Perme, S., Lau, K., Echeverria Boan, M., Tansel, B., and Duncan, M. 2020. Cathodic polarization behavior of steel with different marine fouling morphologies in seawater. *Journal of Materials in Civil Engineering*, 33(8), 04021179.

COMSOL AB. 2023a. Cathodic protection of steel in reinforced concrete [Application example]. COMSOL Multiphysics@. <https://www.comsol.com/model/cathodic-protection-of-steel-in-reinforced-concrete-11106>

COMSOL AB. 2023b. Oxide jacking of reinforced concrete [Application example]. COMSOL Multiphysics@. <https://www.comsol.com/model/oxide-jacking-of-reinforced-concrete-92611>

Korec, E., Jirásek, M., Wong, H. S., and Martínez-Pañeda, E. 2023. Phase-field chemo-mechanical modelling of corrosion-induced cracking in reinforced concrete subjected to non-uniform chloride-induced corrosion. *Theoretical and Applied Fracture Mechanics*, 129, Pp. 104-123. <https://doi.org/10.1016/j.tafmec.2023.104123>

Bard, A. J., Faulkner, L. R., and White, H. S. 2022. *Electrochemical methods: Fundamentals and applications* (3rd ed.). Wiley.

International Organization for Standardization. 2022. ISO 12696:2022 — Cathodic protection of steel in concrete. International Organization for Standardization. <https://www.iso.org/standard/77205.html>

NACE International. 2022. NACE SP0169-2022: Control of external corrosion on underground or submerged metallic piping systems. NACE International. <https://webstore.ansi.org/standards/nace/nacesp01692024>

Jones, D. A. 2018. *Principles and prevention of corrosion* (2nd ed.). Pearson.

European Committee for Standardization. 2004. EN 1992-1-1: Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings. European Committee for Standardization.

British Standards Institution. 1999. BS EN 1536: Execution of special geotechnical work – Bored piles. British Standards Institution.

European Committee for Standardization. 2022. EN 12696:2022 — Cathodic protection of steel in concrete. European Committee for Standardization.

NACE International. 2013. NACE SP0169-2013: Control of external corrosion on underground or submerged metallic piping systems. NACE International.

Byrne, A. 2015. *Cathodic protection for reinforced concrete structures*. Dublin Institute of Technology. <https://arrow.tudublin.ie/cgi/viewcontent.cgi?article=1116&context=engschcivart>

Feng, X. 2020. Protection performance of the submerged sacrificial anode-conductive mortar system for reinforced concrete structures in splash zones. *Corrosion Science*, 170, 108617.

Wang, F., Zhang, J., and Liu, Y. 2020. A comparative investigation on cathodic protection of zinc alloy, magnesium alloy, and aluminum alloy as sacrificial anodes on chloride-induced corrosion of reinforced concrete. *Construction and Building Materials*, 264, 120129.