

# Numerical modeling and performance analysis of sacrificial anode-based cathodic protection on underground pipelines using finite element method

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## ABSTRACT

Corrosion of underground pipelines within the oil and gas industry has high potential to cause structural failure and environmental contamination, necessitating an effective protection system such as Sacrificial Anode Cathodic Protection (SACP). This study aims to design and simulate a cathodic protection system using numerical simulation to evaluate its effectiveness in mitigating corrosion. A finite element method-based simulation was conducted to analyze the potential distribution and current density on pipelines with both linear anode configurations and a staggered configuration. The simulation results indicate that both configurations meet the protection criteria set by NACE SP-0169, with potential values more negative than -850 mV (vs Cu/CuSO<sub>4</sub> RE). The staggered configuration exhibited a more uniform potential distribution, ranging from -1032.11 mV to -978.5 mV, compared to the linear configuration, which ranged from -1006.8 mV to -937.6 mV. However, the staggered configuration resulted in higher anode consumption due to increased current density (0.02 to 0.111 A/m<sup>2</sup>) compared to the linear configuration (0.02 to 0.098 A/m<sup>2</sup>). While the empirical linear configuration is simpler and requires less anode consumption, its current distribution is less optimal. In contrast, the staggered configuration provides more uniform and effective corrosion protection.

**Keywords:** cathodic protection, sacrificial anode, corrosion, underground pipeline, numerical simulation, finite element method.

## INTRODUCTION

Corrosion is an electrochemical process that leads to the gradual degradation of metallic materials when interacting with the surrounding environment. Globally, corrosion represents a major technical and economic challenge. According to the NACE International IMPACT study released in 2016 [1], the global cost of corrosion was estimated at approximately USD 2.5 trillion annually, equivalent to 3.4% of the global gross domestic product (GDP) based on 2013 economic data [2, 29]. These costs encompass direct expenses including corrosion control measures (coatings,

cathodic protection systems, corrosion-resistant alloys), equipment replacement, and repair activities, as well as indirect costs such as production losses from unplanned shutdowns, safety-related incidents, and environmental remediation. The study further indicated that implementing corrosion prevention best practices could yield savings of 15–35% of these costs.

Several countries have documented serious incidents linked to corrosion-related infrastructure failures. In the United States, the PHMSA Pipeline Corrosion Report documented that corrosion was responsible for 18% of significant pipeline

incidents over the period 1988–2008, resulting in 30 fatalities, 100 injuries, and \$551 million in property damage during that 20-year period [3]. In the North Sea region, review studies of offshore structure failures have reported that 60–75% of all damages to offshore steel structures occur due to corrosion-mechanical influences, with analyses of the Norwegian Continental Shelf documenting 296 accidents over a 40-year period (1972–2013) [4]. In the Middle East, corrosion challenges have been documented in Qatar’s oil and gas industry with failure analyses from 2002–2006, where high H<sub>2</sub>S content, elevated temperatures, and aggressive atmospheric and subsurface conditions pose significant threats to infrastructure integrity [5]. These incidents reinforce the critical importance of effective cathodic protection design for underground pipelines, where soil-side corrosion poses persistent integrity threats.

Indonesia faces similar challenges, where corrosion has contributed to operational disruptions and environmental incidents across both onshore and offshore oil and gas facilities. These recurring issues underscore the importance of implementing effective corrosion mitigation strategies, particularly in regions with expanding petroleum exploration and production activities.

Aceh is among the Indonesian regions rich in oil and gas resources. Recent exploration activities in the Andaman Working Areas offshore northern Sumatra have revealed considerable hydrocarbon potential, with discoveries including approximately 6 trillion cubic feet (TCF) of gas-in-place at the Layaran-1 well in South Andaman Block (announced in December 2023) and an estimated total resource potential of 4.965 million barrels of oil equivalent (MMBOE) across the Andaman concession areas [6–7]. This potential is reinforced by the discovery of substantial gas reserves in the Timpan Well within the Andaman II Working Area (WK), alongside continued exploration in the Andaman III and South Andaman blocks [6–7]. It is anticipated that Aceh’s oil and gas industry would continue to grow, increasing investment and making Indonesia’s upstream petroleum sector more competitive. However, a number of technical difficulties, especially those pertaining to the integrity of the oil and gas infrastructure, accompany the increase of exploration and production operations.

Key technical challenges affecting pipeline integrity in such environments include: (1) soil heterogeneity, where varying soil resistivity along

the pipeline route creates non-uniform corrosion conditions and complicates cathodic protection design; (2) coating degradation over time, which increases current demand and creates localized corrosion cells at coating holidays; (3) stray current interference from nearby electrical installations, railways, or other cathodic protection systems that can accelerate corrosion or cause shielding effects; and (4) microbiologically influenced corrosion (MIC) in certain soil conditions, particularly in waterlogged or anaerobic environments containing sulfate-reducing bacteria.

Corrosion remains one of the most critical issues affecting the reliability and safety of pipelines and associated facilities. Its impacts include structural degradation, leakage, operational failures, and environmental pollution, as exemplified by the pipeline rupture that resulted in an oil spill at PT Chevron Pacific Indonesia in Dumai [8]. To mitigate such risks, multiple corrosion control strategies have been implemented for buried pipelines. These include: (1) external protective coatings such as fusion-bonded epoxy (FBE), three-layer polyethylene (3LPE), and coal tar enamel that provide primary barrier protection; (2) cathodic protection systems, either impressed current (ICCP) or sacrificial anode (SACP), which provide electrochemical protection at coating defects; (3) material selection involving corrosion-resistant alloys or higher-grade steels for aggressive environments; and (4) corrosion inhibitor injection for internal corrosion control. Among these, cathodic protection in combination with external coatings remains one of the most widely adopted and effective approaches for underground pipelines.

Cathodic protection works by converting the protected metal structure into a cathode in an electrochemical system, reducing its corrosion rate and extending service life [9]. Effective cathodic protection requires sound system design to ensure long-term performance under varying environmental and operating conditions. To improve design fidelity and reliably predict performance, simulation-based methods have become increasingly important. Numerical methods such as the boundary element method (BEM) [10–11] and finite element method (FEM) [12–13] enable detailed modeling of electrochemical behavior, potential distribution, and current flow within cathodic protection systems, offering insights that are difficult to obtain through empirical approaches alone [14]. In practice, the design of cathodic protection often

relies on empirical approaches based on in NACE SP-0169 and DNV-RP-B401. This study aims to compare the empirical design and numerical simulation approaches of underground pipeline cathodic protection (sacrificial anode type). Then, the study demonstrates feasibility of unconventional design that is beyond the scope of empirical approach with the objective of optimizing corrosion protection effectiveness and supporting the integrity of oil and gas infrastructure.

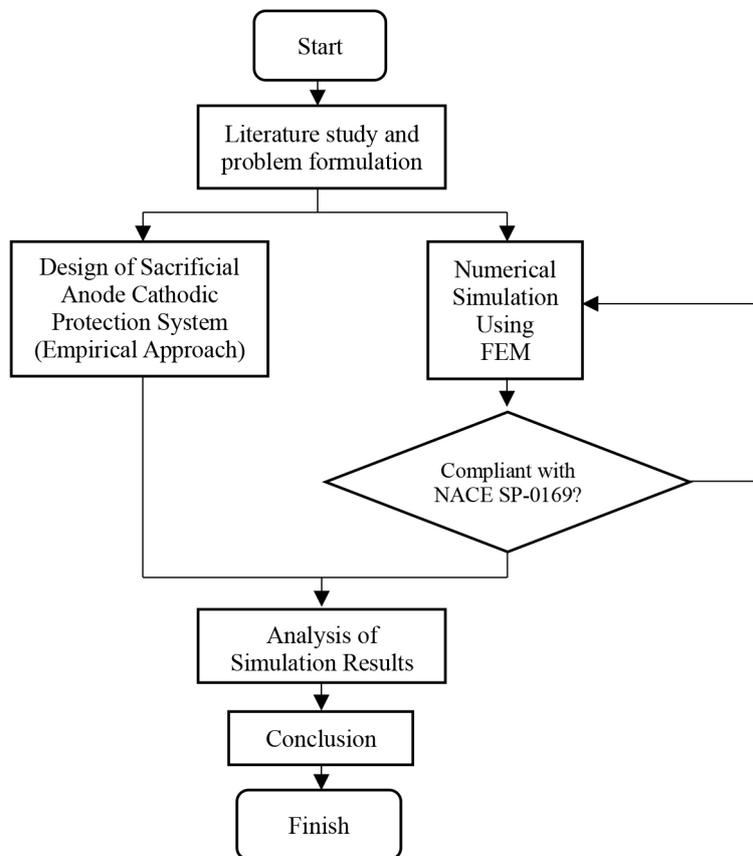
a negative (cathodic) potential of at least -850 mV measured with respect to a saturated copper/copper sulfate reference electrode (CSE) should be achieved on the structure surface, with the protective current applied. Additionally, the standard recommends that potentials should not exceed -1200 mV (vs. Cu/CuSO<sub>4</sub>) to avoid overprotection effects such as coating disbondment and hydrogen embrittlement of susceptible steels. These criteria serve as the benchmark for evaluating simulation results in this study.

**METHODS**

The workflow of this study is given in Figure 1. The design and evaluation of cathodic protection systems in this study follow the criteria established in NACE SP-0169 ‘Control of External Corrosion on Underground or Submerged Metallic Piping Systems’ [20]. This standard, originally developed by NACE International (now AMPP - Association for Materials Protection and Performance), provides industry-accepted criteria for cathodic protection effectiveness. The primary criterion specifies that

**Materials**

Designing a sacrificial-anode cathodic protection system for underground pipelines requires material and environmental data, including specifications for the pipe, anode, and surrounding soil. In this study, the pipeline is modeled using ASTM A106 Grade B steel, which is commonly protected using sacrificial-anode cathodic protection systems [15]. The underground pipeline specifications are summarized in Table 1. Table 2 shows the anode design properties used in this study.



**Figure 1.** Workflow of the study, involving comparison of established numerical simulation of cathodic protection and empirical approaches

**Table 1.** Underground pipe specifications [16]

Properties/dimension	Remark
Material	A106 Gr B
Diameter (OD)	0.2191 m
Length (L)	36 m
Current density (Cd)	30 mA/m <sup>2</sup>
External coating	3 LPE (3 Layer polyethylene)
Coating breakdown	10%

**Table 2.** Sacrificial anode specification

Properties/dimension	Remark
Anode	Magnesium – High alloy potential type 5D3
Outer diameter (OD)	152 mm
Length (L)	305 mm
Anode capacities	1100 Amp-hr/Kg
Anode weight	2.3 Kg
Anode potential	-1.7 V
Utility factor	85%

The soil used in the design is considered homogeneous with a resistivity of 100 Ohm.m. This value was selected based on comprehensive soil resistivity surveys conducted in Indonesia [17-18], which identified resistivity values ranging from 13.6 to 1337 Ohm.m depending on lithology, moisture content, and depth. The selection of 100 Ohm.m represents a moderately conservative design condition for several reasons: (1) it falls within the typical range for clay-loam soils commonly encountered in Indonesian pipeline corridors; (2) according to NACE guidelines, soils with resistivity below 1000 Ohm.m are considered corrosive and require cathodic protection; (3) it provides a representative baseline that allows the cathodic protection system to be evaluated under reasonably challenging conditions without being overly pessimistic. The use of a homogeneous soil model represents a simplification; actual field conditions would exhibit spatial variation, which is acknowledged as a limitation of this study.

**Empirical design of sacrificial anode cathodic protection system**

The empirical design of SACP in this study was based on DNV-RP-B401: Cathodic Protection Design. The equations used in the design are as follows [19]:

Surface area of protected pipe:

$$A_c = \pi \times OD \times L \tag{1}$$

where:  $A_c$  – cathode surface area, i.e., the external surface area of the pipe to be protected (m<sup>2</sup>);  $OD$  – outer diameter of pipe (m);  $L$  – length of pipe (m).

Current protection:

$$I_c = A_c \times f_c \times i_c \tag{2}$$

where:  $I_c$  – total current protection (A);  $f_c$  – coating breakdown;  $i_c$  – current density of metal (A/m<sup>2</sup>).

Total weight of anode:

$$M_{total} = \frac{I_c \times t \times 8760}{c \times u} \tag{3}$$

where:  $M_{total}$  – total weight of anode (kg);  $t$  – protection time (year);  $c$  – anode capacity (A-h/kg);  $u$  – utility factor; 1 year = 8760 hour.

Number of anodes:

$$n = \frac{M_{total}}{M_{anode}} \tag{4}$$

where:  $n$  – number of anode (unit);  $M_{anode}$  – weight of an anode (kg).

Displacement between anodes

$$S_a = \frac{L}{n} \tag{5}$$

where:  $S_a$  – displacement between anodes (m).

**Electrochemical model of corrosion**

Corrosion is modeled as an electrochemical process, whereby cathodes and anodes experience electrochemical reactions that produce potential in the electrolyte. The distribution of this potential in the electrolyte is governed by Laplace’s equation for potential distribution [21]:

$$\kappa \nabla^2 \phi = 0 \tag{6}$$

where:  $\phi$  is the potential (in Volt), and the flux or the current density is  $\frac{\partial \phi}{\partial n}$  (in A/m<sup>2</sup>), and  $\kappa$  in conductivity (in Ohm.m).

In this approach, the cathodes and anodes are the sources of the electrochemical current and potential. Application of the governing equation above (Equation 6) with its boundary conditions

to the cathodic protection case is visualized in Figure 2. The domain of the Laplace's equation is the soil, with the pipeline and the anodes creating the internal surface (internal boundaries) of the soil. The external boundaries (assigned as  $\Gamma_1$ ) of the domain are the soil's surface and the soil cutoff where the analysis is still deemed relevant. These boundaries are assumed to be the points where the flux or current density vanish in the domain, due to distance from the sources (the cathodes and anodes). Therefore, on boundary  $\Gamma_1$ , a zero-flux Neumann boundary condition ( $\frac{d\phi}{dn} = 0$ ) is applied, indicating that no current passes normal to this boundary. This represents an electrically insulating surface at the soil-air interface where the current cannot flow into the air domain.

The internal boundaries are where the soil meets the pipeline's and anode's surfaces, and assigned as  $\Gamma_2$  (the pipe or the cathode) and  $\Gamma_3$  (the sacrificial anodes). The cathodes and anodes (or collectively the electrodes) are either assigned as Dirichlet boundary (known potential value) or Neumann boundary (known current density value). On boundary  $\Gamma_2$ , which is the pipe surface (cathode), a boundary condition of current density  $0.003 \text{ A/m}^2$  is given, determining the interaction between the pipe and the electrolyte medium to ensure cathodic protection system effectiveness. Meanwhile, on boundary  $\Gamma_3$ , which is the sacrificial anode surface, the potential is set at  $\phi_a = -1.7 \text{ V}$  to create a sufficient potential

difference between anode and cathode, allowing protective current flow to the pipe and ensuring the pipe remains protected from corrosion. Then, the complete boundary condition equations are stated as follows:

$$\Gamma_1 : \frac{\partial \phi}{\partial n} = 0 \tag{7}$$

$$\Gamma_2 : \frac{\partial \phi_c}{\partial n} = 0.003 \frac{\text{A}}{\text{m}^2} \tag{8}$$

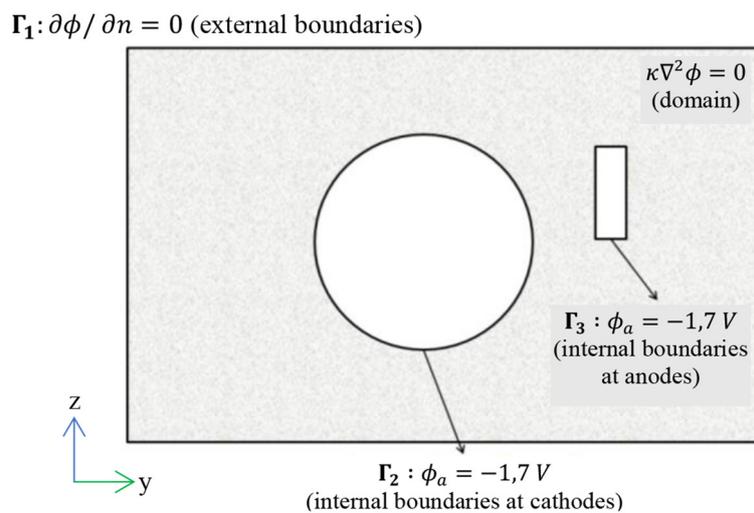
$$\Gamma_3 : \phi_a = -1.7 \text{ V} \tag{9}$$

As for the specific case in this study, the dimensions of the domain and its boundaries representing underground pipeline and the sacrificial anodes are given in Table 3.

### Numerical simulations

The electrochemical model of corrosion is the basis for numerical simulations. Numerical simulations were carried out through the finite element method (FEM) in COMSOL Multiphysics. The FEM analysis procedure consists of the following sequential steps:

1. Geometry creation: A three-dimensional model of the soil domain, pipeline (cathode), and sacrificial anodes is constructed with appropriate dimensions based on the empirical design calculations.
2. Equation 6 with its boundary conditions (Equation 7 to 9) are numerically solved through



**Figure 2.** Schematic representation of the sacrificial anode cathodic protection (SACP) system model showing boundary conditions. The model domain represents the soil (as electrolyte) where the Laplace equation ( $\kappa \nabla^2 \phi = 0$ ) governs potential distribution. Boundary  $\Gamma_1$  (top surface) represents the soil-air interface with zero-flux condition ( $\frac{d\phi}{dn} = 0$ ). Boundary  $\Gamma_2$  (pipe surface, acting as cathode) has a prescribed current density of  $0.003 \text{ A/m}^2$ . Boundary  $\Gamma_3$  (anode surface) has a fixed potential of  $\phi_a = -1.7 \text{ V}$  vs.  $\text{Cu/CuSO}_4$ . Not to scale

FEM by COMSOL. The boundary conditions defined in Section 2.3 are applied to the respective surfaces (insulating boundaries, cathode surface with current density condition, and anode surface with fixed potential).

3. Mesh generation: The domain is discretized using tetrahedral elements with mesh refinement near electrode surfaces where steep potential gradients are expected. An extremely fine mesh setting is employed to ensure numerical accuracy.
4. Solving: The system of linear equations is solved using a stationary solver to obtain the steady-state potential distribution throughout the domain.
5. Post-processing: Results are extracted including potential values at specified points on the pipe surface and current density distribution on the anode surfaces for subsequent analysis.

In this study, a two-dimensional model of a sacrificial anode cathodic protection (SACP) system for underground pipelines is developed to evaluate current distribution and corrosion potential. The cathodic protection design is formulated within a corrosion electrochemistry framework. In COMSOL Multiphysics, key inputs for the SACP simulation include electrode potentials, electrolyte conductivity, and metal current density. The system geometry, including the anode-to-pipeline separation distance, is also specified. The simulated potentials are evaluated against the NACE SP-0169, which considers cathodic protection effective when the potential is  $\leq -850$  mV (vs Cu/CuSO<sub>4</sub>). To avoid overprotection, the lower limit of  $-1200$  mV is also considered, since excessive polarization may lead to cathodic disbondment and hydrogen embrittlement [20].

### Model and mesh

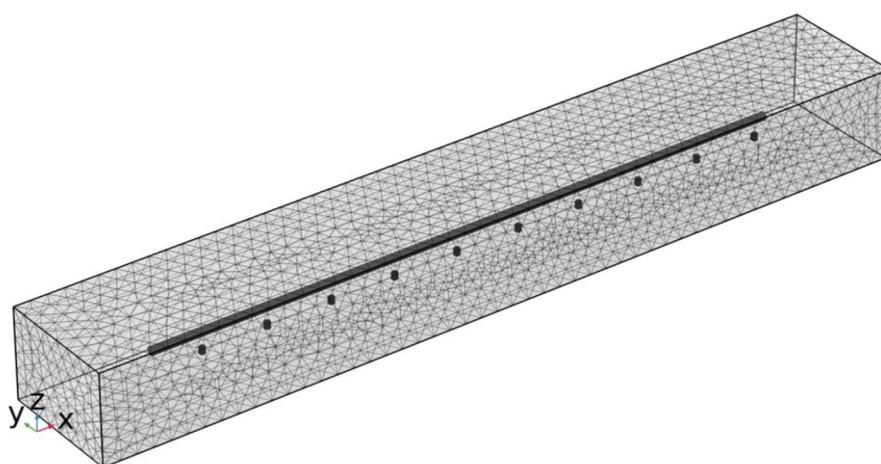
The (three dimensional) model for the underground pipeline along with the empirically designed 10 anodes are illustrated in Figure 3. The model is discretized into 1,406,065 tetrahedral elements (Table 3). The illustration of the mesh can be viewed in Figure 3, where the mesh is already optimized to ensure the curved shape of the pipeline and anodes are preserved.

### Determination of data collection points for numerical simulation results

COMSOL simulation outputs are evaluated to characterize the potential distribution along the buried pipeline and to assess the effectiveness of cathodic protection. Four circumferential sampling locations are used to represent the potential field around the pipe: 0° (nearest the anode, typically exhibiting the most negative potential), 90° and 270° (perpendicular to the anode, capturing lateral distribution), and 180° (opposite

**Table 3.** Geometrical model and meshing parameter

Domain properties	Value (m)
Width	5
Depth	7
Height	46
Pipe and anodes properties	As given in Table 1 and Table 2
Mesh properties	Value
Number of tetrahedra elements	1,406,065
Number of triangle elements	74,440



**Figure 3.** FEM Mesh visualization of the underground pipeline SACP model

the anode, where the largest potential drop may occur). These measurements are used to map the circumferential potential distribution and to evaluate cathodic protection effectiveness in accordance with NACE SP-0169 (Figure 4).

### Modification of anode configuration

To examine how anode configuration influences cathodic protection performance, a series of simulations is performed by varying both the number and placement of anodes. The baseline case uses 10 anodes based on an empirical design; however, the layout is modified from a linear arrangement to a staggered pattern to improve the distribution of protective current. The anode count is then reduced to 7 and 4 while maintaining the staggered configuration to assess the resulting changes in protection coverage and system efficiency. Performance is evaluated against the NACE SP-0169 criterion to determine cathodic protection effectiveness.

## RESULTS AND DISCUSSION

### Empirical design results of sacrificial anode cathodic protection system

The DNV-RP-B401-based design yields key parameters, including pipe surface area, required protection current, total anode mass, number of anodes, and anode spacing for effective protection. The design results are summarized in Table 4.

The design results show that the protection system requires 10 anodes with a total weight of 20.88 kg, installed at 3.6 m spacing to promote a uniform distribution of protective current. A required current of 0.074 A is sufficient to meet corrosion protection criteria. These parameters, determined using an empirical design approach, were transferred to the numerical simulations.

### Numerical simulation results based on empirical design

Potential distribution along the pipe is visualized in Figure 5. The simulation results in Figure 5 show the potential distribution along the pipeline, consistent with the expected behavior of a cathodic protection system. Regions closer to the anode exhibit more negative potentials, as reflected by the color-scale gradient, indicating stronger

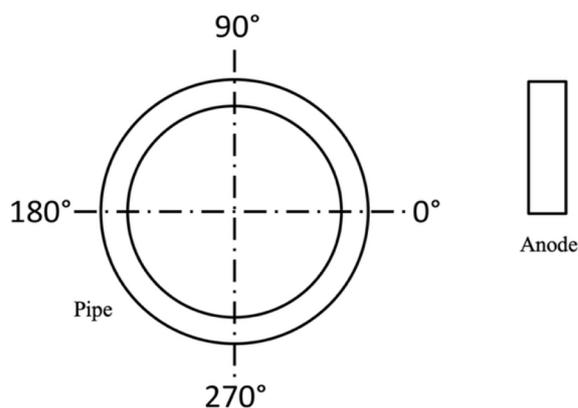


Figure 4. Point for data collecting from simulation result

Table 4. Empirical design results of sacrificial anode cathodic protection system

Parameter of empirical design	Value	Unit
Surface area of protected pipe ( $A_c$ )	24767	m <sup>2</sup>
Total current protection ( $I_c$ )	0.074	A
Total weight of anode ( $M_{total}$ )	20.88	kg
Number of anode (n)	10	piece
Displacement between anodes ( $S_a$ )	3.6	m

polarization and higher protective current density in these areas. With increasing distance from the anode, the potential becomes progressively less negative, suggesting that the protective current spreads over the pipe surface and decreases with distance. Overall, this pattern indicates that the system distributes protective current effectively, providing corrosion protection along the pipeline. A clearer comparison of potential values at the selected measurement locations is presented in Figure 6.

The simulations indicate that the pipe-to-soil potentials at the four measurement locations range from  $-1006.8$  to  $-937.6$  mV (vs. Cu/CuSO<sub>4</sub>), satisfying the NACE SP-0169 criterion for effective protection ( $\leq -850$  mV). These values suggest that the entire pipe remains protected from corrosion while avoiding overprotection that could lead to coating disbondment or hydrogen embrittlement. The circumferential potential variation is 69.2 mV, with the most negative potential at 0° ( $-1006.8$  mV) and the least negative at 180° ( $-937.6$  mV). This gradient indicates stronger polarization near the anode while more distant regions remain within acceptable protection limits.

In addition, the protective current distribution indicates that the highest current density occurs at the two ends of the sacrificial anode, reaching

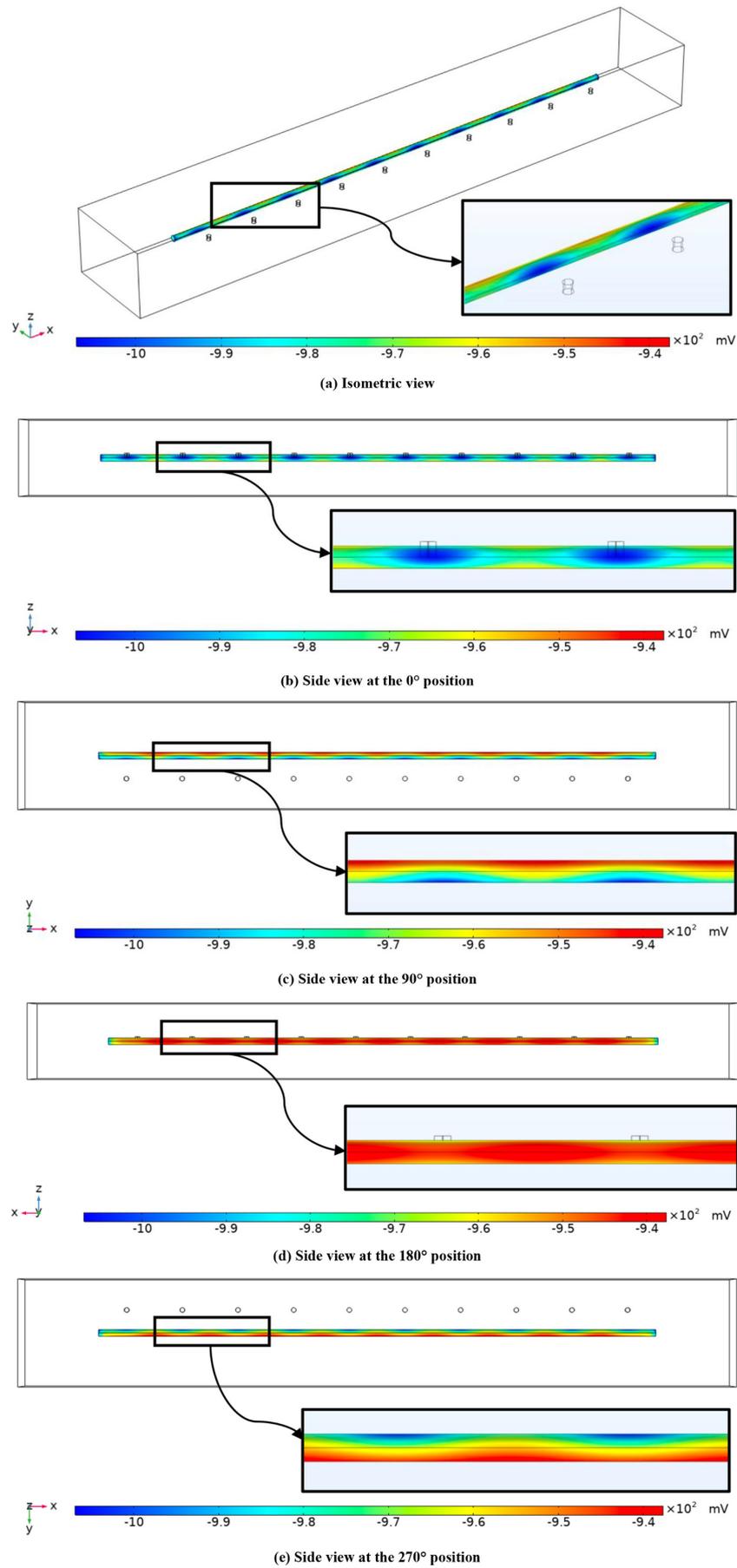
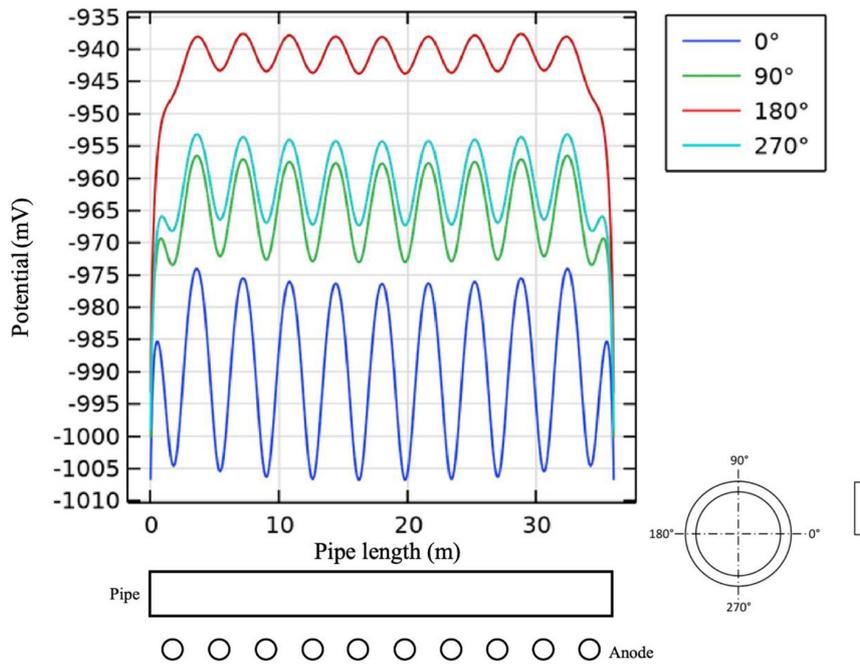


Figure 5. Visualization of potential distribution on an underground pipeline



**Figure 6.** Potential values along the pipeline length at all points

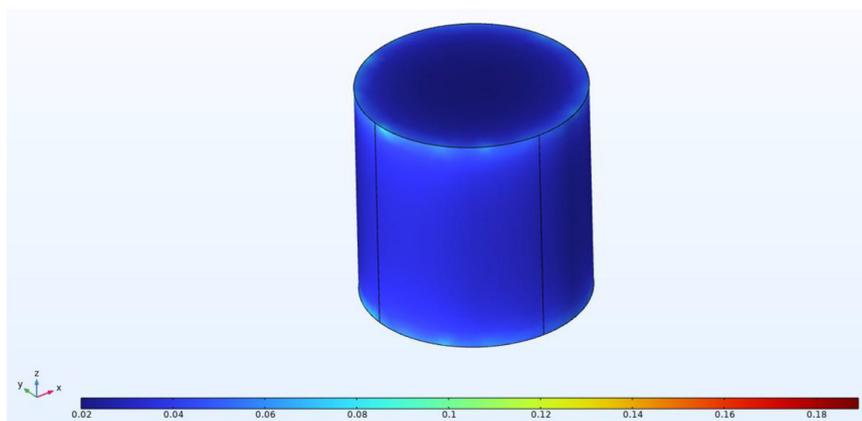
approximately 0.02–0.098 A/m<sup>2</sup>, as shown in Figure 7, whereas the midsection of the anode exhibits its lower current density and is therefore consumed more slowly. This behavior is consistent with the edge effect, in which the electric field – and consequently the current density – tends to concentrate near edges and corners of conductive materials. In cathodic protection systems, this intensified field at the anode ends (tips) promotes faster anodic dissolution, leading to more rapid degradation at the anode ends than at the center.

Beyond the edge effect, anode consumption is influenced by the anode geometry, electrolyte resistivity, and the anode-to-structure spacing and orientation. The electrochemical characteristics of the anode material also affect the spatial distribution

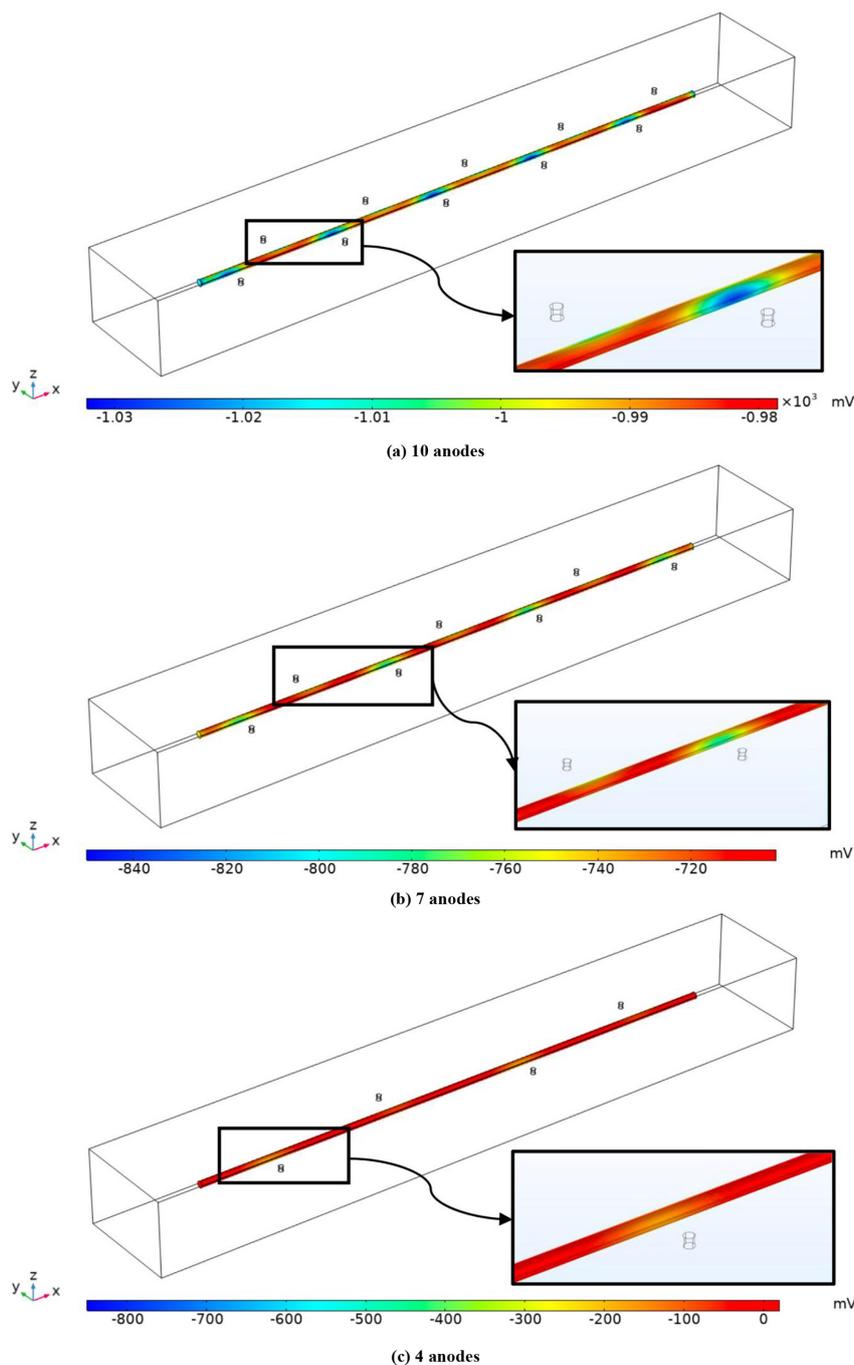
of anodic dissolution, contributing to non-uniform ion release along the anode surface. Over time, these differences in consumption rate may reduce protection uniformity and degrade overall system performance, thereby affecting the reliability of corrosion protection. Overall, the DNV-RP-B401–based design provides effective protective current distribution and satisfies the NACE SP-0169 criterion for adequate cathodic protection

**Numerical simulation results of anode configuration modification**

The potential distribution pattern on the pipeline after anode configuration modification can be seen in Figure 8.



**Figure 7.** Visualization of current density distribution on the sacrificial anode



**Figure 8.** Visualization of potential distribution on the underground pipeline after modification

Figure 9(a) shows that modifying the anode configuration to a staggered configuration with 10 anodes produces a more stable potential distribution compared to the linear configuration, with a range of -1032.11 to -978.5 mV, more uniform than the initial empirical design range of -1006.8 to -937.6 mV. This change improves the effectiveness of protective current distribution, reduces the risk of underprotected zones, and ensures the entire pipe surface remains within protection

limits according to NACE SP-0169, thus increasing pipe resistance to corrosion.

Figure 9(b) indicates that reducing the anode count to seven results in a less negative potential distribution, with values between -786.62 and -701.56 mV, bringing parts of the pipeline close to – or above – the minimum protection criterion specified in NACE SP-0169. The reduction is more pronounced in the four-anode case (Figure 9(c)), where potentials range from -182.52

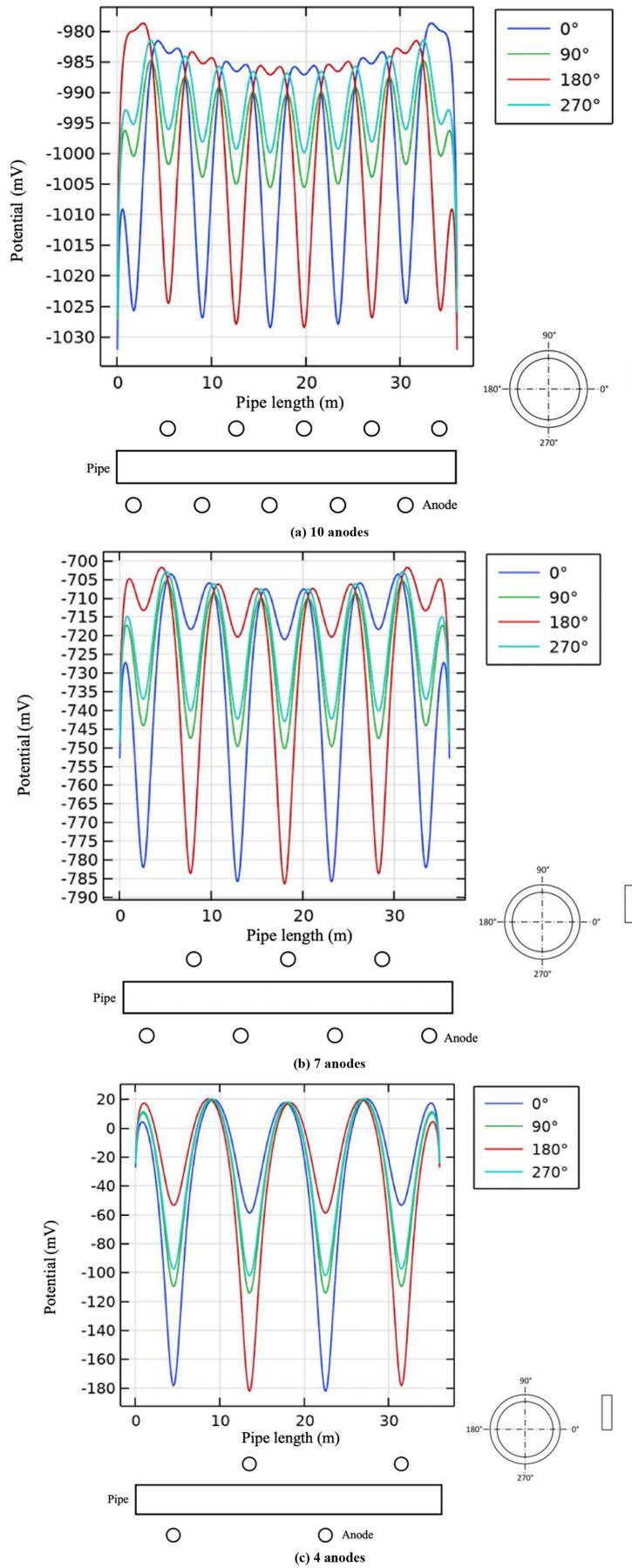


Figure 9. Potential values along the pipeline length at all points after modification

to 20.5 mV, suggesting that most of the pipeline receives inadequate protection and is therefore highly susceptible to corrosion.

Reconfiguring 10 anodes into a staggered layout produces a more uniform distribution of protective current than the empirical linear arrangement, which tends to create underprotected regions at locations farther from the anodes. Nevertheless, anode quantity remains the primary

determinant of protection effectiveness: decreasing the number of anodes substantially degrades cathodic protection performance.

In addition, the protective current density is non-uniform along the anodes in both linear and staggered configurations, with peak values concentrated near the anode ends. This behavior is evident from the color gradients along the anode surface in Figure 10.

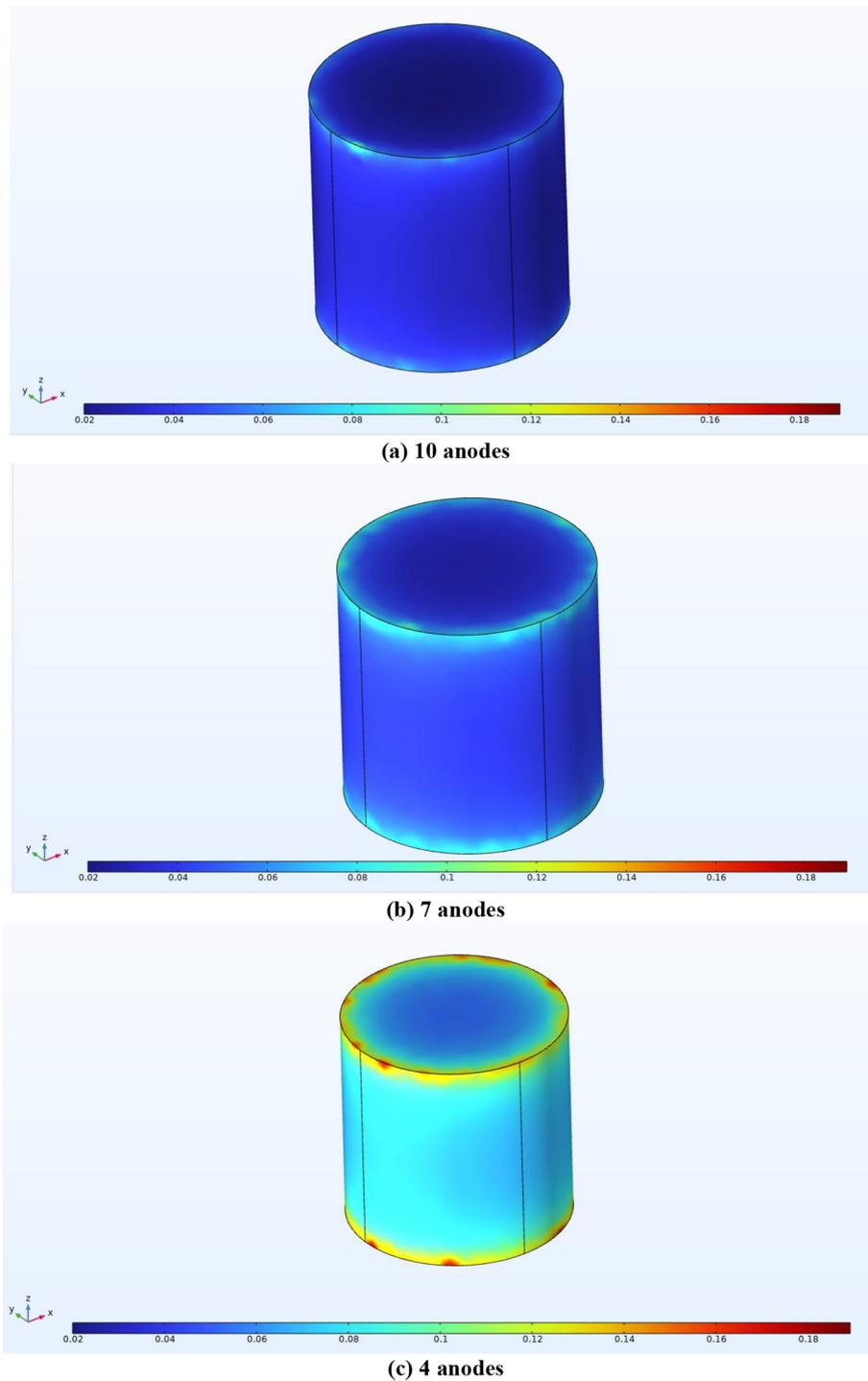


Figure 10. Visualization of current density distribution on the sacrificial anodes after modification

Adopting a staggered layout with 10 anodes produces a broader current-density range (0.02–0.111 A/m<sup>2</sup>) than the linear arrangement (0.02–0.098 A/m<sup>2</sup>). This improves protection coverage but also increases the anode dissolution rate. When the anode count is reduced to seven, the peak current density rises to 0.156 A/m<sup>2</sup>, and it increases further to 0.189 A/m<sup>2</sup> with four anodes, leading to more uneven consumption and accelerated degradation at the anode ends.

Overall, the staggered configuration distributes protective current more effectively but is associated with faster anode consumption than the linear layout, potentially reducing system service life. In contrast, the linear configuration is more economical but tends to provide less uniform protection.

The simulations indicate that the empirical (linear) design and the modified (staggered) configuration exhibit clear differences in potential distribution and current density. The staggered layout yields a more uniform potential profile, but it also results in higher current densities, which can accelerate anode consumption and potentially reduce the service life of the cathodic protection system. A comparison of both designs across selected parameters is summarized in Table 5.

### Comparison with literature and validation

The simulation results obtained in this study demonstrate good agreement with published findings in the cathodic protection literature. Abootalebi et al. [22] used boundary element method to optimize electrode positioning in sacrificial anode cathodic protection systems and demonstrated that anode placement significantly

affects protection uniformity. Their optimization approach showed that strategic positioning of anodes can improve potential distribution on protected structures. This principle supports the present study’s finding that the staggered configuration, which distributes anodes on alternating sides of the pipeline, provides more uniform protection compared to the linear arrangement where all anodes are positioned on one side. Attarchi et al. [23] simulated linear anode configurations alongside coated and uncoated pipes and showed that anode-pipe distance and spacing must be tuned to balance current spread versus local over-protection, with optimal distances depending on pipe diameter and soil resistivity.

The edge effect phenomenon observed in this study, where current density is highest at anode ends (Figure 7 and Figure 10), is well-documented in the literature. Mansouri et al. [24] developed three-dimensional finite element models of buried sacrificial magnesium anodes and demonstrated that maximum current discharge occurs at the top and bottom edges of anodes, with maximum material depletion occurring in these areas – a phenomenon they explicitly identified as the “anode end effect”. Their modeling reproduced field observations of aged anodes exhibiting greater mass loss at the ends compared to middle sections. Shirshahi et al. [25] extended this work with transient 3D models including anode corrosion and deposit formation, again predicting strong spatial non-uniformity of current output with geometry controlling where dissolution concentrates.

The selection of 100 Ohm.m soil resistivity in this study falls within the range commonly investigated for sacrificial anode cathodic protection systems. Attarchi et al. [26] performed

**Table 5.** Comparison of empirical design and configuration modification

Criteria	Empirical design (linear configuration)	Configuration modification (staggered configuration)
Potential range	From -1006.8 to -937.6 mV	From -1032.11 to -978.5 mV
Current density	From 0.02 to 0.098 A/m <sup>2</sup>	From 0.02 to 0.111 A/m <sup>2</sup>
Potential distribution	Less uniform; sections farther from the anode approach the protection limit, increasing the risk of underprotection.	More uniform, reducing unprotected zones.
Anode consumption rate	More controlled anode consumption.	Faster anode consumption.
Protection effectiveness	Some pipeline areas are at risk of underprotection due to suboptimal current distribution.	More uniform protection along the pipeline.
Anode service life	Longer due to slower anode consumption.	Shorter due to faster anode consumption.
Long-term efficiency	More economical due to less frequent anode replacement, although protection is less optimal in some areas.	Requires more frequent anode replacement but provides more stable protection.

FEM optimization of cathodic protection for buried vessels across soil resistivities of 10–500 Ohm.m and found that increasing soil resistivity increases potential differences on the protected surface, though optimized anode layouts can limit this effect. The validity of FEM approaches for cathodic protection modeling has been established through numerous validation studies. Xu and Cheng [27] conducted both experimental and numerical studies of cathodic protection effectiveness at corrosion defects on pipelines, demonstrating good agreement between simulated and measured potential distributions. Ghobadi et al. [28] compared simulation results with experimental measurements for cathodic protection of oil well casings and reported good agreement in single-layer soils, with larger scatter observed only in multilayer soil conditions.

The current density values and potential distributions obtained in this study are also consistent with field measurements reported in DNV-RP-B401 recommended practice [19], which provides design guidelines based on extensive operational experience with cathodic protection systems.

It should be noted that direct numerical or experimental comparisons of linear versus staggered sacrificial anode layouts specifically for cylindrical buried pipelines remain limited in the published literature. However, the transferable design principles from the studies cited above consistently indicate that reducing maximum anode-pipe distance, avoiding large gaps between anodes, and distributing anodes more evenly around the protected structure all contribute to improved potential uniformity. The present study's finding that the staggered configuration provides 22% reduction in potential variation (from 69.2 mV to 53.6 mV) compared to the linear pattern represents a quantitative contribution to this body of knowledge for underground pipeline applications.

### Model limitations

While the FEM simulation provides valuable insights into cathodic protection system performance, several limitations should be acknowledged when interpreting the results. The model assumes uniform soil resistivity of 100 Ohm.m throughout the computational domain. In actual field conditions, soil resistivity varies spatially due to changes in moisture content, temperature, soil composition, and geological stratification.

This heterogeneity can create localized areas of inadequate protection or overprotection that are not captured by the homogeneous soil assumption employed in this study. Future work could incorporate spatially varying resistivity fields based on geoelectrical survey data to better represent real-world conditions.

The simulation represents steady-state conditions and does not account for transient behavior inherent in cathodic protection systems. Factors such as seasonal variations in soil moisture and temperature, progressive anode depletion over the service life, and gradual degradation of protective coatings all introduce time-dependent effects that influence system performance. A pseudo-transient or fully time-dependent model incorporating anode mass loss kinetics would be required to predict long-term system behavior and remaining service life.

Although a three-dimensional model was employed, the analysis focuses on specific cross-sectional measurement points and may not fully capture complex current flow patterns near geometric discontinuities such as pipe bends, tee connections, or at the ends of the protected section where current paths become three-dimensional in nature.

## CONCLUSIONS

A sacrificial-anode cathodic protection system for underground pipelines was designed and evaluated using empirical approaches and numerical simulation. The simulations indicate that the DNV-RP-B401-based design meets the NACE SP-0169 criterion for effective corrosion protection. Anode placement strongly influences both protective-current distribution and anode consumption. Compared with the linear layout, a staggered arrangement produces a more uniform current (and potential) distribution, reducing the likelihood of underprotected regions. However, the staggered configuration also increases current density, which accelerates anode dissolution and may shorten system service life.

Anode quantity is likewise a primary factor controlling protection effectiveness. Reducing the number of anodes decreases the level and uniformity of protection, with the 10-anode case providing the most reliable coverage, whereas the 7- and 4-anode configurations increase the risk of underprotected zones and corrosion. Therefore, an optimal cathodic protection design should balance

anode count and installation configuration against protection uniformity, current demand, and anode consumption. In practice, a linear configuration tends to be more economical in anode utilization, while a staggered configuration offers more uniform protection but may require more frequent anode replacement.

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