Modeling the Cathodic Protection System for a Marine Platform Jacket

Masood Hajigholami, Keyvan Raeissi, and Hamidreza Salimi Jazi, *Department of Materials Engineering, Isfahan University of Technology, Isfahan, Iran*
Saeid Shabani, *Subsea R&D Center, Isfahan University of Technology, Isfahan, Iran*

The influence of a sacrificial anode cathodic protection (CP) system designed for corrosion protection of a marine platform jacket was modeled using the finite element method. A numerical model was applied to calculate the distributions of potential and protective current density (CD) on the jacket and to evaluate anodic CD output from the anodes in the two environments of the Persian Gulf and the Caspian Sea. The optimum design for the CP system was determined. The results indicated uniform potential distribution and mass loss rate of anodes in this optimized design. The modeling results were verified by field measurements.

Sacrificial anodes are commonly used in cathodic protection (CP) systems for fixed offshore platforms. Sacrificial anode system design in accordance with various international standards is simple.[1-3] Sacrificial anodes should be well distributed to provide a uniform potential.[4] Focusing on areas not fully protected at the design stage is vital since the subsea repair costs may be more expensive than the additional cost of a more elaborate design. Possible problems can be recognized during continuous monitoring.[5-6]

The feasibility of the galvanic corrosion modeling of sacrificial anodes in contact with steel has been studied.[7-9] With the development of computer hardware and numerical modeling software, the finite element method (FEM) has become a powerful tool for studying galvanic corrosion and CP systems.[10-12] The boundary element method (BEM) has been used for modeling with mixed results.[13-14] To simulate distributions of local potentials inside corrosion defects of a pipeline, Xu, et al.[15] developed a FEM model using commercial software that provides convenient computation techniques.

This study is a continuation of that work using COMSOL† Multiphysics 4.2a software to assess the performance of sacrificial anode systems designed for platforms in the Persian Gulf and the Caspian Sea. With the distribution of the anodes optimized, a physical platform model was placed in a real marine environment in order to verify the simulated results. The correlations between the potential and current density (CD) obtained from experimental potentiodynamic polarization measurements were applied as the boundary conditions.

Finite Element Method Modeling

The electrochemical corrosion phenomenon is described through the mathematical formulation for an electroneutral, isotropic electrolyte solution in a steady state condition.[10] For this electrolyte system, the potential is subject to the Laplace equation, Equation (1):

$$\nabla^2\varphi = 0 \tag{1}$$

†Trade name.

TABLE 1. THE CALCULATED CURRENT OUTPUT OF ANODES AND REQUIRED CP CURRENT IN THE PERSIAN GULF AND CASPIAN SEA

Marine Environment	Current Output of Anodes (A)	Current Demand (A)
Persian Gulf	0.60	0.16
Caspian Sea	0.19	0.16

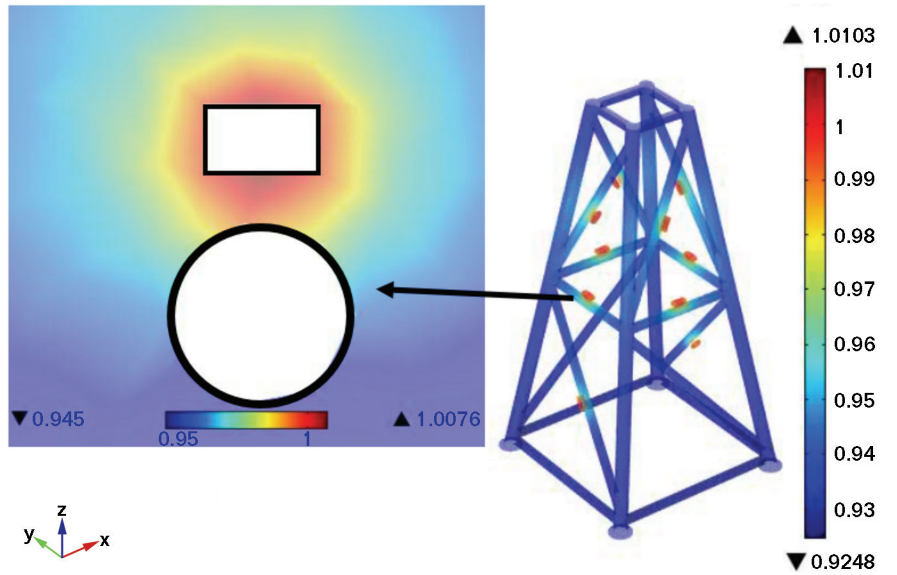

FIGURE 1 Anode positions and potential contour plot (V) for the optmum design in the Persian Gulf.

where φ is the potential. The boundary conditions related to the electrolyte and the electrodes are presented as Equations (2) through (4):

$$\varphi = \varphi_0 \quad (2)$$

$$i_c = f_c(\varphi_c) \quad (3)$$

$$i_c = f_a(\varphi_a) \quad (4)$$

where φ is the potential and φ_0 is the given initial constant value of the electrolyte potential; i is the polarized CD of the electrodes; and $f_c(\varphi_c)$ and $f_a(\varphi_a)$ are the nonlinear functions describing the relationship between the potential and CD of the anode and cathode, respectively. The platform model, designed according to Lan's model,[13] and various anode distributions were developed in the software. The volume mesh type used for modeling was a free tetrahedral shape, and the software determined the optimum sacrificial anode arrangement.

Materials and Methods

Model Construction

The physical platform model was made of steel tubes welded together. The jacket had four 60-mm diameter legs, 12 horizontal support tubes, and eight vertical cross-support tubes. The ends of all platform legs were sealed using rubber lid caps. Zinc anodes were installed on the platform. The anodes were 60-mm long, 25-mm wide, and 15-mm tall with a weight of 0.25 kg each. The conductivity of seawater in the Persian Gulf and the Caspian Sea was measured as 4.9 and 1.63 S m^{-1}, respectively.

Potentiodynamic Polarization Readings and Boundary Conditions

The electrochemical experiments were carried out in natural seawater using a three-electrode corrosion cell kit. The reference electrode was a saturated silver/silver chloride (Ag/AgCl) electrode; a platinum wire was applied as the counter electrode; and the working electrodes were carbon steel and zinc specimens mounted in epoxy resin with an exposed surface area of 1 cm^2. The potentiodynamic curves were drawn at a constant scan rate of 1 mV s^{-1}. Each test was repeated three times to confirm accuracy. CDs of the anodic and cathodic reactions were derived from the polarization curves using the Tafel equations[15] shown in Equations (5) through (8):

$$i_{anode} = 0.053 \times 10^{\frac{\varphi_{anode}+1.139}{0.059}} \text{ in Persian Gulf} \quad (5)$$

$$i_{cathode} = -0.00079 \times 10^{\frac{\varphi_{cathode}+0.662}{-0.126}} \text{ in Persian Gulf} \quad (6)$$

$$i_{anode} = 0.1271 \times 10^{\frac{\varphi_{anode}+1.0773}{0.065}} \text{ in Caspian Sea} \quad (7)$$

$$i_{cathode} = -0.00396 \times 10^{\frac{\varphi_{cathode}+0.682}{-0.156}} \text{ in Caspian Sea} \quad (8)$$

Due to the larger exposed area of the cathode (platform) compared to that of the zinc anodes, the steel corrosion potential was set as the initial value for the seawater potential. Its values for the Persian Gulf and Caspian Sea were –0.632 and –0.649 V, respectively.

Field Validation of the Model

To obtain field potential measurements for three continuous days, the physical platform model was placed in the harbor of Iran's Amir Abad Port in the Caspian Sea. The same procedure was used in the Persian Gulf. On the submerged zone of the marine platforms, the formation of calcareous scale (an aging effect) under satisfactory CP conditions gradually reduced the required protective current.[6] Because of time considerations, only the initial stages of polarization were considered in this study. A saturated Ag/AgCl reference electrode and a voltmeter were used to record the potential of selected sites on the structure.

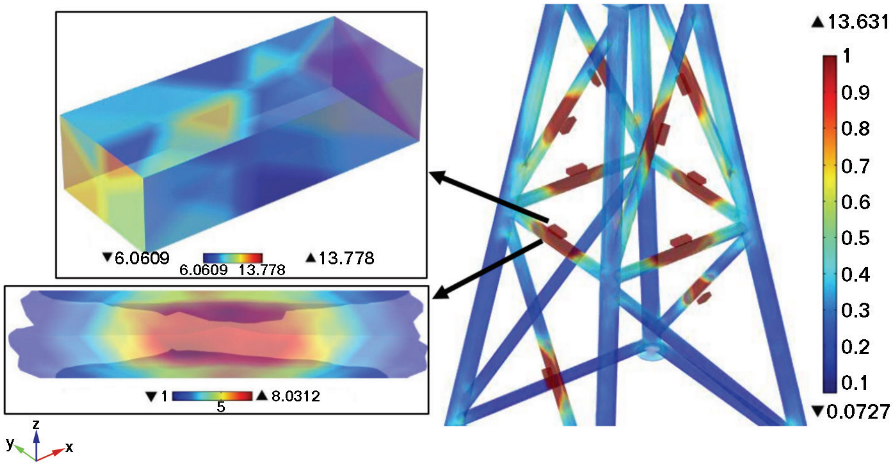

FIGURE 2 CD output of anodes contour plot (A·m^{-2}) and protective CD contour plots (A·m^{-2}) for the optmum design in the Persian Gulf.

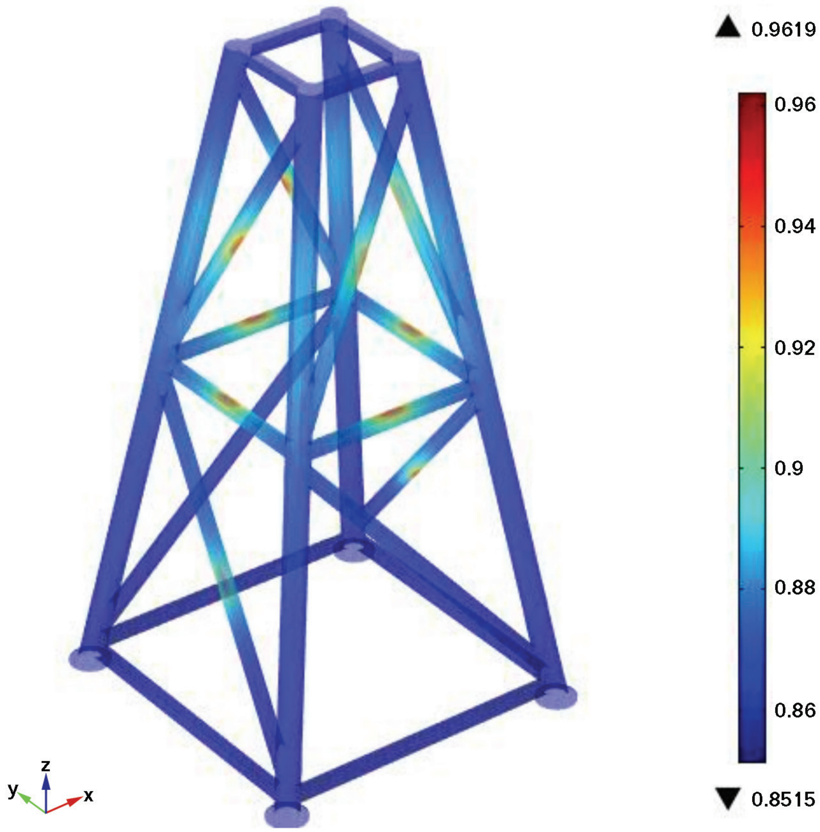

FIGURE 3 Anode positions and potential contour plot (V) for the optmum design in the Caspian Sea.

Selecting the Number of Anodes

The sacrificial anode system for the uncoated jacket was designed according to the DNV-RP-B401 criterion.[3] The CD for CP was 65 $\frac{mA}{m^2}$; therefore, a total of 10 anodes would be required to protect the jacket for a design life of one year. The sacrificial anode current output was calculated through Ohm's law. The current output of anodes in the Persian Gulf and Caspian Sea, listed in Table 1, exceeded the anticipated current demand.

Results and Discussion

Optimizing the Arrangement of Anodes

The objective of modeling this sacrificial anode system was to achieve uniform potential distribution over the platform surfaces and uniform mass loss rate of the anodes. This design optimization of the system is important—it can reduce the maximum protection potential and corrosion CD over the surface of the platform, and minimize the risk of sacrificial anode depletion before the end of their required design life, since some anodes may be consumed more quickly than others.[14]

The anodes were distributed on support tubes in an almost uniform manner in the optimum design. The optimum anode positions and the contour plot of potential distribution on the jacket in the Persian Gulf are shown in Figure 1. The potentials of the steel jacket are between –925 and –999 mV. The potentials are more negative in areas adjacent to the anodes, while the cathodic polarization is reduced along both the longitudinal direction and the circumference. The optimum protective CD distribution plot on the jacket is shown in Figure 2. CD peaks are observed in areas adjacent to the anodes, while the protective CD decreases exponentially to its minimum value in other areas. In some studies,[9] the anodic dissolution rate of iron often decreases with increasing protective CD. In this optimum design, the anodic dissolution rate of the platform achieves its minimum value.

The current flow in an equivalent electrical circuit, which represents the sacrificial anode system with a cathode and a sacrificial anode, is calculated using Ohm's law in Equation (9):[1,6]

$$i_{flow} = \frac{E_a - E_c}{R_a + R_c + R_e} \quad (9)$$

where i_{flow} is the current flow in the equivalent circuit, which is proportional to protective CD; E_a and E_c are the potentials associated with the anode and cathode, respectively; R_a is the resistance associated with an anode; R_c is the cathode resistance; and R_e is the electrolyte resistance. Regarding the distance between an anode and the cathode surface, the R_e between an anode and the area adjacent to that anode is less than the R_e between the anode and other elements of the structure.

Considering Equation (9), the protective current provided to the area adjacent to an anode is greater than the current provided to other areas. According to the relevant literature, strong evidence from offshore potential measurements indicates that the R_c value may be locally high at complex nodes and locally low in areas adjacent to an anode. By Ohm's law, the protective CD is maximized in the areas adjacent to anodes, while it is minimized in the areas adjacent to complex nodes. Protection potentials shift to more negative values with increases in the CD received.

With the uniform distribution of CD illustrated in Figure 2, the highest and lowest mean current outputs of the anodes in the optimum design are 113 and 93 mA, respectively. Since the current output of a sacrificial anode is directly related to its mass loss rate,[14] and the ratio value of the highest to lowest anode mass loss rates for this design is 1.22, all anode consumption is relatively uniform during the design life. In the optimum design, the sacrificial anode system produced the maximum CD output for the anodes. Using CD outputs, the total current output from the sacrificial anode system can be calculated.[14] The mean current output of the anodes is 1 A.

Since a greater spread of potentials produces increased risk, the variation of assumed simulation conditions would cause corrosion. In addition to this consideration, the uniformity of the anodes' mass loss rates was assessed, since the highest efficiency of the sacrificial anode system design indicates that all anodes have reached the utilization factor simultaneously. This helps to avoid early installation of costly retrofit systems, which may be needed if the consumption rate of some anodes is faster than others.[3,14] Since the potential distribution on the jacket and the mass loss rates of all anodes were uniform, it was concluded that this design provides the optimum arrangement of anodes on the jacket.

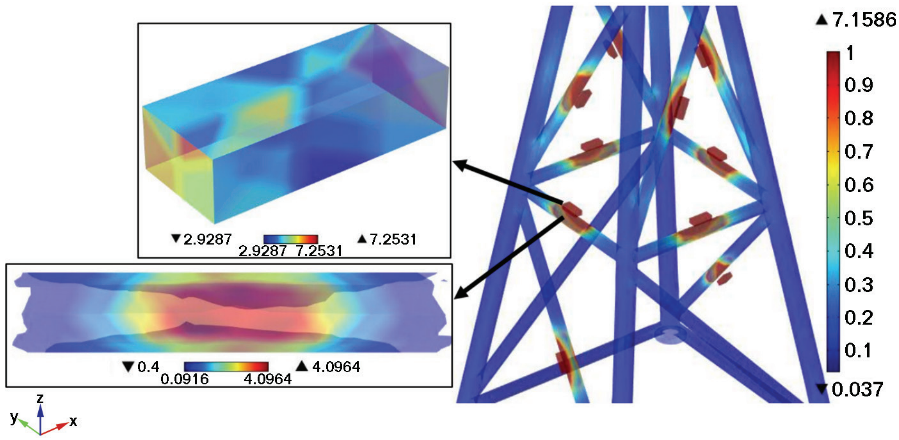

FIGURE 4 CD output of anodes contour plot (A·m⁻²) and protective CD contour plots (A·m⁻²) for the optmum design in the Caspian Sea.

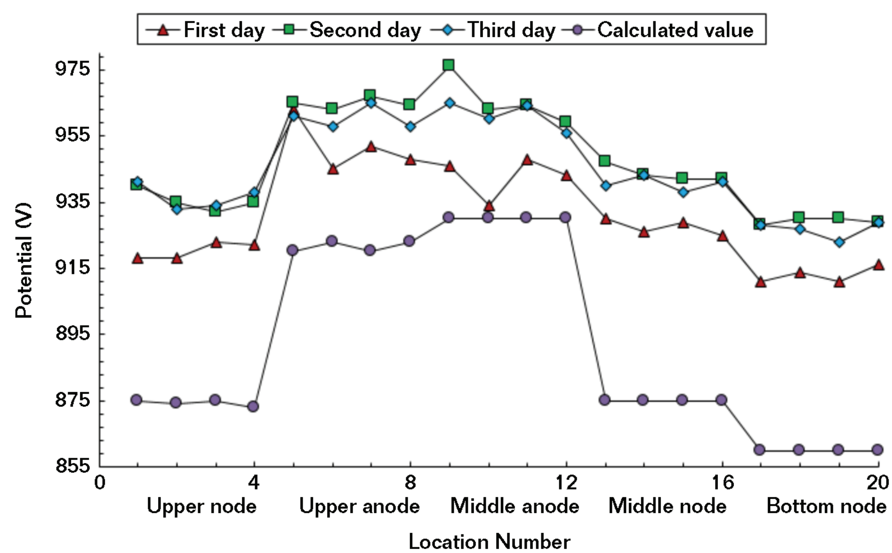

FIGURE 5 Comparison of the calculations and field-measured potentials at selected sites in the Caspian Sea.

Sacrificial Anode System Modeling in the Caspian Sea

The contour plots for the optimum calculated potential and protective CD distribution on the jacket model in the Caspian Sea are illustrated in Figures 3 and 4, respectively. The protective CDs on the jacket here are lower than those for the Persian Gulf. The protection potentials shift in the electropositive direction compared to those in the Persian Gulf and the potential over the jacket could be below a critical value. The mean current output of the anodes is 0.52 A. Although this represents a significant reduction compared to the results for the Persian Gulf model, the anode mass loss rates in the Caspian Sea are uniform and appropriate. This difference in current output is probably related to the greater conductivity of the Persian Gulf water.

Comparison of Field Measurements and Finite Element Method Calculation Results

The field validation measurements were carried out to justify the applicability of FEM calculations to simulate the sacrificial anode system. The potential values of selected sites obtained from the FEM model and the field measurements for the platform jacket in the Caspian Sea are shown in Figure 5. The potential of the structure gradually reaches a constant value, corresponding to steady state. The same trend obtained by calculation is found in situ for each part of the jacket. In contrast to the modeling results, the actual potentials of support tubes that are not immediately adjacent to anodes exhibit better protection levels than were predicted.

Conclusions

For a jacket in seawater protected by applying a sacrificial anode system, the distributions of potential and protective CD and anodic CD outputs of anodes were simulated through COMSOL software. The optimum arrangement of anodes to reach uniform potential distribution and mass loss rates was successfully determined by FEM. The influence of water quality on the potentials and protective and anodic CD distributions was also determined. Due to the credibility of the optimized sacrificial anode system design, the modeling results are in good agreement with the in situ results in the Caspian Sea. The FEM simulation, therefore, was applied successfully for modeling the sacrificial anode system for steel jackets in marine environments.

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MASOOD HAJIGHOLAMI is a master student at the Department of Materials Engineering, Isfahan University of Technology, Isfahan 841-8311, Iran, email: masudhajigholami@gmail.com. He is involved in numerical simulation through FEM and BEM as well as research in the field of corrosion.

KEYVAN RAEISSI is a professor in the Department of Materials Engineering, Isfahan University of Technology, email: k-raeissi@cc.iut.ac.ir. He has spent the last 13 years teaching advanced electrochemistry, advanced corrosion, corrosion inhibitors, corrosion in welding joints, paint and converting coatings, and pyrometallurgy. He has published more than 100 journal articles.

HAMIDRESA SALIMI JAZI is an associate professor in the Department of Materials Engineering, Isfahan University of Technology, email: hrjazi@cc.iut.ac.ir. He teaches and conducts research and development in the area of surface treatments and biomaterials engineering. He has published more than 70 papers.

SAEID SHABANI is a faculty member and head of the Material and Structure Group at the Subsea R&D Center, Isfahan University of Technology, email: sshabani@cc.iut.ac.ir. He has conducted research in marine environments for 24 years. He has published more than 20 marine project reports and more than 30 papers. MP