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Optimizing anode location in impressed current cathodic protection system to minimize underwater electric field using multiple linear regression analysis and artificial neural network methods

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ABSTRACT

Design of impressed current cathodic protection (ICCP)-anode locations to minimize underwater electric field is important to increase the survivability of naval ships. However, the evaluation of all ICCP-anode location scenarios is time-consuming process even though it is conducted by numerical simulation, especially boundary element method (BEM). To solve this problem, the randomly selected cases of ICCP-anode location in 3, 4 and 5-pair, which were produced by the beta distribution model, were simulated using BEM simulations. Then, the optimized ICCP-anode location scenario from the cases was verified by statistical methods (multiple linear regression and artificial neural network). Predictions of ICCP-anode location and underwater electric field were more correlated with the artificial neural network than the multiple linear regression analysis. Also, the selected ICCP-anode locations were verified by the artificial neural network considering data interactions. Thus, the application of an artificial neural network can be more useful for designing ICCP-anode location that minimizes underwater electric fields.

1. Introduction

Among various corrosion prevention methods, cathodic protection, which is usually used in conjunction with coatings, is commonly applied to prevent degradation of structures or components exposed to a corrosive environment [1–7]. The goal of cathodic protection is to shift the potential of the protected structure to the negative potential range, which is a range that likely prevents corrosion [8]. The theoretical basis for the cathodic protection is based on an Evan's diagram, which indicates the relationship between the applied current and potential of the protected surface [9,10]. As the applied cathodic current density increases, the potential of the anode falls, and the anodic dissolution rate decreases accordingly.

Although impressed current cathodic protection (ICCP) can be used to prevent corrosion, it is also associated with the distribution of the underwater electrical potential (UEP), which is known as the signature of the ship, and influences survivability in military applications. This is because galvanic corrosion occurs between the different metallic structures in contact with the electrolyte, and corrosion is influenced by current flowing from the ICCP system [11–15]. However, an inadequately designed ICCP system that has incorrect anode locations and an incorrect quantity of anodes may negatively affect both the protective efficiency and the distribution of the UEP. Thus, the design of ICCP systems is important to increase the survivability of naval vessels. The anode location, quantity and output current in the ICCP system are key factors for suppressing the underwater electric field [14].

Studies [16–20] suggest that the distribution and intensity of the underwater electric field are strongly related to the ICCP-anode location, quantity and output current, and the signature can be reduced by optimizing the ICCP-anode location, quantity and output current. Prior to the 1980 s, the ICCP systems were designed by rule of thumb and engineering judgment, which may lead to high underwater electric fields due to unsuitable designs. Although computer simulation techniques based on the boundary element method (BEM) were used to predict the cathodic protection performance and underwater electric field, the optimization of design of ICCP-anode location, quantity and output current are still not perfect because it is difficult, time consuming and expensive to consider all scenarios [21–23]. Thus, an additional approach to optimize ICCP design is required for efficient optimization of cathodic protection and signature silencing.

Recently, statistical methods have been applied to solve various different engineering problems that cannot be solved intuitively. There

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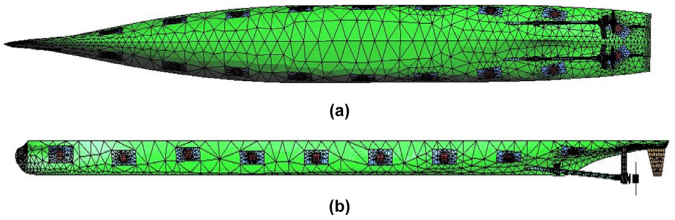


Fig. 1. 3D model of the ship consisting of hull, shafts, rudder and propeller with 10 pair-ICCP anodes and dielectric shields: (a) bottom and (b) side views.

are numerous statistical methods for the optimization problem, but the proper selection and application of these methods is difficult. In this study, multiple linear regression analysis and artificial neural network methods were applied to predict all scenarios involving ICCP-anode location and quantity in a time effective manner. Then, the optimized ICCP design was selected to minimize the underwater electric field. The concept and calculation theory of these two methods were different, which means that it is hard to determine the proper method for the ICCP design. Thus, in this study, these two methods were applied and compared to identify the better method.

2. BEM simulation

The 3D model of the ship used in this study consisted of a hull with a length of 103 m, a width of 13 m, a height of 6 m, and two shafts, rudders and propellers. In addition, 10 pairs of ICCP anodes (1×1 m^2) and dielectric shields (2×4 m^2) were installed in the 3D ship model with the same distance in the x-direction to investigate ICCP-anode locations and quantities of anodes. This configuration was chosen because the x-location of the anodes primarily influences cathodic protection and the underwater electric field. Eight sacrificial anodes (brick-shape) were also installed on each rudder and shaft support. Fig. 1 shows a meshed model of the ship with 16,156 quadrilateral or triangular elements, which was modeled in GID program including several CAD repairing tools and mesh generators. In this model, the x-axis and y-axis are parallel and vertical to the keel of the ship, respectively, while the z-axis is vertical to sea level. After modeling the structure, the designed structure model was imported into the commercial boundary element method (BEM) software (BEASY CP10.0r15).

In a BEM, the potential was based on the governing equation and was calculated using the following boundary conditions [24,25]:

$$\nabla^2\Phi = 0. \tag{1}$$

$$\Phi = \Phi_0, \text{ on } \Gamma_1 \tag{2}$$

$$I = I_0, \text{ on } \Gamma_2 \tag{3}$$

$$I_a = f_a(\Phi_a), \text{ on } \Gamma_{3a} \tag{4}$$

$$I_c = f_c(\Phi_c), \text{ on } \Gamma_{3c} \tag{5}$$

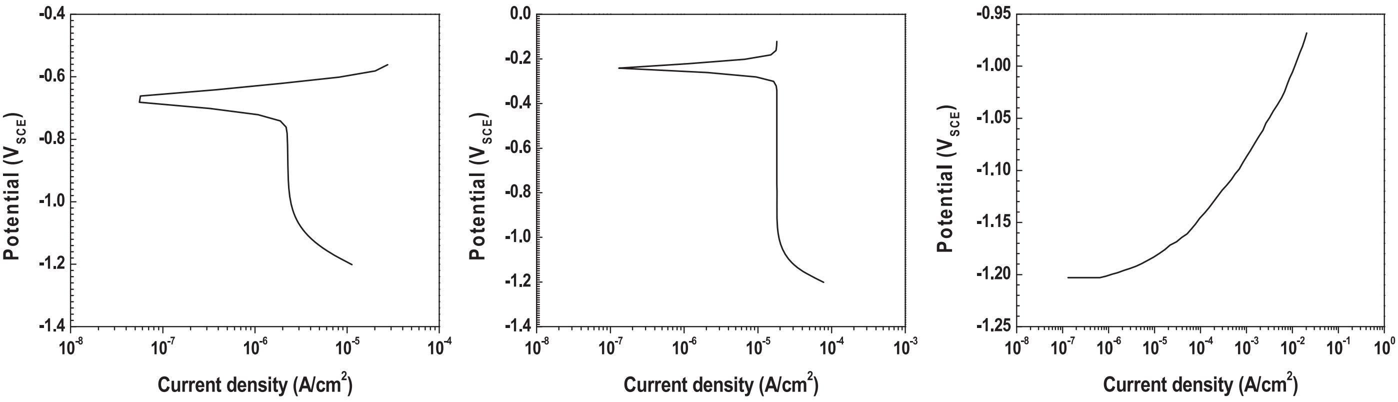
Here, k (S/m) is the conductivity of seawater (4 S/m in this study), Φ is the potential of the ship surface, Γ is the entire surface of the electrolyte domain, including Γ_1, Γ_2, Γ_{3a}, and Γ_{3c}, and I is the current across the boundary. Φ_0 and I_0 are given constant values for the potential and current, respectively. $f_a(\Phi_a)$ and $f_c(\Phi_c)$ are functions that indicate the relationship between the potential and current of the anode and cathode, respectively. Polarization curves of the hull (HY-80) (at a 15% coating damage condition), the propeller (NAB), and sacrificial anode (Zn) in seawater were derived as the boundary conditions via piecewise linear interpolation. The polarization curves were measured via potentiodynamic polarization experiments, and the potential was scanned from +150 mV relative to the open-circuit potential to −1200 mV vs. a saturated calomel electrode (SCE) at a scan rate of 0.166 mV/s. Fig. 2 shows the polarization curves of each material used in this study.

Electric fields caused by CP and corrosion were interpreted with internal points along the keel line (every 1 m), where the highest signature of the ship was at a depth of 14 m from (−150 m, 0 m, 14 m). The maximum average electric field was used in this study to decrease the complexity of the prediction problem.

3. Methodology

3.1. Data preprocessing

The total number of arrangement cases for 3, 4 and 5 pairs were 120, 210 and 252, respectively. Since simulating all cases takes a long time, the 23 cases were randomly selected in 3, 4 and 5 pairs by the beta distribution method. The beta distribution is a family of continuous probability distributions defined as the specific interval [0, 1] parameterized by two positive shape parameters (α and β). Fig. 3 shows the beta distribution use for cases of 3, 4 and 5 pairs. Locating ICCP anodes on one side is generally not practical because uniformly distributed cases are more efficient for cathodic protection and the underwater electric field. Thus, the parameters of the beta distribution for selecting ICCP-anode locations were set as high as possible to select uniformly distributed ICCP-anode cases. After the selection of 69 cases, the ICCP applied current was optimized to minimize the underwater electric field using a sequence linear programming method for the 69 cases.



(a) (b) (c)

Fig. 2. Polarization curves of (a) HY80, (b) NAB and (c) Zn.