Numerical Simulation of a Cathodic Protection System on a Semi-submerged Offshore Structure

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Abstract

This paper presents an experimental study which seeks to further the understanding of how the variables of current supply, insulation radius, and coating properties in an impressed current anode cathodic protection system are related. Numerical simulation methods were used to evaluate the relationship between these variables on a simplified computer model. The results demonstrated an exponential relationship between the insulation radius and current supply, which became steeper with deficient coatings and shallower with enhanced coatings.

Introduction

Corrosion is a major factor in structural design, particularly in marine environments (Diaz 2001). It severely affects the integrity and service life of all structural metals and alloys, including steel reinforcement in concrete structures (DNV 1993). Engineers need to design structures in such a way that corrosion is prevented and a long service life is guaranteed.

For ocean vessels and offshore structures, it is standard practice to adopt a corrosion protection system, also known as a cathodic protection system (Huang 1998). Because the degree of corrosion is highly dependent on environmental variables, taking such variables into account is an important part of the protection process. However, the complexity of these variables’ relationship to the protection process makes designing optimized cathodic protection systems very challenging (Huang 1998).

Numerical simulation methods are commonly used to streamline this process. When
used in conjunction with data monitored from existing cathodic protection systems, numerical analysis is a powerful tool for advancing knowledge of cathodic protection and designing effective protection systems (Huang 1998).

In this study, numerical analysis is used to determine the relationship between the parameters of current supply \( I_c \), insulation radius, and coating properties \( f_c \) in an impressed current anode cathodic protection system. This study is important because the relationship between these variables is unknown and present calculations rely solely on rough rule-of-thumb approximations. Once a formal relationship between these variables is developed, the accuracy of future corrosion protection system design can be improved, which will result in longer service lives for protected structures.

**Background**

Ocean corrosion, formally known as galvanic corrosion, is a substantial factor in structural design in marine environments. Galvanic corrosion occurs when metals are in contact in the presence of an electrolyte (Schweitzer 1988). According to their chemical properties, one metal, or a portion of metal, will become negatively charged (anode) with respect to another metal or portion of metal (cathode) (Dexter, 2003). Because of the potential difference between these charged metals, electric current will flow between them through the medium of the vessel or structure: which acts as an external conductor (Diaz 2001). Ions will then be transferred through the electrolyte medium of the ocean water (Diaz 2001).

Galvanic corrosion is an electrochemical process (Schweitzer 1988). Reduction occurs at the cathode and oxidation occurs at the anode. The result of oxidation is a rapid deterioration or chemical alteration of the metal in the negatively charged areas (Schweitzer 1988).

Factors which influence the rate of corrosion include the electrical potential difference between the anode and the cathode, the relative surface areas of the anode and cathode (Dexter 2003), the oxygen content of the electrolytic ocean water, and the environment (Huang 1998). The environment plays a vital role through the factors of temperature, salinity, pH, fluid velocity, and the presence of biological molecules that can form films on the structure surface which hinder or change the nature of corrosion (DNV 1993).

To guard against corrosion, a protection system is usually developed. The most common protection method is to paint the structure with a protective coating (Diaz 2001). This coating limits the surface area and hinders the flow of ions, thus dramatically reducing corrosion. However, it is not full proof as the coatings are often scratched or damaged during construction and may quickly wear out in the harshly corrosive ocean environment (DNV 1993).

To guard against this, cathodic protection is typically employed in conjunction with
coatings (Diaz 2001). Cathodic protection systems use anodes attached to the surface of the structure in a distributed pattern to provide additional protection. Anodes are more active metals (due to their material properties or through connection to an external direct current source) than the structures being protected and serve to reduce electric current flow through the structure: a key factor in the electrochemical corrosion process (DNV 1993). The use of anodes for corrosion prevention is usually referred to as cathodic protection, signifying that the use of such anodes makes the structure the cathode and thus it is unaffected by corrosion (DNV 1993).

An impressed current anode cathodic protection system is considered in this study. The anodes of such a system are typically platinum on a substrate of titanium, niobium, or tantalum, connected to an external current source (usually a transformer-rectifier) (DNV 1993). The current supplied to the anodes is carefully controlled either manually or automatically to keep the potential of the anode at a level which hinders the electrochemical corrosion reaction.

It is important to note that impressed current anodes do not provide uniform protection of the structure. Areas of the structure close to the anodes receive a higher degree of protection than those areas furthest from the anodes (Huang 1998). Thus, effective design of the distribution of and current supply to these anodes is very important to maintain complete protection. The range of potentials used for complete protection is typically -0.80 to -1.10 volts relative to silver / silver chloride / seawater (Ag/AgCl/seawater) (DNV 1993).

Often, a greater current is supplied than is necessary to achieve a potential of -1.10 V (rel Ag/AgCl/seawater) in order to facilitate protection of a larger surface area. In such cases, areas near the impressed current anode receive what is called “overprotection” and potentials higher than -1.10 V (rel Ag/AgCl/seawater) are achieved (DNV 1993).

Overprotection often results in the disbonding of protective coatings, since they are typically only resistant up to potentials of -1.10 V (rel Ag/AgCl/seawater) (DNV 1993). Furthermore, potentials higher than -1.10 V (rel Ag/AgCl/seawater) also accelerate the discharge of hydrogen atoms at the metal surface, a normal product of cathodic protection occurring at the cathode. When high amounts of hydrogen atoms are discharged, the hydrogen will become absorbed into the metal matrix. This can cause hydrogen induced stress cracking (HISC), particularly in materials with high tensile loads and/or internal stresses (DNV 1993).

In order to guard against overprotection and the problems associated with it, the areas surrounding impressed current anodes are often insulated. The insulation radius will be set such that the potential at the interface between the insulated and non-insulated area is -1.10 V (rel Ag/AgCl/seawater). At present, no satisfactory equations exist for the relationship between the current supply to an impressed current anode and the insulation radius required to prevent overprotection around it, and rough rule-of-thumb approximations are used. Furthermore, because there are no established equations, numerical analysis methods must be used. This study seeks to demonstrate the
relationship between these variables, as well as their relation to the coating properties of
the structure.

**Parameters and Equations**

The following parameters are used with the equations below in order to calculate the
current demands of a cathodic protection system.

\[
\begin{align*}
  c_a & \quad \text{anode current capacity} \\
  I_a & \quad \text{anode current output} \\
  I_c & \quad \text{current demand} \\
  t_f & \quad \text{design life} \\
  I & \quad \text{anode length} \\
  \rho & \quad \text{resistivity} \\
  R_a & \quad \text{anode resistance} \\
  \varepsilon & \quad \text{electrochemical efficiency} \\
  A_a & \quad \text{anode surface area} \\
  n & \quad \text{number of anodes} \\
  u & \quad \text{anode utilization factor} \\
  E_{ca} & \quad \text{protective potential} \\
  i_c & \quad \text{design current density} \\
  m & \quad \text{net mass of individual anodes} \\
  A_c & \quad \text{cathode surface area} \\
  C_a & \quad \text{total anode current capacity} \\
  E_{ca}^0 & \quad \text{closed circuit anode potential} \\
  M & \quad \text{net mass of all anodes} \\
  f_c & \quad \text{coating breakdown factor} \\
  k_1, k_2 & \quad \text{constants dependent on the coating properties}
\end{align*}
\]

When developing a cathodic protection system, the goal is to select and orient the anodes
in such a way that a corrosion-resistant potential is established on the entire surface of the
structure (Huang 1998).

The first parameter to be calculated for this process is the current demand for the three
main protection states: initial, final, and average. Initially, a certain amount of current is
needed to polarize the structure. This is called the initial current demand (DNV 1993). Once
the structure is polarized, the final current demand takes into account the current
demand necessary to repolarize the structure should the surface be damaged (DNV 1993). Finally, the average current demand is the current needed to maintain protection of the
structure under normal operating conditions (DNV 1993). Initial, final and average
current demands are calculated using the following equation (DNV 1993).

\[
I_c = A_c \cdot f_c \cdot i_c
\]  

(1)

where,

\[
f_c = k_1 + k_2 \cdot t_f
\]  

(2)

Once the current demand has been calculated, the mass of anodic material necessary to
protect the structure can be determined using the following equation (DNV 1993).

\[
M = \frac{I_{c(average)} \cdot t \cdot 8760}{u \cdot \varepsilon}
\]  

(3)

Another important variable in cathodic protection is the resistance of the anode. This
variable is dependent on the anode type. To calculate this resistance, one of the following
equations is used (DNV 1993).
For long \((l \geq 4r)\) slender stand-off anodes: 
\[
R_a = \frac{\rho}{2 \cdot \pi \cdot l} \left( \ln \frac{4l}{r} - 1 \right)
\] (4)

For short \((l < 4r)\) slender stand-off anodes:
\[
R_a = \frac{\rho}{2 \cdot \pi \cdot l} \left( \ln \left[ \frac{2l}{r} \left( 1 + \left( \frac{r}{2l} \right)^2 \right) \right] + \frac{r}{2l} - \left( \frac{r}{2l} \right)^2 \right)
\] (5)

For long flush-mounted \((l > 4 \times \text{width/thickness})\) anodes: 
\[
R_a = \frac{\rho}{2 \cdot S}
\] (6)

For short flush-mounted bracelet and other flush-mounted shapes: 
\[
R_a = \frac{0.315 \cdot \rho}{\sqrt{A}}
\] (7)

Once the anode resistance has been calculated, the anode current output needed can be calculated using the following equation (DNV 1993).
\[
I_a = \frac{E^0 - E^o}{R_a}
\] (8)

To calculate the individual anode current capacity, the following equation is used (DNV 1993).
\[
c_a = m \cdot \varepsilon \cdot u
\] (9)

To ensure full protection, the following limits are set in place during the iterative numerical analysis used to determine anode sizing (DNV 1993).
\[
C_a = n \cdot c_a \geq I_c \text{ (average)}
\] (10)
\[
n \cdot I_a \text{ (initial)} > I_c \text{ (initial)}
\] (11)
\[
n \cdot I_a \text{ (final)} > I_c \text{ (final)}
\] (12)

**Experimental Setup and Instrumentation**

**Simplified Model**

To determine a relationship between insulation radius and current supply in an impressed current anode cathodic protection system, a simplified computer model was developed. Its simplicity enabled time-efficient simulations, and ensured that other factors (such as complex geometries) did not affect the results.

The model developed was a rectangular prism, with dimensions: 20 m. by 20 m. by 10 m. Two impressed current anodes were added to the model: one centered on the top and the other centered on the bottom of the model.
Figures 1 and 2: The simplified model (top and bottom views) as plotted in Tecplot9. The impressed current anode is shown in black.

The model was generated using an executable file developed by the Department of Naval Architecture and Ocean Engineering of Dalian University of Technology, using nodal coordinate information supplied by another data file (also prepared by the department). While generating the model, the executable file also calculates the anodic parameters (type, dimensions, mass, resistance) necessary for cathodic protection calculations.

**Insulation Radius and Protection Potential Diagrams**

Once the basic model has been generated, a second executable file developed by the
Department of Naval Architecture and Ocean Engineering of Dalian University of Technology is used to model the insulated area (according to the radius value supplied by the user) on the original model. The areas around both the top and bottom anodes are equally insulated.

![Figure 3: The simplified model (top view) with insulated area marked in white as plotted in Tecplot9.](image)

This second executable file also performs the calculations given in the equations section of this report, and generates a map of the potential distribution generated by the impressed current anodes.

![Figure 4: Potential distributions and insulation (top view) as plotted in Tecplot9.](image)
Figure 5: Potential distributions and insulation (bottom view) as plotted in Tecplot9.

Along with the insulation and potential data, the second executable file also outputs the potential reading at the interface between the insulated and non-insulated areas, as well as the lowest potential on the surface of the model. This information is used to determine whether the current supply and insulation radius data are compatible. If the data range was between -1.10 V rel Ag/AgCl/seawater (at the interface) and -0.80 V (minimum potential on the structure), the results may be used. Otherwise, they must be discarded.

**Simulations**

The simulations completed for this experiment took into account three variables: insulation radius, current supply, and coating properties. The other parameters of cathodic protection were held constant.

For the first set of simulations, coating properties were held constant at the initial values supplied by the executable file, while the values of radius and current supply to the anodes were varied.

Insulation radius and current supply combinations were supplied to the two executable files, and then simulations were run. When a radius/current supply combination resulted in a value within a two percent error of the desired potential range (-1.10 to -0.80 V rel Ag/AgCl/seawater), the data point was recorded. The rest of the data points were discarded.

Once good data points at 500 mV intervals had been developed in the available radius ranges (0 to 9.25 m.), the coating property data in the two executable files was adjusted. The effectiveness of the coating data was multiplied by a factor of three, and the tests were run again.

When sufficient data points have been developed in the available radius ranges with
those coating properties, the coating data was again adjusted. This time, the original coating properties were multiplied by a factor of one third, and the tests were run again.

The results of all three sets of simulations were collected and plotted using Microsoft Excel.

Results

The data taken during the three sets of numerical simulations is recorded in the tables below.

Table 1: Insulation Radius versus Current Supply for normal Coating Properties

<table>
<thead>
<tr>
<th>Current Supply (mV)</th>
<th>Insulation Radius (m)</th>
<th>Insulation Interface Potential (mV)</th>
<th>Minimum Potential on Model (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2125</td>
<td>0.0</td>
<td>1100.079</td>
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<td>2500</td>
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<td>727.7326</td>
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Table 2: Insulation Radius versus Current Supply for good (times 3) Coating Properties

<table>
<thead>
<tr>
<th>Current Supply (mV)</th>
<th>Insulation Radius (m)</th>
<th>Insulation Interface Potential (mV)</th>
<th>Minimum Potential on Model (mV)</th>
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</table>
Table 3: Insulation Radius versus Current Supply for poor (times 1/3) Coating Properties

<table>
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<th>Current Supply (mV)</th>
<th>Insulation Radius (m)</th>
<th>Insulation Interface Potential (mV)</th>
<th>Minimum Potential on Model (mV)</th>
</tr>
</thead>
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</table>

When plotted together, the three cases showed the following trends:

Effect of Increasing Current Supply on Insulation Radius

A roughly exponential relationship between insulation radius and current supply is apparent. Furthermore, the steepness of the exponential curve is clearly a function of the coating properties. It is evident that the better (more efficient) the coatings, the shallower the curve. It is also evident that more deficient (less efficient) the coatings, the steeper the curve.

Conclusions

This research demonstrated an exponential relationship between current supply and insulation radius in an impressed current anode cathodic protection system. It has also demonstrated that the steepness of this exponential relationship is dependent on the protective coating properties of the structure. These relationships are important to future numerical analysis and cathodic protection system design, as they will improve the accuracy of future calculations.
Future Research

For this research, a simplified model was used. In the future, the Dalian University of Technology’s Department of Naval Architecture and Marine Engineering will perform similar tests on a much larger and more detailed model as part of ongoing research by Dr. Huang Yi. Once the results are obtained, they will be compared with those of this study, to determine the accuracy of the simplified model.

Because the interaction of the variables of ocean corrosion is complex, more research must be performed to refine the effectiveness of cathodic protection. Through continued simulation, data collection from existing systems, and research, corrosion protection knowledge will progress and cathodic protection systems will continue to improve. This will lead to longer service life on structures and vessels in ocean environments.

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