Simulation of sacrificial anode protection for steel platform using boundary element method

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\begin{abstract}
In the present paper, an offshore platform model dealing with sacrificial anode protection was simulated using boundary element method. The potential and current density were calculated, and the distribution trend of the data was analyzed. To evaluate the computation results, proper physical model was built in a given dimension. The physical platform model was placed in a marine environment modeling tank that was designed to simulate the real marine environment with seawater, and the calculation data were compared with those from laboratory experimental work. This study showed that the boundary element method is a powerful tool for the sacrificial anode protection of marine structures.
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\section{Introduction}
Sacrificial anode protection is an important anti-corrosion technique for offshore structures. The mechanism is that the sacrificial anode such as magnesium, zinc or aluminum that has a negative potential is connected to the steel structures, and provides the extra electrons to the steel structures. For the consideration of safety and convenience, sacrificial anodes have been widely used in the field of marine oil and gas platform. In most conditions, the design of the sacrificial anode protection system depends on the experience of the corrosion engineers under the guidance of some standards or criteria, such as NACE RP0176 and DNV RPB401. However, the number and the location of the anodes for marine structure have many uncertainties which depend on the corrosion engineer.

Boundary element method (BEM) has been utilized to modeling the cathodic protection systems in early 1980s. Danson and Warne \cite{1} began to apply the BEM to corrosion engineering problems; they applied the method to the Conoco Hutton Tension Leg steel structures. Aoki \cite{2,3} also published some literatures for BEM application in galvanic corrosion research, and predicted the corrosion rates through this method. Zamani \cite{4} showed that the BEM technique is effective for corrosion modeling of a ship. Brebbia, Adey and Niku \cite{5–10} had engaged subsequent work for the corrosion and cathodic protection modeling, and they stated that the commercial programs like BEASY provided convenient calculation techniques. Jimmy \cite{11,12} used the BEASY software to simulate the galvanic corrosion of magnesium coupled to steel, and the modeling predictions and the experimental measurements have good agreements. With the rapid growth of computer hardware and computing technology, the BEM corrosion modeling has a great development.

Comparing with the finite element methods (FEM), the BEM only requires the meshing of boundary while the FEM requires the whole body of the structures. As in the cathodic protection systems, electrochemical reactions occur on the surface of the metal, only the surface need to be modeled. Especially for the large scale marine structures or the pipelines with many kilometers, the BEM will mesh and calculate the boundary element with higher efficiency.

The aim of this paper is to simulate the potential distribution of the steel platform protected by aluminum sacrificial anode in marine environments. The calculated results were compared to those obtained from the laboratory experiments. The character of cathode and anode were taken into account using the polarization curve technique as the boundary condition. The potential distribution of different nodes were calculated and measured.

\section{BEM simulation}
For the need of computation, some simplifications were made: the solutions in the container is uniform and electro-neutral, there is no concentration gradient in the electrolyte solution. The wall of the container is electric insulative, there is no flow current...
leakage from the container. Under the above assumptions, the transport of the species and the flow of current in the container are governed by the Laplace equation:

\[ \nabla^2 \phi = 0 \]  

The Laplace equation can be solved using the following boundary conditions:

\[ \phi = \phi_0, \quad \Gamma_1 \]  
\[ I = I_0, \quad \Gamma_2 \]  
\[ I_a = f_a(\phi_a), \quad \Gamma_3a \]  
\[ I_c = f_c(\phi_c), \quad \Gamma_3c \]  

The boundary conditions are illustrated in Fig. 1.

The construction of the boundary conditions is an essential procedure in the modeling of corrosion and CP systems with BEASY. The model and its surrounding environment (seawater) is confined within a bounding box whose size is approximately 20 times the size of the studied structure. As no electric current flows from the object, the vector sum of the current is zero, which is the second boundary condition for the mathematical computation. On the surface of cathode and anode, the relation between potential and current density meets the polarization curve state, which is the third boundary condition. For boundary element simulation, the first and second boundary conditions are the identified conditions, and the third condition has different changes with the marine environment and different materials.

3. Experimental

On the surface of cathode and anode, many complex electrochemical reactions happened; the polarization character is the reflection of these reactions. The polarization data will be used to solve the model. The polarization curve of steel cathode was measured in seawater environment using a conventional three-electrode cell assembly. A rectangular platinum mesh was used as the counter electrode and a saturated calomel electrode as the reference electrode. The working electrode was a cylindrical, mild steel specimen. The steel electrode was mounted in epoxy resin such that only 1 cm² cross-section of the cylinder was exposed to the solution. Before the experiments, the working electrode was polished gradually using 600, 800 and 1200 grid waterproof abrasive papers; washed with distilled water; degreased with acetone and washed with ethanol; and finally dried in a cold air stream. Electrochemical experiments were carried out using a Parstat 2273. The polarization curve measurement performed a scan starting from -0.2 to +0.2 V vs. open circuit potential at a scan rate of 0.5 mV/s. The electrochemical impedance studies were carried out using AC signals of 10 mV amplitude for the frequencies ranging from 100 kHz to 0.01 Hz at open circuit potential. Therefore, in this project, great deals of polarization curves in different marine environment and under different temperatures were tested.

The physical platform model was made with steel. The jacket structure had four legs and three layers in the vertical direction. The bottom layer had a dimension of 80 x 80 cm² and the upper layer had a dimension of 30 x 30 cm². The height of the platform was 160 cm. Besides the four legs, the platform had 12 support tubes in horizontal direction, and 16 cross support tubes in the vertical direction. All four legs were 60 mm in diameter and 2 mm in thickness, and all support tubes were 40 mm in diameter and 2 mm in thickness. Every joint was welded tightly and polished with abrasive paper. The end of all tubes was sealed with lid caps.

The anode cathodic protection system was designed according to NACE RP0176 criterion. The lifetime of galvanic anodes was determined using equation:

\[ L = \frac{W u}{E} \]

There into, \( L \) is the design lifetime of the anodes in years, \( W \) is the net mass of the anodes in kg, \( u \) is the utilization factor of the anodes, \( E \) is the consumption rate of the anode in kg/(A a), and \( I \) is the mean current output during the lifetime in ampere.

In this physical experiment, the design lifetime of aluminum anodes is 10 years, the utilization factor is 0.8. To simplify the computation process, the shape of the anode is cylindrical. For the platform, the galvanic anodes should be designed to produce the required protective current to provide sufficient protection on the steel structure. The typical current density for cathodic protection in this design is 100 mA/m². Then the total current demand is determined by the value of cathode area and the design current density.

After the installation of anodes, the physical platform model was placed in the marine environment modeling tank of Institute of Oceanology, Chinese Academy of Sciences, which was illustrated in Fig. 2. The modeling tank can effectively model the flow of the tide following the natural law according to the accurate control system. The fresh seawater was pumped into the storage tank, and the waves were generated from a paddle wave maker. The seawater level was controlled through a siphon tube. The salinity and the pH value can also be adjusted in the seawater tank.

4. Results and discussion

The polarization curves were obtained in the electrochemical experiment, one of which was illustrated in Fig. 3. For the purpose of BEM computation, the polarization was divided into a piecewise linear curve. The relation between potential and current density from the polarization data was input into the material file in the form of data pairs. Another function of the data is to check
the computation results, and all of the simulation results should be in the range of the given value.

The established model and boundary condition parameter were introduced into the solver of BEASY software. Maximum number of iterations and the solution tolerance were also assigned with the specific values. Then the software will execute the computation process of cathodic protection modeling.

The calculated potential distribution was illustrated in the contour plot on the platform model in Fig. 4. The potential value was in the range of $-931.65$ and $-1031.1$ mV. The potential in the area attached to anode is the lowest value, $-1031.1$ mV, and increase with the location away from the sacrificial anode site. The same trend was also found in the current density distribution which is illustrated in Fig. 5. In the local structural map for current density distribution, the contour can clearly demonstrate the value change as the distance varies.

To evaluate the modeling calculation results, 16 representative sites of the physical platform were selected, and the potential of these sites was monitored using voltmeter. Fig. 6 shows the potential data from modeling calculation and from experimental measurements. As the results shown in Fig. 6, the maximum error of the data was $15$ mV, whose relative error was about $1.61\%$, and the deviation from modeling calculation and from laboratory experiments is small enough that BEM modeling could provide good design of the sacrificial anode protection for marine structures.

5. Conclusion

In the present work the potential and current density distribution of the platform protected with sacrificial anodes in seawater was calculated using the boundary element method. The calculation results were compared with those from the laboratory measurements. The modeling can effectively reflect the potential
and current density distribution of the platform. According to the experimental validation, the computation results satisfied the proper range of the corrosion protection. The BEM modeling was proved to have high efficiency for simulating the sacrificial anode protection of steel structures in marine environments.

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References


