Validation as construction design method of anti-corrosion process for marine steel structures using COMSOL Multiphysics® through mock-up sheet piles

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Abstract: In this paper, I show one example for application of numerical simulations using COMSOL Multiphysics® to construction design of anti-corrosion method for steel structures in seawater [1]. Here in order to check whether the simulation model is useful in the optimization for electrodes arrangement, which is the most important factor in construction design, I tried validation by comparison between simulation results and experimental results through mock-up sheet piles model. As the results, I could verify that potential distributions obtained from experimental results were consistent with ones by simulations, and then numerical simulation model by COMSOL Multiphysics® is proper application to optimize electrodes arrangements. I show the detail below.

Keywords: Anticorrosion, electrodes arrangement, calcareous deposits, electrodeposition,

1. Introduction

Steel structures in Japanese harbors are important infrastructures, but most of them were constructed in 1960's. Then they are becoming older and the maintenance and repair are one of big problems in our society, proper and more economic anti-corrosion method is needed.
In many different kinds of anti-corrosion methods for steel structures in seawater, there is a method using calcareous deposits coating [2-3].
In this method, electrodes were set near the structures in seawater and impress electric current for forming the deposits on the steel surface.
The deposits coating is composed of $CaCO_3$ and $Mg(OH)_2$, the deposits plays a role to prevent corrosion from the surface. The reason is that they are alkaline material and $CaCO_3$ decreases diffusion of dissolved oxygen from sea water to the steel surface.
But the thickness and quality of coating are known to be influenced by the electric current or potential distributions, the distributions become non-uniform in complicated shaped structures, and optimization about arrangement of electrodes is needed so as to set the distributions to proper and uniform conditions. Thus optimization of electrodes arrangements is one of the most important factors in construction design for this process.
Then in order to check whether the simulation model is useful in the optimization, I tried validation for numerical simulation using COMSOL Multiphysics® by comparison between simulation results and experimental results through mock-up sheet piles model. Here I will show some of contents and results below.

2. Chemical Reactions

In calcareous deposition process, the electrodes were set counter to the ferrous structures in seawater so as to form calcareous deposits on the steel surface by external power supply.

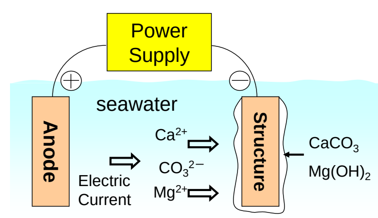

Figure 1. Description for calcareous deposition process in seawater

Here if the cathodic current is impressed to the steel structure, pH around the steel surface is increased, then calcareous deposits composed of $CaCO_3$ and $Mg(OH)_2$ is formed onto the surface as the following equations [4-5]:

$$H_2O+1/2O_2+2e \rightarrow 2OH^-$$
or
$$2H_2O+2e \rightarrow 2OH^- +H_2$$

$$OH^-+HCO_3^- \rightarrow H_2O+ CO_3^{2-}$$

$$CO_3^{2-}+Ca^{2+} \rightarrow CaCO_3$$
and
$$2OH^-+Mg^{2+} \rightarrow Mg(OH)_2$$

These calcareous deposits consist of two layers, $Mg(OH)_2$ layer play the role to prevent corrosion of steel by alkali, $CaCO_3$ serves a function to decrease the diffusion of dissolved oxygen in sea water onto the steel surface [6]. But in range of proper current density and thickness, the thickness of calcareous deposits coating is known to be proportional to electric current impressed on the steel surface [3]. Then I regard uniformness in electric current distributions the same as ones of coating thickness below.

3. Numerical Model

The process and experiments are modeled via the Secondary Current Distribution interface in Electrodeposition module offered by COMSOL Multiphysics® in a three-dimensional space. In this simulation, seawater was seen as electrolyte, and the potential distributions in seawater were solved. I show the fundamental equations needed to this model below.
First the conservation of mass must be maintained for each of the species throughout the system, and is expressed as:

$$\frac{\partial C_i}{\partial t} = -\nabla \cdot N_i + R_i$$

R_i = Rate of accumulation/removal of species i by electrochemical reactions

It was assumed that electroneutrality was maintained throughout the system, and is expressed as:

$$\sum -z_i C_i = 0$$

At the next step, the flux of each of the ions in the electrolyte is given by the Nernst-Planck equation as follows:

$$N_i = -D_i \nabla C_i - z_i u_i F C_i \nabla V$$

$$u_i = \frac{D_i}{RT}$$

N_i = Mass transport vector (mol/m2.s)
D_i = Diffusivity of species i in the electrolyte (m2/s)
C_i = Concentration of species i in the electrolyte (mol/m3)
z_i = Charge of species i in the electrolyte
u_i = Mobility of species i in the electrolyte (mol.m2/J.s)
F = Faraday's constant (A.s/mol)
V = Electrolyte potential (V)

At last, the fluxes at the model boundaries are determined by the established electrochemical reactions and the Butler-Volmer equation.

$$i = i_0 \left[exp\left(\frac{\alpha_a n_e F \eta}{RT}\right) - exp\left(\frac{\alpha_c n_e F \eta}{RT}\right) \right]$$

$$\eta = E - E_{eq}$$

$$\frac{dn}{dt} = \frac{1}{n_e F}$$

α_a = Anodic charge transfer coefficient
α_c = Cathodic charge transfer coefficient
E = Electrode potential (V)
E_{eq} = Equilibrium potential (V)
i = Electrode current density (A/m2)
i_o = Exchange current density (A/m2)
n_e = Number of electrons involved in the electrode reaction
η = Activation overpotential
I = Electric current flowing through the system
n = Number of moles of species

4. Experimental and Simulation Set-up

First I show about experimental setup [1].
Here to mock-up sheet piles, optimization about the proper arrangement of electrodes were considered through both of the simulations and experiments.
In these cases, I prepared about 200 liters natural seawater in plastic tanks, set the mock-up steel sheet piles and aluminum electrodes in them.
The materials of mock-up sheet piles were all carbon steel, surfaces on one side were prepared by grid blast, and ones on another side were coated by the epoxy-paint for the insulation and anti-corrosion during these experiments.
Also aluminum prisms were set as electrodes in seawater, and the wiring between them and sheet piles were set for the application of electric current.
Moreover, for comparison with results from simulations, 18 saturated calomel reference electrodes were set on the surfaces of sheet piles, the potential distributions were measured experimentally.
Here I choose two patterns of electrodes arrangements.
I show them below.
In the first case, the electrode was set far counter to the bare sides of sheet piles as shown in Figure 2. This pattern is general arrangement. I put this pattern (a) here.
In another case, the electrodes were set into concave parts of sheet piles each as shown in Figure 3. I put this pattern (b) here.
At next, I explain about setup of simulations [1].

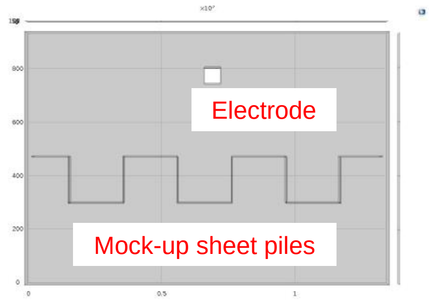

Figure 2. Description for setup of electrodes arrangements in pattern (a)

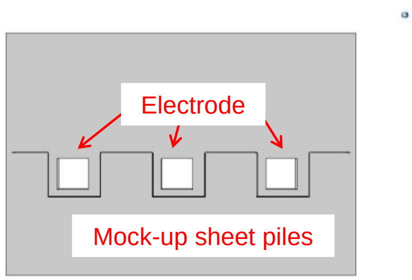

Figure 3. Description for setup of electrodes arrangements in pattern (b)

In these simulations, seawater was set to electrolyte, the stationary studies were used, and the electric potential distributions in seawater were solved.
In these calculations, the surfaces of sheet piles were set to cathodic electrodes and the ones of aluminum electrodes were set to anodic electrodes. Here the literature data was used about electrolyte conductivity of seawater, the relations between charge transfer and overpotential on the surfaces of electrodes were used the equations obtained from polarization measurements in laboratory experiments.

5. Results and Discussion

First I show the results of simulations [1].
In the case of general electrodes arrangement, pattern (a), the potential distribution on the surfaces of sheet piles was non-uniform and the potentials on the surfaces of convex sides of sheet piles face to electrodes were about 0.10V lower than ones of concave sides as shown in Figure 4.
On the other hands, in another case, pattern (b), the potential distribution on the surfaces of sheet piles was more uniform than pattern (a), the differences of potential between convex sides of sheet piles and concave sides were decreased to about 0.05V by change of electrodes arrangements as shown in Figure 5.
At the next step, in order to validate the results of simulations, I measured and summarized the potential distributions experimentally using

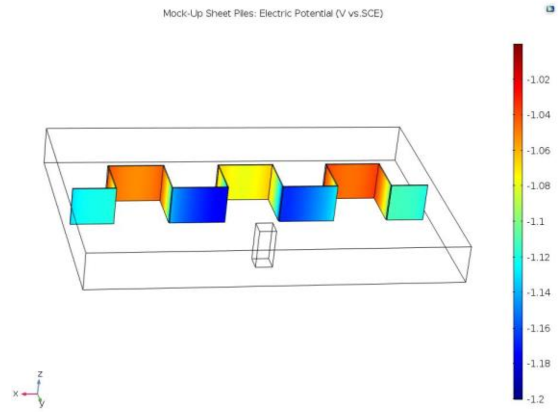

Figure 4. Result for electric potential distribution on the surface of mock-up sheet piles in case of electrodes arrangement pattern (a) by numerical simulation

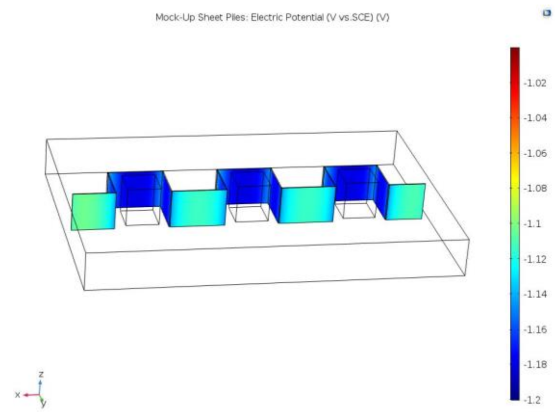

Figure 5. Result for electric potential distribution on the surface of mock-up sheet piles in case of electrodes arrangement pattern (b) by numerical simulation

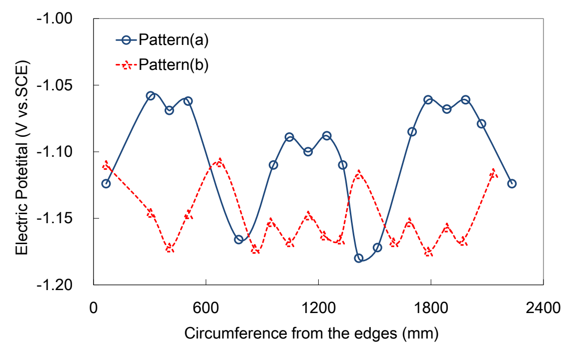

Figure 6. Comparison of electric potential distribution on the surface of mock-up sheet piles between one in case of electrodes arrangement pattern (a) and pattern (b) by experiments

saturated calomel reference electrodes set on the surfaces of sheet piles in each patterns.
As shown in Figure 6, potential distributions obtained from experiments were consistent with ones of simulations in both cases, then the change of

electrodes arrangements from pattern (a) to pattern (b) results to decrease ununiformity of potential distributions as predicted by simulations.
These results mean that numerical simulation model by COMSOL Multiphysics® is proper application to optimize electrodes arrangements.

6. Conclusions

In many different kinds of anti-corrosion methods for steel structures in seawater, there is a method using calcareous deposits coating. Here in order to check whether the simulation model is useful in the optimization, which is the most important factor in construction design, I tried validation for numerical simulation using COMSOL Multiphysics® by comparison between simulation results and experimental results through mock-up sheet piles model. As the results, I could verify that potential distributions obtained from experiments were consistent with ones by simulations, and then numerical simulation model by COMSOL Multiphysics® was proper application to optimize electrodes arrangements.
I will utilize these results to establish more efficient construction design in this process.

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