Numerical analysis assisted monitoring method for the coating condition on a ballast tank wall

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Abstract

We developed the numerical analysis assisted monitoring method for the coating condition on a ballast tank wall. We proposed that the coating condition is evaluated with the surface resistance. We developed the identification method to obtain the whole surface resistance from the differential potential induced by the impressed current from an optional anode inside a tank. We introduced differential potential measurement and inverse analysis to obtain the surface resistance representing the coating condition. The potential measurement and quantitative evaluation were conducted in the actual ship. The verification was performed and there was the good agreement between the proposed method and the preliminary visual inspection.
Keywords: corrosion analysis, numerical analysis, surface resistance, inverse problem, coating condition, ballast tank.

1 Introduction

In order to prevent corrosion loss, it is very important to inspect the coating condition inside the ballast tank of ship, such as oil tankers, LNG ships and cargo ships. The current inspection standard defines that the ratio of paint defect surface area in the total surface is visually inspected every two or three years periodically. However, the current visual inspection has some problems, such as the dangerous and dark environment for inspectors, the inaccurate evaluation result depending on the inspector's skill and the time consuming and heavy labor required in order to inspect all the hundreds of tank compartments. In order to overcome these issues,

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a quantitative, safe, economic and efficient monitoring method for the coating condition is extensively expected.

A ballast tank filled with seawater is easily corroded. Corrosion protection by the paint on the metal surface inside the tank, which improves the insulation for the corrosion current, is conducted. The paint has problems with age-related degradation and incipient failure. To protect from the corrosion caused by these problems, plural sacrificial anodes are usually installed in the tank. When seawater is loaded in the tank, the surface of the inside tank becomes cathode and the protective potential works, because of the anode effects. The worse the coating condition becomes, the worse the insulation of the paint becomes and the lower the surface resistance becomes. Therefore, there is the possibility that the coating condition can be evaluated with the monitoring of the surface resistance.

On the other hand, the potential measurements are sometimes conducted for the evaluation of the cathodic protection. However because the environmental factors, such as temperature, affect the measured potential and the potential is determined by the number of anodes and the coating condition, the coating condition could not be evaluated directly by the potential measurement.

In this paper, we developed the numerical analysis assisted monitoring method for coating condition on ballast tank wall. We proposed the coating condition is evaluated with the surface resistance. We developed the identification method to obtain the whole surface resistance from the differential potential induced by the impressed current with an optional anode. We introduced differential potential measurement and inverse analysis to obtain the surface resistance representing the coating condition. The potential measurement and quantitative evaluation were conducted in the actual ship. The verification was performed.

2 Proposed method

2.1 Coating condition and surface resistance

The relationship between potential ϕ[V] and current density i[A/m^2] in an electrolyte near the metal surface represents the function called polarization curve as shown in Eqn. (1). The function is normally non-linear and is determined experimentally. The polarization curve depends on kinds of metal, electrolyte and environmental conditions such as temperature, pH, and concentration of oxygen. In this paper, it is noted that the potential ϕ at a certain location in electrolyte is defined with referring to the metal and has the inverse sign of the potential E employed in electro-chemistry in which the potential is defined to a reference electrode such as SCE or Ag/AgCl.

$$\phi = -f_m(i) \tag{1}$$

Let us consider the small change of Eqn. (1).

$$\delta\phi \simeq -\frac{df_m}{di}\delta i = -R \cdot \delta i \tag{2}$$

$$R \equiv \frac{df_m}{di} \tag{3}$$

The surface resistance $R[\Omega m^2]$ makes the relationship between the potential change and the current density change. When the resistance is big, it indicates high insulation. Therefore, we propose that the coating condition can be indicated by the surface resistance R. In the case that the non-coating surface resistance is R_0, the ratio of the paint defect area against total surface area can be evaluated with the following [6] (Eqn. (4)):

$$\alpha = \frac{R_0}{R} \tag{4}$$

2.2 Summary and procedure of proposed monitoring method

Let us describe the proposed monitoring method in this section.

An optional anode and an Ag/AgCl reference electrode for potential measurement are placed in the seawater filled in a tank to be inspected as shown in Figure 1. The potential changes at several location in the tank with reference electrode are measured in the two cases. The first case is that the prescribed current is impressed with an optional zinc anode and the second case is that no current is impressed. Each case is represented with subscript "ON" and "OFF" respectively in the following. The differential potential $\delta\bar{\phi}(= \bar{\phi}_{ON} - \bar{\phi}_{OFF})$ is calculated from the results.

Potential in any point is calculated with various R using a numerical analysis. It is assumed that the surface resistance R is constant in this numerical model. Let us consider the residual of the measured differential potential $\delta\bar{\phi}$ and the numerically

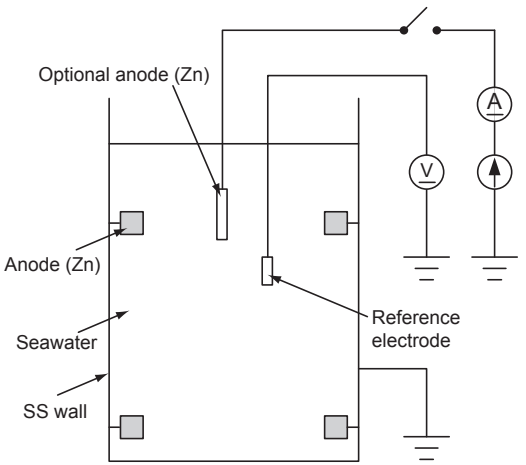

Figure 1: Simple measurement model in ballast tank.

calculated $\delta\phi(R)$. (Eqn. (5))

$$F(R) = \sum_{j}^{N} \{\delta\bar{\phi}_j - \delta\phi_j(R)\}^2 \tag{5}$$

Where N is the number of the combinations of the potential measurement points and the anode locations.

Obtaining the surface resistance R is to search R which minimizes Eqn. (5). The general optimization method, such as Brent's method [5], can be applied for searching R.

2.3 Analysis method for differential potential

In this section, numerical analysis method to calculate the potential $\phi(R)$ or the differential potential $\delta\phi(R)$ for the assumed surface resistance R is described.

First, let us consider the mathematical model of the electrical field in the tank. It is assumed that the surface of electrolyte domain Ω is surrounded by $\Gamma(=\Gamma_d + \Gamma_n + \Gamma_m)$, where Γ_m is the metal surface, and the potential and current density are prescribed on Γ_d and Γ_n respectively. The potential ϕ in 3-D homogeneous electrolyte domain Ω satisfies the Laplace's equation:

$$\nabla^2\phi = 0 \quad in\ \Omega \tag{6}$$

The general boundary conditions are given with

$$\phi = \phi_0 \quad on\ \Gamma_d \tag{7}$$

$$i\left(\equiv \kappa\frac{\partial\phi}{\partial n}\right) = i_0 \quad on\ \Gamma_n \tag{8}$$

$$-\phi = f_m(i) \quad on\ \Gamma_m \tag{9}$$

where ϕ_0 and i_0 are the prescribed values of potential ϕ and current density i, respectively, $\partial/\partial n$ is the outward normal derivative, and κ is the conductivity of the electrolyte. The actual boundary condition for numerical analysis is described in Table 1 in section 3.3.

The potential ϕ_{ON} and ϕ_{OFF} correspond to the case (ON) with the optional anode and the case (OFF) without it respectively.

$$\delta\phi = \phi_{ON} - \phi_{OFF} \tag{10}$$

Since the two potentials ϕ_{ON} and ϕ_{OFF} satisfy the Laplace equations, the differential potential $\delta\phi$ also satisfies the equation.

$$\nabla^2(\delta\phi) = 0 \quad in\ \Omega \tag{11}$$

Eqn. (11) implies that in case there are two boundary conditions for one model, the following three conditions are applied instead of Eqn. (7) to (9).

$$\delta\phi = \phi_{ON\,0} - \phi_{OFF\,0} \quad on\ \Gamma_d \tag{12}$$

$$\delta i = i_{ON\,0} - i_{OFF\,0} \quad on\ \Gamma_n \tag{13}$$

$$-\delta\phi = f_m\,(i_{ON}) - f_m\,(i_{OFF}) \simeq \frac{df_m}{di}\delta i \quad on\ \Gamma_m \tag{14}$$

In case that δi in Eqn. (14) is small, the approximation becomes better in terms of Taylor expansion. Also, the constant term of polarization curve in Eqn. (1) representing open circuit corrosion potential can be eliminated and it only depends on the surface resistance $\frac{df_m}{di} = R$. Eqn. (1) becomes Eqn. (15)

$$\delta\phi = -R \cdot \delta i \tag{15}$$

The constant term depends on the environmental conditions such as temperature, pH, concentration of oxygen and the reference electrode offset. But the differential method without the term has advantages on them, in case that the same reference electrodes are used in the short-time measurement. This formulation easily eliminates the effect of open circuit corrosion potential and reference electrode offset. If the potential or current density are constant in two boundary conditions, the differential boundary conditions are zero according to Eqn. (12) or Eqn. (13).

A boundary element method is employed for the numerical analysis to solve Eqn. (11) with Eqn. (12) to Eqn. (14). The formulation of the boundary element method is the same as the standard boundary element method with Eqn. (6) to Eqn. (9).

3 Verification of differential method

3.1 Experiment summary

Potential measurement was conducted in a ballast tank of the 23 year-old LNG ship. The LNG ship has ten ballast tanks and each ballast tank partitioned to approximately ten compartments with bulkheads transversely and vertically. One of the compartments is measured by the present method. Five years have passed since the paint-coating of the ballast tank was repaired. The measured compartment is a rectangular parallelepiped (L 3.75 m × W 4 m × H 12.8 m) filled with seawater up to 7.6 m in height. There were eight zinc anode electrodes (L 0.1 m × H 0.1 m × W0.5 m) in the seawater within the compartment as shown in Figure 2.

The measurements were conducted with the optional anode (ϕ15 mm×L150 mm) and both (ON) and (OFF) were measured. The potential along the center line was measured with an Ag/AgCl reference electrode every 0.2 meters back and forth between top and the bottom of the seawater. The current from the optional zinc anode was measured. HIOKI 8422-50 logger and HIOKI 3257-50 DMM were used for the potential and current measurement respectively.

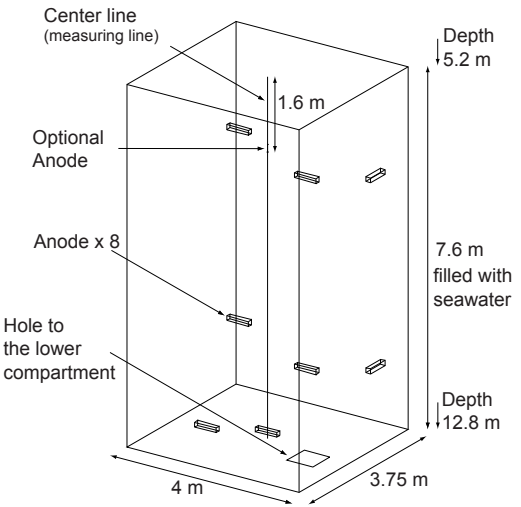

Figure 2: Ballast tank compartment with seawater.

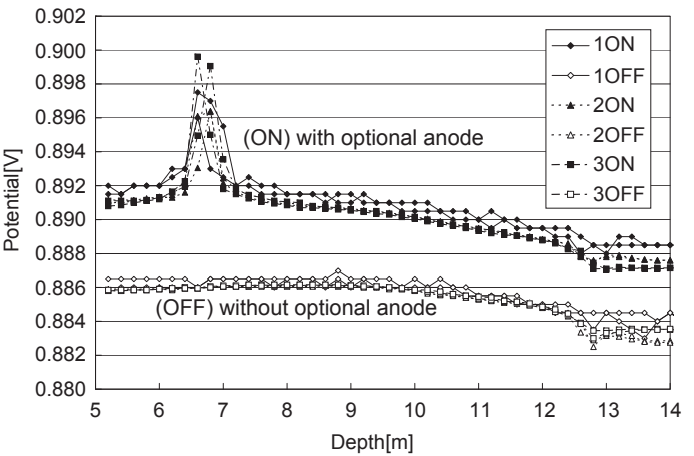

Figure 3: Potential distributions (optional anode depth 1.6m from seawater surface).

3.2 Measurement results

One set measurement takes about fifteen minutes. The optional anode was located at the depth of 1.6m from the seawater surface in the first three sets (Fig. 3). The electrode measuring the potential was attached to the cable on edge. The depth of Figure 3 is actually the cable length from the ballast tank ceiling and the depth more than 12.8 meters shows that the electrode reached the bottom.

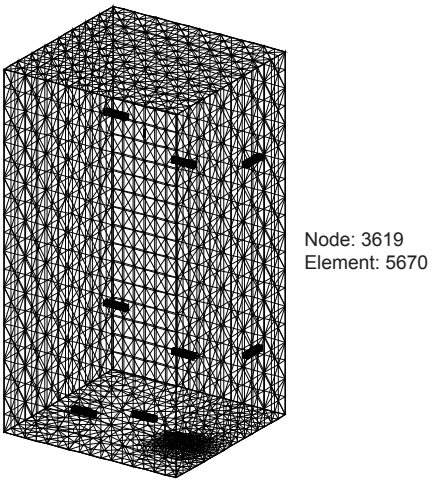

Figure 4: Mesh for compartment.

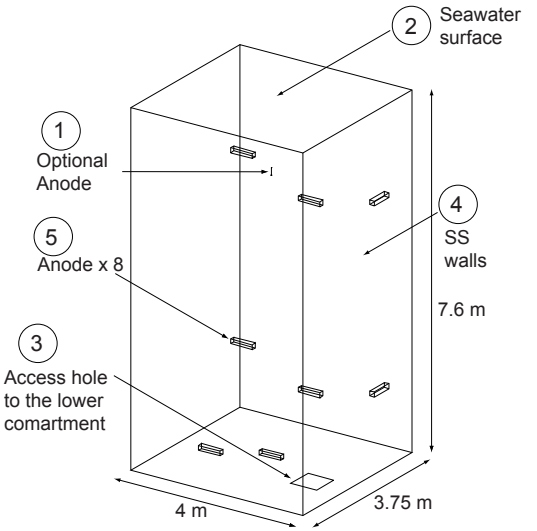

Figure 5: Ballast tank compartment with seawater.

3.3 Numerical analysis and surface resistance identification

In order to verify the proposed differential method, the differential potential distribution within the tank are compared between the numerical result and the experimental result.

Firstly, the differential potential distribution within the tank shown in Figure 2 was measured. The experimental condition is set to be the same in the former section.

Table 1: Boundary conditions of differential model for the compartment.

No.	Boundary condition	Place
①	δI =30 [mAmps]	Optional anode side (ON)
②	δi=0	Seawater surface
③	$\delta\phi$=0.005 [V]	Access hole to the lower compartment
④	$\delta\phi = -R_{SS} \cdot \delta i$	SS (walls) R_{SS}=1000, 500, 200, 100, 50, 20, 10, 5 or 2 [Ωm^2]
⑤	$\delta\phi = -0.16\delta i$	Zn (anodes)

Secondly, the tank is modeled as shown in Figure 5 for the numerical analysis. The boundary element mesh in Figure 4 was used and the elements are all constant triangle elements. The number of the elements and nodes are 5670 and 3619, respectively. The boundary condition is applied as shown in Table 1. The surface resistance of the anodes is set to be 0.16 [Ωm^2]. The total current amount of the optional anode is set to be 30mA and the access hole boundary condition is set to be $\delta\phi$=0.005 [V] from the experiment. The differential potential distributions are calculated for nine cases whose surface resistances R_{SS} are varied.

The numerical results for nine cases of the surface resistances are shown in Figure 6. It shows that the whole potential is high when the surface resistance is high. The maximum voltage of the sidelobe of the optional anode is 0.005 [V].

Thirdly, the surface resistance was estimated by minimizing the residual function Eqn. (16). The residual function consists of three residuals between measurement and calculated differential potential at the depth of seven meters. The minimization was performed with the brute-force search.

$$F(R_{SS}) = \sum_j \{\delta\bar{\phi}_j - \delta\phi(R_{SS})\}^2 \tag{16}$$

The both numerical and experimental potential distributions are shown in Figure 7 and they show good agreement. It is noted that the good agreement can be achieved even if the open circuit corrosion potential is unknown, polarization curve is non-linear and unknown and there are the offsets of reference electrodes.

The paint defect ratio is lower than 0.2% under the assumption of the surface resistance of bare SS $R_0 = 1[\Omega m^2]$. (See Eqn. 4) This result agrees with the preliminary visual inspection.

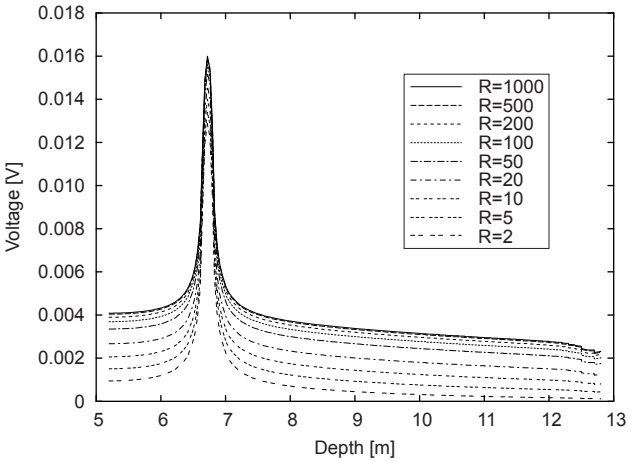

Figure 6: Voltage distributions with various surface resistances.

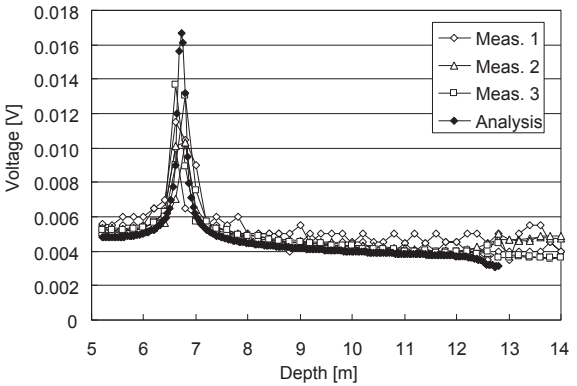

Figure 7: Voltage distributions (depth 1.6m from seawater surface, SS surface resistance: 500 [Ωm^2]).

4 Conclusion

We developed the quantitative monitoring method for coating condition inside a ballast tank. We proposed the coating condition is evaluated as the surface resistance. We developed the identification method to obtain the whole surface resistance from the differential potential induced by the impressed current from an optional anode inside a tank. We introduced differential potential measurement and inverse analysis to obtain the surface resistance representing the coating condition. The potential measurement and quantitative evaluation were conducted in the actual ship.

The both numerical and experimental potential distributions agrees well with the differential method. The good agreement can be achieved even if the open circuit corrosion potential is unknown, polarization curve is non-linear and unknown and there are the offsets of reference electrodes. The paint defect ratio calculated from the differential method agrees with the preliminary visual inspection.

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