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Optimizing the sacrificial anode cathodic protection of the rail canal structure in seawater using the boundary element method

Yong-Sang Kim[a], Jeongguk Kim[b], Dooho Choi[c], Jae-Yong Lim[d], Jung-Gu Kim[a,*]

[a] School of Advanced Materials Science and Engineering, Sungkyunkwan University, 300 Chunchun-Dong, Jangan-Gu, Suwon 16419, Republic of Korea
[b] New Transportation Systems Research Center, Korea Railroad Research Institute, 176 Chelodo Bangmulgwan-ro, Uiwang, Gyeonggi 16105, Republic of Korea
[c] Department of Advanced Materials Engineering, Dong Eui University, 176 Eomgwangno, Busan 47340, Republic of Korea
[d] School of Mechanical Engineering, Daegu University, 201 Daegudaero, Gyeongsan, Gyeongbuk 38453, Republic of Korea

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ABSTRACT

This paper deals with the cathodic protection design for axle/wheel and rail of '*rail-canal system*' in the ocean. The cathodic protection design was carried out using the boundary element method and was verified by the physical miniature tests. The optimum cathodic protection designs were determined based on the cathodic potential distribution and anode lifetime provided by the simulation. The unprotected physical miniature experienced widespread corrosion, whereas the protected miniature was covered with calcareous deposit, indicating that the surface was fully protected from corrosion. This study demonstrated that the boundary element can be applicable to the cathodic protection design of rail-canal structure.

1. Introduction

A ship canal is that provide a shortcut for transport ships to avoid lengthy detours. With the recent increase in demand for ship canals desire to reduce the cost of cargo transport, there are plans to extend both the existing ship canal in Panama, and build additional ship canals in Nicaragua, Colombia [1,2]. However, conventional canal waterways are enormously expensive to construct and have long lock gate operation times. Also, overland routes are interrupted by canal construction, resulting in environmental problems and restrictions in national land use. To address these drawbacks in waterway canals, the Korea Railroad Research Institute (KRRI) has proposed a '*rail-canal system*', in which a large vessel is transported not along waterways but on land, so as to replace conventional waterway canals [3]. The rail-canal system process is illustrated in Fig. 1. However, the corrosion problems caused by a marine environment should be addressed to provide safe and long-term operations for rail-canal systems.

Sacrificial anode cathodic protection (SACP) is a widely used anti-corrosion method for offshore structures. The mechanism is that galvanic current flows from a sacrificial anode such as magnesium (Mg), zinc (Zn) and aluminum (Al) to the protected structure when the anode and protected structure are electrically connected in a conducting environment [4]. In general, the design of SACP follows the international cathodic protection criteria, including NACE RP0176 and DNV RPB041. However, important SACP design factors such as the selection, location and number of anodes are determined by the corrosion engineer due to complex conditions and uncertainties [5]. Thus, studies on SACP design for various offshore structures are required to ensure the adequate design of SACP.

The boundary element method (BEM) is an element method that only requires meshing of the boundary on the modeling structure, so it can more effectively mesh and calculate the boundary elements compared to other element methods [5]. Due to this advantage, BEM has been widely utilized for the cathodic protection design of enormous structures such as ships, offshore structures and underground pipeline systems [5–9]. Various studies [10–12] have showed that the use of BEM results in excellent cathodic protection system designs. Simulations of galvanic corrosion related to the SACP using the BEM method were in good agreement with the experiment results [13,14].

In this study, the SACP of rail canal structure parts (wheel/axle and rail) in a seawater environment was simulated using BEM. It was difficult to apply an organic coating to these parts due to the continuous friction and stress. Thus, a huge current is needed for impressed current cathodic protection (ICCP) without the organic coating, and this may cause an electrical accident. Therefore, SACP is applied for the cathodic protection method of rail canal structures. The optimum selection, location and size of the sacrificial anodes were determined, and the optimized cathodic protection design was investigated using physical miniature tests.

* Corresponding author.
E-mail address: kimjg@skku.edu (J.-G. Kim).

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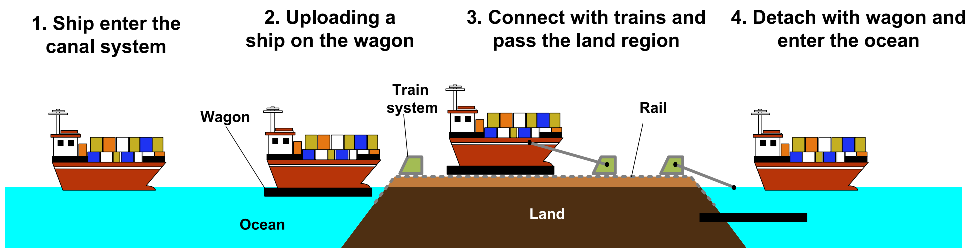

Fig. 1. Schematic of rail-canal system.

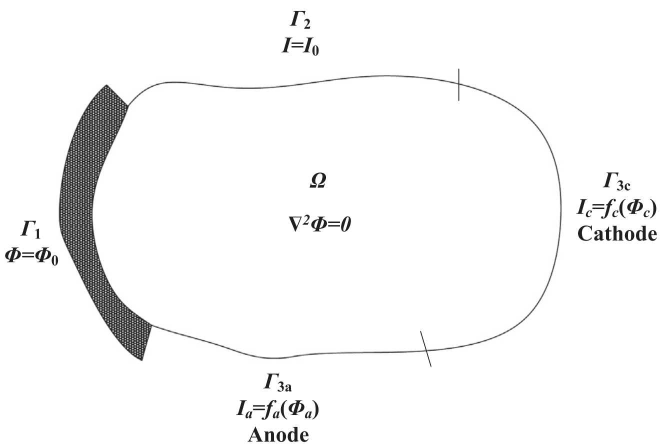

Fig. 2. Boundary conditions for the cathodic protection computation.

2. BEM simulation

Adey and Niku [15] have provided the mathematical formulation for a uniform, isotropic electrolyte domain Ω as shown in Fig. 2. Some simplifying assumptions were made to assist in the computation including: (i) the solution must be uniform and electro-neutral, (ii) there is no concentration gradient in the electrolyte solution, and (iii) the boundary of the container was electrically insulating, so there was no flow current leakage from the container. Following these assumptions, the potential obeys the Laplace equation:

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

The Laplace equation is solved using the following boundary conditions:

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

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

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

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

Γ is the entire surface of the electrolyte domain which includes Γ_1, Γ_2, Γ_{3a} and Γ_{3c}. Φ is the potential, and I is the current density across the boundary. Φ_0 and I_0 are given constant values of potential and current density, respectively. $f_a(\Phi_a)$ and $f_c(\Phi_c)$ are functions that indicate the relationship between the potential and current density of the anode and cathode, respectively.

Wheel/axle and rail models were created in the Rhinoceros 3D drawing software based on the real shape and dimensions of the structures. The dimension data include the length, height, width, diameters and so on. The inner parts of structure were not modeled to avoid computational errors. Three-dimensional models of wheel/axle and rail structures with detailed dimensions are shown in Fig. 3(a) and (b), respectively. Also, the cathodic protection system information was used to provide the size, location and form for simulating the cathodic protection process. The size of the anode and the anode location were changed during the process of cathodic protection design, and the form of the anode was rectangular to simplify the computation process. After modeling the structure, the designed structure model was imported into the BEASY software.

Setting the boundary conditions is an essential step in modeling corrosion and cathodic protection systems with BEASY. The model structure and surrounding environment (seawater) are enclosed within a rectangular box that was approximately 30 times bigger than the modeling structures. In order to avoid current flow from the object, the vector sum of the current was zero. The conductivity of the environment was fixed to 3.75 S/m. The relationship between the current and potential of the cathode and anode gives the polarization state; therefore, the cathode and anode electrochemical properties were determined according to the input polarization data.

3. Experiments

3.1. Materials

The axle/wheel and rail materials were based on carbon steel. The axle had a nominal composition (wt%) of 0.45% C, 0.30% Si, 0.75% Mn, 0.010% P, and 0.001% S, while the wheel had a nominal composition of 0.64% C, 0.25% Si, 0.73% Mn, 0.015% P, 0.003% S, and 0.025% Cu. The rail had a nominal composition of 0.85% C, 0.5% Si, 0.64% Mn, 0.003% P, and 0.003% S. Zn and Al sacrificial anodes were used in this study. The Zn anode had a nominal composition of 0.050% Al, 0.04% Cu, 0.02% Pd, and 0.001% Mg. The Al anode had a nominal composition of 0.05% Fe, 0.05% Si, 0.01% Cu, 3.5% Zn, 0.03% In, and 1.0% Mg. Synthetic seawater from ASTM D-1141 was used, and its chemical composition is listed in Table 1.

3.2. Potentiodynamic tests

The polarization data for the cathode and sacrificial anode materials were needed to carry out the simulation. The cell used for carrying out potentiodynamic tests was a conventional three-electrode cell. A purified carbon rod was used as the counter electrode, and a saturated calomel electrode (SCE) was used as the reference electrode. The working electrodes for axle/wheel, rail and sacrificial anodes (Al, Zn) were rectangular cubes of 1×1×0.3 cm, and these were mounted in epoxy resin with an exposed area of 1 cm^2. Before the tests, the working electrode was abraded with wet SiC paper (initially 220, 400, 600 and 800 grades), washed with distilled water, degreased with acetone, washed with ethanol, and finally dried in nitrogen gas. Potentiodynamic tests were carried out using a Bio-Logic VSP-300