Invited paper

Analysis of stray current corrosion problems using the boundary element method

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ABSTRACT

Today's offshore and ocean going structures and buried structures are fitted with systems which work to inhibit the rate at which the structure corrodes in the aggressive marine or soil environment. These operate by setting up an electrostatic field in the water surrounding the structure which causes a desired voltage and current density distribution over its surface area. These cathodic protection (CP) systems are carefully designed to offer the structure a uniform protection over its surface with the most economical use of anodes.

When a structure which is protected in this way approaches a large block of some metallic or other conducting material, the block can interfere with the operation of the CP system by drawing current away from some areas and supplying it to others. This can give rise to localized corrosion problems, particularly on the material of the block. This is known as 'stray current corrosion'.

This paper discusses the problem of stray current corrosion, and describes how the problem may be modeled numerically using the boundary element method. Examples are given to show how the method is easily applicable to general geometries.

Keywords: Boundary element method, corrosion, stray current, electrostatics, electrochemistry.

INTRODUCTION

Whenever an electrical current flows through an electrolyte such as seawater or soil, the resistance of that electrolyte causes a potential gradient to form. The magnitude of this gradient is determined by the current (I) and the electrolyte resistance (R) as follows:

$$E = IR$$

When a conductor, such as a metal pier or pipe, is placed in this potential field, a current can be generated in this conductor which causes a phenomenon called "stray current corrosion". Stray current corrosion can be caused by the systems used to protect ship hulls and buried structures, called cathodic protection systems, by the DC electrical systems used to power trolley cars, and by a number of other sources. Stray current corrosion is of immense economic importance, since it has led to such problems as rapid failure of buried natural gas pipelines and water mains, and costly repairs to ship structures and piers.

An easy way to understand the cause of stray current corrosion is to consider the case of a ship's impressed current cathodic protection system and it's interaction with a steel sheet piling of a neighboring pier. A ship impressed current cathodic protection system consists of a power supply with its negative terminal connected to the ship's hull and its positive terminal connected to a special device called an anode. The power supply forces current out of the anode, through the seawater, and into the ship's hull to complete the circuit. The action of the current causes a shift in electrochemical potential of the steel of the ship's hull which slows or stops the normal tendency of steel to corrode in seawater. This technique is used to control corrosion on all large ships and most small ones. A variety of this technique is even used to protect outboard motors on small craft. On large ships, the current being delivered by the anodes is typically controlled by monitoring the amount of potential shift of the steel hull using special electrodes called reference cells. The current is usually adjusted to give a fixed steel potential near the controlling reference cell.

A ship may dock near a large metallic object such as the steel sheet piling on the pier to which the ship is tied. This creates the following situation, illustrated in figure 1. Current flowing from the ship's anode through the seawater to the ship hull encounters a resistance due to the resistivity of seawater. If the sheet piling is closer to the anode than sections of the ship hull, the current has an alternate path that it may follow. It can travel through a much shorter seawater path to the piling, through the low resistance steel of the piling until it gets close to the ship hull, then through another short seawater path between the piling and the hull to complete the circuit.

At the point where the current enters the piling, the steel is protected from corrosion the same way as the ship hull is protected by the cathodic protection system. Unfortunately, where the current leaves the piling to enter the seawater, the opposite occurs. The corrosion of the steel piling in this area is dramatically increased. The magnitude of the resulting stray current corrosion depends on how much of the cathodic protection current takes the alternate path through the piling. To take the ordinary path, the current must flow through a long seawater path, which has some resistance:

$$R_{sw-long}$$

The alternate path requires that the current flow through a shorter seawater path with resistance:

$$R_{sw-short1}$$

enters the steel through a surface resistance called the polarization resistance:

$$R_{p1}$$

flows through the steel piling with nominal resistance, exits the piling through another polarization resistance:

$$R_{p2}$$

and flows through another short seawater path with resistance:

$$R_{sw-short2}$$

For much current to take the path through the piling that causes stray current corrosion:

$$R_{sw-long} > R_{sw-short1} + R_{p1} + R_{p2} + R_{sw-short2}$$

Unfortunately, in this situation more happens than just stray current corrosion. The total resistance between anode and hull on the ship's cathodic protection system is lowered due to the presence of the pier. This creates a lower *IR* drop, which affects the potential read by the reference cell on the ship hull. Since the reference cell reads a different potential than it should, it will alter the current being delivered by the anodes until it reads the "proper" potential. The change in protection current going to the ship hull may lead to underprotection, with resulting ship corrosion, or overprotection, which can cause blistering of the hull paint.

Another example of stray current corrosion is shown in figure 2. Here, an underground water main is being catholically protected by anodes mounted remotely. A buried natural gas pipeline running perpendicular to the protected watermain is in a perfect position to shunt some of the current from the high-resistance soil path, creating a serious stray current corrosion problem in the gas pipeline which can threaten property and safety.

Stray current corrosion is extremely difficult to quantify in the laboratory. The resistances involved have complex geometrical dependence. Fortunately, computer modeling is ideally suited for predicting this phenomenon.

BOUNDARY ELEMENT FORMULATION

Galvanic corrosion and cathodic protection systems have been simulated using the boundary element method for some years, both in research and industrial organizations [1-3]. The problem involves the solution of the Poisson equation to find the electrostatic field in the sea-water, i.e. where u represents the voltage, or potential, at any point in the sea-water,

$$\nabla^2 u = 0$$

This equation is solved subject to a set of boundary conditions which become non-linear over the portions of the boundary which model the interaction between metallic surfaces and the water. These polarization conditions are of the form

$$q = f(u)$$

where q is the current density passing between the metal and the water, and f is a non-linear function which depends on a wide variety of factors such as temperature, water velocity, depth, salinity, etc. Thus the particular polarization curves used in an analysis may vary greatly according to the geographic location of the structure to be protected. The function f is also dependent on the history of current density which has occurred on each piece of the metallic surface.

The standard BEM formulation for linear potential flow [4,5] may be used, i.e.

$$\int_\Gamma q^* u d\Gamma = \int_\Gamma u^* q d\Gamma$$

where Γ is the boundary of the sea-water region, which is largely made up of the surface area of the structure to be protected. The current density, q, *is* the spatial derivative of the potential u. The terms q^* and u^* are known functions of geometry, which are the 'fundamental solutions'. By dividing the boundary Γ into elements, the integrals in the above expression can be evaluated numerically to leave a matrix equation

$$[H]\{u\} = [G]\{q\}$$

where the square matrices H and G are the influence matrices whose coefficients are the integrals of the fundamental solutions to the potential flow problem. The vectors u and q contain the values of voltage and current density, respectively, at the node points of the boundary elements. When polarization is not considered, this can be solved directly by applying fixed voltage or current density conditions, thereby reducing the matrix equation to one with the same number of unknowns as equations. When the non-linear polarization conditions are considered, the matrix equation needs to be solved iteratively.

When the stray current corrosion concept is introduced, it is necessary to add a further set of equations to the matrix system. This results from the most simple concept that for each metallic component in the system, conservation of current applies. A summation of total current over the surface of each 'unit' should come to zero. So in the example shown in figure 1, the summation of current over the boundary elements modeling the ship hull should be zero, and likewise the summation of the current over the elements modeling the piling should also be zero.

This adds an equation to the matrix system for each of these components, in which the terms in the row of the H matrix are all zero and the terms in the row of the G matrix are a representative area associated with each node. If the node is not on the component (e.g. ship, pier, etc.) for which the matrix row is being written, the term in the row of the G matrix is set to zero. The area is needed because the vector q represents not current but current density. Thus the outcome of this equation is that the left hand side (zero) is equal to the sum of the current density multiplied by area terms over the surface of the component.

In this way the system of equations to solve is only marginally larger than that used to solve the system in the absence of a stray current problem.

TEST EXAMPLE

As an example of the application of the BEM to stray current problems, the BEASY boundary element code [6] is used to predict the galvanic corrosion on pipe sections filled with quiescent seawater. The pipes are made up of 3ft and 10 ft lengths of 70-30 copper-nickel and alloy 625. When these two materials are electrically joined in an electrolyte, the electrochemical differences between the two materials cause a current to be set up in the seawater. This is called galvanic corrosion, and involves the initiation of an electrostatic field inside the pipes without need of a direct power source.

The pipe configuration tested was as follows:

305cm length Cu-Ni -- 91.4cm length Cu-Ni -- 305cm length Inconel

The center pipe length was electrically insulated from the outer two lengths, and these outer two lengths were electrically connected to each other. So the example contained two components over which the current should sum to zero. A schematic diagram of the example is given in figure 3.

The pipe was modeled using quadratic boundary elements as shown in figure 4. The electrolyte was divided into three subregions (or "zones") in order to reduce the aspect ratio of each zone for numerical reasons. This division was made at the interfaces naturally provided by the three different pipe sections. The two longer pipes were included in the same group for current summation, and the elements on the short central copper-nickel pipe were included in a group of their own, forcing the total current flowing through that section to sum to zero as shown above. In view of the probable steep potential gradients around the pipe joints, the mesh was refined in that area and graded out to larger elements at the less active areas in the outer portion of the model.

This pipe configuration was tested experimentally, and the results are compared against the boundary element solutions in figure 5. The boundary element results generally follow the trends shown by the experimental results, though there was a difference of around 20% in the potential values seen. In addition, there was also an area of oscillating results in one portion of the longer copper-nickel pipe. This area has been shown in an averaged form in the figure, using a dashed line, as it was clear that the trend of the results followed the general behavior of the experimental results.

The difference between the absolute potential values which was noted in the comparison in figure 5 is being investigated and will be described in a future publication. Cathodic protection analysis is particularly sensitive to a number of variables which define the electrochemical properties of the metal submerged in a particular electrolyte. The authors believe that it is most likely that a better knowledge of the polarization characteristics will lead to an improved correlation with experimental results.

CONCLUSIONS

This research has shown how a simple modification to a standard non-linear cathodic protection analysis package can be made to extend the field of its application to stray current corrosion. By defining element groups over which the current is forced to sum to zero, a large number of independent conducting objects can be modeled in complex stray current corrosion problems.

The research highlights the need to establish the most accurate polarization data available in order to model with confidence the rapidly varying potential fields found in this type of problem. The use of this algorithm in modeling real life situations of ships in dock or pipelines which pass close to each other is of clear benefit to industry and government agencies, and a better understanding of the mechanism of stray current corrosion will lead to large savings in repair and replacement of corroded structures.

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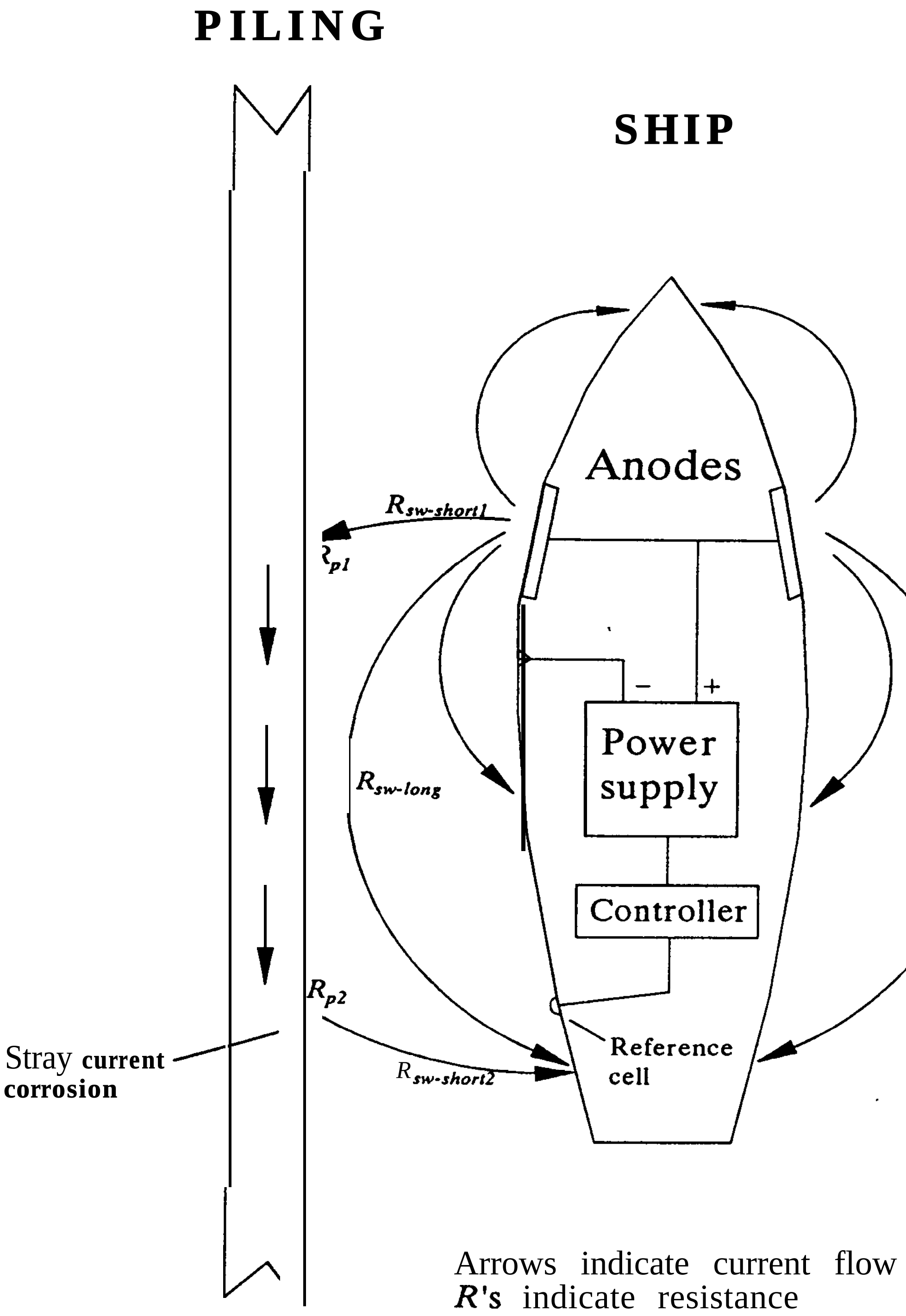

Figure 1. Stray current corrosion of piling near ship

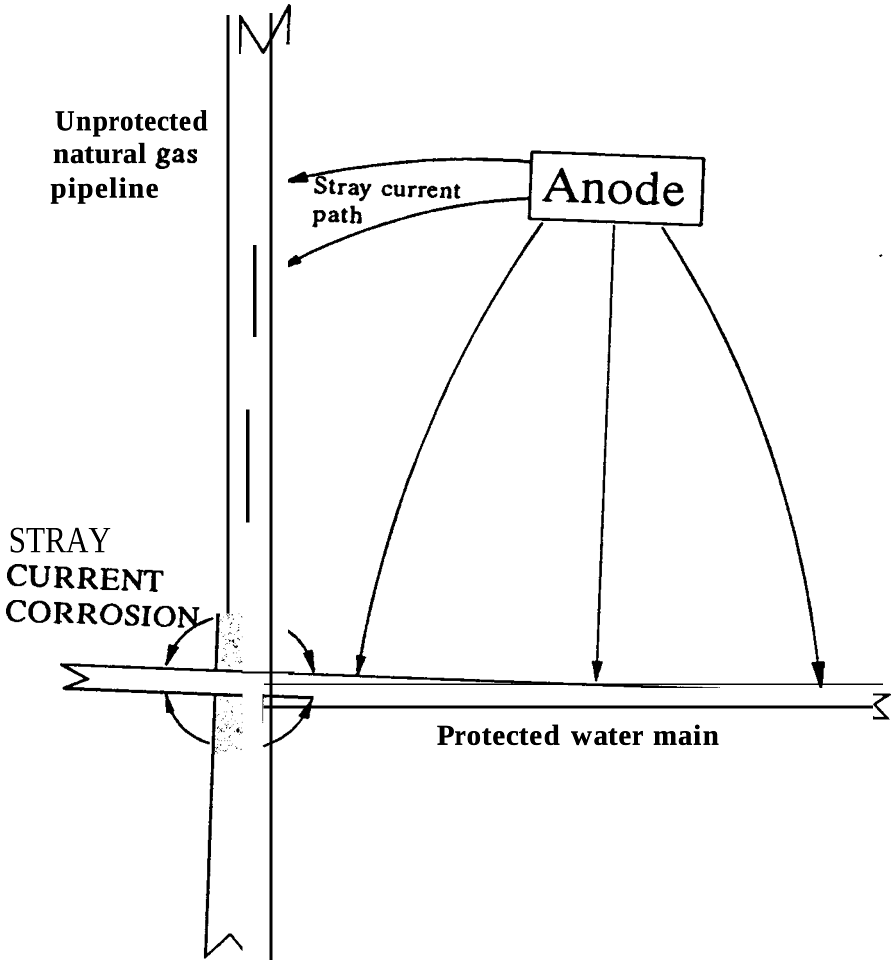

Fig. 2. Stray current corrosion of pipeline example

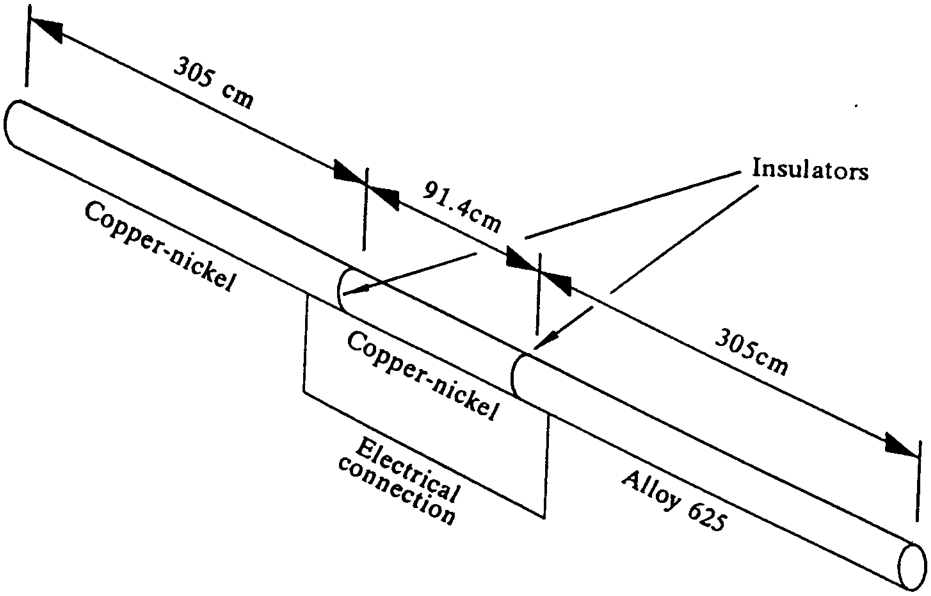

Fig. 3. Layout of example pipe problem

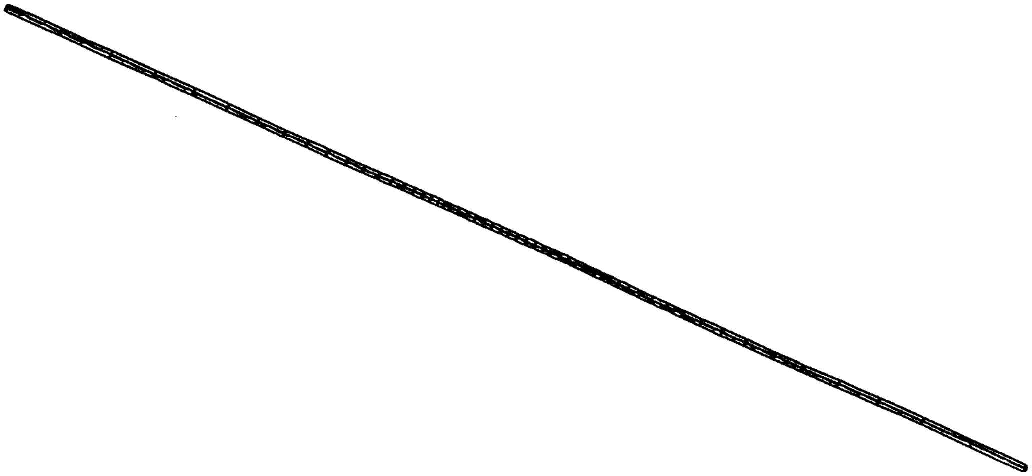

Fig. 4. BEASY model for pipe example

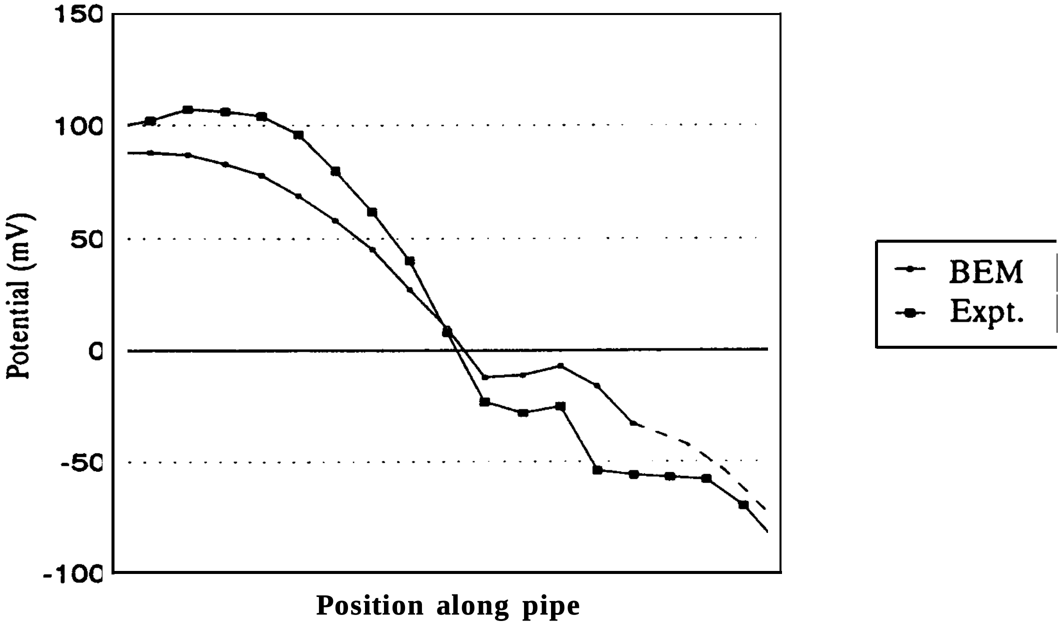

Fig. 5. Comparison of potential results along example pipe