Mathematical Models for Cathodic Protection of an Underground Pipeline with Coating Holidays: Part 2 — Case Studies of Parallel Anode Cathodic Protection Systems

M.E. Orazem, J.M. Esteban,* K.J. Kennelley,** and R.M. Degerstedt***

ABSTRACT

A boundary element mathematical model was used to assess the influence of cathodic protection (CP) design parameters on performance of a parallel-ribbon sacrificial anode CP system for coated pipelines. The model accounted for current and potential distributions associated with discrete holidays on coated pipelines that expose bare steel to the environment. Case studies, based on the CP system used to provide protection to the Trans-Alaska pipeline, were selected to show conditions under which a given CP system will and will not protect a pipe. In the cases studied, Mg ribbons provided adequate protection in 50 kΩ-cm soil, but almost no additional protection was achieved by retrofitting Mg anodes to a CP system using Zn ribbons if the Zn ribbons remained connected to the pipe. The model also was used to show the lack of sensitivity of aboveground on-potential surveys to localized corrosion on the buried pipe.

KEY WORDS: anodes, boundary elements, cathodic protection, coatings, films and film formation, holidays, modeling, pipelines

INTRODUCTION

Two- (2-D) and three-dimensional (3-D) mathematical models were developed for cathodic protection (CP) of underground pipelines by parallel-ribbon anodes.1,3 These computer models calculate the current and potential distributions at the pipeline and anodes for specific CP design parameters that include the pipeline-anode configuration, coating thickness and resistivity, holiday size and location, anode types and number, soil resistivity, and polarization data for bare steel in the given environment. The 2-D model provides results for "slit" holidays on a coated pipeline. This geometry describes a worst-case scenario because the holiday extends over the entire length of the pipeline. The 3-D model offers a more realistic view because circular or rectangular holidays of various sizes can be simulated on a coated pipeline.

The objective of the present work was to demonstrate, through case studies, the utility of using mathematical models to assess performance of existing or proposed CP systems.

MATHEMATICAL MODEL

Method of Solution

Prediction of the current and potential distribution associated with a CP system requires the solution of Laplace's equation \( \nabla^2 \phi = 0 \). This equation can be written in rectangular coordinates as:

\[
\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0
\]  

This is the governing equation for soils or solutions of uniform resistivity in which concentration gradi-
TABLE 1
CP Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline</td>
<td>121.92-cm (48-in.)-OD FBE-coated pipeline, 162.88-cm (6-ft) burial depth.</td>
</tr>
</tbody>
</table>
| Coating characteristics | FBE coating thickness = 0.5842 mm (23 mils)  
                          | FBE coating resistivity = 5 × 10^{-12} Ω-cm                                 |
| Zn anodes           | Located below the pipeline, open-circuit potential = -0.95 V_{Cu-CuSO4}     |
| Mg anodes           | Located above the pipeline, open-circuit potential = -1.70 V_{Cu-CuSO4}     |
| Polarization curve  | See Figure 1, V_{an} = -560 mV_{Cu-CuSO4}                                    |
| Thaw bulb           | 2-D case: 3.66 m square (12 ft by 12 ft, see also Reference 2)             |
|                     | 3-D case: 3.66 m (12 ft) from pipe OD                                        |
| Holiday size        | 2-D case: 1.27-cm (1/2-in.) "slit" holiday                                 |
|                     | 3-D case: 5.715-cm (2 1/4-in.)-diam circular holiday                         |
| Soil resistivity    | 5, 20, 50, and 100 kΩ-cm                                                    |

Model Parameters

Model parameters used for the simulations are listed in Table 1. They included the pipeline diameter and burial depth, anode types and number, pipeline-anode configuration, coating thickness and resistivity, holiday size and location, soil resistivity, polarization data for bare steel in a specific soil environment, and the radius of the thaw bulb (or melt zone) that would form around a pipeline buried in permafrost (e.g., the Trans-Alaska Pipeline System [TAPS]).

Automated mesh generators (or gridmakers) were developed to allow the user to specify the outer diameter and location (or depth) of the buried pipeline and the position of the parallel-ribbon anodes relative to the pipeline. The anode type (e.g., Mg, Zn, or high-performance MgI) dictated the value of potential used in the model calculations. The outer edge of the domain was delimited by an insulator boundary that represented, for example, the thaw bulb (or melt zone) around the pipeline in a permafrost.

Coating characteristics were specified by coating thickness and resistivity. A coating defect for the 2-D model was defined to be a portion of bare metal on the coated circumference of the pipe representing a "slit" holiday running the entire length of the pipeline. The holiday for the 3-D model could be circular or rectangular in shape and was located at the midpoint of the coated pipeline section. The 3-D gridmaker allowed the user to specify the length of a pipeline section to be discretized.

The polarization curve for bare steel in a given environment is an important parameter of the model because it determines the current and potential distribution at the holiday surface. The current density was given by \( i(\Psi) = 10^\frac{\Psi - E_{Fe^{2+}}}{\beta_{Fe^{2+}}} - \frac{1}{i_{lim,O_2}} + 10^\frac{\Psi - E_{O_2}}{\beta_{O_2}} - 10^\frac{\Psi - E_{H_2}}{\beta_{H_2}} \) (2)

where \( \Psi \) is the potential of the pipe relative to a reference electrode located in the electrolyte adjacent to the pipe surface. The first term represents the corrosion reaction, the second term represents oxygen reduction, and the third term represents hydrogen evolution. The parameters \( E_{Fe^{2+}}, E_{O_2}, \) and \( E_{H_2} \) are "effective" equilibrium potentials that include the influence of the exchange current density \( (i_0) \). The parameters \( \beta_{Fe^{2+}}, \beta_{O_2}, \) and \( \beta_{H_2} \) are the Tafel slopes for the respective reactions, and \( i_{lim,O_2} \) is the
TABLE 2
2–D Model Results, 1.27-cm (1/2-in.) Slit Holiday

<table>
<thead>
<tr>
<th>Case</th>
<th>Resistivity (Ω-cm)</th>
<th>$I_{M1}$ (mA)</th>
<th>$I_{M2}$ mA</th>
<th>$I_{M3}$ mA</th>
<th>PD at Holiday(\textsuperscript{A}) (V\textsubscript{Cu-CuSO\textsubscript{4}})</th>
<th>CP Criterion(\textsuperscript{B}) (\textsuperscript{E}) –850 mV</th>
<th>100 mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Zn anodes</td>
<td>5,000</td>
<td>-0.744</td>
<td>0.744</td>
<td>—</td>
<td>-0.874 to -0.882</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td>-0.543</td>
<td>0.543</td>
<td>—</td>
<td>-0.727 to -0.751</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>50,000</td>
<td>-0.285</td>
<td>0.285</td>
<td>—</td>
<td>-0.661 to -0.689</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td>-0.157</td>
<td>0.157</td>
<td>—</td>
<td>-0.632 to -0.658</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>2: Zn anodes and Mg anodes</td>
<td>5,000</td>
<td>-1.345</td>
<td>-11.860</td>
<td>13.205</td>
<td>-0.996 to -1.000</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td>-0.697</td>
<td>-2.685</td>
<td>3.382</td>
<td>-0.842 to -0.872</td>
<td>Marginal</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>50,000</td>
<td>-0.435</td>
<td>-0.952</td>
<td>1.387</td>
<td>-0.689 to -0.731</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td>-0.240</td>
<td>-0.459</td>
<td>0.689</td>
<td>-0.648 to -0.687</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>3: Mg anodes (Zn disconnected)</td>
<td>5,000</td>
<td>-4.50</td>
<td>—</td>
<td>4.50</td>
<td>-1.100 to -1.140</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td>-1.352</td>
<td>—</td>
<td>1.352</td>
<td>-0.977 to -1.027</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>50,000</td>
<td>-0.664</td>
<td>—</td>
<td>0.664</td>
<td>-0.807 to -0.878</td>
<td>Marginal</td>
<td>Yes</td>
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<td></td>
<td>100,000</td>
<td>-0.385</td>
<td>—</td>
<td>0.385</td>
<td>-0.675 to -0.739</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

(\textsuperscript{A}) PD = potential distribution.  
(\textsuperscript{B}) CP criterion: –850 mV\textsubscript{Cu-CuSO\textsubscript{4}} or 100-mV polarization with respect to corrosion potential of –560 mV\textsubscript{Cu-CuSO\textsubscript{4}}.

TABLE 3
2–D Model Results, 5.715-cm (2 1/4-in.) Diameter Circular Holiday, 2,4384-m (8.0-ft) Pipeline Section

<table>
<thead>
<tr>
<th>Case</th>
<th>Resistivity (Ω-cm)</th>
<th>$I_{M1}$ (mA)</th>
<th>$I_{M2}$ (mA)</th>
<th>$I_{M3}$ (mA)</th>
<th>PD at Holiday (V\textsubscript{Cu-CuSO\textsubscript{4}})</th>
<th>CP Criterion (\textsuperscript{E}) –850 mV</th>
<th>100 mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Zn anodes</td>
<td>5,000</td>
<td>-0.1514</td>
<td>0.1514</td>
<td>—</td>
<td>-0.870 to -0.894</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td>-0.1124</td>
<td>0.1124</td>
<td>—</td>
<td>-0.718 to -0.783</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>50,000</td>
<td>-0.0624</td>
<td>0.0624</td>
<td>—</td>
<td>-0.654 to -0.707</td>
<td>No</td>
<td>Marginal</td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td>-0.0350</td>
<td>0.0350</td>
<td>—</td>
<td>-0.627 to -0.671</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>2: Zn anodes and Mg anodes</td>
<td>5,000</td>
<td>-0.3074</td>
<td>-35.96</td>
<td>36.27</td>
<td>-0.988 to -1.029</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td>-0.1498</td>
<td>-8.938</td>
<td>9.087</td>
<td>-0.837 to -0.921</td>
<td>Marginal</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>50,000</td>
<td>-0.956</td>
<td>-3.548</td>
<td>3.644</td>
<td>-0.682 to -0.781</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td>-0.0547</td>
<td>-1.769</td>
<td>1.824</td>
<td>-0.644 to -0.709</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>3: Mg anodes (Zn disconnected)</td>
<td>5,000</td>
<td>-1.256</td>
<td>—</td>
<td>1.256</td>
<td>-1.105 to -1.184</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>20,000</td>
<td>-0.3754</td>
<td>—</td>
<td>0.3754</td>
<td>-0.984 to -1.085</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>50,000</td>
<td>-0.1753</td>
<td>—</td>
<td>0.1753</td>
<td>-0.835 to -0.996</td>
<td>Marginal</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td>-0.1050</td>
<td>—</td>
<td>0.1050</td>
<td>-0.683 to -0.867</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

mass-transfer limited current density for oxygen reduction.

CASE STUDIES

Computer simulation can assist the corrosion engineer in studying the influence of design parameters on performance of proposed CP systems. Two issues were addressed in this work. The first was a hypothetical situation where improvements were proposed to an existing inadequate CP design. The second was the extent to which potential readings made above ground were sensitive to underprotected holidays on the underside or top of the pipe.

Remedial CP Design

The system under consideration was similar to the CP system installed on TAPS. Continuous Zn anodes were installed on TAPS because impressed-current CP systems could not deliver uniform current distribution over the long distances between available power supplies. Distribution of CP current also was hindered by the presence of permafrost and discontinuous permafrost, which can increase soil...
resistivity and create localized areas of over- and underprotection. To overcome the distribution problem, two Zn ribbon anodes were placed in the bottom of the pipeline ditch and connected directly to the pipe at 500-ft to 1,000-ft (150-m to 300-m) intervals. The pipeline, being warm, had a thaw bulb which surrounded the pipe and provided a more uniform and lower resistance environment for the Zn anodes than the frozen bulk soil outside the thaw bulb. Direct connection of the Zn ribbons to the pipe was used to minimize connection failures at test stations caused by avalanches, animals, maintenance equipment, and vandals. In addition, the presence of telluric currents was a serious concern to original designers of the CP system. It was hoped that the Zn anodes would help to absorb and discharge these currents safely, thus reducing the risk of damage to the pipeline. The Zn ribbon has performed these functions for 20 y and continues to be the back bone of the TAPS CP system. Additional Mg anodes and impressed-current systems have been added over the years to supplement the Zn ribbons where needed.

The case studies described were motivated by a desire to investigate predicted performance of the CP system in the presence of discrete coating holidays that expose bare steel.

Three cases were considered:

Case 1 — The "existing" pipeline-anode configuration has been illustrated previously. Design parameters are given in Table 1. A 122-cm (48-in.) outer-diameter (OD), fusion-bonded epoxy (FBE) coated pipeline was buried 183 cm (6 ft) below ground level. Two parallel-ribbon Zn anodes were located 1.9 m (4 ft) below the pipe center and 0.9 m (3 ft) on either side. (The geometry shown in Figure 2 of Esteban, et al., represented a quadrant of a 3-D cell geometry.) The holiday was located at the bottom of the pipeline, between the Zn ribbon anodes. A 1.27-cm (1/2-in.) slit holiday was used for the 2-D cases, while a circular holiday 5.715 cm (2 1/4 in.) in diameter was used for the 3-D cases.

Case 2 — The second case represented a remedial CP design where two Mg anodes were overlaid 1.9 m (4 ft) above the pipe center and 0.9 m (3 ft) on either side. The Zn anodes remained connected to the pipeline.

Case 3 — The third case referred to the remedial Mg anode CP system in Case 2, but with the Zn anodes disconnected.

Polarization curves were obtained from measurements of current and instant-off potentials. The polarization curve used is illustrated in Figure 1, where the corrosion potential \(E_{corr}\) was \(-0.560\) V vs a copper-copper sulfate (Cu-CuSO\(_4\)) electrode. The potential of the solution adjacent to the Zn anode was set to \(-0.95\) V\(_{Cu-CuSO_4}\) while the solution potential at the Mg anode was \(-1.70\) V\(_{Cu-CuSO_4}\). The FBE coating thickness was 0.5842 \(\mu\)m (23 mils) with a resistivity of 5 x 10\(^{12}\) \(\Omega\)-cm. Calculations are presented for different soil resistivities.

RESULTS AND DISCUSSION

Results of the 2-D and 3-D models for the studies described are listed in Tables 2 and 3, where \(I_{pipe}\), \(I_{Zn}\), and \(I_{Mg}\) represent the total current associated with the pipe, the Zn anode, and the Mg anode, respectively. For all cases, the protection current delivered by the anodes to the pipeline decreased as the medium (i.e., the soil or water) became more resistive. The total current and the potential distribution at the holiday were tabulated as a function of pipeline-anode configuration and soil resistivity. The potential and current density distribution at the holiday was nonuniform, as shown in Figure 2 for the case of Mg anodes in 20,000 \(\Omega\)-cm soil (Case 3, 2-D geometry). Most of the protection current flowed to the holiday, as illustrated in Figures 2 and 3 (Case 3 in 5,000 \(\Omega\)-cm soil, 3-D geometry), where the current density at the holiday was 6 to 7 orders of magnitude greater than at the coated portion of the pipeline. A series of calculated on-potential surveys (i.e., with the anodes connected to the pipeline) illustrated the potential distribution in the medium that could be compared directly to field measurements (Figures 4 through 11).

2-D Model

Calculated on-potential contours are presented for Case 1 in Figure 4, which shows a 2-D cross section of the pipe-anode systems. The pipe was a cylinder coated everywhere except at the defect. The defect was a 1.27-cm (1/2-in.) strip extending the length of the pipe. The anodes were Zn ribbons parallel to and extending the length of the plane. The potential was most cathodic at the Zn anodes (\(-0.95\) V\(_{Cu-CuSO_4}\)) and reached a value of \(-0.66\) V\(_{Cu-CuSO_4}\).
FIGURE 2. (a) Pipe potential and (b) current density distribution calculated using the 2-D model for Case 3 in 20,000 Ω-cm resistivity soil.

FIGURE 3. (a) Pipe potential and (b) current density distribution calculated using the 3-D model for a 5.715-cm (2 1/4-in.) circular holiday in 5,000 Ω-cm resistivity soil (pipe at z = -0.00046 ft).

at the bare holiday surface. Current lines, which were perpendicular to the equipotential lines, converged at the holiday.

Results from the 2-D model showed use of the Zn anodes alone (Case 1) did not achieve the -850 mV_{Cu_{2}SO_{4}} CP criterion for protection of the 1/2-in. slit holiday except in the soil of 5,000 Ω-cm resistivity (Table 2). However, the potential at the holiday was shifted by at least 100 mV from the corrosion potential of bare steel (-560 mV_{Cu_{2}SO_{4}} for soil resistivities < 50,000 Ω-cm. The current flow from the Zn anodes to the slit holiday at the bottom of the pipeline in 50,000 Ω-cm resistivity soil could be inferred from the potential survey in Figure 4.

As the -850 mV_{Cu_{2}SO_{4}} CP criterion was not met in 50,000 Ω-cm soils, addition of supplemental Mg anodes was considered (Case 2). As shown in Table 2, only modest increases in protection current to the
pipeline were achieved for this remedial CP system. In 5,000 Ω-cm and 20,000 Ω-cm soils, the calculated potentials at the holiday were shifted to significantly more negative potentials than obtained in Case 1. The −850 mV\textsubscript{Cu-CuSO\textsubscript{4}} CP criterion was not met in 50,000 Ω-cm soils. The reason for this lack of protection was that a significant portion of the current flowing from the Mg anodes provided CP to the Zn ribbons (from 65% in 100 kΩ-cm soil to 90% in 5 kΩ-cm soil). The current on the Zn ribbon was cathodic; thus, no CP was provided by the Zn. Interaction of the existing Zn ribbons with the new Mg ribbon overlay was evident from the calculated on-potential survey in 50 kΩ-cm soil (Figure 5).

Parasitic consumption of the Mg ribbon anodes could be avoided by disconnecting the Zn ribbons from the CP system (Case 3). The Zn ribbons were disconnected in the computer program by removing the Zn surfaces from the cell geometry. As shown in Table 2, there was a significant shift to more negative potentials for all soil resistivities. In contrast to Case 2, where a significant portion of the current provided by the Mg anode passed to the Zn, all the current from the Mg anodes was used to protect the pipeline. The calculated potential survey for the Mg anode CP system is shown in Figure 6 for 50,000 Ω-cm resistivity soil. Even through the anodes were placed at the opposite side of the pipe from the holiday, the −850 mV\textsubscript{Cu-CuSO\textsubscript{4}} CP criterion was met approximately in the 50,000 Ω-cm resistivity soil.

3-D Model

Results of the 3-D model presented were for a 2.44-m (8-ft) pipeline section with a discrete circular holiday 5.72 cm (2 1/4 in.) in diameter. This pipe length was typically used for direct comparison to full-scale experimental measurements obtained in a test pit filled with water.\textsuperscript{1} Pipe length sections ranging from 12.2 m to 30.5 m (40 ft to 100 ft) were used for comparison to the CP system at the Alesksa Nordale test site.\textsuperscript{3} General trends observed for the 2-D geometry were similar to predicted behavior of the CP systems using a 3-D cell geometry.

The calculated potential surveys in Figures 7 through 10 represent two views of the potential distribution within the soil surrounding the buried pipe. The (a) panels of these figures (over-the-line potential survey) correspond to a cross section extending the length of the pipe. To reduce computational time and memory requirements, advantage was taken of symmetry. The holiday was located at the right side of the over-the-line potential survey, and a reflection of the mapping could be used to show the complete potential distribution along the pipe extending on both sides of the holiday. The over-the-line potential survey did not show location of the anodes because the anodes were off-center to the pipe. The (b) panels of these figures are the radial potential surveys which provided the potential distribution extending in a radial direction from the pipe at \( z = 0 \). Location of the anodes is evident. Figure 7 shows current converged at the holiday and was contributed by the entire length of the Zn ribbon.

As shown in Table 3, the Zn anodes alone (Case 1) did not achieve the −850 mV\textsubscript{Cu-CuSO\textsubscript{4}} CP criterion for protection of the circular holiday except in 5,000 Ω-cm soil. The less stringent 100 mV polarization criterion was met for soil resistivities < 50,000 Ω-cm. The calculated radial potential survey for the Zn anode CP system in 50,000 Ω-cm soil (Figure 7) showed...
most of the potential drop occurred in the vicinity of the holiday.

The failure to meet the -850 mV\textsubscript{Cu-CuSO\textsubscript{4}} CP criterion in 50,000 \(\Omega\)-cm soils motivated addition of supplemental Mg anodes (Case 2). As for the 2-D calculations, only modest increases in protection current to the pipeline were achieved for this remedial CP system if the Zn ribbons were left connected to the pipeline (Table 3). A small circular holiday offered more resistance to current flow than a slit holiday running the length of the pipeline. Consequently, the 3-D model results for Case 2 showed that > 95% of the current supplied by the Mg anodes was used to cathodically protect the Zn ribbons for all soil resistivities. The current flow in 50,000 \(\Omega\)-cm soil could be inferred from the calculated over-the-line and radial potential surveys in Figure 8.

Results obtained by disconnecting the Zn ribbons were in good agreement with those obtained for the 2-D calculations. As shown in Table 3, there was a significant shift to more negative potentials for all soil resistivities. The -850 mV\textsubscript{Cu-CuSO\textsubscript{4}} CP criterion was met approximately in the 50,000 \(\Omega\)-cm resistivity soil. The calculated over-the-line and radial potential surveys for the Mg anode CP system in 50,000 \(\Omega\)-cm soil are given in Figure 9. The current lines converged at the holiday where the most significant potential drop occurred.

**Aboveground Surveys of On-Potential**

The mapping of calculated on-potentials in Figures 7 through 9 showed that, although the potential at the holiday was considerably more positive than

-0.6 V\textsubscript{Cu-CuSO\textsubscript{4}}, no discernible corresponding shift in on-potentials was seen at the ground level (top of the respective figures). The potential drop was localized at the holiday where current lines converged, thus, a holiday located at the underside of the pipe did not shift the potential at the ground level. Changes in the ground level potential could be seen when the holiday was located at the top of pipe. Results presented in Figure 10 were obtained for 0.305 m by 0.305 m (12 in. by 12 in.) holiday in 100,000 \(\Omega\)-cm water. The

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**FIGURE 6.** Calculated potential distribution for Case 3 using a 2-D model: parallel ribbon Mg anodes with Zn anodes disconnected, 50 k\(\Omega\)-cm soil, 1.27-cm (1/2-in.) slit holiday.

**FIGURE 7.** Calculated potential distribution for Case 1 using a 3-D model: parallel ribbon Zn anodes, 50 k\(\Omega\)-cm soil, 5.715-cm (2 1/4-in.) circular holiday: (a) over-the-line potential survey and (b) radial potential survey.
isopotential lines in this case extended to the ground level. A dip in potential was observed above the holiday (Figure 11), but this shift in potential seen at ground level was very small compared to the variation in potential calculated for the surface of the pipe (Figure 12).

**CONCLUSIONS**

- Computer modeling provides the corrosion engineer with a tool to study the influence of design parameters on performance of CP systems.
- The case studies described demonstrated the util-
ity of the boundary element technique to calculate current density and potential distribution in the presence of discrete holidays on a coated pipeline.

- Trends of the model calculations can be used to optimize the pipeline-anode configuration for a given set of operating parameters.
- On-potential surveys are visual aids that identify the current flow around the protected pipeline and can be compared directly to field potential measurements.
- The computer programs require accurate input parameters to provide reasonable predictions, especially for the polarization data of bare steel in the specific environment.

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REFERENCES


FIGURE 10. Calculated potential distribution for a 0.305 m by 0.305 m (12 in. by 12 in.) holiday in 100,000 Ω-cm water: (a) over-the-line potential survey and (b) radial potential survey.
23. R.S. Munn, MP 21, 8 (1982); p. 29-36.