Computer Simulation as an aid to CP System Design and Interference Prediction

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Abstract

Cathodic protection (CP) systems are commonly designed by estimating the overall current demand and then developing an anode configuration sufficient to protect the structure. To a large extent the performance of a CP system is dependent on the skill and experience of the corrosion specialist. As the underground infrastructure becomes more complex these traditional approaches may become less reliable. In an increasingly complex underground infrastructure, stray currents from other sources (such as parallel or crossing pipelines, industrial plants, or electric rail transit facilities) can come into contact with the underground steel structures. These stray currents not only reduce the ability to inhibit corrosion, but in some cases, reverse the CP process and accelerate corrosion in sections of the structure.

Given these factors it becomes imperative that corrosion engineers are able to predict the interaction of underground electrical fields as part of the design process. The difficulty in making reliable estimates for cases where there is a complex interaction of underground electric fields can be overcome by using corrosion simulation software as a design tool. Not only can corrosion simulation software help with understanding complex corrosion behavior but it can also provide a rapid and economic assessment of CP system designs.

In this paper the background and capabilities of computer simulation is described and applications presented of pipeline CP simulation, interference prediction and optimisation.

Introduction

Cathodic protection (CP) systems are used extensively to prevent structures from corroding, especially when failure of the structure will have serious consequences, such as loss of life and/or injury and damage to property and/or environments. When correctly designed and operated these CP systems significantly reduce the rate of corrosion and thereby extend the useful life expectancy of the structure.

Nevertheless, the use of this technique can interfere with other structures. CP interference can occur when neighboring steel structures (i.e. foreign structures), are located within the electric fields of a CP system For example, when cathodically protected pipelines cross over other pipelines. Ships dock at cathodically protected jetties or pipelines approach cathodically protected tanks etc. In these situations the CP systems can accelerate the rate of corrosion on the foreign structure (Figure 1)

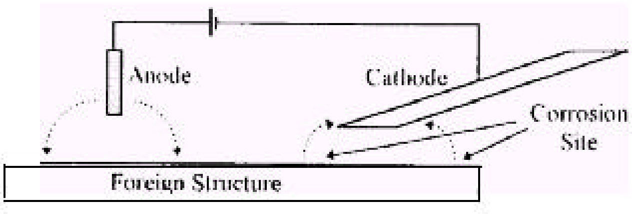

Figure 1. Inducing corrosion on foreign structures by interference

When designing or operating a CP system, it is important to ensure that foreign structures are not damaged by the system. In the past, predicting CP interference before a CP system was installed was difficult. Mitigating unwanted CP interference was a task of adopting very conservative designs combined with extensive post-commissioning programmes of measuring potential shifts on foreign structures. Moreover, defining a criterion for CP interference in terms of a potential shift is fraught with danger. In some cases a particular potential shift may pose a serious threat while in other circumstances the same shift may be insignificant.

It is notable that the assessment of CP interference is often left to the professional judgement of the CP engineer. Clearly, such subjective assessment is unsatisfactory. This article suggests a more scientific approach to the problem.

Ideally, the best approach to assessing CP interference is to determine the change in current density on the foreign structure induced by the CP system Current density is a more reliable parameter with which to assess CP interference because it is directly proportional to metal loss. However, in the past, the lack of a technique for determining how the CP affects the distribution of current on the foreign structure has prevented this approach from being adopted.

Determining the response of the foreign structure to the CP system is not trivial because it is a function of three things:

- The location of the foreign structure with respect to electric fields generated by the CP system
- The magnitude of the electric fields
- The electrochemical response of the foreign structure to the interference.

Until the development of high-speed computers and new computer modelling techniques this has been an insurmountable problem. However, the development of boundary element methods has finally provided the necessary tools to accomplish these tasks.

In this study, the BEASY Corrosion and CP software was used to predict levels of CP interference on buried structures. This information was used in an effort to optimise the CP design and thereby minimise CP interference.

Predicting Pipeline Protection

The protection of pipelines from external corrosion is commonly accomplished by the combination of pipeline coatings with cathodic protection, to protect those portions of the pipeline that are inadequately coated or where the coating contains defects. Defects in pipeline coatings that expose bare steel are termed holidays.

Conventional anode resistance formulas that ignore the current and potential distribution on the pipes are inadequate for the modelling of pipelines with holidays. Current and potential distribution must also be considered when modelling multiple pipelines. Factors such as variations in coating quality and stray current interference have an effect on the quality of the cathodic protection system.

Another major factor in the design and maintenance of the underground infrastructure (e.g. pipelines, storage tanks, tunnels etc) is the electrical interference (electrical pollution) from power lines, railways and other electrical sources. Traditional resistance formulas are inadequate in modelling these complex interactions.

Modelling the Underground Infrastructure

In this application the performance of the cathodic |protection systems protecting two pipelines placed in a right-of-way with 0.6m of separation is investigated. One of the pipes leaves the right of way at a 45° angle halfway along the length of the pipes modelled. Each pipe had an outer diameter of 1.8m that included a coating thickness of 6.0×10^{-4}m. The depth at which the pipes were buried was 3.0m.

A series of remote anode groundbeds were allocated to each separate pipe CP system and staggered at intervals along the length of the pipes. The anodes had a length of 18.3m, a diameter of 0.3m and were modelled as being 79.2m below the surface of the soil. This distance was sufficiently far for the anodes to be considered remote.

The area of interest in the analysis was near the bend in the 45° pipe. To model the current and potential distributions around the circumference of the two pipes, 3-dimensional boundary elements were used to discretise the surface of the two pipes for a length of 13.7m on either side of the 45° bend, as can be seen in

Figure 3. Beyond this region, BEASY ‘tube’ elements were used which assume a uniform radial current density distribution. Tube type elements are adequate for situations in which the average distribution of potential and current density along the pipeline is sufficient. (I.e. the variation around the circumference of the pipe is not required) The potential levels and current demand can be used for design purposes but the impact of very localised defects cannot be represented with this type of element. The pipes were enclosed in a far field boundary modelling zero normal flux density as is shown in Figure 2 below.

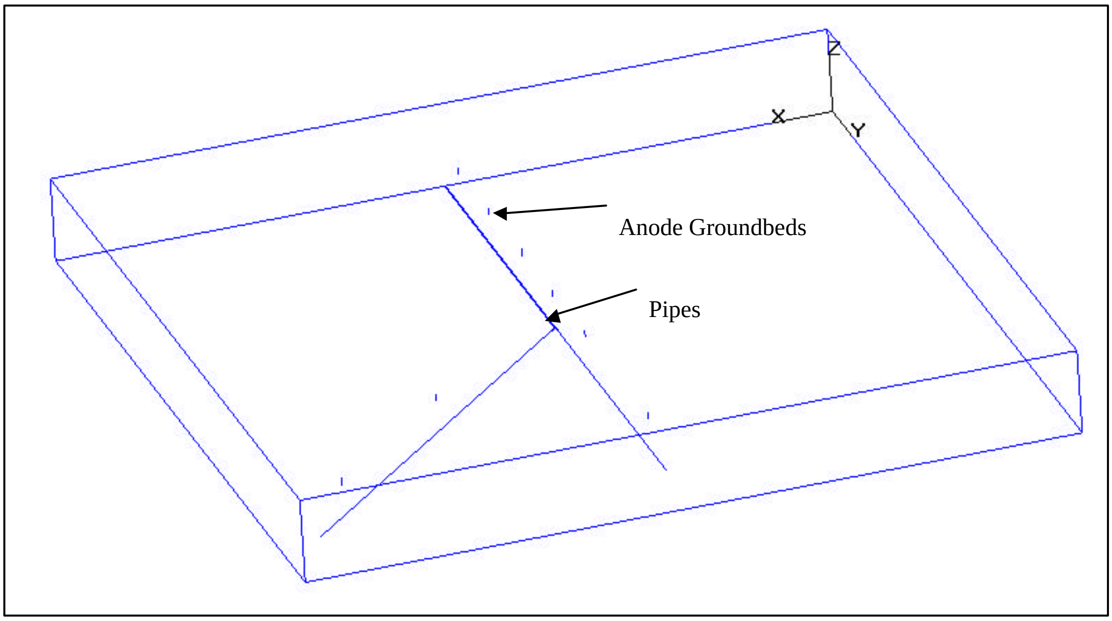

Figure 2. BEASY model showing geometry surfaces of the far field boundary, the anodes and the two pipelines.

Coated Pipes

Pipes with coated surfaces can be modelled in several ways. The coating can be considered to be a perfect insulator, a highly resistive barrier to current or a selective barrier to ionic transport, allowing water, dissolved gases and ionic species to permeate through to the pipe. It was assumed in the analysis that the coating is a highly resistive barrier, with a resistivity of 5×10^{10} Ωm. This effectively modelled the coating as an electrical resistor in series with the IR drop through the soil. The current delivered to the coated portion of the pipe can be expressed by

$$i_n = \frac{f - f_{corrosion}}{rd} \qquad (1)$$

Where f is the potential on the surface of the coating, $f_{corrosion}$ is the corrosion potential of the metal under the coating, r is the electrical resistivity of the coating measured in air, and d is the thickness of the coating.

For the first case that was modelled, the straight section of pipe had an undamaged new coating along its entire length. The bent pipe was modelled as having an aged coating along the section parallel to the straight pipe and a new coating after the bend. At this stage, a holiday was not modelled. This case was firstly modelled with a soil resistivity of $1\times10^{3}\Omega$m and then repeated with a value of $5\times10^{2}\Omega$m.

The second case was identical to the first except that a holiday was introduced in the straight pipe. The holiday was at the halfway point of the straight pipe, facing the bend in the adjacent pipe. The boundary condition for the holiday took into account corrosion through polarisation data for steel. In each of the first two cases, the two pipelines were modelled as having separate CP systems. Therefore, a third case was modelled that was identical to the second case, except that the pipes were assumed to be electrically connected. The value of soil resistivity that was used was $1\times10^{3}\Omega$m.

Anode Groundbeds

CP systems use two types of anodes to provide the protective current. Protection using sacrificial anodes involves electrically connecting a metal anode to the pipe that has a corrosion potential that is anodic to that of the steel. Sacrificial anodes are commonly made from magnesium, zinc and aluminium. The use of a non-reactive anode connected to a power supply for the driving voltage is known as an impressed current CP system, and it is this system that has been used in the following analysis. The anodes were impressed current ground beds and modelled a potential of 15V set by a rectifier.

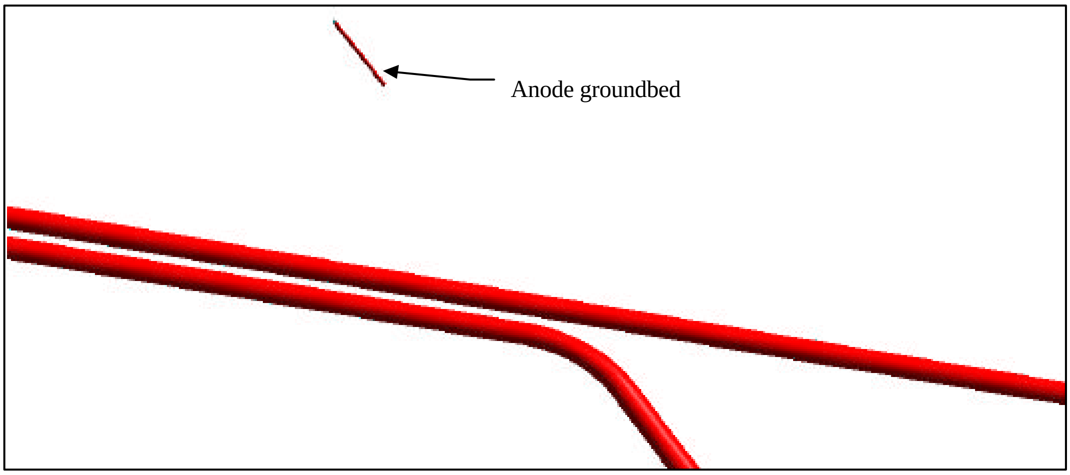

Figure 3. Multiple pipelines model showing remote anode groundbed.

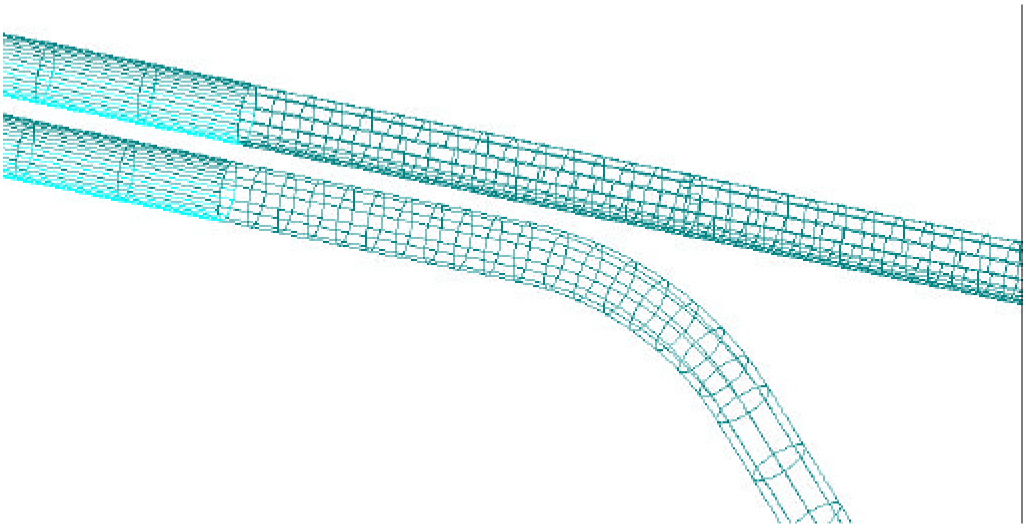

Figure 4. Detailed view of piping mesh showing tube elements (on left) and surface elements.

Case 1

The contour plot seen below in Figure 5 shows the calculated potential distribution on the two pipelines with varying coating quality. The contour plot is of the results with the higher value of soil resistivity. The effect that the bent pipe has on the straight pipe in terms of potential distribution has been plotted below in Figure 6 (high soil resistivity) and Figure 7 (low soil resistivity). The two plots show the results at a location adjacent to the aged coating and at a location away from the aged coating. The aged coating affects the potential distribution around the pipe, whereas in areas away from the aged coating, the potential distribution is relatively uniform around the circumference of the pipe.

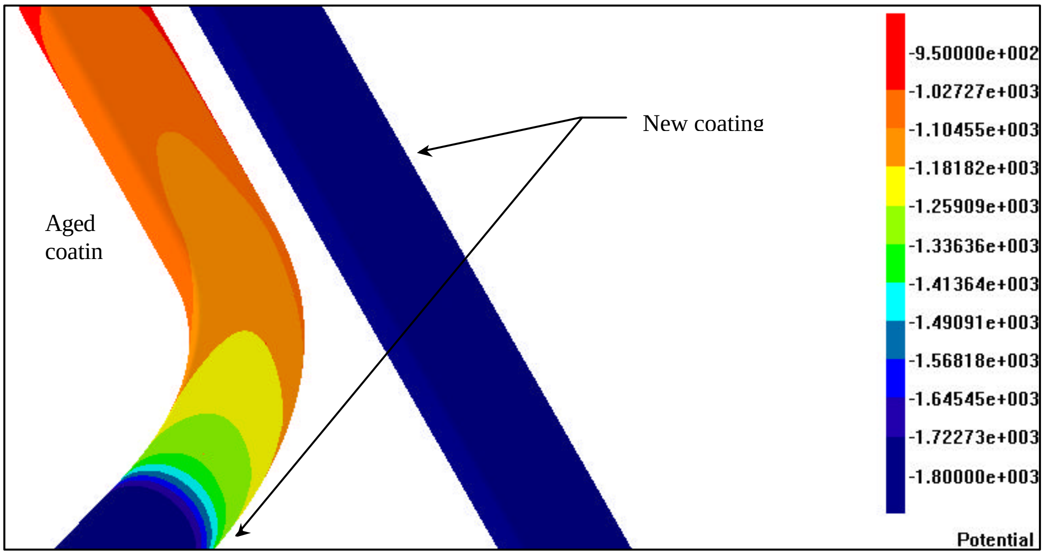

Figure 5. Potential distribution for two pipes with varying coating quality.

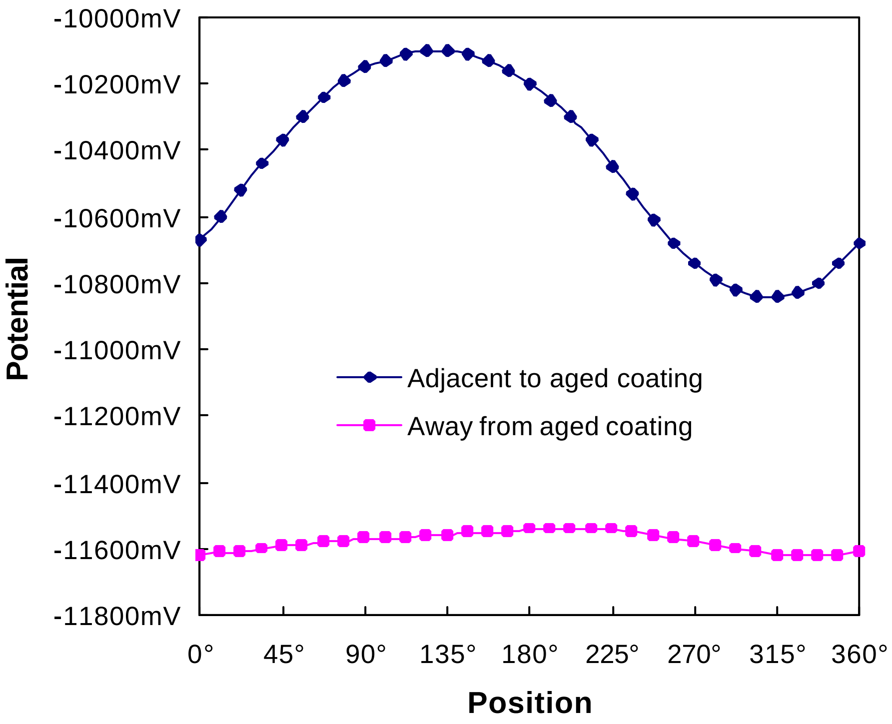

Figure 6. Potential distributions at two locations on the straight pipeline (soil resistivity 1´10^{3}Wm).

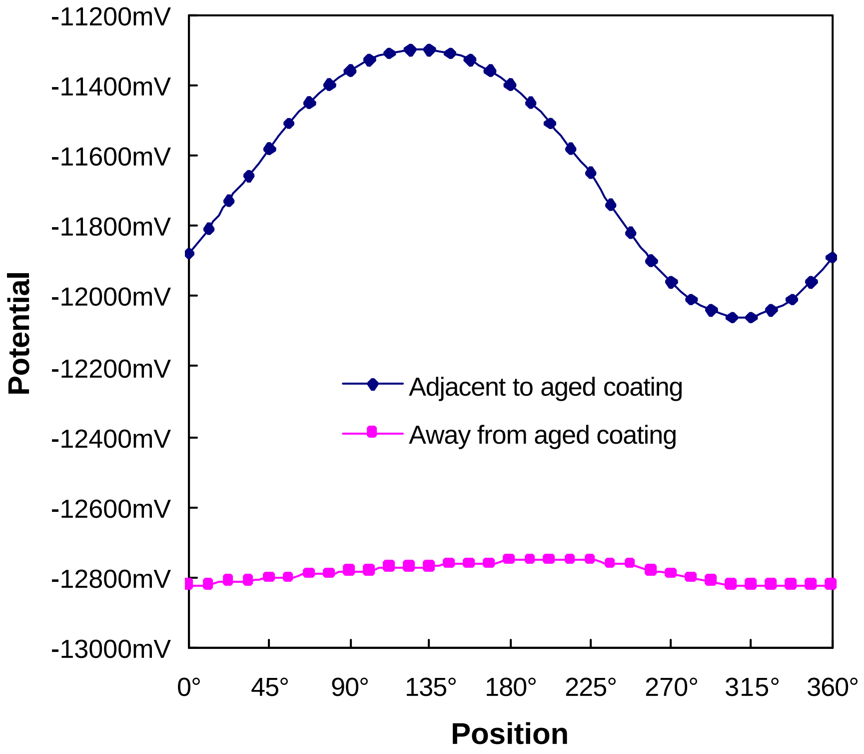

Figure 7. Potential distributions at two locations on the straight pipeline (soil resistivity 5´10^{2}Wm).

Case 2

The aim of the second case analysis was to determine the effect of a holiday in the coating of the straight pipe. The effect of the holiday on the potential distribution on the bent pipe can be seen below in Figure 8. The contour plots of potential and current density on the bent pipe are shown in Figure 9 and Figure 10 respectively. The results in the plots were observed at the location on the bent pipe most affected by the holiday on the straight pipe. It can be seen in Figure 10 that over a small area, the current density reaches a positive value, indicating that this area is behaving anodically. This stray current from the bent pipe does not appear when the value of soil resistivity is decreased.

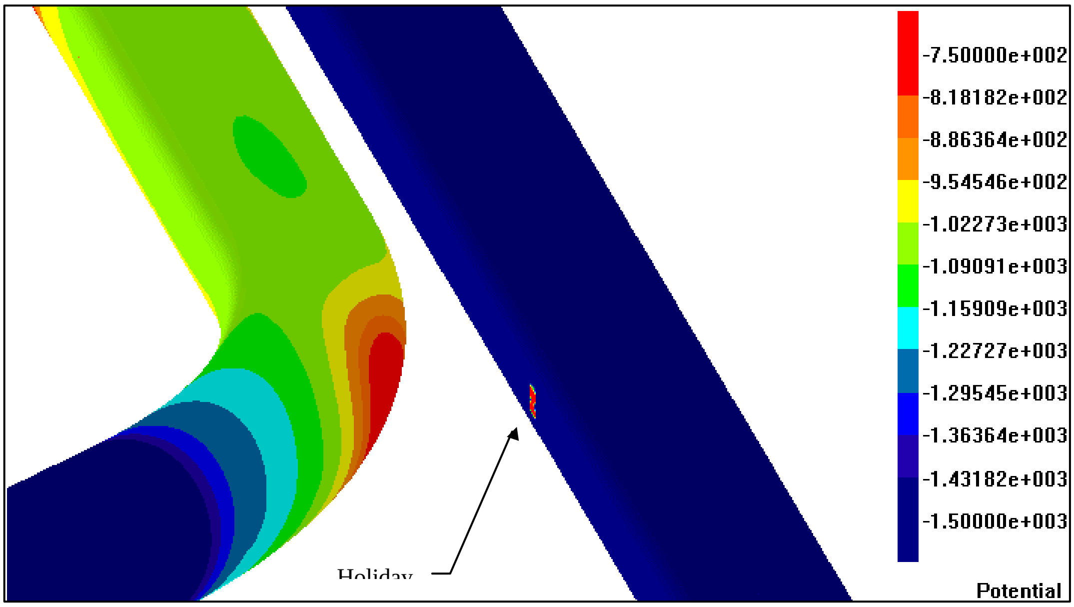

Figure 8. Potential distribution on the pipes with a holiday in the coating of the straight pipe.

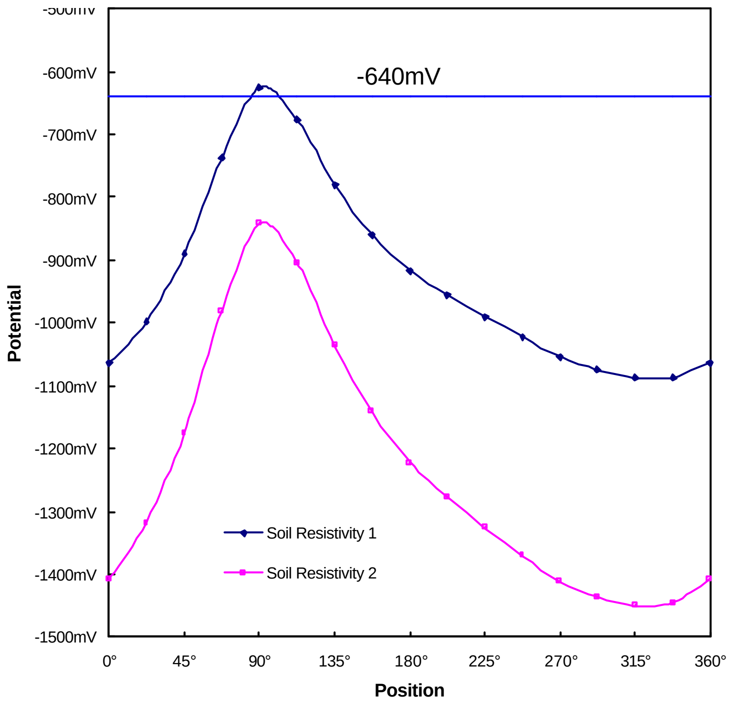

Figure 9. Potential distribution around the bent pipe at the location most affected by the holiday on the straight pipe ("Soil resistivity 1" = 1´10^{3}Wm and "Soil resistivity 2" = 5´10^{2}Wm).

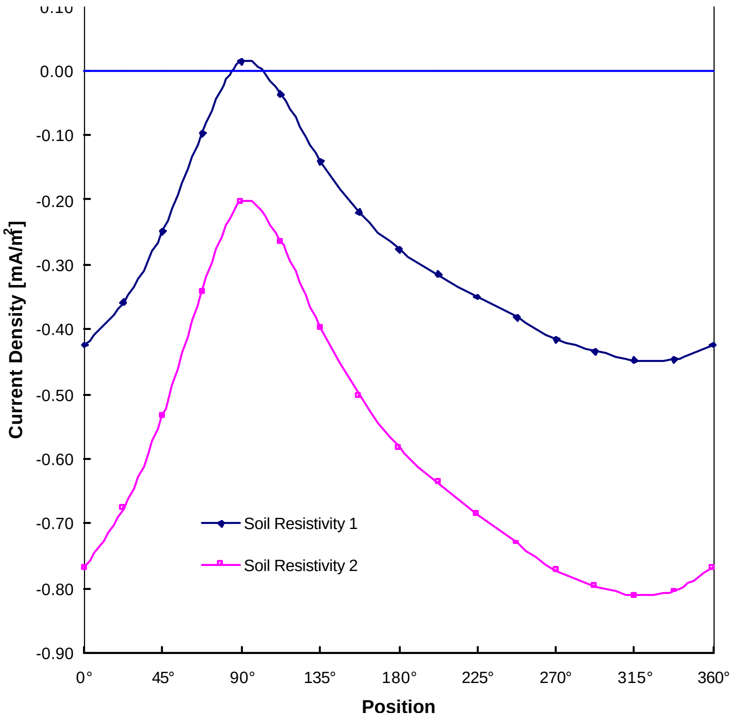

Figure 10. Current density distribution around the bent pipe at the location most affected by the holiday on the straight pipe ("Soil resistivity 1" = 1´10^{3}Wm and "Soil resistivity 2" = 5´10^{2}Wm).

Case 3

The potential distribution for two electrically connected pipes with a coating holiday on one of them is shown below in Figure 11. The analysis was made for a single value of soil resistivity of $1\times10^3\Omega$m. The influence of the aged coating of the bent pipe on the potential distribution on the straight pipe is considerably larger than in the previous cases where each pipe had a separate CP system. Also, the stray current from the bent pipe that was caused by the holiday does not appear in the current distribution plot of Figure 12. The plot was made of results at the location on the bent pipe that was most affected by the holiday in Case 2.

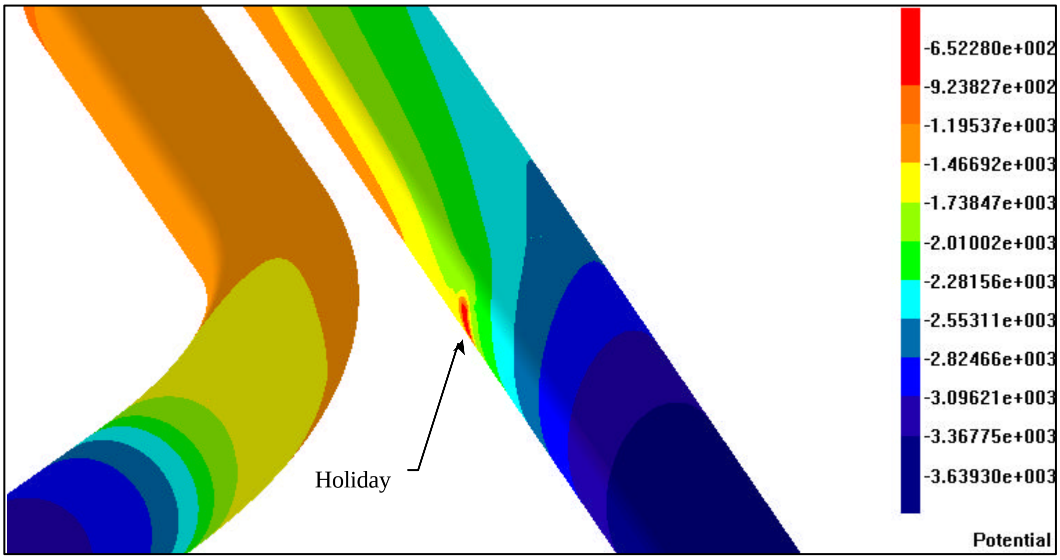

Figure 11. Potential distribution for two electrically connected pipes with a holiday in the straight pipe.

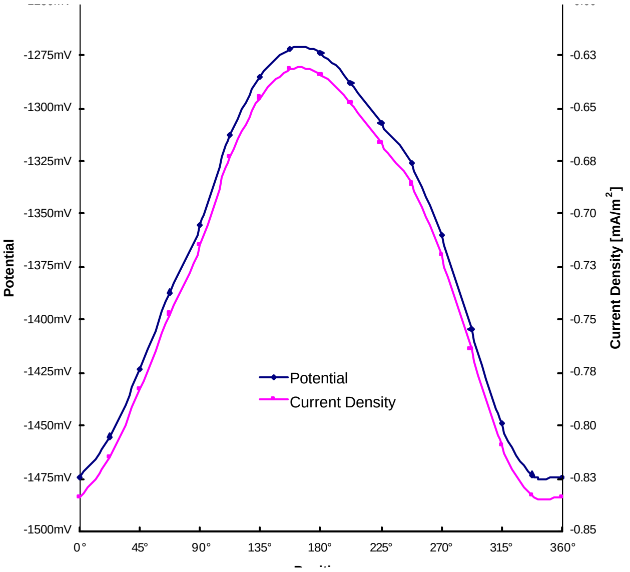

Figure 12. Potential and current distribution for two electrically connected pipes with a holiday in the straight pipe.

Modelling CP Interference near Chemical Storage Tanks

A recent study was carried out by Strong, Adey and Rudas and reported in [1]. In this study the design of a CP system to protect the external surface of floors on a number of large, above ground chemical storage tanks located in close proximity to each other was investigated. This problem offers a significant challenge if CP interference is to be minimized. What makes this task difficult is that, in some cases, the tank floors are uncoated. Thus large CP currents are required to fully protect the steel. The effect of this large current combined with the steel floor being located at ground level and immediately adjacent to buried pipelines and steel foundations creates the ideal situation for CP interference.

Three 56.5 m diameter tanks are positioned 28m apart (84.5 m from tank centre to tank centre) and aligned in a row. The external floors of all three tanks are cathodically protected using four anode groundbeds, as shown in *Figure 13*. Each tank was protected using its own DC power source employing a current of 80A per tank (i.e. total current 240A). The DC circuit was designed so that the two anodes protected each tank floor diametrically positioned 14m from the edge of each tank, with each anode contributing to 50% of the total current requirement for the tank. Thus, the two outer anodes carried a current of 40A each while the two inner anodes discharged a current of 80A each

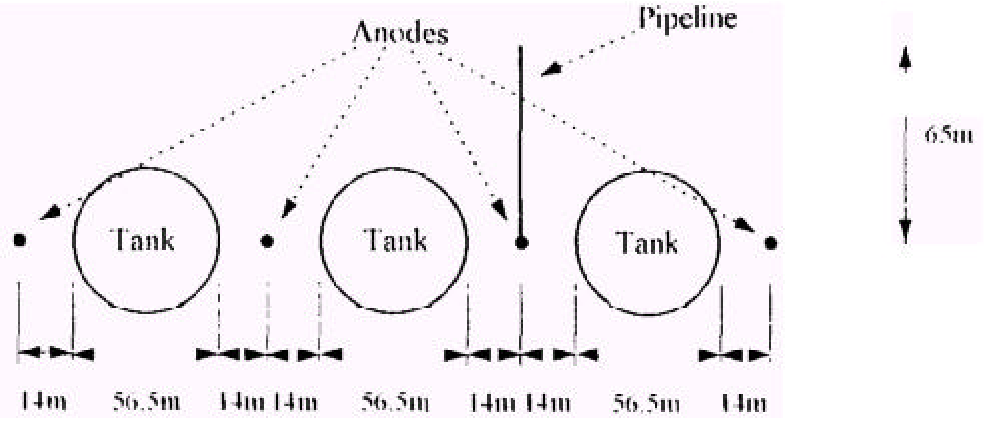

Figure 13. Top view showing the general arrangement of the tanks, the pipeline, and the anodes. Coating defects on the pipeline were located at the extremities of the pipeline

The anodes were 0.2m in diameter. 10m long, and initially buried vertically so that the tops of the anodes were located 20m below the ground surface. To ensure that the CP interference was not underestimated the soil resistivity was assumed to be uniform and equal to the surface resistivity of 50 ohm m. The pipeline was located immediately above one of the inner anodes and extended in a direction away from both the tanks and the anodes. Once again, to ensure that the CP interference was not underestimated, the coating defects were located immediately above the anode and at the extremity of the pipe, i.e. 65m from the anode.

Figure 14 shows the potential distribution over the tank floor with respect to a saturated CuCuSO2 reference electrode, It shows, as predicted, that the centre of the tank receives less protection than do the tank edges. Notably potentials at the centre of the tank are slightly more positive (approximately -82OmV) than the ideal protection criterion of -850mV suggesting that, initially, 80A may not be sufficient to fully protect the tank. The oval shape of the contours is indicative that the anodes are positioned too close to the tanks. To achieve a more symmetrical distribution of protection the anodes would have to be buried at a greater depth

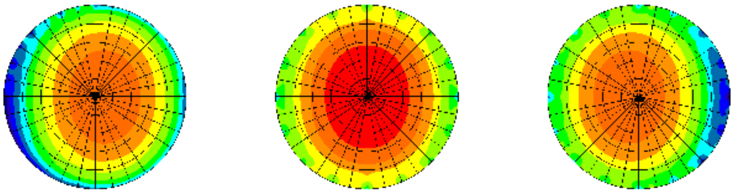

Figure 14 Predicted Potentials on the floors of the tanks

Cathodic Interference on the buried Pipeline

Table 1 summarises the effect of CP interference on the pipe as a function of the size of the coating defect. As intuition may suggest, locating the pipeline within the influence of the anodic field results in CP current being picked up by the pipeline in the vicinity of the anode and being discharged at the remote end of the pipeline. Assuming the worst case scenario that the corrosion process involves formation of Fe, the current densities corresponding to current discharge can be converted to metal loss per year. The severity of this interference is now readily apparent and the results suggest that it would be prudent to undertake further measures to help minimise the interference.

Depth of Anodes m	Area of Coating Defect (cm^2)	Current Density Adjacent to Anode (mA/m^2)	Induced Corrosion Rate Adjacent to the Anode (mm/year)	Current Density at the Remote End (mA/m^2)	Induced Corrosion Rate at the Remote End (mm/year)
20	**500**	-198	-	198	0.2
20	**5**	-442	-	442	0.5
70	**500**	969	1.1	-969	-
70	**5**	2370	2.7	-2370	-

Table 1. CP Interference on the Buried Pipeline

It is interesting to note that the corrosion rate is predicted to be higher when the coating defects are smaller. This suggests that smaller coating defects tend to focus the interference effects, and thus increase the damage caused by the interference on the pipeline.

One possible measure to help minimise the interference effects is to bury the anodes at a greater depth and thereby minimise the anodic interference. Table 1. summarises the effect of lowering the anodes so that the top of the anodes is located at a depth of 70m the model predicts that repositioning the anodes has major effect on interference levels. It not only increases the effect of CP interference but also relocates the corrosion site. Corrosion that was initially located at the remote end of the pipe is now located immediately above the groundbed. This occurs because lowering the anodes removes the anodic field at the ground level. The pipeline is now subjected only to the cathodic field of the tanks. As result current is picked up at the remote end or the pipeline and conducted along the pipeline before being discharged hack into the ground at the point where the pipeline closely approaches the tank floors.

The fact that the current flow inducted by CP interference is reversed by positioning the anodes at greater depths suggests that there is an optimum depth at which anodes could be buried so that interference is minimised. Determining the optimum depth could be evaluated efficiently using computer modelling. This would help to minimise the number of field tests to be undertaken. However, a more detailed model describing the actual resistivity profile of the soil as actual location of the anodes is expected to be very dependent upon this.

Automatic Optimisation of CP Systems

Computer simulation can also be used to automatically optimise the number and location of anodes to achieve protection. Areas of over protection or under protection can be eliminated.

The optimisation technology can be applied to any application but one of the first was the solution of a ship. The ship was protected with an ICCP system including 2 anodes and a centre controlled power supply. The anode currents determine the potential level on the hull surface and an automatic iterative process of adjusting the anode currents and running the BEM software was used to obtain the required solution. A simulated annealing algorithm was used to evaluate the optimum.

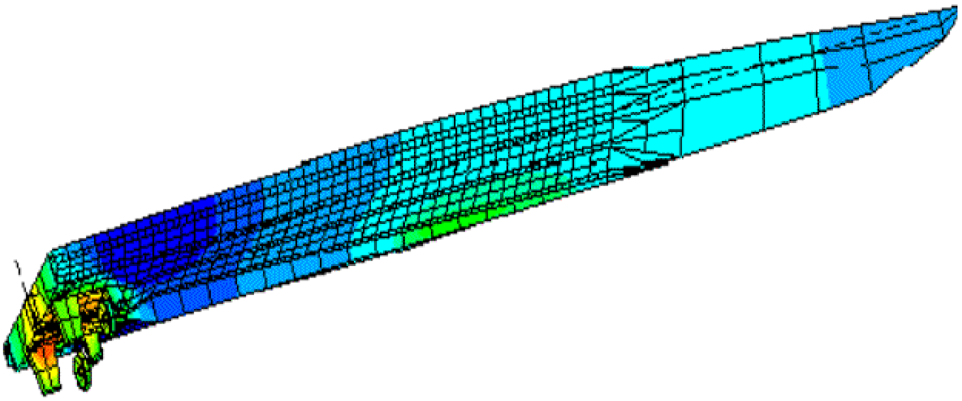

Figure 15 Potential predicted on the surface of the structure

The final optimum location of anode and electric potential on the ship hull is illustrated in Figure 15. The electric potential of the initial anode position at *x* = (15,1) and final optimised location at *x* = (3,3) along a line on the ship hull 1.25 metres below the water line is shown in *Figure 16*.

The result obtained represents a more evenly distributed electric potential on the ship hull. That is one of the most significant benefits of the optimisation process. The reduction in the area of under or overprotection achieved by the optimum process enables the ICCP system to protect the ship hull from corrosion more effectively.

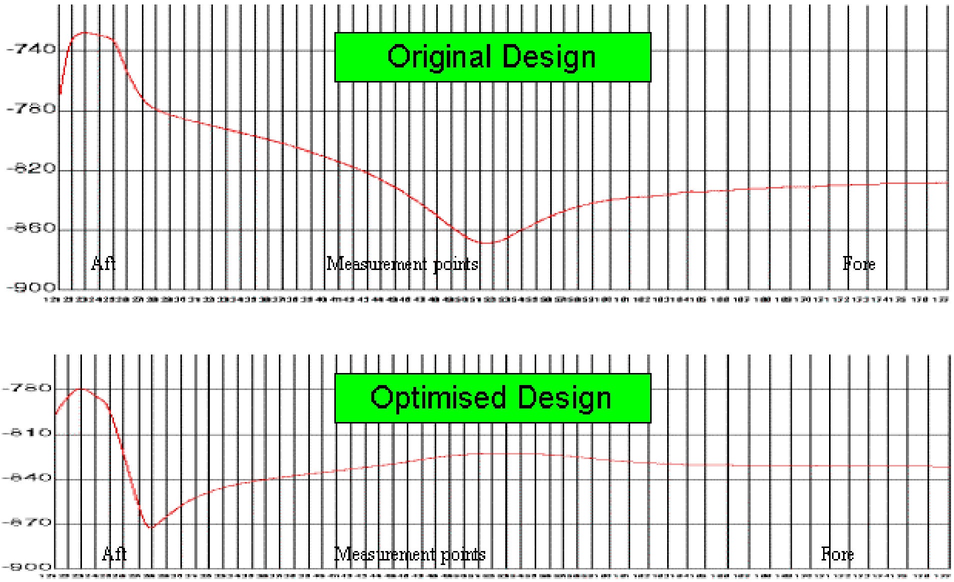

Figure 16 Potential Distribution (mV) on the Ship Hull 1.32m Below Water Line

Conclusion

It has been shown in the analysis that there exist complex interactions between multiple adjacent pipelines, pipelines with changing coating properties or with coating holidays and pipelines with independent CP systems that are subject to stray current interference. These interactions cannot successfully be described by design equations and numerical simulation is required if accurate predictions are to be made.

The approach described here, using the Boundary Element Method software BEASY, provides a computationally efficient method to predict the performance of CP systems and assess the impact of electrical interference. The models are useful not only for the design of new CP systems, but also for the analysis of systems that are undergoing modifications or additions of components.

Using computer modelling it is possible to model CP interference in a manner, which is enlightening regarding the processes at work. It can provide information about the level of interference in terms of a parameter (i.e. current density) that more clearly defines the severity of the effect. Furthermore, it can provide important insight into the factors that influence the magnitude of the effect. This makes BEM a useful tool for the design of CP systems.

Acknowledgments

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