Computer Simulation as an Aid to Corrosion Control and Reduction

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ABSTRACT

The paper discusses the progress of computer modelling techniques and how they have been developed to simulate corrosion control solution.

The basic mathematical techniques are described and how models can be used to predict stray current corrosion and the associated underwater electrical fields.

Three applications are presented. In the first the optimisation of the design of an ICCP system for a ship is described. In the second the stray corrosion between a ship and steel sheet is modelled. In the third the performance of an earthing system is simulated and its impact on a nearby pipeline is predicted.

INTRODUCTION

The durability of components, vessels or structures is an essential design requirement which engineers have to satisfy. Corrosion is just one aspect of durability as failure can occur due to corrosion, fracture or wear. As designs have become more optimised and economic pressure has required long safe working life it has become more critical to ensure the design is durable.

The economic cost of corrosion was estimated some years ago by the US Department of Commerce to be approximately 5% of the Gross National Product. However corrosion not only has an economic cost it can present a threat to life through the collapse of a structure or to the environment through the leak of toxic chemicals.

Computational tools have been extensively used in the design process in many industries in particular to predict and simulate the structural performance.

These software tools are now widely used on computers ranging from PC's to High Performance systems for routine design problems. However up until recently computer simulation of corrosion problems has been restricted to high value projects in the Oil and Gas and Defence industries.

The need to satisfy durability requirements and the availability of low cost personal computers has enabled computer simulation to be applied to aid control corrosion and reduction.

PREDICTION TECHNIQUES

Early predictions of corrosion rate and estimates of adequate cathodic protection (CP) have traditionally been based on case studies and sample exposure tests. Applying these techniques to real structures usually involve extrapolations, use of large safety factors and on-going corrections and maintenance of the system.
The first attempt at computer simulation took place in the late 1960's where the Finite Difference method was applied to the problem [1].

In the late 60's the finite element (FD) method was applied to the problem [2]. This method requires the discretisation of the seawater with a mesh. The solution is found at the intersection points, or nodes, of the mesh. The solution is numerical because the variation of the solution from one node to adjacent nodes is governed by an approximate form of Laplace's equation: FD methods although supplying accurate results in many situations, have major disadvantages. (They are difficult to apply to general three-dimensional geometry). Further results were by Strommen [3], Doig et al. [4].

In the 70's, solutions were sought using finite element (FE) methods [5-11]. As with FD methods the volume to be analysed (the seawater) has to be discretised with a mesh. The mesh this time divides the volume into small elements of finite size, each of which is of simple enough shape for the equations to be solved simply numerically over the volume of the element. For each element a set of equations is obtained. The advantage of FE methods over FD methods is that they are algorithmic and easy to program to cope with general problems. However, creating a finite element mesh is an extremely tedious and time consuming process, particularly for the typical corrosion problem.

The mesh generation process can be largely automated using automatic mesh generation techniques but it is difficult to manage these processes when there are large geometry scale differences in the model. Unfortunately this is exactly the case found in most corrosion control problems where anodes are small compared with the size of the structure and the problem areas are most likely in corners and areas of complex geometry.

In the late 70's another form of numerical technique, boundary element (BE) methods, became available. As the name implies, the method requires elements to be created, but now only on the boundary (or surfaces) of the problem geometry.

The advantages of boundary elements for CP analysis are many folds:

- the meshes are now only on the surface, hence only (equivalently) two-dimensional elements are required. Mesh generators can be used with confidence, and models can be constructed extremely quickly and inexpensively once the geometry is defined.

- Models can be created with fine detail of key or complex areas while modelling the whole structure or large volume of electrolyte.

- BE Methods are very effective and accurate for modelling large or infinite domains as is the case for CP analysis.

The first paper describing the application of boundary element techniques to corrosion engineering problems was published by Danson and Warne[12]. They described the application of an early version of BEASY [27] to the Conoco Hutton Tension Leg Platform installed in the North Sea. The system they described used constant boundary elements and a simple Tafel slope relationship to represent the polarisation. Subsequent developments of BEASY following this initial work are described by Adey, Brebbia and Niku [13 - 18].

Fu [19] was also one of the first to publish work on the application of the Boundary Element technique to Galvanic cells and corrosion. Other work has been published by Gartland [20], Aoki [21], Telles [22] and Zamani [23]. This work is summarised in the review articles by Strommen et al [24, 25] and Munn [26].

THEREORETICAL FOUNDATION FOR COMPUTER MODELLING OF CORROSION

Electrochemical Corrosion

Electro-chemical corrosion is the dissolution of a metal through the oxidation process. Oxidation involves the loss of electrons and normally occurs simultaneously with a reduction chemical reaction but are independent of each other.

Reduction involves the gain of electrons. The electron transfer between oxidation and reduction reaction sites establishes the electrical current required for electro chemical corrosion.

The electrochemical reactions can be visualised in the form of an electro chemical cell. The cell consists of three components. The anode is the site of the oxidation (corrosion) and is electrically connected to the cathode. The cathode is the site of the reduction. The medium surrounding the anode and cathode is the electrolyte.

The key elements which must be represented in a mathematical model of the corrosion process are the anode and cathode electrode kinetics and the electron flow through the electrolyte (for a more detailed explanation see [30]).

Modelling

The flow of current through the electrolyte can be shown to be represented by the Laplace equation.

$$\kappa \nabla^2 E = 0 \tag{1}$$

where E is the potential and κ is the conductivity.

$$I_{x_i} = -\kappa \frac{\partial E}{\partial x} \tag{2}$$

where I_x is current density flowing in x_i direction.

The boundary of the electrolyte (and hence the region to be represented by the mathematical model is defined by the surface area of the anode and cathode and the surface or boundary of the problem (eg the free surface of the sea or the sea bed).

For the reasons stated earlier the boundary element method is used to represent the electrolyte. The boundary element (BEM) approach requires the surface area of the model to be described with elements the shape of which are defined by mesh points or nodes. The user can therefore define any problem by assembling the elements together to cover the surface of the problem.

The mathematical derivation is beyond the scope of this paper but it is clearly defined in [18]. The BEM approach results in a system of linear equation relating the potentials and current densities on the anode and cathode

$$H\ E = G\ I \tag{3}$$

Where **_H_** and **_G_** are co-efficient matrices defined by the BEM, **_E_** is the vector of nodal potentials and **_I_** is the vector of nodal current densities.

The size of the system of equation is defined by the number of nodes used.

By manipulation of these equations the IR drop through the electrolyte can be predicted for any condition on the anode or cathode.

Electrode Kinetics

The electrode kinetics describes the oxidation and reduction process, which take place on the anode and cathode. These processes can be expressed mathematically as non linear relationships involving the current density and potential on the metallic surfaces.

These can be written as

$$i_a = f_a\ (\ E_a\ ) \tag{4}$$

$$i_c = f_c\ (\ E_c\ ) \tag{5}$$

where i_a is the current density on the anodic surface, E_a is the electropotential on the anodic surface, f_a is a function which represents the relationship between the potential and current due to the electrode kinetics, i_c, E_c and f_c describe the conditions on the cathodic surfaces.

In general, these relationships are a function of both chemical and environmental factors. In many cases one of the most important factors is the build up of a calcareous deposit on the cathode (if steel is polarised sufficiently in seawater). This deposit is in addition to any organic film and marine growth being formed.

The scale alters the polarisation behaviour and reduces the effective surface area, introducing an additional physical resistance and consequently introduces a time dependent factor.

Therefore the “polarisation” data describes not only the electrochemical reaction but also the environmental factors and can be generally expresses as:

$$i = f\ (\ E, h, V, D, T, etc) \tag{6}$$

where i is the current density on the surface, E is the potential, V is the flow velocity of the electrolyte, D is the depth, T is the temperature and h is the film thickness.

Other factors include salinity, oxygen content, etc.

Providing data is available describing the sensity of the current density or potential to the environmental factor it can be included in the mathematical model.

Mathematical Model

The main elements of the electrolytic cell are now defined mathematical and can be assembled to form the mathematical model:

Expressing (6) in a vector from

$$I = B(\ E, h, \dots)\ E \tag{7}$$

Therefore

$$H\ E = G\ B(\ E, h, \dots)\ E \tag{8}$$

Finally

$$(\ H - G\ B(\ E, h, \dots))\ E = 0 \tag{9}$$

This non-linear system of equation can be solved to obtain the potential ***E*** and the current density ***I*** [18].

Current Flow through the Structure and Stray Current Corrosion

In the simple electrolytic cell a wire connects the anode and cathode to provide the return path for the electrons. In the mathematical model this return path has to be defined.

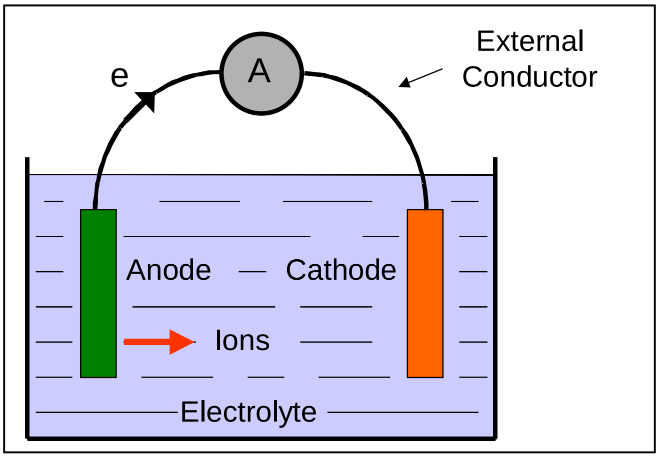

Fig 1. The box or "test tank"

In the simplest case of a structure with sacrificial anodes in, for example the seawater each element is defines a part of the structure surface. Therefore to define the return path these elements must be electrically connected. One way of doing this is to create a box around the structure and defining that the surface of the box is insulated. This can be visualised as creating test tank (the box) and placing the model in it (the anode and cathode elements).

Alternatively the return path electrical connection can be defined explicitly by applying a constraint equation. Assuming the structure return path has zero resistance (i.e. the only IR drop is through the electrolyte) the constraint equation can be written as:

$$\sum_{NumberofElements} \int_s I\ ds = 0 \tag{13}$$

This equation can simply be interpreted as that the summation of the current over the anode and cathode is equal to zero.

Note the anode and cathode currents have opposite signs.

Having solved the system of equations the potential and current density is known at all the nodes on the model and the values in the electrolyte can also be computed.

In most cases only the metallic areas are of interest and the computer model prediction of the current and potential are sufficient. However in some applications the potential field surrounding the structure in the electrolyte (e.g. seawater) is required. Although the boundary elements are only located on the structure the BEM method can provide the solution anywhere in the electrolyte.

The applications of the electric field solution in the electrolyte include the analysis of stray corrosion damage between the nearby structures. Other uses of the electric field include the prediction of the potential above a pipeline with defects in the coating.

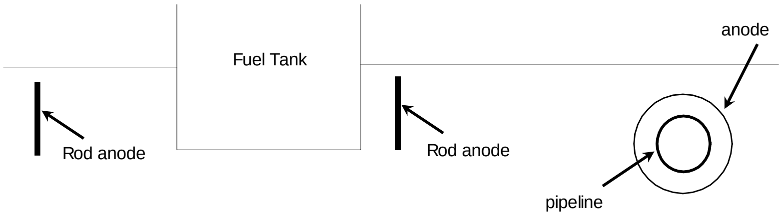

Fig 2. CP system on Fuel Tank and Pipeline

Fig 2 shows an example of a CP system protecting a fuel tank with a pipeline nearby. The rod anodes are electrically connected to the tank and the pipeline bracelet anodes are connected to the pipeline. However the two systems are not connected electrically except through the earth.

The electrical connection can be created in the model by applying constraint equations that imply that the electrical current on the anode and cathode elements is in balance and therefore they are electrically connected.

For all the elements on pipe and bracelet anode

$$\sum_{\text{Element on pipe \& bracelet anode}} current = 0 \tag{10}$$

For all the elements on tank and rod anodes

$$\sum_{\text{Element on tank \& rod anode}} current = 0 \tag{11}$$

Therefore the two systems can exchange current (stray current) but there will be no total loss or gain within the overall system.

This approach can also be used to represent a loss or leakage of current from a system (eg leakage of current to a well from a sub sea production structure).

In this case the summation of current is not zero.

Therefore

$$\sum_{Elementsonstructure} current = I_{leakage} \tag{12}$$

where $I_{leakage}$ is the total current leaking from the system.

This approach can also be used to define independent CP systems, which are not electrically connected but share the same electrolyte.

Corrosion Rate

The corrosion rate can be predicted by the mathematical model, as the weight loss of material is directly proportional to the measured electrical current.

The mass loss according to Faraday's Law:

$$Q = \frac{nFW}{M} \tag{14}$$

where Q is the electrical Charge and Q = $I\,t$, I is the current and t is the time, n is the number of electrons transferred, F is Faradays, W is the weight of reacting species and M is the molecular weight of reacting species.

The mathematical model provides information on the current density I on the metallic surfaces.

Therefore the weight loss can be defined as:

$$w = \frac{IM}{nF} \tag{15}$$

Where w is the weight loss per unit time per unit area.

APPLICATIONS

The optimisation design for ship ICCP system

The design of the corrosion protection system of ship using a sacrificial anode system or impressed current corrosion protection (ICCP) system is a crucial process towards the minimization of electrochemical corrosion on the exterior of the ship hull.

To protect the ship hull from galvanic corrosion the CP system generates electrical potential levels on the ship hull, which inhibit corrosion. The optimum system design goals are to achieve an uniform distributed electrical potential on the ship hull and to ensure that the protection potential is within the specified margin so as to avoid under or overprotection. Therefore a numerical method which predicts the electrical potential and anode current with high accuracy and reliability is required. The Boundary element method is a proficient numerical method that satisfies these requirements for cathodic protection system design of ships [18, 28].

An optimum design is achieved by moving the location of the anodes and reference cells on the ship hull and using the computer model to predict the resulting protection levels on the structure. The design optimisation process therefore consists of a series of calculations of the potential profiles on the hull and components with alternative anode designs. The boundary element software BEASY-CP [27] was used to investigate the ship’s ICCP performance.

A cargo ship with a length of 140 meters was investigated. The geometry of interest in the boundary element model is the wetted surfaces and major appendages of the hull. The model includes only half the ship structure due to the symmetry of construction. The ICCP system consists of 4 anodes and 2 distributed centre-controlled power supplies. Dissimilar materials are included in the model. The two propellers of the ship are made of nickel-aluminium-bronze alloy (NAB) and modelled as solid disks with equivalent surface area as the real elements. The two rudders and shafts are made of steel. The three parts mentioned above are assumed to be uncoated because of the turbulence engendered by propeller movement. Certain parts of the hull, especially in the aft zone, are modelled with damaged paint represented as bare surfaces and perfect painted steel hull as insulated surfaces. The ship is surrounded with infinitive seawater and the boundary of solution domain is assumed to be far away from the regions of interest. The seawater is defined with a constant conductivity of 5 s/m in the computer model. The boundary element discretization is either a 9-point quadrilateral elements or 6-nodes triangular and mesh discretization of the ship which amounts to 1183 elements and 6876 nodes.

Accuracy of the electrochemical analysis is dependent on the material polarisation involved in the boundary element model. Experimental polarisation data [30] was used in the investigation.

The required potential level on the hull surface is obtained through an iterative process of adjusting the anode currents. The criteria of adequate potential level for the protection on the ship hull was set up in the range from -0.78 Ag/AgCl to –0.88 Volts Ag/AgCl on the wetted hull surfaces. The target reference cell reading was set up as –0.83 Volts Ag/AgCl to be achieved in the computer model. It may require a series of iterations by adjusting the two groups of anode currents individually to converge to the required accuracy.

Performance of the ICCP system was evaluated both in static and dynamic status. Computer model was used to evaluate the protection potential, assess the influences of seawater conductivity and predict the damages caused by paint conductivity changes over different service periods.

The appropriate potential level and the anode currents required by individual components were derived from the modelling results. Adjusting the numbers of anodes and their locations then was implemented based on the computation outcomes to achieve the optimum design goal. Based on the distribution of the potential on the ship hull the locations of the reference cell was then determined to represent the overall potential profiles on the ship hull.

The model results were utilised to evaluate the performances of the ICCP system. Figure 3 shows the protection potentials on the ship hull and figure 4 shows the protection potential on the aft part including propellers and rudders. On most of the wetted hull surfaces the ship hull is effectively protected by the ICCP system from corrosion. Potential profile along the hull surface at a depth of 3 meters from the waterline is shown in figure 5. Potential profile on the keel line is shown in figure 6. There exist some areas that are under protected and others where overprotection occurs. The anode currents were adjusted to achieve the best protection level.

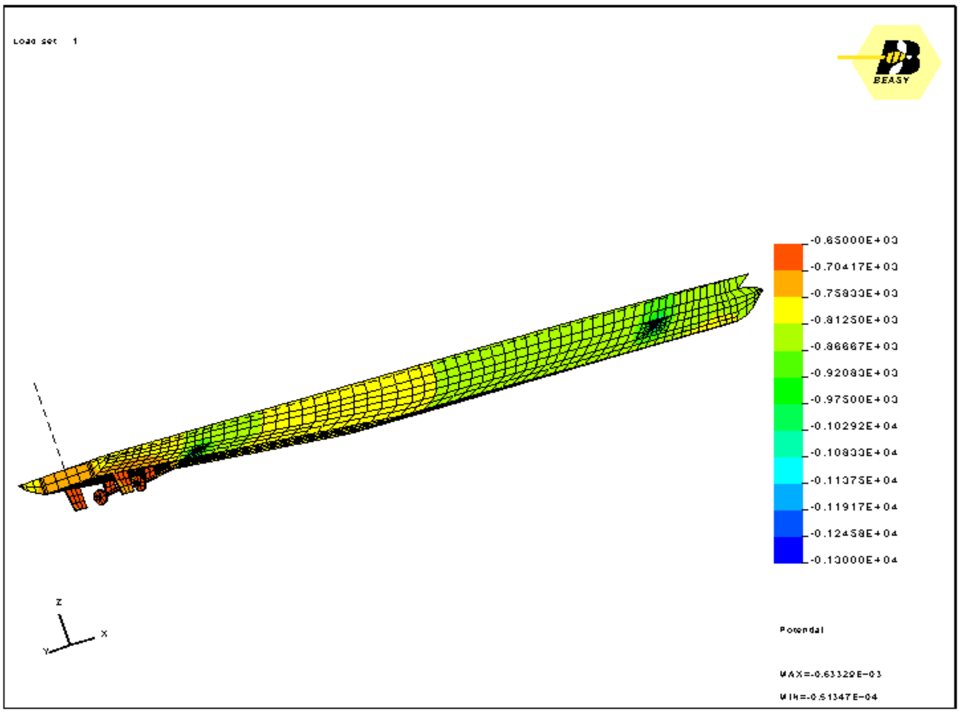

Fig 3. Protection potential on the ship hull

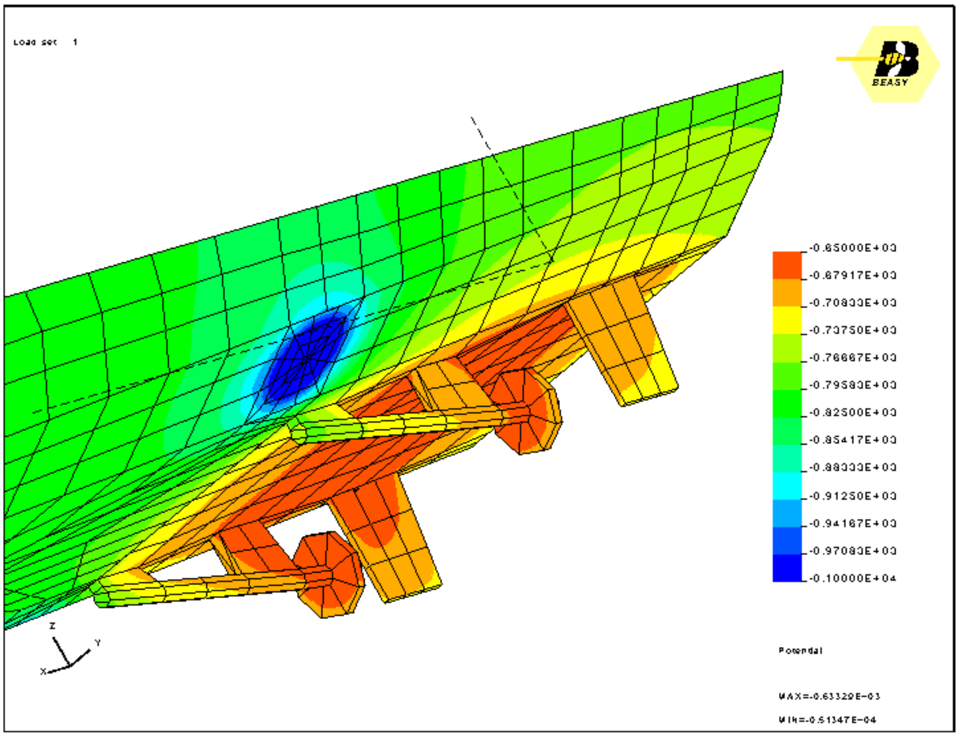

Fig 4. Protection potential on the aft part including propellers and rudders

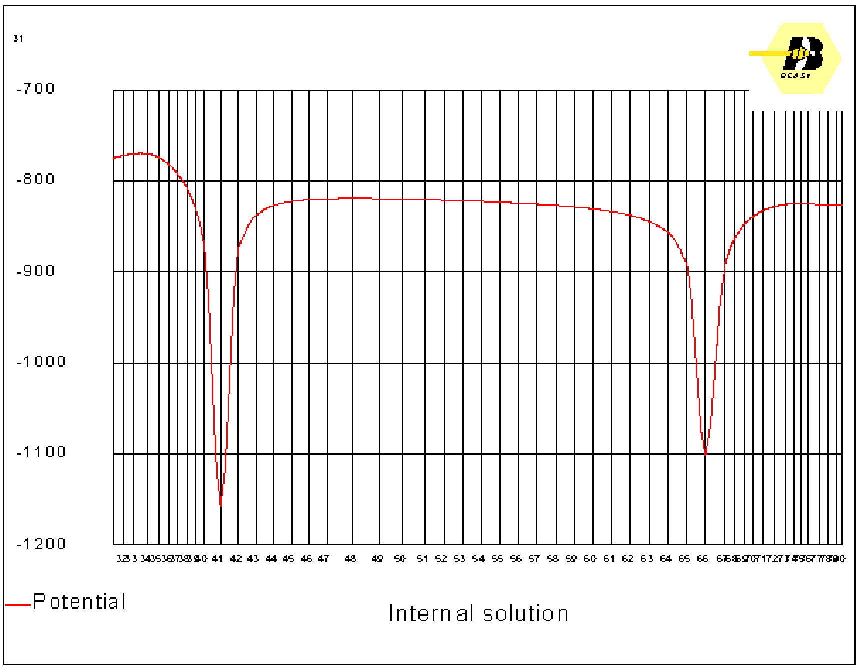

Fig 5. Potential profiles along hull surface at a depth of 3 meters from water line

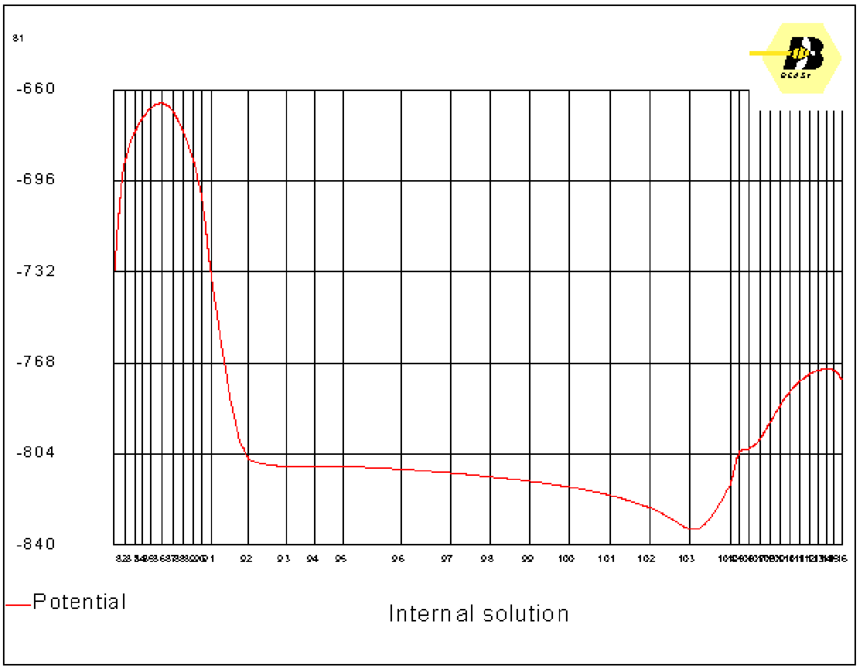

Fig 6. Protection potential profiles along the keel line

To achieve a uniform protection potential on the ship hull, a multi-zone, distributed centre-controlled anodes system is required to satisfy the different requirement for corrosion protection of different zone of the ship hull.

The performance of ICCP system with different operational environments was investigated. The change of current demand with time was estimated by comparing the paint conductivity differences perfect and damaged paint. Total current and individual anode current requirement was calculated based on the boundary element modelling results in perfect and worst painting conditions.

The design parameters of the optimum anode system, such as anode numbers and locations were proposed based on the detailed analysis of the cargo ship. The reference cells were located at positions that provide the best representative to overall potential profile.

Stray current corrosion of between ship and steel sheet

Corrosion can be accelerated by the action of electrical currents entering a metal structure from some external source such as an ICCP system of a ship and then leaving the metal to continue its flow in whole or in part through the seawater.

Stray current corrosion can lead to costly repairs to ship structures and piers. The modelling approach to predict the impact and characteristics of the phenomena was described by Trevelyan and Hack [31].

Simulation was conducted to reveal the damage so as to avoid the stray corrosion.

A boundary element model was build to investigate the impact of stray current corrosion. The previous cargo ship model was used in the investigation. In the boundary element model, a long steel sheet with dimension of 0.5m x 0.8m was located with a distance of 2m to the beam of ship. The current from the ICCP system of the ship chooses the low resistance path, the steel sheet, and not the seawater as it has the higher resistance path. A metallic conductor (such as a pier or other ship) immersed in seawater can drive considerable current from the nearby ICCP system of the ship.

The steel sheet is protected from corrosion when the current enters it. However, corrosion is considerably increased when the current leaves the steel sheet to enter the seawater. The low resistance path from the steel sheet affects the potential on the reference cell and causes an incorrect reading. The ship causes under or overprotection, which can damage the hull and paint. As currents requirement of an ICCP system rely on the reading from the reference cells, significant problems can be caused, as the potential reading of the reference cell will be changed due to the steel sheet.

To achieve the required reading on the reference cell the currents output of the investigated ICCP is about 2 times of original current output due to the short cut path of the steel sheet. Part of the hull surfaces is under protected as a result of the incorrect reading of the reference cell. The potential distribution of the solution from the boundary element analysis is illustrated in figure 7.

The horizontal direction electric current density, both on hull and steel sheet surfaces is illustrated in figure 8. The high current density may be produced by the ICCP currents, which are attracted to the steel sheet. The high current density may produce dangerous voltage on the ship hull near the anodes. The high current density leaving the steel sheet surface may also cause galvanic corrosion and loss of material weight. The weight loss on steel sheet can be calculated based on (14) and (15) and the life of the stray corrosion reaction.

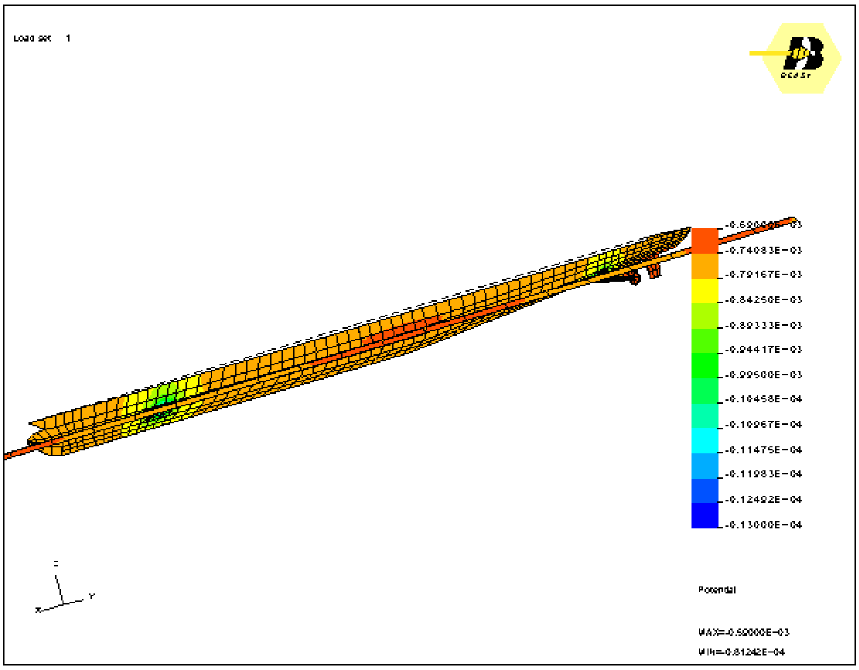

Fig. 7. Potential on the ship hull of a stray current corrosion modelling of a steel sheet near the ship

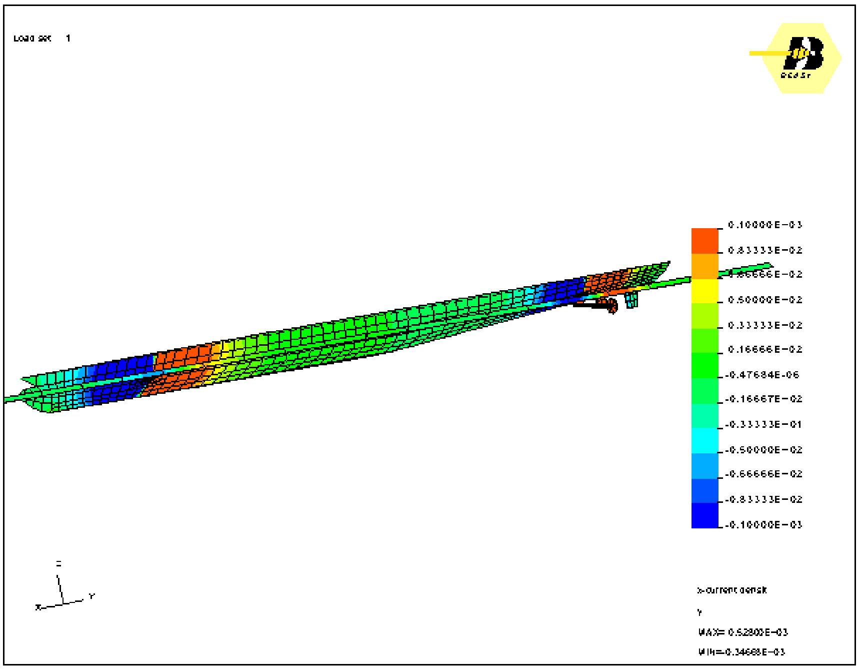

Fig.8. Horizontal direction current density caused of a steel sheet near the ship

Hazard assessment of electrical earthing

This second application demonstrates the power of computer modelling as the same technology can be used to solve a completely different type of corrosion problem [32].

The need for joint occupancy between public utilities has increased in recent years due to costs and difficulties in acquiring the right-of-way for power transmission line systems and underground pipelines. The close proximity of power transmission systems and underground pipelines poses a number of potential hazards: namely, AC induced voltages on the pipeline and large earth voltage gradients associated with electrical earthing systems that occur during fault and lightning discharges. Both effects can expose personnel in contact with the pipeline to lethal voltages, as well as compromise the measures taken to protect the pipeline from external corrosion (i.e. damage the protective coating of the pipeline and/or cathodic protection systems).

Therefore, before any joint occupancy is approved, the potential hazard associated with the proposal needs to be evaluated prior to construction.

Recently, BEASY has been used to help assess the risks of locating a high-pressure gas pipeline close to an earthing grid designed to discharge AC fault and lightning currents. The focus of this work was directed as assessing the voltage rise of the ground directly adjacent to the pipeline, taking into account:

- The geometry of the earthing electrodes
- The separation between the earthing grid and the pipeline, and
- The prevailing soil resistivity modelled as a function of depth.

Given that the maximum fault currents are well defined (they are based on the design of the electrical power system and statistical information obtained about lightning), and that the resistance of the earthing grid must comply with approved standards, then it is possible to calculate the maximum voltage rise of the earthing electrode using Ohm’s Law. The diameter of the electrode, the soil resistivity and the orientation of the electrode govern the amount of current that the electrode will discharge. This, in turn, defines how the voltage gradient around the earthing electrode will attenuate as a function of distance. As long as the closest approach of the pipeline to the earthing grid is located such that the potential of the soil adjacent to the pipeline (with respect to the potential of the soil at a location remote to the earthing grid) is within acceptable levels, then the design, in terms of conductive coupling between the two structures, can be considered safe.

In the past, such calculations had to employ equations that were derived analytically, using uniform soil resistivity and simple geometrical arrangements. However, using BEASY to model the electric field emanating from an earthing electrode buried in a heterogeneous soil, a more accurate assessment of the hazard is achieved.

In this application the earthing system was described using the BEASY rod type elements and consisted of 107 conductors buried to a depth of 800mm. The earthing grid is approximately 15m long and 12m wide. Supplemented with 67 vertical conductors Figure 9 shows the BEM model of the earthing grid and figure 10 and figure 11 shows the detailed view of the BEM mesh on the grid. The earth surface is represented by a symmetry plane so no elements are necessary on the earth surface. A fault voltage of 10kv was applied to the grid.

In the first case the fault total current surge was predicted as 24.9 kA and the equivalent resistance 0.401 Ohm.

In the second case a pipeline was positioned near the grid (approximately 12m). Figure 11 shows the BEM model of the pipeline adjacent to the grid. The fault total current surge increased to 26.4 kA due to current discharging to the pipeline. The equivalent resistance decreased to 0.379 Ohm. The total current flowing to the pipeline was 9.33 kA. Fig 12 shows the electrical potential (voltage) contours in the gound near to the earthing grid under the conditions of discharge. Figure 13 shows the potential distribution along the pipeline.

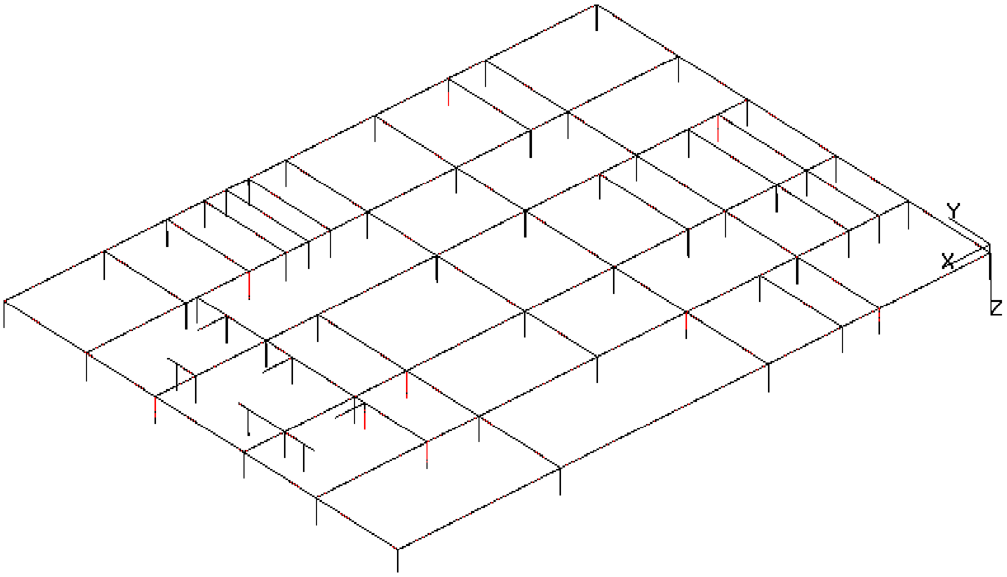

Fig 9. BEM model of the earthing grid

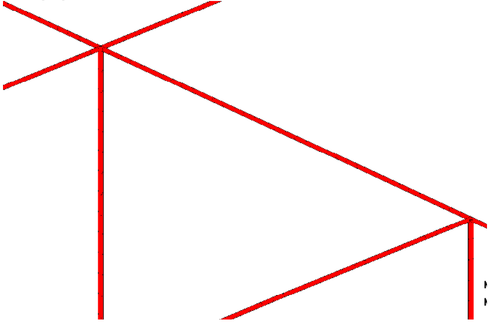

Fig 10. Detailed view of the BEM mesh on the grid

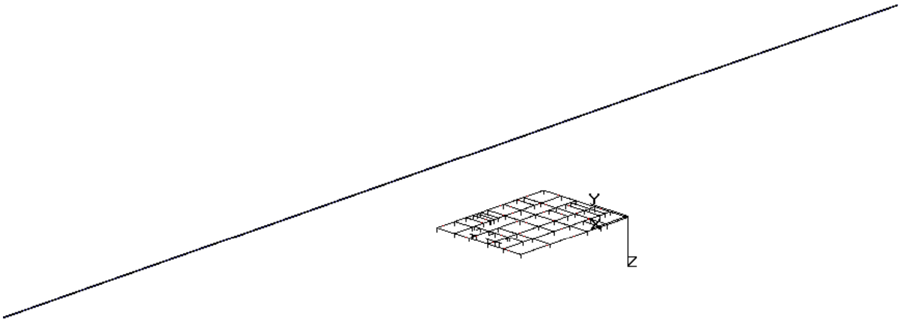

Fig 11. BEM model of the pipeline adjacent to the grid

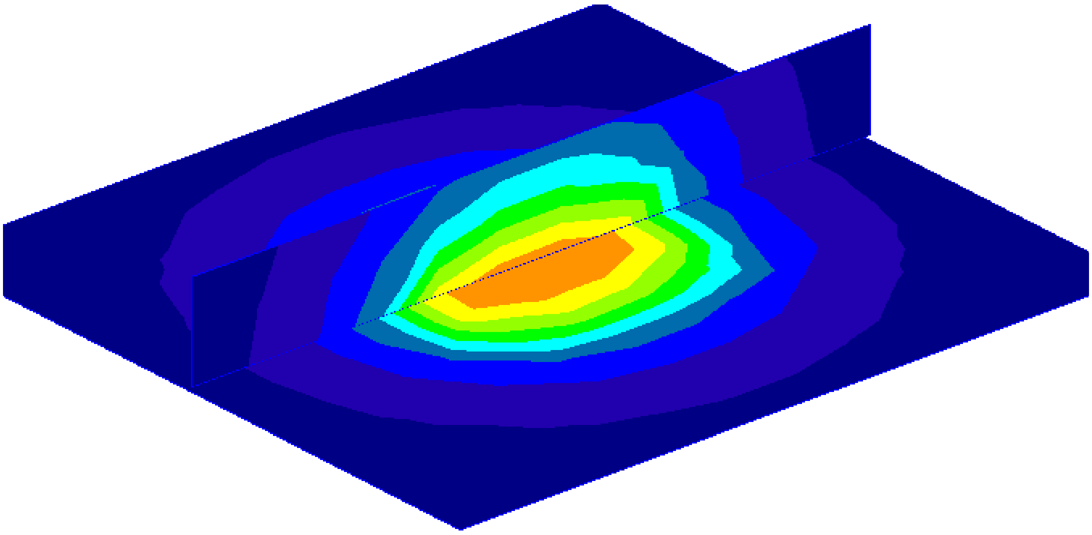

Fig 12. Electrical potential (voltage) contours in the gound near to the earthing grid

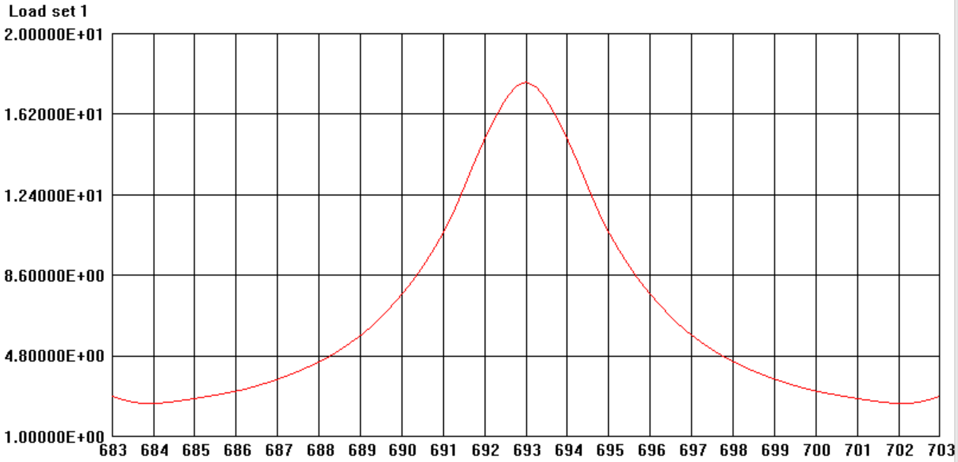

Fig 13. Potential distribution along the pipeline.

CONCLUSIONS

Computer modelling provides is a powerful technique for obtaining the answers required by corrosion engineers when designing of wide range industrial applications on corrosion control and reduction.

In the design optimisation process, especially for high value projects and complex systems, prediction and simulation using a numerical method with high accuracy and reliability is an essential.

The design variables, such as potential distribution and power consumption required in applications can be obtained from computer simulation. The influence of design parameters as well as environments can be simulated in the computer model.

Therefore, the optimum design goals can be achieved and system performance can be improved accordingly.

REFERENCES

1. Fleck, R. N.: MSc Thesis, Numerical Evaluation of Current Distribution in Electrical Systems, MSc Thesis, University of California, Sept 1964.

2. Sale, J. P.: The evaluation of anode configuration for the internal cathodic protection of pipes. Conference on Corrosion and Protection of Pipes and Pipelines.

3. Strommen, R. D.: Computer modelling of Cathodic Protection Systems Utilised in CP Monitoring, OTC 4357, Houston.

4. Doig, P., and Flewitt, P. E. J.: A finite difference numerical analysis of galvanic corrosion. J. of Electrochem. Soc. Vol 126 No 12 pp 2057 – 2063, Dec 1979.

5. Fu, J. W. Paper No. 115, NACE Corrosion Conference, Toronto, Canada, 1981.

6. Helle, H. P. E., Beek, G. H. M., and Ligtelijn, J. T. H., Numerical Determination of Potential Distributions and Current Densities in Multi-Electrode Systems Corrosion/NACE, Vol. 37, No. 9 pp522 – 530, Sept 1981.

7. Fu, J. W.: A Finite Element Analysis of Corrosion Cells, Corrosion/NACE Vol. 38, No 5, pp 9-12, 1982.

8. Kasper, R. G. and April, M. G.: Electrogalvanic Finite Element Analysis of Partially Protected Marine Structures, Vol. 39, No. 5, pp 181-188, May 1983.

9. De Carlo, E. A.: Computer Techniques for Offshore Corrosion Protection. Lockheed Horizons, Winter 1980/81.

10. De Carlo, E. A.: Computer Aided Cathodic Protection Design Technique for Complex Offshore Structures. Paper No. 165, Corrosion/82, March 1982.

11. Fu, W. J., and Chen, S. K.: Finite Element Determination of Galvanic Corrosion during Chemical Cleaning of Steam Generator, Material Performance, pp 33-40, March 1986.

12. Danson, D. J., Warne, M. A.: Current Density/Voltage Calculations using Boundary Element Techniques. NACE Conference, Los Angeles, USA, 1983.

13. Adey, R. A.: Modelling C P Systems, Oilman, June 1985.

14. Adey, R. A.: Niku, S. M., Brebbia, C. A., and Finnegan, J.: Computer Aided Design of Cathodic Protection Systems. Paper presented at the International Conference on Boundary Element Methods in Engineering, Villa Olmo, Lake Como, Italy, 24th-27th September 1985.

15. Niku, S. M.: and Adey, R. A.: A CAD system for the Analysis and Design of Cathodic Protection Systems, Plant Corrosion: Prediction of Materials Performance, Cranfield Institute of Technology, Cranfield, UK, February 1985.

16. Adey, R. A., and Niku, S. M.: Comparison between boundary elements and finite elements for CAD of Cathodic Protection Systems. BETECH Conference, South Australian Institute of Technology, Adelaide, Australia, Nov 1985. Computational Mechanics Publications, Southampton, 1985.

17. Niku, S. M., Brebbia, C. A., and Adey, R. A., “BEASY-CP. A CAD systems for Mathematical Modelling of Galvanic Corrosion and Cathodic Protection Problems”, CADMO 86, Washington, DC, USA, September 1986, Computational Mechanics Publications, Southampton and Springer-Verlag, Berlin & NY, 1986.

18. Adey, R. A., and Niku, S. M.: Computer Modelling of Corrosion using the Boundary Element Method, Computer Modelling in Corrosion. ASTM STP 1154 pp 248-264 (1992) American Society of Testing and Materials, Philadelphia, 1992.

19. Fu, J. W. and Chow, S. K.: Cathodic Protection Designs Using an Integral Equation Numerical Method. Corrosion/82, Paper No. 163, 1982.

20. Gartland, P. O., and Johnsen, R.: COMCAPS – Computer Modelling of Cathodic Protection Systems. Corrosion/85, Boston, Massachusetts, USA., March 1985.

21. Aoki, S., Kishimoto, K., and Sakata, M.: Boundary Element Analysis of Galvanic Corrosion, Boundary Elements VII, Villa Olmo, Lake Como, Italy. Computational Mechanics Publications, 1985.

22. Telles, J. C. F., Wrobel, L. C., Mansur, W. J., and Azevedo, J.P.S.: Boundary Elements for Cathodic Protection Problems. Boundary Elements for Cathodic Protection Problems. Boundary Elements VII, Villa Olmo, Lake Como, Italy. Computational Mechanics Publications, 1985.

23. Zamani, N. G., Porter, J. F., and Mufti, A. a.: A survey of Computational Effects in the Field of Corrosion Engineering, Journal of International Numerical Methods in Engineering. Vol. 23, 1986

24. Strommen, R. et al.: Advances in Offshore Cathodic Protection Modelling using the Boundary Element Method, NACE, Material Performance, pp 23-28, February 1987.

25. Munn, R. S.: A Mathematical Model for a Galvanic Anode Cathodic Protection System. NACE, Material performance, pp 29-32, August 1982.

26. Munn, R. S. A review of the development of Computational Corrosion analysis for special corrosion modelling through its maturity in the Mid 1980’s – Computer modelling in Corrosion ASTM STP 1154 American Study for Testing and Materials, Philadelphia 1991 pp 215-228

27 Computational Mechanics: BEASY-CP User Guide. Computational Mechanics BEASY. Southampton, England, 1996

28. DeGiorgi, V. E., Thomas, E. D. and Luas, K. E.: A Combined Design Methodology for Impressed Current Cathodic Protection Systems. Boundary Element Technology XI, 1996

29. Harvey P. Hack: Atlas of Polarization Diagrams for Naval Materials in Seawater. Carderock Division. Naval Surface Warfare Centre, Apr. 1995

30. DeGiorgi, V. G: Corrosion Basics and Computer Modelling. Industrial Application of the BEM. Computational Mechanics Publication, Southampton, England, 1992

31. Trevelyan, J. and Hack, H. P.: Analysis of Stay Current Corrosion Problems using Boundary Element Method. Boundary Element Technology IX, 1994

32. Strong, G. “Private Communication”, Perth Australia