Optimising a SACP system using Simulation, to achieve uniform anode life and protection potential

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Abstract

Optimisation of sacrificial anode cathodic protection (SACP) systems to achieve uniform anode mass loss rates is desirable, since it helps avoid early installation of costly retrofit systems which may be needed if some anodes are consumed more quickly than others.

Such optimisation is only practically possible through the use of mathematical modelling performed using numerical techniques. A range of numerical methodologies can be applied to simulation of galvanic effects and cathodic protection, and of these it is the boundary element method that is applied in this work. The simulation requires an accurate model of the structure which is to be protected, as well as the anodes, and any other metallic structures which may act as current drains (even though they may not need to be cathodically protected).

The optimisation process first involves simulation of an initial SACP system design. Performance of the design is assessed against criteria which may include anode mass loss rate, most positive allowed potential and remaining anode mass, not only at start of life, but also throughout the design life of the structure. The results of previous assessments are used to guide the selection of the next trial SACP system design, which usually involves changing the number, position or size of anodes. The process is repeated until satisfactory results are obtained.

The objective of this paper is to explore such simulation techniques, and show how they can be combined to provide a practical toolset for SACP system design optimisation. This provides the user with new and significantly more powerful design capabilities which are based on real physics rather than standardised design rules.

The paper goes on to demonstrate application of the optimisation process using as an example a coated jacket structure for which long-term “sigmoidal” polarisation curves provide an appropriate representation of calcareous deposits.
Introduction
The use of simulation is well established as a means to determine the electric fields surrounding an offshore structure or vessel, for example the fields caused by current flowing from sacrificial anodes to the surfaces to be protected. The numerical techniques available include finite element and finite difference methods which require either elements or points distributed throughout the electrolyte (seawater) and the boundary element method (BEM) [1] which by contrast requires elements only on the surfaces of the electrolyte.

Recent developments in the BEM package BEASY have further reduced the meshing requirement, so that only the wetted surfaces of the structure (whether in seawater or buried in the seabed) need to be discretised using elements. This technique uses special “multi-layer” fundamental solutions for three dimensional models, which allow the mathematics to provide the representation of multiple layers of electrolyte, each of which has different resistivity. The multi-layer methodology is used in examples shown in this paper.

The value of such a mathematical development is particularly significant when representing metal surfaces below the seabed, because the steel – in the form of piles and well casings – can drain significant current from the CP system, and the behaviour of that system is also sensitive to the difference in resistivity between the seawater, the seabed and the profile extending down through the mud layer.

Multi-layer Methodology
When dealing with stratified media, the goal of the multilayer methodology is to eliminate the need to model the interfaces between adjacent regions with dissimilar resistivities. These interfaces need to be meshed when using the standard homogeneous BEM.

The underpinning idea of the multilayer approach is to incorporate the stratified nature of the medium into the corresponding Green’s function. Then, the BEM is applied in the same way as in the case of a homogeneous electrolyte.
The Green’s function for the homogeneous Laplace equation is given by:

\[
G_{ij}(x_i, x_j) = \frac{1}{4\pi \|x_i - x_j\|},
\]

where \(x_i\) and \(x_j\) denote the three dimensional coordinates of the source and field points, respectively. In the present approach, this function is replaced by the multi-layer Green’s function, given by:

\[
G(x_i, x_j, m, n) = \frac{1}{4\pi \sigma_m} \sum_{k=1}^{N_{\text{exp}}} \alpha_{ijmn} \exp \left( -\frac{\|x_i - x_j + g_{ijmn}\|}{\sigma_m} \right),
\]

where the subscripts \(m\) and \(n\) indicate the layer of the source and field points, respectively; \(\alpha_{ijmn}\) is the weight coefficient, \(g_{ijmn}\) denotes a displacement vector, \(\sigma_m\) represents \(1/(\text{the resistivity of layer } m)\), and \(N_{\text{exp}}\) is the number of terms employed to represent the function. The coefficients \(\alpha_{ijmn}\) and \(g_{ijmn}\) can be obtained by integrating the corresponding Sommerfeld integrals appearing in the frequency domain formulation of the Laplace equation. The details of their calculation goes beyond the scope of this paper and can be derived from ref [2-5] and references therein.

From a practical point of view, the multi-layer approach helps to reduce modelling time and complexity since the interfaces between layers do not need to be included as part of the geometry. Instead, they can be parameterised, essentially by prescribing the thickness and resistivity for each layer. In addition, the geometrical information (CAD model) representing the structure immersed in the multilayer electrolyte does not need to be modified or adapted in order to integrate it with the environment.

As a consequence of eliminating the interfaces, the final model ends up with a smaller number of degrees of freedom, therefore requiring less computational resources, i.e smaller memory and shorter equation solution time.
In this way, the number of layers does not affect the number of degrees of freedom in the model.

From a computational point of view, it is worth mentioning that one of the advantages of expressing the multilayer Green’s function as shown in eq.(2), i.e. as a convenient superposition of point charges, is that all typical Boundary Element algorithms employed for the homogeneous Green’s function in eq.(1) can be reused, since the integration of terms involving $1/r$ are still required.

In the examples considered in this paper a collocation direct BEM has been adopted.

Note that in general, equation (2) is a numerical approximation to the actual Green’s function, the higher the number of terms in the sum the more accurate is the representation of the environment by the function.

However, there are particular scenarios in which an exact representation can be obtained with a small number of terms. For example a single layer where the top and bottom boundaries have insulating and infinite boundary conditions respectively, corresponds to a half space model where one term representing the image space is enough for an exact representation. Another example is the case of two semi-infinite layers of different resistivity in contact with each other, which yields an exact representation with a small number of terms in the sum.

**Optimisation of SACP System**

The optimisation process involves testing the performance of an initial SACP design, so the starting point is a design which includes anode size, shape and offset, anode material performance characteristics, plus numbers and positions of anodes on the structure. We here concentrate on jacket type structures, although in principle the same techniques can be applied to any structure.

**Selection of anode size and number**

We used standards to design a CP system for the coated steel jacket structure shown in Figure 1. Details of the steel areas are shown in Table 1. Temperate "shallow" conditions were assumed, and a 20 mA/m$^2$ current drain to the buried steel. The coated surfaces were assumed to have 2% breakdown factor in year 0, rising
linearly with time to 38% breakdown factor in year 30. These considerations resulted in total initial current 69 Amps, mid life current 140 Amps, and end of life current 271 Amps.

A long stand-off anode was selected, with height 140mm, width 160mm, and length 1500mm. The end-to-end mounting bar was 50mm in diameter. This resulted in 89.6kg of Al/Zn/In anode material per anode, for which the utilisation factor was taken to be 0.9, and assumed 2000 Amp-hours per kg of anode material. A total of 143 (new) anodes would be required to provide the end-of-life current, and although the anodes will be at least partly consumed by then, this number of anodes was selected for use in the example. The mid-life current was used to determine the total required anode mass, which was 9724 kg. However this was exceeded in the design which provided a total of 12803 kg of anode material.

![Figure 1: The jacket structure, with conductors, piles and well casings, and showing the position of the seabed. Only the part of the structure below the sea surface is shown.](image)
### Table 1: Areas of steel

<table>
<thead>
<tr>
<th>Location</th>
<th>Surface area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetted jacket members (coated)</td>
<td>3690</td>
</tr>
<tr>
<td>Wetted conductors (coated)</td>
<td>627</td>
</tr>
<tr>
<td>Buried piles</td>
<td>767</td>
</tr>
<tr>
<td>Well casings (top 50 m only)</td>
<td>731</td>
</tr>
</tbody>
</table>

**Assessment of performance of the CP system**

To assess performance of the CP system, a model of the jacket, conductors, piles and anodes is constructed. Each of the surfaces in the model is "discretised" into a number of elements, which are associated with a number of "degrees of freedom" (potential and normal current density). The element (or "mesh") creation is highly automated, so is not a difficult task.

Resistivity of the seawater and seabed are required, in this case values of 30 Ohm-cm resistivity for the water and 130 Ohm-cm for the seabed were selected.

Polarisation characteristics of the steel and anode surfaces must be defined, using polarisation curves. In this example the anode closed circuit potential was taken to be \(-1050\) mV (Ag/AgCl/seawater - the reference used throughout this paper), and the anode surface was assumed to polarise through 2.5 mV for every 1000 mA/m² change of current density. If advantage is to be taken of the more negative open circuit potential of such an anode material (at low current density the potential is more negative than the "closed circuit potential" recommended by standards), then a more complex curve is required to reflect the more rapid change of potential at low current densities. Similar consideration applies at very high current density.

The polarisation behaviour of bare steel surfaces in North Sea waters has been characterised by Strommen [6] using data obtained from several surveys of existing structures. The observed long-term behaviour, taking into account all naturally occurring effects (calcareous deposits, water flow etc), fell into a band between the two curves "A" and "B" in Figure 2. The curve "B" can be regarded as a "worst-case" long-term curve (or "sigmoidal" curve, a term used by Hartt and Chen [7] ) relating potential and current density on a bare steel surface.
Figure 2: Extremes of long term relationship between current density and potential, after Strommen[5]

For a coated surface, a conservative approach is to assume that a 50% coating breakdown factor equates to 50% of the surface completely bare of coating. This approach is used in this paper, and current densities in the curve "B" from Figure 2 are scaled to correspond to any required coating breakdown factor.

Behaviour of buried steel surfaces can also be characterised by a polarisation curve, and this method is preferable to simply applying the "standard" current drain of 20mA/m² to the buried surfaces because the latter approach results in an artificial distortion of the electric fields and makes them unrealistic. In the example shown in this paper, we used a polarisation curve for which potential is -677mV at zero current density and potential is -950mV at 20 mA/m² current density.

In order to assess performance of a CP system over the lifetime of a structure, it is necessary to perform time stepping, so as to take account of:

- loss of anode mass and corresponding change of anode size
- change of breakdown factor

It is also instructive to assess performance of the "as-new" anodes using the 30-year breakdown factor, since this gives understanding of the best possible protection
which could be achieved at 30 years by the design if the anodes were not consumed at all. In this example, we choose to use results obtained with the 30-year breakdown factor to guide optimisation of the design, and will afterwards perform time-stepping to check performance through the whole-of-life of the structure.

**Assessment of Design 1 based on as-new anodes combined with 30-year coating breakdown factor**

Positions of the anodes in the initial design is shown in Figure 3. The anodes are roughly uniformly distributed.

Assessing performance of the as-new anodes at 30 years, we find that:

- potentials on steel surfaces are as in Figure 4 (which shows values for both the wetted and the buried surfaces) and in Figure 5 (which shows values for the wetted steel surfaces only)
- cathodic current density on the buried steel surfaces is as shown in Figure 6
- projected anode life is as shown in Figure 7

The total current delivered by the "as-new" anodes is 148 Amps, of which 26 Amps flows to the buried steel. The resulting potentials on the wetted steel range from -923 to -1009 mV for the jacket members, and from -922 to -982 mV for the conductors.

The projected remaining life of the "as-new" anodes in year 30 ranges from 13 to 21 years.
Figure 3: Showing positions of the anodes in design 1

Figure 4: Potentials in year 30 ("new" anodes) on wetted and buried steel surfaces. Design 1.
Figure 5: Potentials in year 30 ("new" anodes) on wetted steel surfaces. Design 1.

Figure 6: Current density on the buried steel surfaces in year 30 ("as-new" anodes). Design 1.
Assessment of Design 2 based on as-new anodes combined with 30-year coating breakdown factor

Positions of the anodes in design 2 are shown in Figure 8. The anode positions have been adjusted to move those which in design 1 had longest remaining life to positions close to those which had short remaining life. This is a relatively easy operation, during which use is made of the graphical display of anode remaining life.

Other quantities which can be displayed graphically for the anodes include:

- whether/not the anode has reached its utilisation factor (in which case it is automatically switched-off)
- the consumption factor
- anode current
- mass loss rate
- remaining mass

Assessing performance of the as-new anodes at 30 years, we find that:

- potentials on wetted steel surfaces are as in Figure 9
- projected anode life is as shown in Figure 10

The total current delivered by the "as-new" anodes is 148.5 Amps, of which 26 Amps flows to the buried steel. The resulting potentials on the wetted steel range from -929
to -1007 mV for the jacket members, and from -929 to -983 mV for the conductors. The projected anode remaining life ranges from 15 to 20 years.

**Figure 8:** Showing positions of the anodes in design 2

**Figure 9:** Potentials in year 30 ("new" anodes) on wetted steel surfaces. Design 2.
Assessment of Design 3 based on as-new anodes combined with 30-year coating breakdown factor

Positions of the anodes in design 3 are shown in Figure 11. Again the anode positions have been adjusted to move those which in design 2 had longest remaining life to positions close to those which had short remaining life. Other anodes were simply moved along the member to which they were attached.

Assessing performance of the as-new anodes at 30 years, we find that:

- potentials on wetted steel surfaces are as in Figure 12
- projected anode life is as shown in Figure 13

The total current delivered by the "as-new" anodes is 148.6 Amps, of which 26 Amps flows to the buried steel. The resulting potentials on the wetted steel range from -946 to -1005 mV for the jacket members, and from -945 to -981 mV for the conductors. The projected anode remaining life ranges from 16 to 19 years.
Figure 11: Showing positions of the anodes in design 3

Figure 12: Potentials in year 30 ("as-new" anodes) on wetted steel surfaces. Design 3.
Conclusions reached at this stage regarding the optimised design

When looking at the end-of-life potentials using the “as-new” anodes, it is clear design 3 has a smaller range of anode remaining life than design 2, indicating that no anode will be fully consumed a great deal earlier than the others. In addition, the protection potentials demonstrated by design 3 are more negative than those for design 2.

However although testing the design using methods shown above does give an easy way to optimise, it is nevertheless essential to test the whole-of-life performance of the CP system, since this process takes account of the reducing anode size as anode material is consumed.

This process is demonstrated in the following section for Design 3.
Assessment of Design 3 using time-stepping to assess whole-of-life performance.
The time-stepping process uses results at year 0 to calculate anode material loss over the period of the time step. This is expressed as a value of anode consumption factor for each anode in the model at the end of the time step, and simulation performed at the new time takes into account the changed sizes of the anodes, as well as the changed coating breakdown factor. The length of the time interval is generally chosen to be around 5 years. Results at the new time are again used to calculate mass loss over the period of the next time step, and this is repeated as long as required. In this case time stepping continued to year 30, and results are shown below at years 1, 15 and 30.

Variation of protection potential over the life of the structure is shown in Figure 14, while projected anode remaining life at year 30 (this time taking into account anode mass loss over the life of the structure) is shown in Figure 15.

The extreme potentials on wetted steel surfaces are shown in Table 2 at years 0, 15 and 30.

From Figure 15 it can be seen that the range of anode life at year 30, calculated by time stepping, is from 2 to 7 years, which is in strong contrast to the range from 16 to 19 years which was based on "as-new" anodes in Design 2 and year 30 breakdown factor.

Whereas the range from 16 to 19 years suggested that anode consumption was well balanced, the range from 2 to 7 years is less convincing, and this prompted a further adjustment to the CP system design. The resulting Design 4 is evaluated in the next section.
Figure 14: Protection potentials at years 0, 15 and 30 for Design 3, taking into account change of anode size and change of coating breakdown factor.

Figure 15: Anode remaining life at year 30 for Design 3, obtained after time stepping from year 0 to year 30.
<table>
<thead>
<tr>
<th>Year</th>
<th>Most positive potential on wetted steel (mV)</th>
<th>Most negative potential on wetted steel (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1008</td>
<td>-1043</td>
</tr>
<tr>
<td>15</td>
<td>-975</td>
<td>-1022</td>
</tr>
<tr>
<td>30</td>
<td>-931</td>
<td>-996</td>
</tr>
</tbody>
</table>

Table 2: Range of protection potential on wetted steel in years 0, 15 and 30 for SACP system design 3

**Assessment of Design 4 based on as-new anodes combined with 30-year coating breakdown factor**

Positions of the anodes in design 4 are shown in Figure 16. Again the anode positions have been adjusted to move those which in design 3 had longest remaining life (as shown in Figure 15) to positions close to those which had short remaining life. Thus for example the bottom horizontal members which in design 3 (Figure 11) had two attached anodes now have 4 attached anodes in design 4 (Figure 16). The total number of anodes remains at 143.

Assessing performance of the as-new anodes at 30 years, we find that:
- potentials on wetted steel surfaces are shown in Figure 17
- projected anode life is shown in Figure 18

The total current delivered by the "as-new" anodes is 148.6 Amps, of which 26 Amps flows to the buried steel. The resulting potentials on the wetted steel range from -949 to -1010 mV for the jacket members, and from -947 to -985 mV for the conductors (extremes for wetted steel are shown in Table 3). The projected anode remaining life ranges from 15 to 21 years.
Figure 16: Showing positions of the anodes in design 4

Figure 17: Potentials in year 30 ("as-new" anodes) on wetted steel surfaces. Design 4.
Figure 18: Projected remaining life (in years) for the "as-new" anodes with breakdown factor at 30-year value. Design 4. Anodes only shown on the left, anodes and members shown on the right.

<table>
<thead>
<tr>
<th>Year</th>
<th>Most positive potential on wetted steel (mV)</th>
<th>Most negative potential on wetted steel (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>-947</td>
<td>-1010</td>
</tr>
</tbody>
</table>

Table 3: Range of protection potential on wetted steel in year 30 for SACP system design 4. Values calculated using "as-new" anode size.

<table>
<thead>
<tr>
<th>Year</th>
<th>Current flowing to buried steel (Amps)</th>
<th>Current flowing to wetted steel (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>26</td>
<td>123</td>
</tr>
</tbody>
</table>

Table 4: Total current flowing to buried and wetted steel at end of life, for SACP system design 4. Values calculated using "as-new" anode size.
Assessment of Design 4 using time-stepping to assess whole-of-life performance.

Variation of protection potential over the life of the structure is shown in Figure 19, while projected anode remaining life at year 30 taking into account anode mass loss over the life of the structure, is shown in Figure 20.

From Figure 20 it can be seen that the range of anode life at year 30, calculated by time stepping, is from 3 to 6 years. This is a (small) improvement over the corresponding range (2 to 7 years) for Design 3.

Clearly optimisation of the SACP system has produced a better design, but there is a law of diminishing returns. In this example, we chose to stop the optimisation process at this stage.

The range of potential on the wetted steel is shown in Table 5 for start, middle and end of life for Design 4.

Table 6 shows the current flowing to the buried steel and to the wetted steel, at start, middle and end of life.

The state of polarisation of the structure at end-of-life can be seen in Figure 22, which shows the long-term curve as a solid green line, with polarisation of each part of the structure shown as red dots. It is clear that the structure is well polarised, with low maintenance currents.

If a CP system was inadequately designed, so that the anodes could not deliver enough current to polarise the structure, the simulation would reflect this fact. In such a case, potentials would be more positive, and current densities bigger. The structure would be on the "nose" of the sigmoidal curve at around -650 to -800 mV in Figure 22.

Because the simulation method used allows acquired calcareous deposits to dissipate if the CP system cannot maintain them, it can be concluded that for Design
the remains of the anodes at year 30 would be able to re-polarise the structure in the event that calcareous deposits were lost as a result of a storm.

Figure 19: Protection potentials at years 0, 15 and 30 for Design 4, taking into account change of anode size and change of coating breakdown factor

Figure 20: Anode remaining life at year 30 for Design 4, obtained after time stepping from year 0 to year 30
Figure 21: Showing anode remaining life in year 0, year 15, and year 30, for a small part of the structure and SACP design 4

<table>
<thead>
<tr>
<th>Year</th>
<th>Most positive potential on wetted steel (mV)</th>
<th>Most negative potential on wetted steel (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1010</td>
<td>-1042</td>
</tr>
<tr>
<td>15</td>
<td>-980</td>
<td>-1022</td>
</tr>
<tr>
<td>30</td>
<td>-934</td>
<td>-1000</td>
</tr>
</tbody>
</table>

Table 5: Range of protection potential on wetted steel in years 0, 15 and 30 for SACP system design 4. Values calculated by time stepping which takes into account change of anode size with mass loss.

<table>
<thead>
<tr>
<th>Year</th>
<th>Current flowing to buried steel (Amps)</th>
<th>Current flowing to wetted steel (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>28</td>
<td>7</td>
</tr>
<tr>
<td>15</td>
<td>27</td>
<td>67</td>
</tr>
<tr>
<td>30</td>
<td>25</td>
<td>121</td>
</tr>
</tbody>
</table>

Table 6: Total current flowing to buried and wetted steel at start, middle, and end of life, for SACP system design 4
Discussion

In the early years of the life of a structure, when the coating breakdown factor is small, the wetted steel surfaces do not require significant current for adequate protection, but the buried steel is a continuous drain on the CP system, as shown by the data in Table 6.

This continuous drain of current to the buried steel combined with the large variation through time of current to the wetted steel makes it more difficult to achieve a balanced design in which all anodes reach consumption factor at about the same time. It is in this type of situation that simulation can provide the insight and understanding which can allow an effective design to be achieved.

An optimal design based on a single state of the coating will not be so optimal at other stages of life, so whole-of-life assessment is important.
The effect of anode size change on current to buried and wetted steel can be seen by comparing current in year 30 shown in Table 4 and Table 6. The total current delivered by the reduced-size anodes is 2% less than by the "as-new" anodes.

The corresponding effect on structure potential of anode size change as mass is lost can be seen by comparing extremes of potential in year 30 shown in Table 3 and Table 5. The anode size reduction causes the most positive potential to become more positive by 13 mV.

**Conclusions**

This paper has demonstrated how simulation can be used to assist optimisation of the design of a SACP system on a jacket structure, and has shown that whole-of-life assessment of system performance is important, in particular for coated structures.

The methods demonstrated in this paper provide insight into the real physical effects which influence CP system performance, and allow the CP designer to adjust the system accordingly.

The use of sigmoidal long-term curves has been demonstrated, with discussion of the benefits of using such a curve.

**References**


