Advanced Cathodic Protection Design by Finite Element Method (FEM)

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Agenda

1. Principles of Finite Element Method modelling applied to CP
2. CASE 1: CP of tank bottom internal surface
3. CASE 2: Cathodic protection retrofitting

Principles of Finite Element Method modelling applied to Cathodic Protection

Current and potential distribution in CP systems

- Cathodic protection is a surface related matter: protection conditions are achieved at each point of the structure when the cathodic current density is equal to the **protection current density** and **potential is within the correct protection range**. The relationship between current density and potential at metal-electrolyte interface depends on electrode reactions and typically they are *non-ohmic*, i.e. *non linear*.

- Potential and current at the surface to be protected, i.e. the cathode, also depend on **potential and current distributions in the bulk of the electrolyte**.

- Prediction of potential and current distribution is an issue in several cathodic protection applications, in design as well as in operating, monitoring, inspection and retrofitting contexts.

Current and potential distribution in CP systems

The potential and current distributions in homogeneous electrolyte are governed by:

- the Laplace's equation and

$$\nabla^2 \emptyset = 0$$

- The Ohm law:

$$i = -k \times \nabla \emptyset$$

where:

$\emptyset$ is the potential
i is the current density, and
k is the conductivity of the electrolyte.
∇^2 is the Laplace operator:

$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$ and ∇ is the vector field $\nabla = \left(\frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}\right)$

The electrode potential can be assumed to be constant and the potential at the electrode solution interface is:

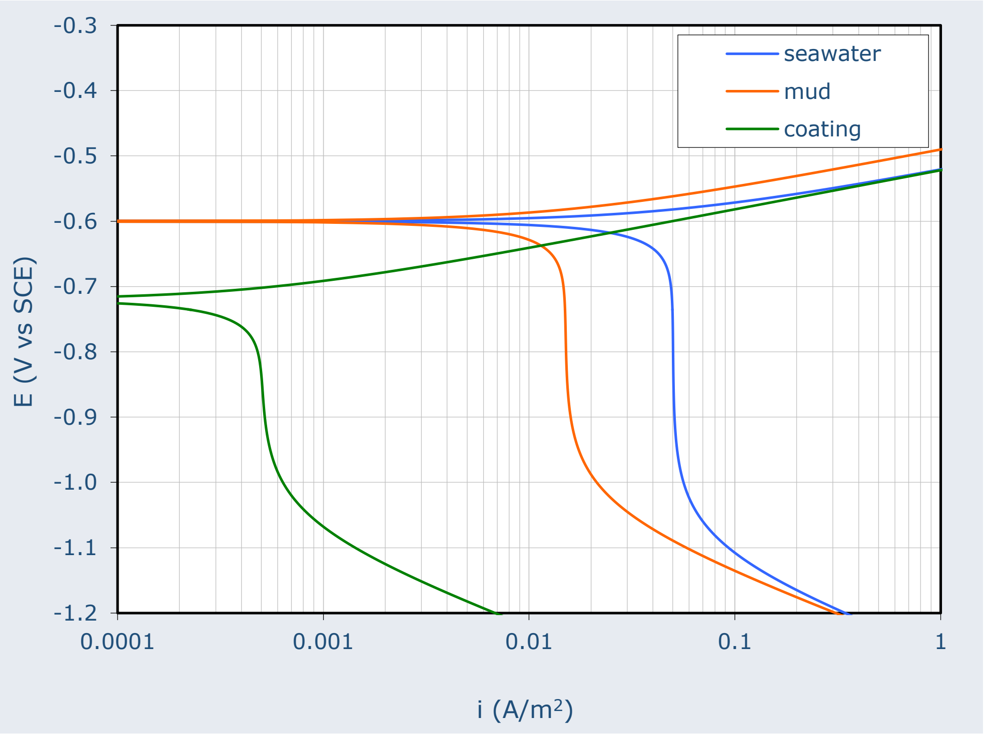
Where η is the overvoltage.

$$\emptyset = \mathbf{const} - \eta$$

Electrode behavior of steel

The electrode behavior of steel in natural waters or soil is conveniently described by the polarization curve shown here.

In a cathodic protection system, the protection current is mainly controlled by the oxygen diffusion limiting current and, at negative potential, by the hydrogen evolution current.



Current distribution in CP systems

The local current density at cathode surface is controlled by the following factors:

- Geometry of the system
- Conductivity of the environment
- Activation overpotential
- Diffusion overpotential
- Hydrodynamics.

Three main types of current distribution are generally considered:

- **Primary distribution**: when the influence of interface overpotential contributions is negligible
- **Secondary distribution**: the activation overpotential are also considered, and
- **Tertiary distribution**: both the activation and diffusion overpotentials have to be taken into consideration. Transport and migration of ions are considered to take into account for concentration variations in solution.

The Finite Elements Method - FEM

Analytical resolution of potential and current distribution is feasible in case of very simple geometries, not for complex ones.
Numerical methods are available to solve the Laplace equation; they are:

- The Finite Element Method (FEM)
- The Finite Difference Method (FDM)
- The Boundary Element Method (BEM).

The Finite Element Method - FEM

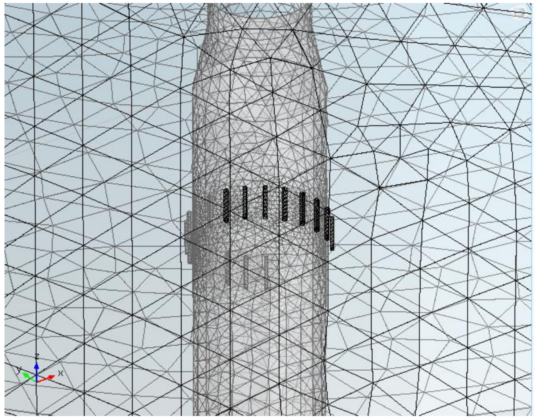
- Finite Elements Method (FEM) is a numerical technique for solving boundary value problems
- It minimizes an error function, generating a stable solution
- It solves simple equations over small subdomains (finite elements) approximating a complex equation over larger domains
- FEM allows to model the geometry of intricate structures and to study the large number of variables affecting corrosion and protection control
- International standards, as for instance Norsok M-503, suggest the application of FEM techniques for advanced CP design

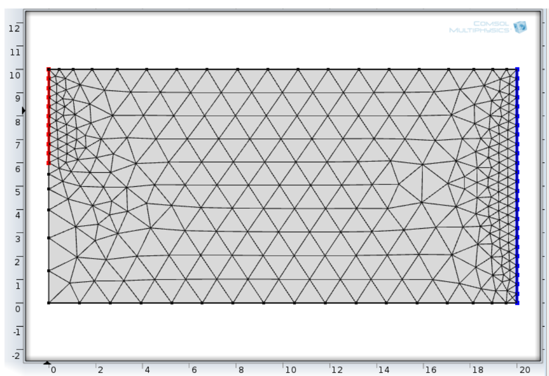
The Finite Elements Method - FEM

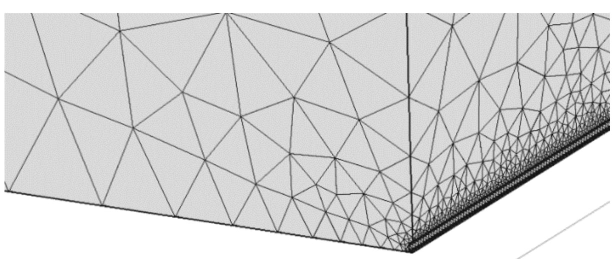
Advantages in CP engineering using FEM analysis

- Realistic virtual model of structures with accurate knowledge of current and potential distribution
- Improved design of spacing, anode size, placing and other geometrical factors affecting cathodic protection distribution
- Identification of under- and over-protected zones and optimization or verification of anode positioning
- Prediction of galvanic anodes consumption
- Optimization of the positions of permanent reference electrodes in complex structures
- Prediction of the evolution with time of protection conditions.

Geometry and mesh



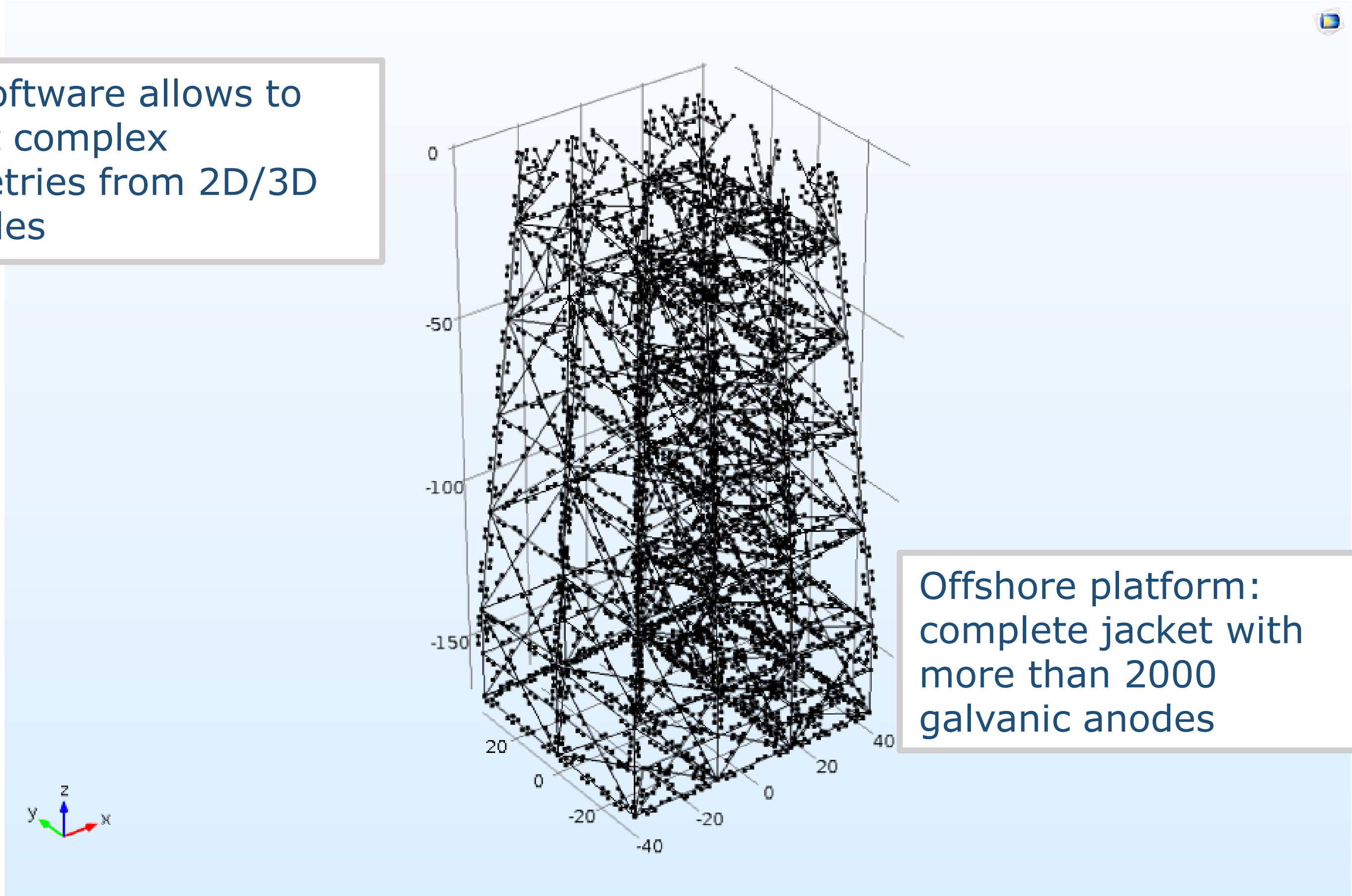




- Modelling takes into account for primary and secondary current distributions
- The domain is meshed by dividing the domain in small subdomains called elements, with different geometry (in 3D tetrahedral elements are mainly used)
- The number of elements is typically in the order of $10^5 \div 10^6$
- Mesh refinement is adopted for a more accurate solution near anodic and cathodic surfaces where the potential gradient could be greater

Geometry and mesh

FEM software allows to import complex geometries from 2D/3D CAD files



Offshore platform: complete jacket with more than 2000 galvanic anodes

FEM analysis. Cases of interest

FEM analysis: examples of cases of interest

- Design of CP systems for offshore structures with galvanic anodes
- CP retrofitting of offshore platform
- CP monitoring: reference electrode positioning and measurements interpretation
- CP of subsea pipelines with galvanic anodes
- CP of tank bottoms
- CP with galvanic anodes of heat exchangers and vessels
- CP inspection measurements interpretation
- Design of CP systems for subsea pipelines
- Interference at isolating joints.

CASE 1: CP of tank bottom internal surface

Cathodic Protection of tank bottom internal surface

- The bottom of above ground crude oil storage tanks consist of **welded steel sheets**, with thickness normally in the range of 6÷8 mm.
- The important difference between lower and upper side of the tank bottom is that lower side is not accessible, while the **upper side can be visually inspected and repaired** during shutdowns along the operating life
- In crude oil storage tanks, the upper side of the bottom is typically in contact with **water** originally entrapped or emulsified in the oil which **separates** by gravity permanently wetting the tank bottom.

- Internal corrosion can be caused by **oxygen dissolved** in water, or by **hydrogen reduction** in case of acid waters
- The consolidated approach to prevent internal corrosion is the **combination of an organic coating**, intended to reduce the metal surface in contact with water and consequently the protection current demand, **with galvanic anode CP** sized to maintain the bare steel surfaces below the protection potential

CP Design

Design of the galvanic anodes CP system shall consider a number of aspects, including:

- Metallic **surfaces** to be protected including surfaces which can drain anode current
- **Water** phase chemical analysis and **protection current density**
- **Design life**.

- In addition, **water hold-up** shall be considered in order to guarantee that protection conditions would be permanently achieved all over the tank bottom.

- Water hold-up determines the **maximum allowed spacing** amongst adjacent anodes.
- Cathodic protection is accomplished in accordance with applicable normative, but shall be integrated with case-by-case **verifications of the** galvanic anode **distribution**.

Study cases

The use of **Finite Element Method (FEM)** modelling is proposed as an advanced tool for optimization of anode spacing based on the expected potential distribution.

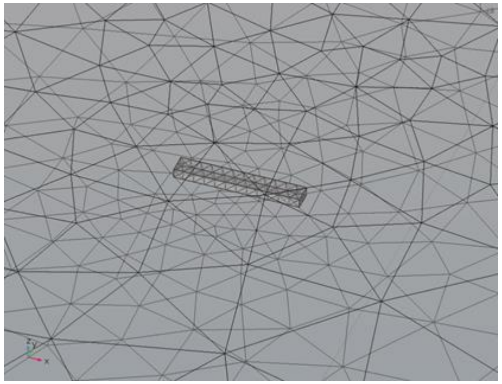
1. The first analysed subcase is the **throwing power of flush mounted anodes**, from which anode spacing depends. Modelling has been performed on a real end-life anode size. This is the most frequent case for protection when a **significant water hold-up** is present.

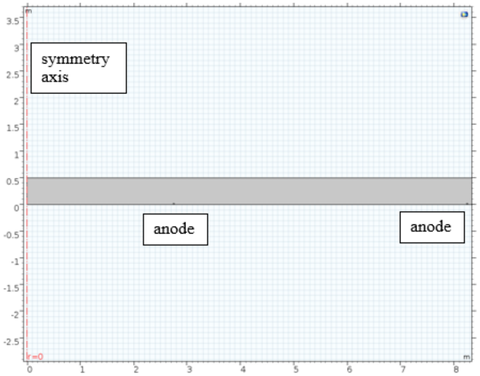
2. Whenever the risk of **low water hold-up** is high, CP design by **zinc ribbon** can be a viable alternative, since complete anode wetting is ensured. For this second subcase, spacing of helix positioning has been investigated.

In both subcases, modelling results have been compared with **empirical formulae** available in literature.

Methodology

- All cases described were modelled with Comsol® Multiphysics
- For flush mounted anode, the geometry is representative of the **end-life anode size** in a real case. Due to coating on the lower face, this surface has been considered as insulated.
- In the case of zinc ribbon, square sections, placed on tank bottom and with variable spacing, were used. It is assumed that this geometry is representative of **helix positioning**.





- Cathodic surface is the bottom line in case of tank protected by zinc ribbon and the bottom surface of cylinder in case of flush mounted anode.
- **Coating breakdown factor** equal to 25% has been conservatively considered as final value at the end of design life. Coating breakdown has been applied as reducing factor to protection current

Methodology

- As far as **boundary conditions** are concerned, **constant potential** equal to the anode potential was applied to **anodic surfaces** of galvanic anode systems.
- At the **cathodic surfaces**, the following equation, based on **Tafel equations** and oxygen limiting current, was applied:

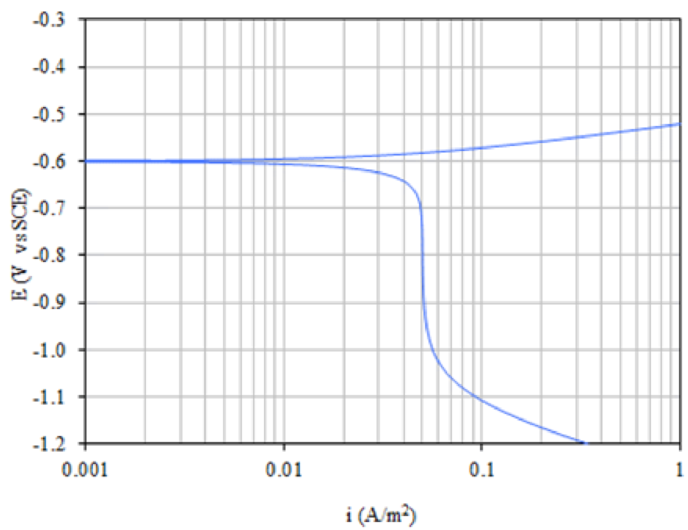
$$i = i_{corr} \cdot e^{\frac{-2.303(E-E_{corr})}{b_a}} - i_L - i_{H_2} \cdot e^{\frac{-2.303(E-E_{H_2})}{b_{H_2}}}$$

Summary of parameters

Parameter	Unit	Value
$i_{corr}=i_L$	mA/m²	50, 75, 100, 125, 150
E_{corr}	V vs SCE	-0.65
b_a	mV/dec	60
i_{H2}	A/m²	0.00002
E_{H2}	V vs SCE	-0.80
b_{H2}	mV/dec	120
cb	-	25%
Water hold-up (H)	m	0.05, 0.1, 0.2, 0.3, 0.4, 0.5
Resistivity (ρ)	Ωm	0.1, 0.2, 0.5, 1
E_{anode}	V vs SCE	-1.05

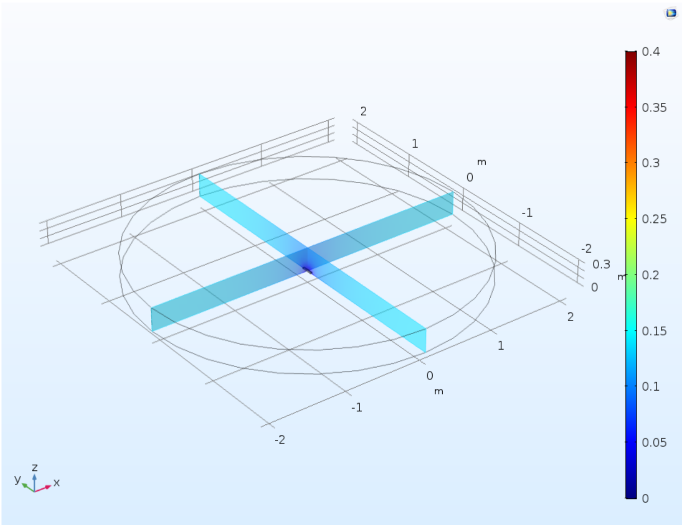
Protection current density

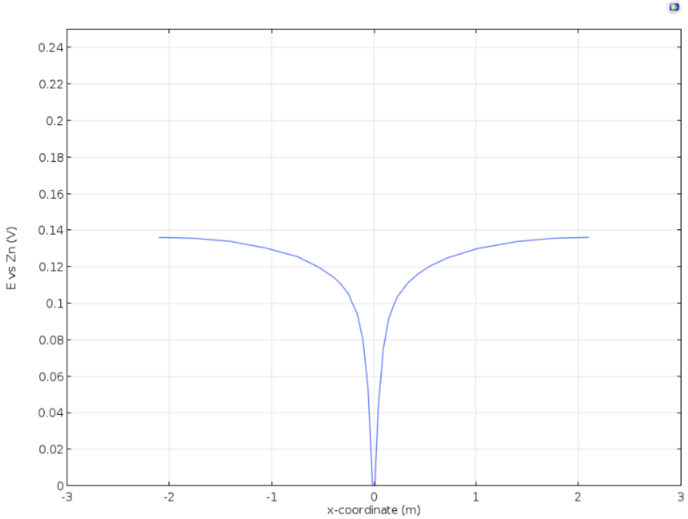
- As far as corrosion and CP are concerned, the **oxygen concentration** is the key parameter
- For above ground tanks, in which the oil phase can be considered in equilibrium with the atmosphere, the oxygen concentration in the water phase would be obtained from the **Henry’s Law**
- In practice, because the maximum solubility of oxygen in oil is averagely 80 ppm, the drained water can be considered as oxygen saturated, that is the range **5÷12 ppm depending on temperature**.
- In conclusion, the **oxygen limiting current density** can be estimated as a minimum in the range **50÷120 mA/m²**.



Subcase 1A: Comparison of results obtained by FEM and empirical equations for flush mounted anodes

- The first case study is aimed to verify conservativeness of available **empirical throwing power formulae** through the application of FEM modeling
- **Iterative runs** have been carried out by varying the radius of protected surface surrounding the anode
- It has been found that with **2.1 m** radius, corresponding to 4.2 spacing ΔL between anodes, protection conditions, assumed to be +150 mV vs Zn for protection in anaerobic condition, are achieved





Subcase 1A: Comparison of results obtained by FEM and empirical equations for flush mounted anodes

- According to Lazzari, the **throwing power** Lmax of galvanic anode inside a pipe or through a layer can be calculated as:

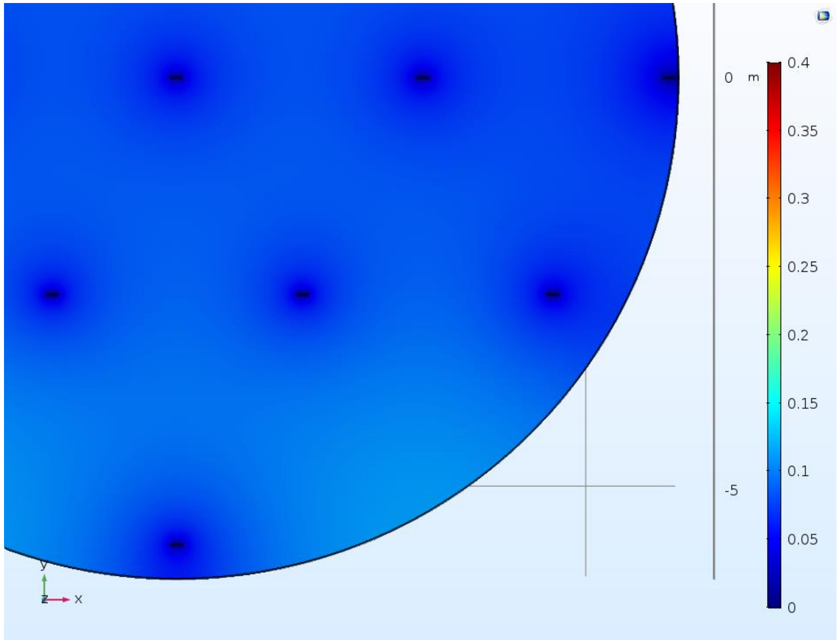
$$L_{max} \cong \frac{1}{\sqrt{2}} \sqrt{\frac{\Delta V \cdot \varphi}{(\rho + 0.8) \cdot (i + 0.1)}}$$

- Where ΔV is the driving voltage in mV, in this case 150 mV, φ is the diameter of the pipe or the width of the layer, ρ the water resistivity in Ωm and i the current density in mA/m^2
- Assuming φ equal to the water hold-up H, the maximum throwing power of anode is equal to **1.54 m** (< 2.1 m)

- Calculated value is then **conservative** with respect to the real potential distribution expected on tank bottom based on FEM modelling

Subcase 1A Comparison of results obtained by FEM and empirical equations for flush mounted anodes

- In fact, by verification of the final positions of anodes on the tank bottom with 3 m spacing, i.e. 2 times the throwing power of 1.5 m, it can be observed that maximum potential is much lower than the limit value of +0.15 V vs Zn and that **CP design was conservative**
- Application of **FEM modelling** is always recommendable since the real geometry and number and distance of anodes may produce some mutual **synergistic or interference effects**.



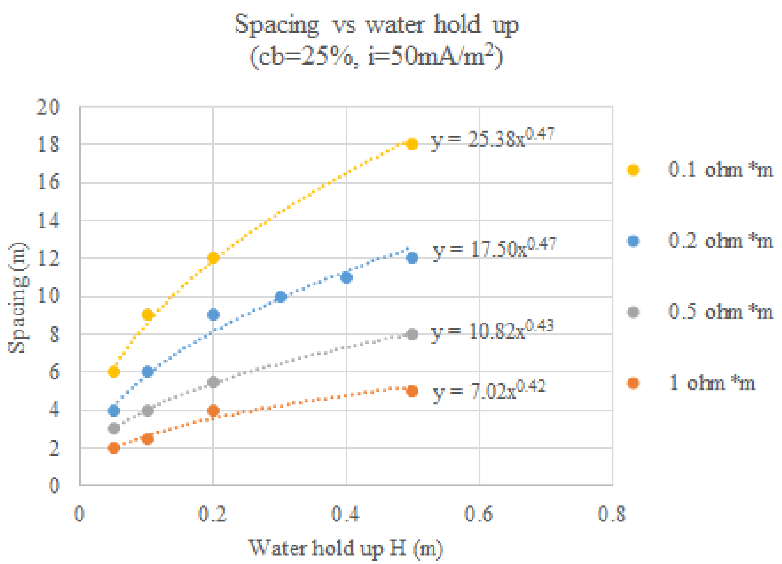
Subcase 1B: Protection by zinc ribbon

- A number of simulations have been carried out, by **varying parameters**
- Simulation runs have been iteratively performed until reaching protection target, and only final results are reported
- The second part of the table provides results for **sensitivity analysis** with respect to the **protection current density**.

Spacing	i_L	cb	Resistivity (ρ)	Water holdup H	max potential E	max potential E
m	A/m²	%	Ωm	m	mV vs SSC	mV vs Zn
5.0	0.05	25%	0.2	0.1	-958	92
6.0	0.05	25%	0.2	0.1	-921	129
7.0	0.05	25%	0.2	0.1	-887	163
8.0	0.05	25%	0.2	0.1	-839	211
9.0	0.05	25%	0.2	0.2	-900	150
10.0	0.05	25%	0.2	0.3	-921	129
11.0	0.05	25%	0.2	0.4	-927	123
12.0	0.05	25%	0.2	0.5	-928	122
2.0	0.05	25%	1	0.05	-911	139
2.5	0.05	25%	1	0.1	-935	115
4.0	0.05	25%	1	0.2	-893	157
5.0	0.05	25%	1	0.5	-921	129
3.0	0.05	25%	0.5	0.05	-894	156
4.0	0.05	25%	0.5	0.1	-906	144
5.5	0.05	25%	0.5	0.2	-905	145
8.0	0.05	25%	0.5	0.5	-905	145
6.0	0.05	25%	0.1	0.05	-923	127
9.0	0.05	25%	0.1	0.1	-906	144
12	0.05	25%	0.1	0.2	-917	133
18	0.05	25%	0.1	0.5	-920	130
Current density sensitivity analysis						
10	0.05	25%	0.2	0.3	-921	129
9	0.075	25%	0.2	0.3	-893	157
7	0.1	25%	0.2	0.3	-919	131
6	0.125	25%	0.2	0.3	-927	123
5.5	0.15	25%	0.2	0.3	-925	125

Subcase 1B: Protection by zinc ribbon

- In a first step, spacing result data (ΔL) have been plotted vs water hold-up H, as a function of seawater resistivity.



- All interpolation curves have a similar trend with a dependency that is approximately described by:

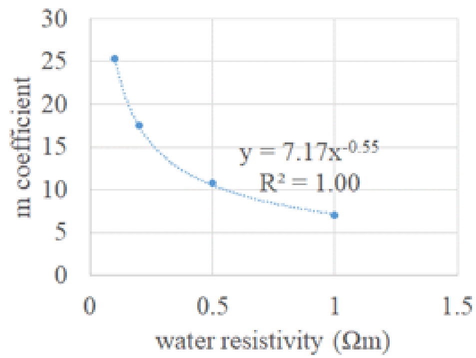
$$\Delta L \propto m \cdot H^{1/2}$$

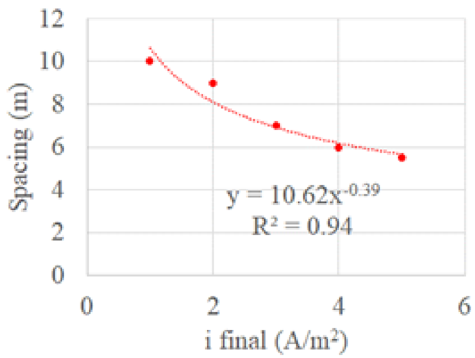
- The coefficient m is variable depending on the water resistivity.

Subcase 1B: Protection by zinc ribbon

- Values have been then expressed as a function of it
- An approximately parabolic dependency was found, then

$$m \propto const \cdot \frac{1}{\sqrt{\rho}} \Rightarrow \Delta L \propto const \cdot \frac{1}{\sqrt{\rho}} \Rightarrow \Delta L \propto const \cdot \sqrt{\frac{H}{\rho}}$$





- In a second step, the dependency on the total final current density *i*, calculated by i_L multiplied by *cb*, was investigated
- The relationship between spacing and final current density is once again of parabolic type

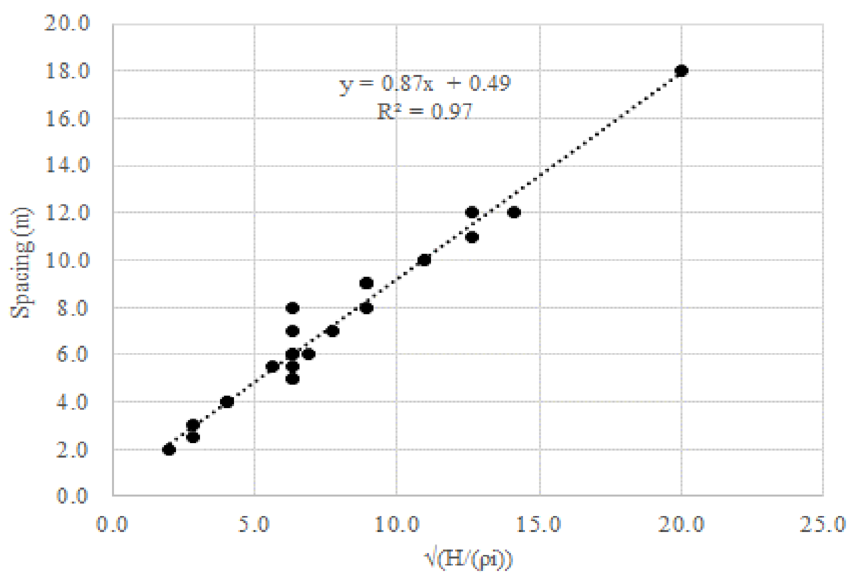
$$\Delta L \propto const \cdot \sqrt{\frac{1}{i}} \Rightarrow \Delta L \propto const \cdot \sqrt{\frac{H}{\rho i}}$$

Subcase 1B: Protection by zinc ribbon

- By plotting previous parameters, the following formula for maximum zinc ribbon anode spacing in tanks with water hold-up *H* can be derived:

$$\Delta L = 0.5 + 0.9 \cdot \sqrt{\frac{H}{\rho i}}$$

- Where maximum spacing ΔL (in m) and water hold-up H are expressed in m, water resistivity ρ in Ωm and final current density i in A/m^2



Subcase 1B: Protection by zinc ribbon

- Previous equation includes the effect of **<u>driving voltage</u>** (150 mV), since protection potential and anode potential are fixed
- The equation assumes the **<u>typical aspect of throwing power relationships</u>**, i.e.:

$$\Delta L = const \cdot \sqrt{\frac{\varphi}{\rho i}}$$

- Where in this case the characteristic length φ is coincident with water hold-up H.

CASE 1 - Conclusions

- Cathodic protection of **above ground storage tank internal** surface has been investigated.
- The application of **Finite Element Method (FEM) modelling** has been considered in order to improve and optimize anode spacing.
- Two subcases have been analyzed:
  - throwing power from **flush mounted anode**, i.e. the typical solution adopted when a significant water hold-up is expected and
  - protection by **zinc ribbon** on tank bottom, i.e. the most appropriate solution for cases where small water hold-up is foreseen.
- Empirical formulae available in scientific literature has been confirmed to be conservative with respect to simulation results, and suitable for CP design. However further **optimization** can be achieved through modelling, due to the possibility to verify the final **realistic distribution** on tank bottom.
- For the zinc ribbon, a **simple formula** for calculation of spacing in case of circular and helix positioning has been derived from simulation data.

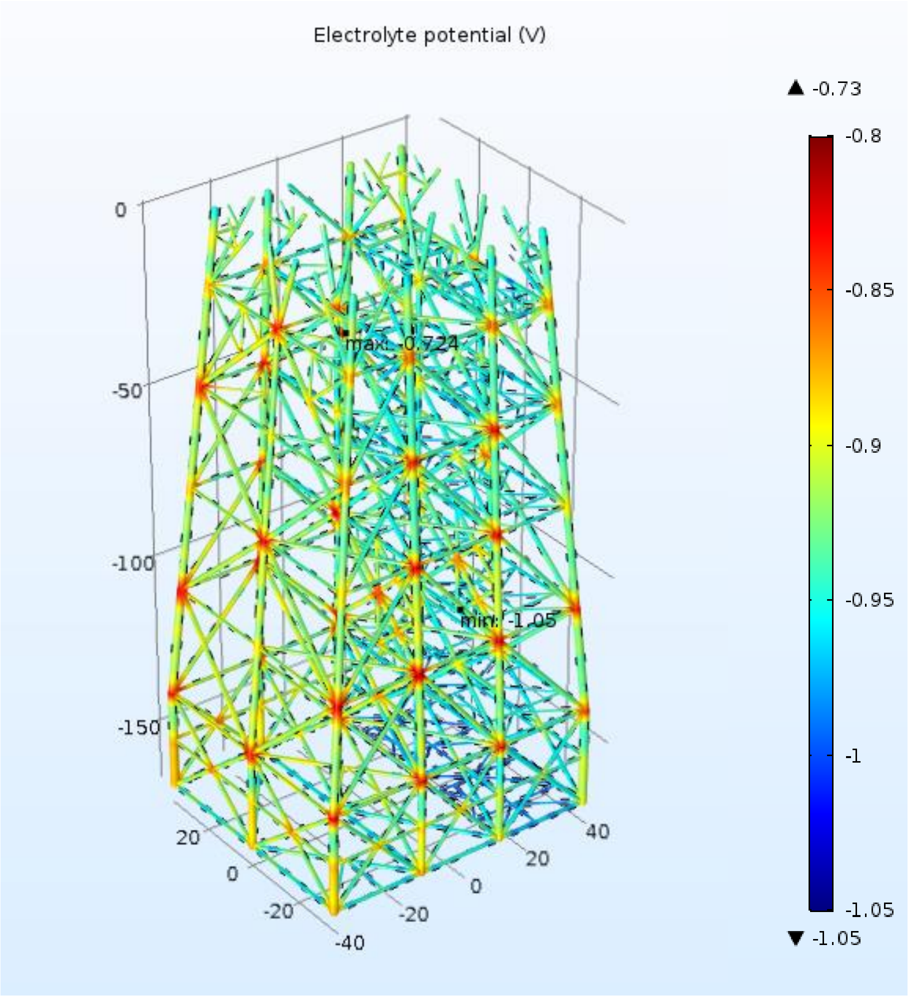
CASE 2: Cathodic Protection retrofitting

Cathodic Protection Retrofit

- Sometimes offshore assets need to be maintained beyond their design life, because production is still significant.
- This requires a **requalification** process, including also **CP retrofit**.
- Currently, no specific international standards are available for the design of CP retrofitting systems. However the design of CP retrofit systems is significantly different from the case of new structures:
  - the **installation** of CP retrofit systems is carried out with the facility at site, not in the yard.
  - **protection current** for in-service assets is strongly influenced by the **calcareous deposit** covering these structures.

CP Modeling

- **Modeling** of the electrical field represents an essential tool in CP retrofit design, allowing to verify **current demand, protection conditions** and to select the most adequate anodic configuration.
- In some cases it even allows to identify conditions where no retrofitting is required, with consequent **savings** for oil companies.



Case Histories

- This section of the presentation illustrates a few case histories of applications of the Finite Element Method (FEM) and Boundary Element Method (BEM) modeling, taken from **CP retrofit projects**:

  - Subcase 2A Offshore platform protected by galvanic anodes
  - Subcase 2B Offshore platform retrofitted by impressed current system
  - Subcase 2C Subsea pipeline retrofitted by galvanic anode sleds
  - Subcase 2D Single Point Mooring retrofitted by galvanic anodes clamp and pods

- The geometry and main environmental parameters were modelled. Boundary conditions included the corrosion electrochemical processes.

Subcase 2A: Offshore platform protected by galvanic anodes

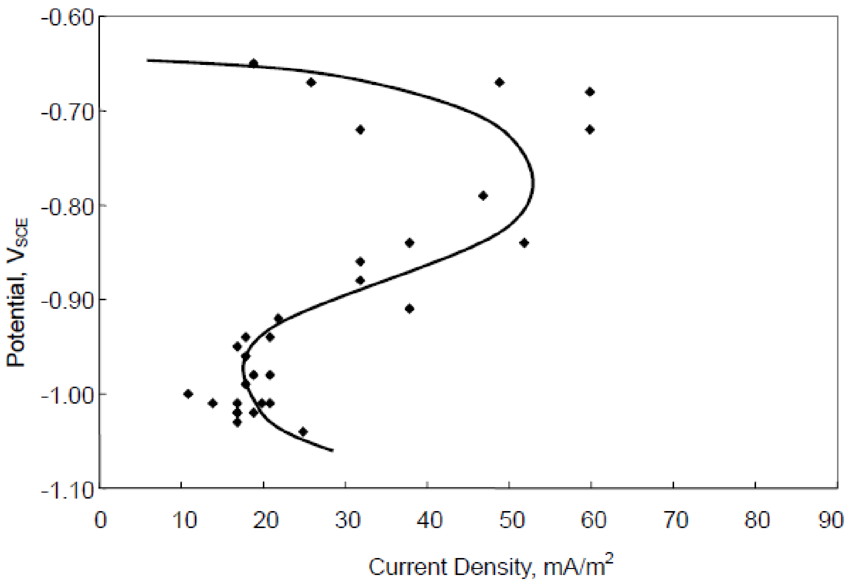
- Removal of a number of slender stand-off aluminum anodes and the installation of new structures on a platform jacket

Aim: **to verify any need of retrofit intervention**.

Two conditions were considered:

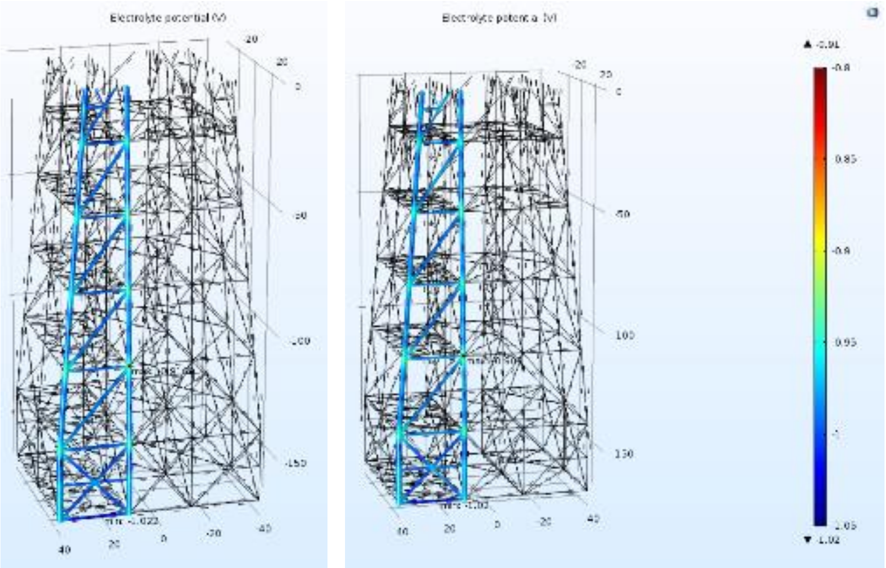
- Present-day scenario: expected maintenance current density of 25 mA/m^2 due to the formation of a protective calcareous deposit on cathodic surface at potentials lower than -0.90 V vs Ag/AgCl
- Worst case scenario: anodes at end life and repolarization required; expected current density of 50 mA/m^2. Cathodic surface is assumed to have lost or damaged protective layer of calcareous deposit Potential approaches -0.80 V vs Ag/AgCl owing to depolarization

Hartt et al.



Subcase 2A: Offshore platform protected by galvanic anodes

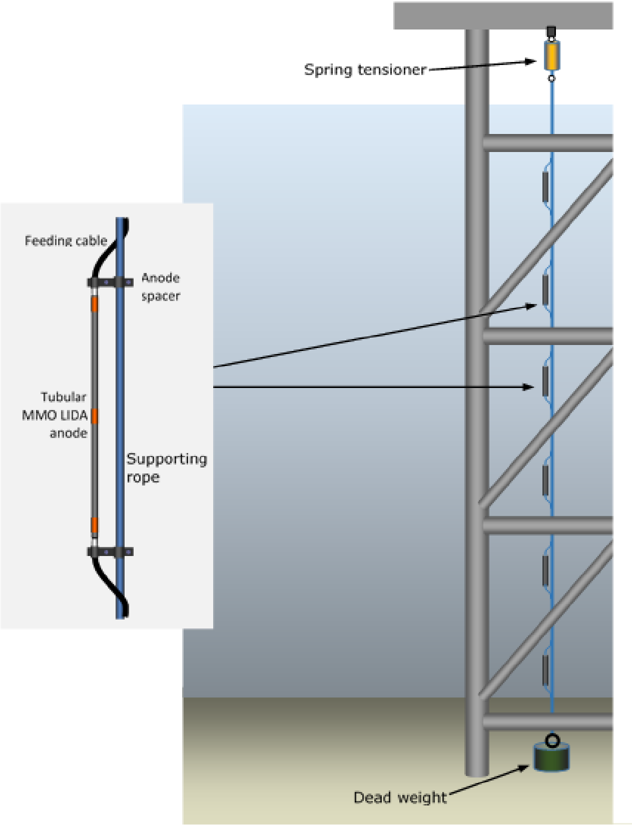
- FEM results pointed out that the platform structure is currently in good **protection conditions** (-0.88÷1.05 V vs AAC), in perfect accordance with the results of the **inspection campaign** performed one year before anode removal.
- Under the **worst case scenario** the jacket still remains in correct protection conditions, even if the nodes are close to the limit for full protection.



- Removal of anodes does not have significant impact on the overall and local protection conditions of the platform, and therefore a **retrofit intervention was unnecessary**.
- Additional local **measurements confirmed** the potential **values predicted by model**. Also the current density value at cathode has been therefore confirmed and validated.

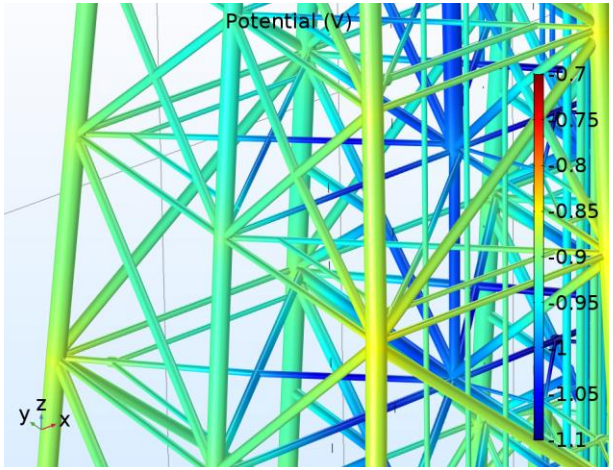
Subcase 2B: Offshore platform retrofitted by impressed current system

- An **offshore platform** installed in 100 m water depth reached the end of the original design life, however the original galvanic anode (GA) CP system was not yet depleted and the structure **was in protection conditions**
- In order to achieve requalification and **life extension**, retrofitting of the CP system was foreseen
- Impressed current retrofit system was considered, the selected solution was the **tensioned string of anodes (TSA)**, based on Ti-MMO.
- Analogous system (TSRE) is provided with zinc reference electrodes
- Modeling has been performed considering 30 mA/m^2 current density at cathode

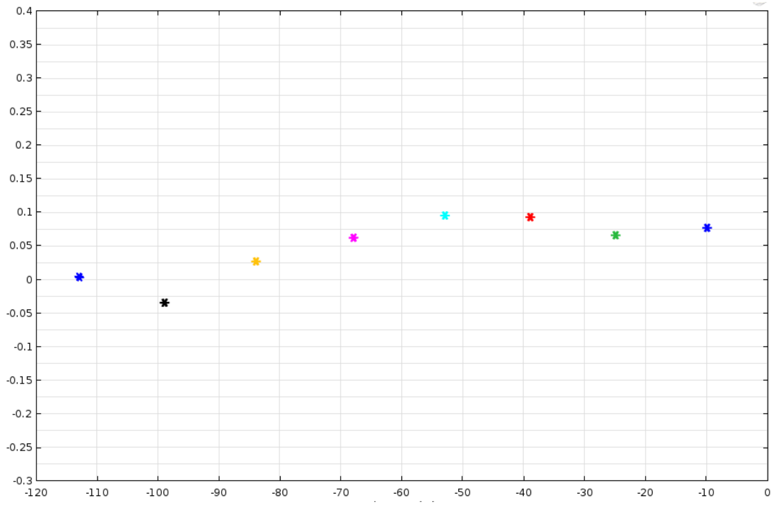


Subcase 2B: Offshore platform retrofitted by impressed current system

- **Protection conditions** are reached on all the platform elements.
- Any occurrence of **overprotection** conditions has been verified: bracing and other elements near titanium anodes have negligible and acceptable overprotection values.
- Anyway, no high strength steels susceptible to hydrogen embrittlement have been used for this platform and appurtenances



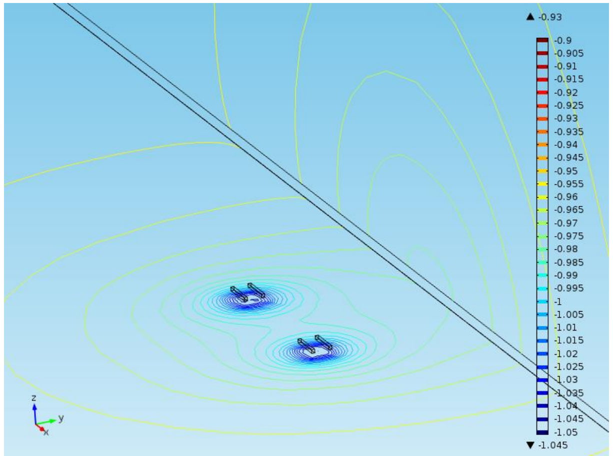
BEM modeling results for potential distribution (V vs Ag/AgCl)



Potential (V vs Zn) vs elevation (m) predicted for reference electrodes of TSRE

Subcase 2C: Subsea pipeline retrofitted by galvanic anode sleds

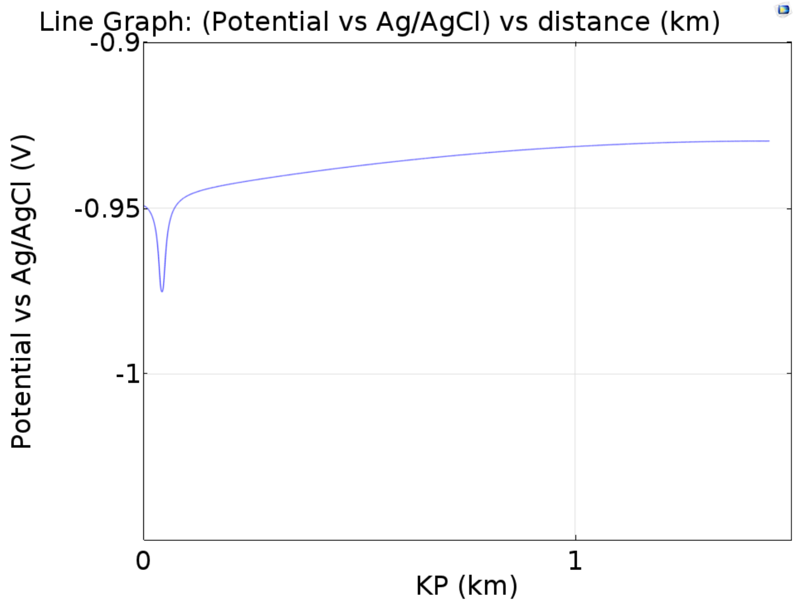
- The use of **GA sleds** with **aluminium anodes** have been considered.
- The subsea pipeline (3 km long, 16" diameter), is protected by bracelet galvanic anodes. During last CP inspections, anode consumption was found to be in the range 50÷100%.
- Thus **retrofitting** of the existing CP system was investigated. Selected CP retrofitting system was based on 8 sleds, each one with 2 anodes.



- FEM analysis has been carried out in order to verify that the installation of n. **4 sleds at each end** provides CP of the whole pipeline.
- Both small evenly distributed defects and large defects localized in middle zone, i.e. the worst case, were modelled.

Subcase 2C: Subsea pipeline retrofitted by galvanic anode sleds

- Results showed that the pipeline potentials are always in the **protection range** -0.90 to -1.05 V vs Ag/AgCl. Also in this case, modeling results were found to be in line with **subsea CP inspection data**.



potential along the pipeline (note: only half pipeline shown)

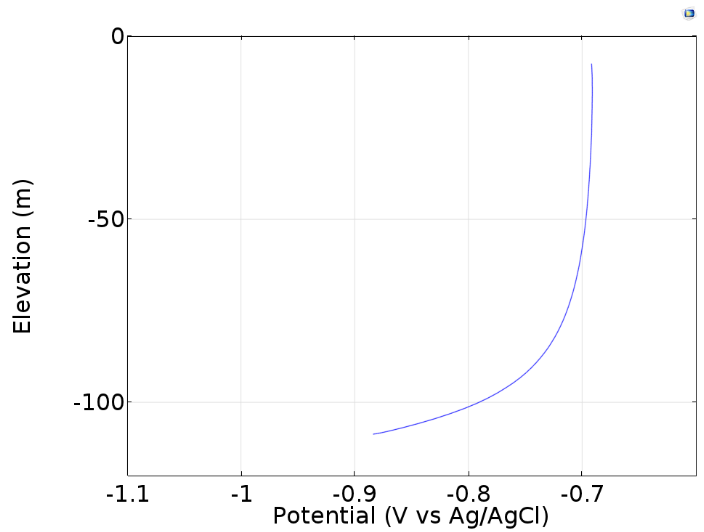
- Support of FEM was essential in order to define the locations of anode sleds near the ends of this pipeline, resulting in **optimization of installation** activities and **reduction of costs**.

Subcase 2D: Single Point Mooring retrofitted by galvanic anodes clamp and pods

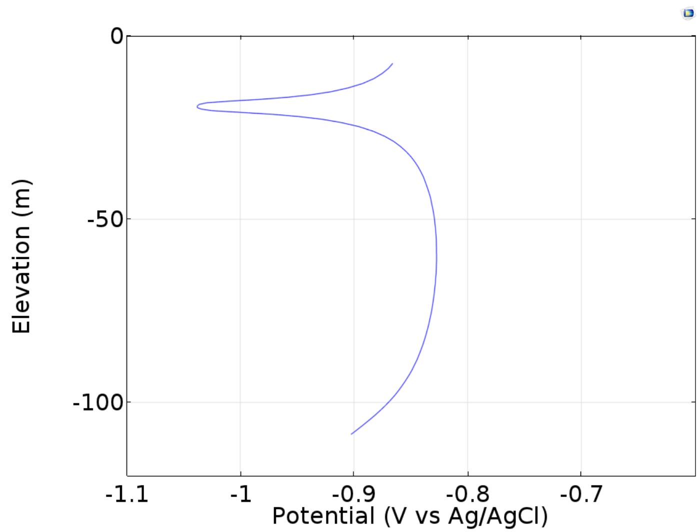
- The SPM was installed in late ‘80s, it is 100 m height with coating applied only for a few meters in the splash zone.
- Owing to the **lack of availability of electrical power** sources, retrofitting with galvanic anode systems has been considered and developed.
- At first, the possibility to protect the entire structure only with **anode pods** (with slender stand-off aluminum anodes) laid on sea bottom was analyzed.
- In order to provide protection for overall structure, an **integration of anode pods with a clamp** supporting additional slender stand-off aluminum anodes, fixed in the upper zone, has been developed.

Subcase 2D: Single Point Mooring retrofitted by galvanic anodes clamp and pods

- FEM model showed that, with **anode pods only**, protection was achieved for about 20 m from the bottom, whereas protection current could not reach the middle and upper portions of the SPM column.
- With mixed solution (**pods + upper clamp**), modeling showed that **protection is achieved** even in the middle zone of the column



Anode pods



Anode pods + Upper clamp

CASE 2 - Conclusions (1/2)

- A number of **application cases** of **FEM/BEM modeling** to design of cathodic protection **retrofit** systems have been discussed.
- No standards are currently available for the design of CP retrofit systems, and a **different approach** and design bases, taking into account the actual polarization of structures, shall be considered. In such a frame, modeling can provide an important tool for CP engineer in order to select and later optimize protection system.
- The use of modeling provides a **realistic picture** of the conditions of the structure, and help with the decision of apply CP retrofit actions or not.
- When conditions require to start with retrofit, in particular when it is possible to rely on galvanic systems not totally depleted yet and structures well polarized and covered by calcareous deposit, FEM/BEM modeling assists in the selection of **most effective solution**, together with considerations related with installation and economic issues.

CASE 2 - Conclusions (2/2)

- Configuration of the protection system is **optimized** with respect to **layout**, verifying throwing power of anodes and absence of under-protected areas, considering presence of coating, such as for pipelines, or bare metal surface conditions typical of platform jacket, SPMs, and other structures.
- For impressed current systems, **risk of overprotection** with consequent possible hydrogen embrittlement of susceptible steels and coating disbonding, if any, is avoided by ensuring that optimal protection range is not exceeded.
- Also the **interpretation of monitoring and inspection data** is enhanced by comparison and extrapolation with data provided by the model of protection and current density distribution.

Thanks for your attention!

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Questions