

Effect of Soil Conductivity on the Design of Cathodic Protection Systems Used in the Prevention of Pipeline Corrosion

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Abstract. One of the most influential factors affecting the rate of corrosion of a buried pipeline and the design of the cathodic protection systems is the conductivity of the soil. The present paper is designed to study the effect of this factor on the design of cathodic protection systems, i.e. the current required to achieve comprehensive protection. Several corrosive environments were studied within the laboratory. The classification of environment corrosivity approved by ASTM was the base of the categorization of these environments. These environments were simulated by adding certain amount of distilled water mixed with weighed amount of sodium chloride to the soil. Several runs were carried out, whereas the conductivity of the soil and the linear polarization curves for the cathode and the anode were obtained during each run. The boundary element method (BEM) was used to compute the total current required using linear polarization curves as the boundary conditions for calculations. The BEASY software based on BEM was used to compute the total current required. The relationship between the total current and the soil conductivity values were drawn. Two equations governing and controlling this relationship were derived.

1. Introduction

Designing and optimization by utilizing computer programs have been applied primarily to cathodic protection systems in the seawater of relatively high uniformity and conductivity. Buried structures have not been modeled readily because of the added complexity of a non-uniform, low conductivity electrolyte. However, modeling would appear to be a likely candidate for future development in impress-current cathodic protection systems in view of the large current and potential field that must be present and the inaccessibility of the protected surfaces in buried structure. As computation methods develop, modeling will probably become further limited by a lack of experimental data to feed the model. Polarization data as a function of time and scale formation have not been determined for most practical environmental conditions (Jones, 1996).

The selection of a suitable current density output is critical for the cathodic protection designers. Indeed, some publications are misleading in that they imply that a fixed current density is sufficient to provide cathodic protection in all circumstances. The current density requirement is extremely dependent on the structure corrosion rate that stated before cathodic protection system is applied. For example, if the surrounding environment of the structure is alkaline, there is little chloride present, the diffusion rate is very low and the structure is not actively corroding, a very low current density is sufficient to prevent any corrosion. At the opposite extreme, areas with minimal cover, a warm, wet, fluctuating environment with high oxygen and chloride levels will have a very high current density requirement (Tomashov, 1996). When a metallic structure is immersed or buried in a conductive medium, the ability of the medium to carry current will influence the magnitude of galvanic currents and cathodic

protection currents as well (ASTM G-57, 1995). Soil is a complex, dynamic environment that changes continuously and seasonally, both chemically and physically.

Amaya and Aoki (2005) introduced certain objective function (Eq. 1) describes the relationship between the current density required (in terms of power) and several parameters such as the polarization curves of the electrodes (cathode and anode), the depth of the anode and the cost to lay the anode underground, etc.

$$P(i, x) = f(i_e) + k_{zo} z_e \quad (1)$$

where:

P = the power in Watt

x = the distance of the anode in meter

i = is the current density in A/m^2

$f(i_e)$ = the polarization curves of cathode and anode

k_{zo} = the coefficient to lay the anode underground

z_e = the depth of the electrode

The precise determination of the soil conductivity and its relationship to cathodic protection current will affect the performance and economics of any cathodic protection system. This work is an attempt to establish a relationship between the soil conductivity and the required cathodic protection current.

2. Theoretical background and Experimental Procedure

2.1. Theoretical background

A variety of computational methods have been applied to the analysis of cathodic protection systems. These methods have been used on a wide variety of structures. There are significant advances in modeling applications, but still some areas in which computational modeling approach can be further developed and even improved. More complex models for electrochemical system can be treated with general numerical techniques. The choice of these packages is based on software characteristics (availability, cost and support), hardware requirements, generality, and efficiency. The model provides a powerful technique to obtain the required solutions. Sun and Liu (2000) use Newton-Raphson iterative method for the calculation of current and potential distribution of cathodic protection models with nonlinear polarization curves. Boundary element technique has been found to be suitable for modeling corrosion problems (Yan *et al.*, 1993) as only the surface has to be defined and values of potential and

current density are computed with high accuracy on the metal surfaces. These processes give prediction and simulation with high accuracy and reliability (Degiorgi *et al.*, 1999).

The equation governing the current flow and the potential in the electrolyte can be derived from first principles. The continuity equation (charge conservation) requires that the current per unit volume I relate to the charge q by (Jia *et al.*, 2004):

$$-\nabla \cdot I = (\delta q / \delta t) \quad (1)$$

For a system in steady state, $(\delta q / \delta t) = 0$. Taking into account the relationship of electric field intensity, E ,

$$E = -\nabla \Phi \quad (2)$$

and Ohms law,

$$I = k E \quad (3)$$

where k is the conductivity of the electrolyte. The continuity equation transforms to

$$\nabla \cdot k \nabla \Phi = 0 \quad (4)$$

For an electrolyte with uniform, isotropic conductivity, k is a constant, so that,

$$\nabla^2 \Phi = 0 \quad (5)$$

Therefore, for a uniform, isotropic electrolyte, the potential obeys Eq. (5) which is the Laplace equation. The current density, at any point inside the electrolyte (soil) can be evaluated by (Jia *et al.*, 2004).

$$I_{xi} = -k (\delta E / \delta xi) \quad (6)$$

where

I_{xi} is the current density flowing in xi direction

κ = soil conductivity at a point x

The BEM is the most flexible method to solve Laplace equation. This method was the focus of this study. The boundary element method (BEM) reduces Laplace's equation (Eq. 5) for the electrolyte domain to surface equation by the application of Green's Theorem. The structure's surface is discretized into a number of surface elements, and Laplace's equation is transformed to a linear system of Eqs. (1) and (2). BEASY software provides the facility to solve Laplace's equation (Eq. 5) by converting the method

of solution to numerical methods with a set of linear equations.

The governing Eq. (6) will be the base of the designing approach of the cathodic protection system. This equation is re-written as below:

$$i_{(x)} = - \kappa_{(x)} (dE/dx) \quad (7)$$

where:

$i_{(x)}$ = the current density vector in A/m^2

κ_x = soil conductivity at a point x in $ohm^{-1}.m^{-1}$

dE = difference in potential at point x in V

dx = difference in distance along the pipe length at point (x) in m

2.2. Material

2.2.1. Cathode material

The cathode in this system is the pipeline, which is generally manufactured from carbon steel, the chemical compositions, fabrication history of specimens are all required. Sizes and wall thickness of the selected pipe samples are presented in Table 1. Beyond material traceability, another vital element of process control is monitoring and controlling critical variables such as the welding process. The balance of properties required depends on the intended use of the pipeline, to obtain strength and toughness requires complex thermo-mechanical treatment of the steel. The large pipe sample is used for the transportation of the crude oil and petrochemical products, while the small one is used for the transportation of natural gas. These pipelines were manufactured based on the American Standards for Testing and Materials (ASTM), standard No. ASTM A-53.

2.2.2. Anode material

The type of anode utilized in the application of cathodic protection systems is playing a very important role in both types of CP techniques, impressed current and sacrificial anode. The selection of anode type for cathodic protection systems is based on engineering and economic considerations. Various anodes types are commercially available. The anode selection has implications for the size, layout and number of zones and also has important implications in the current distribution and maximum density that can be applied. In this study, the impressed current cathodic protection system has been investigated. Of the types of anodes used in impressed current, high silicon iron cast anode is the most widely utilized.

3. Laboratory Tests and Techniques

The purpose of the laboratory measurement, in this work, was to collect data to establish the optimum design of the cathodic protection system. The reliable way to determine the corrosion rate and the effectiveness of the utilized cathodic protection system is to expose the metal to real service conditions and assess the corrosion in that particular case (Ailor, 1973).

The following laboratory tests were considered and achieved according to specific engineering standards.

3.1. Soil conductivity measurement

In clayey soils, a significant portion of the conductivity (electrical conduction) occurs within the ionic structure of the clay minerals and the soil moisture. The soil conductivity will be responded to several factors such as the variations in water content and variation in clay content (Northwest Geophysical Associates, 1997).

Four different soils were selected for soil conductivity tests. These sites are Riyadh, Jeddah, Madinah, and Qassim. The selection was based on the existing buried pipeline projects located nearby these selected areas. The conductivity of the selected pipe samples was measured in-situ (as collected). Also, the measurement of soil resistivity with a specific amount of distilled water mixed with sodium chloride was implemented by using Perspex box. This box was constructed with approximately dimensions (100 x 150 x 300 cm) and filled to a depth of 40 cm with soil sample. The amount of distilled water was with a certain amount of sodium chloride to simulate various environments based on the corrosivity classification standards (Escalante, 1995).

3.2. Electrochemical techniques

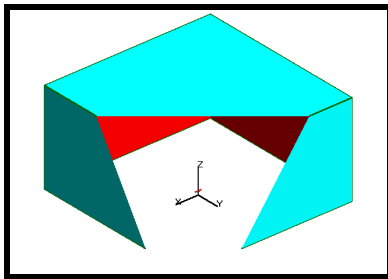
Although the burial of metal specimens can provide positive evidence of soil corrosivity, the testing is time-consuming and specimens must be unearthed to provide the data. Within recent years, however, electrochemical technique methods have been developed, which can provide a numerical value for the corrosion rate and which can be conducted remotely. This procedure permits the corroding specimen to remain undistributed in its environment. Electrochemical studies to determine corrosion rates of buried metals in soil have already been reported by Schwerdtfeger (1961), Lindberg (1967), and Jones and Lowe (1969).

Table 1. Pipelines characteristics

Standard Specification	Grade	Application	Pipe Size	Outside Diameter (mm)	Wall Thickness (mm)	Length (mm)
ASTM	A53	Carbon Steel Pipes for Industry Piping	Large	180	7.92	1000

Three electrodes are used: the working electrode which is the pipe samples (the metal of interest), the reference electrode, i.e. in this study copper/copper sulfate was used to measure the potential of the working electrode, and the counter electrode (stainless steel mesh) which was used to apply current to the working electrode (Jones, 1981). ACM instrument potentiostat was used for measurements.

For the calculations purposes, the creation of a pipeline model with 7500 m length and outside diameter of 0.273 m was carried out as illustrated in Fig. 1. The total surface area of this pipe was $4.432 \times 10^3 \text{ m}^2$ high silicon iron cast 8 anodes were installed 20 m distance away from the pipeline. Each anode was 2.14 m length with 0.12 m as an outside diameter and the surface area of each anode was 0.806 m^2 . It is very important to notice that the specifications of this model were based on the existed cathodic protection system. The polarization data of the cathode and anode is playing very significant and important role in determining the value of the protection current given by the anode.

**Fig. 1. Model soil box for coated pipe.**

Ten completed runs of calculations took place in this stage as shown in Table 2. The total current required to protect the above mentioned pipeline was calculated by applying the model techniques and considering the polarization data of the cathode and anode as the boundary condition. The boundary conditions are given and included within the material file data. This material file data has to have a certain format as shown in Table 2. The data tabulated in this file is consisting of the polarization data measured with respect to copper/copper sulfate for the cathode and the anode. Also, the conductivity values, the formation, season data and the name of the reference electrode, etc., are tabulated in this material file.

The methodology of investigation and studying the effect of the soil conductivity (resistivity) on the current density required for the protection (power) is that, for each run implemented by the model, the total current will be calculated and then compared with the total current applied within the existed cathodic protection system.

Table 2. Soil resistivity measured and maintained during electrochemical tests

1	Essentially Non-corrosive	50,000	2
2	Essentially Non-corrosive	25,000	4
3	Mildly Corrosive	12,500	8
4	Moderately Corrosive	6,250	16
5	Corrosive	4,167	24
6	Corrosive	3,125	32
7	Highly Corrosive	2,000	50
8	Highly Corrosive	1,250	80
9	Extremely Corrosive	1,000	100
10	Extremely Corrosive	833	120

Table 3 shows the results of the achieved runs where the total current required for the cathodic protection system was calculated. It is very obvious from the table that, with increasing the soil conductivity, the total current i is increased. This relationship is vice versa between the resistivity and the total current required, i.e., with decreasing soil resistivity, the total current required is increased.

The values of Table 3 were plotted in Fig. 2, where x-axis is representing the soil conductivity in mS/m, and the y-axis is representing the total current required (given) to the cathode (pipeline) to achieve the protection in mA.

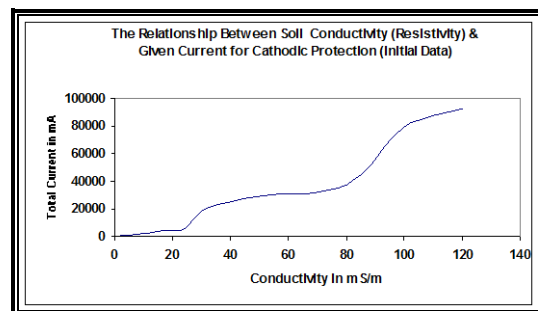
**Fig. 2. The relationship between soil conductivity (resistivity) and given current for cathodic protection system (initial data).**

Table 3. The results of model runs

No.	Resistivity (ohm.cm)	Conductivity (mS/m)	Total Current (mA)
1	50,000	2	474
2	25,000	4	952.6
3	12,500	8	1912
4	6,250	16	3803
5	4,167	24	5688
6	3,125	32	20564
7	2,000	50	29131
8	1,250	80	37462
9	1,000	100	79000
10	833	120	92488

After performing the fitting and trying to find the best trend line matching the results plotted in Fig. 3, general mathematical equations describing this figure are given and presented in Eqs. (8) and (9). These mathematical functions were defined within two main conductivity zones as per the following equations.

$$I = C_1 \times \kappa \quad \text{where } 2 \leq \kappa \leq 60 \quad (8)$$

$$I = C_2 \times e^{C_3 \times \kappa} \quad \text{where } 120 \leq \kappa \leq 61 \quad (9)$$

where:

I = Total current required in mA

e = Exponential function

κ = Soil conductivity in mS/m

C_1 = Constant in (mA. m/mS) depends on the boundary conditions

C_2 = Constant in (m/mS) depends on the boundary conditions

C_3 = Constant in (m/mS) depends on the boundary conditions

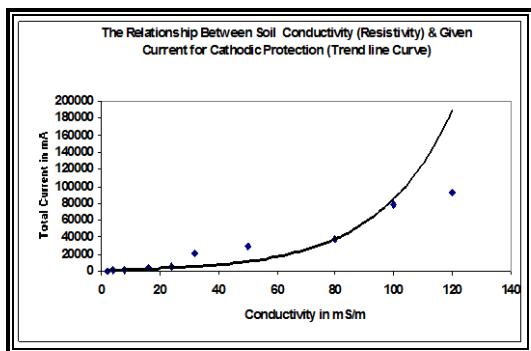


Fig. 3. The relationship between soil conductivity (resistivity) and given current for cathodic protection system (trend line curve).

After solving the above equations and considering the polarization data for the cathode and anode as the boundary conditions, the following two empirical equations were obtained.

$$I = 237 \kappa \quad (10)$$

where $2 \leq \kappa \leq 60$

$$I = 1895 \times e^{0.0373 \times \kappa} \quad (11)$$

where $120 \leq \kappa \leq 61$

It is very clear from the above two equations that the total current increased due to the increase in soil conductivity. On the other hand, when the soil conductivity is decreased, soil ohmic resistance increases and, as a result, total current decreases. In the second interval (Eq. 11), surface kinetics dominates and a secondary current distribution is obtained, and this means that the current required to perform the protection will not be an infinite value due to the formation of deposits on the pipe surface, while primary current distribution is obtained, in the first interval where Eq. 10 is valid. Moreover, the above two equations are valid only for a pipeline with a total length of 7500 m and 8 anodes. In other words, the coefficients of these equations are dependent on the boundary conditions of the system, and the formation of surface deposits on the pipe. Figure 2 is describing the relationship between the soil conductivity and total current required according to the above two equations.

The soil conductivity is playing two main roles in this case. The first one is with increasing the humidity of the soil, the possibility of corrosion becomes more and this means more impressed current has to be given to stop this phenomenon. On the other hand, in low soil conductivity (high ohmic resistivity) cathodic protection system, the ohmic potential drop between the anode and the portion of the pipe (cathode) furthest from the anode is significantly greater than that of the portion of the pipe closest to the anode. It is possible, therefore, to overprotect the portion of the pipe that is facing (closest) to the anode while the part furthest from the anode is receiving the proper and suitable amount of the protection current. The region of the pipe that is under protection is subject to corrosion, whereas hydrogen evolution can occur on the overprotected regions. In such cases, the distribution of the current has to be uniform and constant along the pipe to avoid having this problem.

3. Conclusions

The work presented here is a series of studies that examine the effect of soil conductivity on cathodic protection systems applied for the protection of buried pipelines. After the processes of design and calculations we have drawn the following points:

1. The Boundary Element Method (BEM) technique has been found to be very suitable for modeling corrosion problems and cathodic protection systems.
2. In the Boundary Element Method, only the protected surface has to be defined and values of potential and current density are computed with high accuracy on the metal surface.
3. Computer simulation of cathodic protection systems can now be undertaken with the confidence of utilization of software systems.
4. The set of software programs using boundary element method approach gave accurate predictions of the potential and current density distributions for varied soil conductivities, various environment conditions, and various design factors.
5. Two equations governing and controlling the relationship between the total current required for the protection and the conductivity values were derived. These two equations are valid within two separate areas. The first one was a liner equation, while the second one was an exponential equation.
6. Conductivity (resistivity) of the soil is playing two important roles in the design criteria of cathodic protection systems. The first role is occurring when placing the anode in a high conductivity environment; more uniform current and potential distribution will take place. In case of current distribution, the higher soil conductivity the higher current passing through the soil and as a consequence the lower in power consumption. Moreover, for the potential distribution, the lower in soil conductivity, the higher in potential needed to drive the current, and as a consequence the higher in power consumption. The second role is where the hydrogen evolution may occur in the surface of the cathode facing the anode due to the high value of the potential.

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تأثير موصلية التربة على تصميم نظم الحماية المهبطية المستخدمة في الوقاية من تآكل خطوط الأنابيب

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الكلمات المفتاحية: موصلية التربة، الاستقطاب الخطي، الحماية المهبطية.

ملخص البحث. يؤثر التوصيل الكهربائي للتربة تأثيراً بالغاً على معدل تآكل خطوط الأنابيب المدفونة فيها، وبذلك يؤثر على تصميم نظم الحماية المهبطية المستخدمة في الوقاية والحد من التآكل الذي تتعرض له هذه الخطوط. تهدف هذه الورقة إلى دراسة تأثير هذا العامل على تصميم نظم الحماية المهبطية وخاصة كمية التيار اللازم لتحقيق الحماية الشاملة لهذه الخطوط. جرت دراسة عدة بيئات تآكلية مصنفة حسب تصنيف الجمعية الأمريكية لفحص المواد داخل المختبر. هذه البيئات هي محاكاة للظروف الواقعية التي تتعرض لها هذه الأنابيب. جرت اختبارات وقياسات للتوصيل الكهربائي للتربة وكذلك اختبارات منحنيات الاستقطاب الخطي لكل من المهبط والمصعد. طريقة حدود العناصر استخدمت لحساب تيار الحماية المهبطية الكلي واتخذت منحنيات الاستقطاب الخطي حدوداً قصوى لهذه الطريقة. من خلال هذه الحسابات جرى استنتاج العلاقة بين تيار الحماية المهبطية الكلي وموصلية التربة وأمثلة التوصيل معادلات رياضية تمضحاً عن شكلها مباشر العلاقة بين موصلية التربة