Review: Electrical study of pipe – soil – earth system

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Abstract: The rate of discharge through the stray electrolytic capacitor between the pipe and the remote earth is to be considered as the corrosion current. The electrochemical properties of the soil, which are the soil resistivity of the soil volume, the relative permittivity of the soil layer around the pipe and the chemical properties which could be considered as the pH of the soil film layer around the pipe, are affected directly by the humidity change. When considering the room temperature and by neglecting the effect of CO_2 content in the soil, these values of the electrochemical properties of any soil returns back to its initial conditions after soil dryness to its initial condition. This means that corrosion rate will also be changed during the humidity change around the pipe segment. So, when considering the fact that the pipeline will not be changed or replaced and the surrounding medium around it will not be changed or replaced by another kind of soil, then the behavior of the electrical parameters (stray electrolytic capacitance, stray potential, surface created charge) of the pipe-soil-earth system will act as a print of this combination of this pipe and this soil. The average error reduced to be less than ± 5% for the general equations of the electric parameters while the print curves & constants at natural condition with and without applying cathodic protection system in terms of the electrochemical properties around the pipe were deduced. This will help to study both the corrosion problem and cathodic protection for a complete pipeline by an electric concept with an electric analogue circuit which is the aim of this study. This will help, in the future, in the choice of pipeline route, pipeline cathodic protection design and cathodic protection maintenance process for the pipe line along its route, however long it is. One of the most critical problems in CP systems is the effect of a sudden change of the soil humidity around the protected pipe line. The behavior of the protection current demand of the pipe-soil-earth system during the change of the electrochemical properties of the soil could be plotted as protection current print which will be always valid in all times as the pipe-soil-earth system is maintained and without any external interference. In other words, if the system is subjected to humidity change, there will be another new protection current demand with new print for this pipe-soil-earth system to keep the pipe cathodically protected. Of course, as a result of humidity change, the pipe to soil potential will be changed. This paper tries to calculate segmental pipe to soil potential along the pipe line without the need of both the test point and $Cu/CuSO_4$ half cell by a general equation of the pipe to soil potential which is function of both the segmental protection current and the soil factor around the pipe segment during such humidity change. Another critical problem in CP systems is the presence of the earthing network beside the protected pipe line. The behavior of the stray potential between the external surface of the pipe and earth could be plotted as stray potential print which will be always valid in all times as the pipe-soil-earth system is maintained and without any external interference. This paper tries to calculate pipe to soil potential along the pipe line without the need of $Cu/CuSO_4$ half cell by the deduction of a general equation of the pipe to soil potential which is function of an electric quantity and system's print. In other words, the aim is to deduce a correlation between pipe to soil potential and both of the measured stray potential of the pipe segment and the measured soil factor around it in the presence of an earthing grid.

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1. Introduction:

At humidity equal to zero, the soil medium around pipeline could be considered as a dielectric material which has its relative permittivity. If the humidity is increased, the soil medium is considered to be as an electrolyte associated with a change happened in the values of the relative permittivity, resistivity and pH of the soil. This change happened in the electrochemical properties of the soil will continue by increasing the humidity but these values will return back to their original values, or nearby initial values, after soil dryness. This nature of the soil medium between isolation medium and electrolytic medium according to the percentage of the humidity could be studied electrically.

If two dissimilar electrodes buried in a box which is containing a soil medium, a corrosion current will take place between these electrodes due to the difference in electrodes' natural potential while a capacitance in nano farad could be measured between these dissimilar electrodes (through the soil). The potential difference, the capacitance and the corrosion current between the positive and negative electrodes are electric quantities. Then, it may be possible to understand the corrosion and cathodic protection by an electrical concept beside the electrochemical and thermodynamic concepts.

Now the corrosion may be described electrically by the equation: ($Q = C \times V$), while the rate of discharge dQ/dt is equal to the corrosion current from the +ve electrode to the –ve one [1] [2]. The same concept could be applied on the system of buried pipeline and the surrounding soil medium. The pipeline may be considered the +ve electrode while the remote earth may be considered the –ve electrode. In case of pipe-soil-earth system, the behavior of the electrical parameters (stray potential $V_{P\text{-}PE}$, stray capacitor $C_{P\text{-}PE}$, surface total charge Q and protection current I_P) of the pipe-soil-earth system, during the change of the electrochemical properties of the soil, with and without applying cathodic protection system, could be plotted as an electrical parameter PRINT which will be always valid in all times as the pipe-soil-earth system is maintained and without any external interference [6] [7] [8] [9] [10]. Once the system is changed by replacement another pipe with different dimension and/or the replacement of the soil (or by humidity change), there will be another new electrical parameter PRINT for the new pipe-soil-earth system.

Also, the buried pipe line segment with soil surrounding medium could be simulated electrically by an electric circuit where the system is subjected to the law $Q = C \times V$ between the pipe surface and remote earth. This is where each of circuit electric parameter could be obtained by an equation which is function of the measured electrochemical properties of the soil (soil factor), 4th degree polynomial at room temperature but the A's constants are different for each electric quantity. The constants of each equation (A's) are considered to be as a PRINT of such pipe-soil-earth system [10] [12]. The useful of these PRINTS are to obtain complete electrical data correlated with many cathodic protection levels which help, after complete erection of the pipeline, in defining the pipe to soil potential of any pipe line segment through its length by measuring the protection current and / or the stray potential with of course computing of the soil factor at the pipe segment from direct field measurements [14][15]. The average error of the electrical parameters equations is reduced to be less than ± 5%. The most important advantage of such electrical analogue circuit of pipe-soil-earth system is the possibility to simulate a complete pipeline-soil-earth system by an electric circuit and to convert the corrosion problem and cathodic protection of the pipeline to an electric problem [11] [13].

One of the most critical problems in CP systems is the presence of the earthing network beside the protected pipe line. The question now is: To what extent, the earthing grid would affect the cathodic protection system? In this review, we tried to calculate the pipe to soil potential along the pipe line without using $Cu/CuSO_4$ half cell by measuring both the stray potential and/or the protected current of the pipe and the soil factor around the pipe. In other words, a direct correlation between the pipe to soil potential and the electrical parameters of the pipe for all boxes under test are deduced.

In the near future after completing such electrical studies of the pipe-soil-earth systems, this will help in corrosion monitoring and the maintenance of c.p systems. Not only has that but also to define the most suitable route of the pipe line, before the erection process, which generates the minimum surface charge. The most important result is that: the pipe to soil potential of any buried pipeline could be obtained segmental along its route without the need of both the test point and $Cu/CuSO_4$ half cell. This is by the use of the new electric study of the pipe-soil-earth system [14][15].

2. Literature Review

The only way in which atoms of the metal may detach themselves from the surface and enter the solution is in the form of positively charged ions. In electrochemical concept of corrosion process, for buried metal pipe in the ground, the following equations describe the corrosion process:

At the anode

$Fe\ (solid) \rightarrow Fe^{++}\ (ion) + 2e^-\ (electrons)$

At the cathode

$2H^+\ (hydrogen\ ions) + 2e^- \rightarrow H_2\ (gas)$

Or $2H^+ + ½\, O_2\ (air) + 2e^- \rightarrow H_2O$

Or $O_2 + 2\, H_2O + 4e^- \rightarrow 4\, OH^-\ (hydroxyl\ ion)$

Then,

$Fe^{++} + 2(OH)^- \rightarrow Fe(OH)_2$

$Fe^{+++} + 3(OH)^- \rightarrow Fe(OH)_3$

In the proposed electrical concept of the corrosion process of bare pipe-soil-earth system, the anodic reaction and the surrounding soil around the pipe may be represented, electrically, by formation of a charged electrolytic stray capacitor as shown in Fig.1 and Fig.2a [1] [2]. The electrolytic capacitor is consisting of pipe segment as the positive electrode, thin film of soil layer as the dielectric material of the capacitor and an imaginary co-axial earthing cylinder as the negative electrode. This is while for coating pipe-soil system, the stray capacitor may be considered as cylindrical capacitor with compound dielectric materials (coating of the pipe + thin film soil layer) as shown in Fig.2b [1] [2]. The formation of Fe (OH) $_2$ & Fe (OH) $_3$ in the electrochemical concept may be understood electrically by the positive charge discharged through the electrolytic stray capacitor to the imaginary co-axial earthing cylinder of radius r_3 (self discharge of the capacitor). The rate of discharge is equal to the stray corrosion current (equivalent to electron loss).

In other words, the cathodic reaction at the imaginary co-axial earthing cylinder (the negative electrode) and formation of hydroxyl ion (OH^-), detach the positive ion from metal surface and form ferric oxides. Electrically, it may be understood as the discharge of the positive charge from the positive electrode to the imaginary grounded negative electrode through thin film of soil layer as shown in Fig.1. The above clarification could be summarized as follow:

The electric concept of corrosion for pipe-soil-earth system may be written by the following proposed concept:

"Due to surrounding medium effect around metal structure buried in the ground, the charge created on metal outer surface area (o.s.a) builds up a potential through a stray electrolytic capacitor between metal o.s.a and an imaginary coaxial earthing cylinder where rate of discharge is equal to the corrosion current "[1][2].

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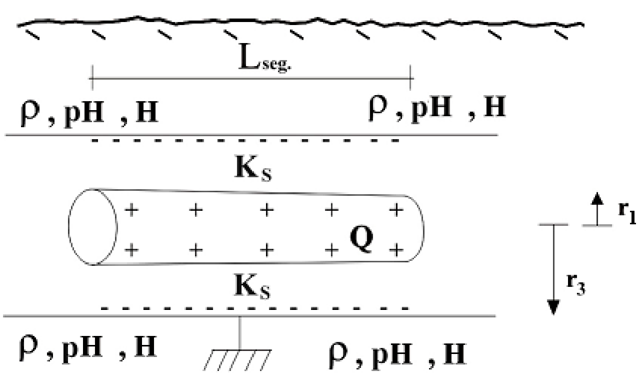

Figure 1: Proposed electrical concept of bare pipe segment with soil medium

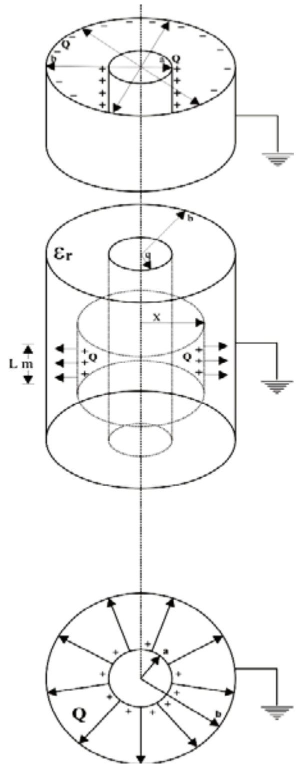

Figure 2a: Bare pipe segment with an imaginary Coaxial earthing cylinder form a charged electrolytic capacitor

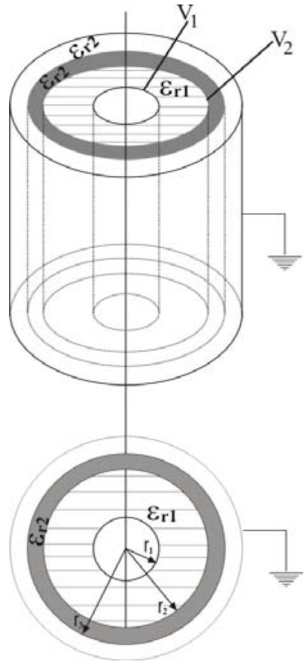

Figure 2b: Cylindrical capacitor of the pipe seg. and the compound dielectric of coating material and soil layer

The dielectric constant of the soil layer around the pipe K_S acts with the dielectric constant of the pipe coating material K_C as a coaxial cylindrical capacitor with compound dielectric. As K_C of the coating material is decreased, the total capacitance value is decreased (two capacitors are in series) then charge is decreased .That's to say, the corrosion process (electrons losses) is decreased. If deterioration of coating material occurred, then K_C is increased i.e. total capacitance value of the compound dielectric is increased .That's to say that corrosion process (electrons losses) is increased as the created charge on metal outer surface area Q will be increased . Now, what are these electrical prints? What is the equivalent electrical circuit of bare pipe segment-soil-earth system with and without applying cathodic protection system? How to calculate the pipe to soil potential from these electrical prints? .

3. The Soil Factor

As the values of the electrochemical properties of any soil medium are changed by the change of humidity, they return back to their initial conditions, or nearby the initial values, after some time, when humidity returns back to its initial value. Then we can define a new factor named the soil factor as:

"The soil factor is the instantaneous or present value of the electro-chemical properties of the soil based on the electrical properties at Humidity equal to 10% "[1] [2] and is equal to:

$S_f = (1/Ks)pH\ H\ \log\rho$ at room temperature (1)

Dimension of $[S_f] = [1/K_S]\ [pH]\ [H]\ [\log\rho] = \Omega.m\ \%$

(% is added to differentiate between S_f and ρ)

Where:

S_f = soil factor

Ks = Dielectric constant of the soil at H = 10%
(a reference value of this property)

pH = power of Hydrogen of the soil

ρ = Soil resistivity in Ω.m. at H = 10%
(a reference value of this property)

H = Humidity of the soil %

Fig. 3 shows the range of the soil factor S_f and the range of humidity for ten soils under test.

The importance of this new parameter, the soil factor, is that it is combining all parameters which can affect directly on the cathodic protection level or in corrosion process (the effect of temperature and CO_2 could be added in future studies). Such electrical parameters which can be obtained by a direct measurement from the field only one time then use both the humidity & pH in the soil factor calculations. This means that if it is possible to study the relationship between the soil factor and the electrical parameters (C, V, Q and I_P) of the pipe-soil system at natural condition with and without applying cathodic protection system, then the electrical parameters PRINTS of the pipe-soil-earth system could be obtained.

The soil factor can be considered to be as the main key of many studies based on the proposed electrical concept of corrosion. For an example, the general equation of the natural stray capacitance, without applying CP, between external surface area of bare pipe segment and earth is obtained in terms of the soil factor with an average error less than ± 5% and its print curves are obtained for pipe-soil-earth system for 10 different soils [3][10]. Also, the general equation of both the natural stray potential and the natural surface charge, without applying CP, are obtained in terms of the soil factor with an average error less than ± 5% and their print curves are obtained for pipe-soil-earth system for 10 different soils [4] [5] [10]. Also, by the use of this new parameter, the soil factor, it is possible to find a correlation between the electrical parameters and the electrochemical properties of the soil, with applying CP, at different humidity and at many cathodic protection levels with the results to be considered as an electrical parameters print or as a data sheet of this pipe-soil-earth system [6] [7] [8] [9] [10].

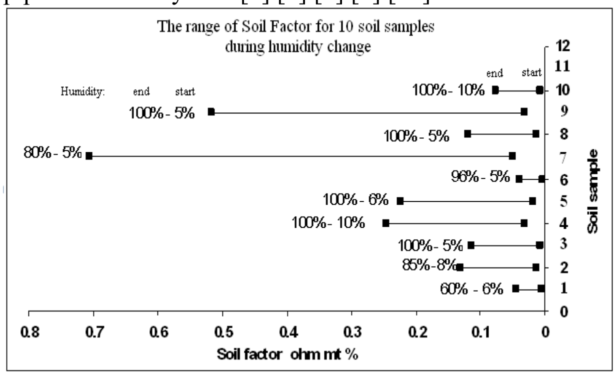

Figure 3: The range of the soil factor & humidity range for the soils under test

4. Circular ΔV PIG Idea: [1][2]

This is a new idea of the voltage drop technique to measure the protection current I_P passed through the buried pipeline. By considering a pipe line with total length L m, if such length is divided into segments with length L m./segment Then:

Total length L = segment length L_{Seg} × number of segments n

Electrically, the pipe line could be considered as:

total resistance = segment resistance × number of segments n as shown in Fig.3.

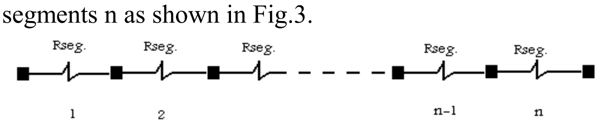

Figure 3: Electrical analogue resistance of the total pipe line length

Now if the voltage between circular points a & b of the segment is measured, as shown in figure 4, then the instantaneous measured protection current will equal to:

$$Ip = \frac{\Delta V}{R_{seg.}}$$

That means that an additional circular voltage drop canister could be added in the future with the available intelligent pig to measure the protection current I_P. Figure 4 shows such canister, and in the meantime by using GPS technology to determine the segment position. By the use of this voltage drop canister which pigged with the intelligent pig and by the use of GPS system, each segment flow current I_P could be measured.

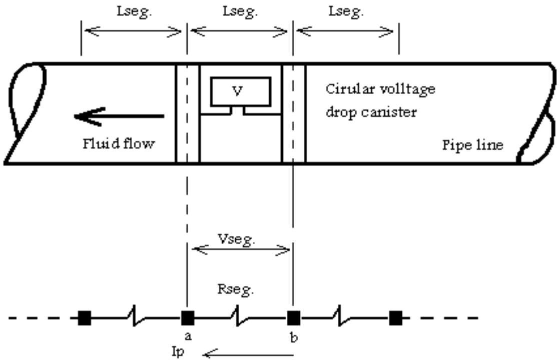

Figure 4: Idea of voltage drop canister to be pigged with the fluid through the pipeline

Then by measuring the humidity around this pipe segment, the soil factor could be determined. Finally, from the ONION curves obtained before [9] (which correlate I_P, S_F and $V_{H.C}$), the equivalent pipe to soil potential of this buried pipe segment could be determined without the need of test point and without the need of $Cu/CuSO_4$ half cell. The most important result is that: the pipe to soil potential of any buried pipeline could be obtained segmental along its route without the need of any test points. This target could be achieved by another technique which is a direct calculation of the pipe to soil potential from a general equation. This paper deduces this general equation of the pipe to soil potential for all boxes under test.

A. Experimental Natural Prints And The Re-Calculated General Equations Of The Electrical Parameters For Buried Bare Pipe -Soil- Earth System With And Without Applying Cathodic Protection System

5. Case1:

5.1 Pipe – Soil – Earth System Without C.P System

5.1.1 The Experiment

At natural condition system without any influence of any external systems such as cathodic protection systems, pipe crossing.... (only bare pipe + soil + point earth), the experiment is consisting of a system with bare pipe segment (2.1cm diameter, 1mm thickness and 31.1cm length), buried in a soil with humidity equal to 10% and the soil have soil resistivity equal to ρ Ω.m, soil power of hydrogen pH and soil relative permittivity K_S. Table 1 shows the different kind of soils used in this experiment and the range of humidity.

When considering the system pipe-soil-earth for ten different kind of soil as shown in table 1, the test procedures are as follow:

1) Calculate the value of the soil factor according to the eq.1 :
2) Measure both the stray potential $V_{P\text{-}PE}$, the stray capacitance $C_{P\text{-}PE}$ and the correspondent pipe to soil potential $V_{H\text{-}C}$ by using $Cu/CuSO_4$ half cell. Calculate total surface charge $Q = V_{P\text{-}PE} * C_{P\text{-}PE}$
3) Increase the Humidity and calculate the new value of the soil factor.
4) Repeat steps 2 & 3 until humidity around the pipe segment reaches its maximum as shown in table 1.
5) Change this type of soil by another kind of soil and repeat all the steps done before.
6) Repeat again the steps for 10 different kind of soil shown in table 1.
7) Build up the results table.

5.1.2 Analysis

If we plot the measured electric quantity (natural stray potential $V_{P\text{-}PE,}$ natural stray capacitance $C_{P\text{-}PE}$ and surface total charge Q) individually as y axis in terms of the correspondent measured soil factor as x axis, we will obtain such following curves as shown in figures 5&6. Except box 4 and box 13, the curves and equations show eight boxes which could be expressed by a 4^{th} degree polynomial equation with an average error equal to zero percent. Table 2 shows the error table for the 10 different soil resistivity.

5.2 Electrical Parameters Print Curves For Pipe – Soil – Earth Under Test

By considering the measured soil factor as x axis against the measured electrical parameter (stray potential $V_{P\text{-}PE,}$ stray capacitance $C_{P\text{-}PE}$, surface total charge Q) as y axis, the next following print curves were obtained for the pipe - soil - earth systems under test as shown in figures 5&6. The stray capacitance is illustrated by group a, figures 5a & 6a. The stray potential is illustrated by group b, figures 5b & 6b. The surface total charge is illustrated by group c, figures 5c & 6c. All points resulting from the experiment could be represented by a trend line for each measured electric quantity and could be represented by a PRINT for each pipe-soil-earth under test, with 4^{th} degree polynomial equation. The average error for all equations is less than ± 5%. The above result is very important. This proves that it may be possible to complete this electrical study of pipe-soil-earth system to find an electric circuit diagram of this combination of pipe segment-soil-earth system which is one of the real targets. This means that, beside the electrochemical and thermodynamic concepts of corrosion, it is possible to have an electric concept of the corrosion process and to convert both the corrosion and cathodic protection problems into an electric problem.

Table 1: 10 different kind of soil and operating range of H & pH

Kind of soil		ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
Box under test		1	4	9	10	13	18	19	24	27	28
Resistivity Ω m		31	37	43	62	125	138	1382	2010	5654	7539
Relative permittivity K_S		138	66	86	43	51	274	22	154	43	355
Humidity %	Start	6	8	5	10	6	5	5	5	5	10
	End	60	85	100	100	100	100	96	80	100	100
pH	Start	7.8	7.3	7.8	7.8	7.3	7.6	7.2	7	7.2	6.7
	End	7	6.5	6	6	5	5	5.3	7	6	7

Table 2: Error table for 10 different kinds of soil and operating range of Humidity

Kind of soil		ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
Box under test		1	4	9	10	13	18	19	24	27	28
Polynomial degree		4^{th}	4^{th}	4^{th}	4^{th}	4^{th}	4^{th}	4^{th}	4^{th}	4^{th}	4^{th}
V_{P-PE} Error %		0	± 30	0	0	0	0	0	0	0	0
C_{P-PE} Error %		0	± 30	0	0	± 20	0	0	0	0	0
$Q_{TOT.}$ Error %		0	± 50	0	0	± 25	0	0	0	0	0
Humidity %	Start	6	8	5	10	6	5	5	5	5	10
	End	60	85	100	100	100	100	96	80	100	100

5.3 Stray Potential General Equation For Pipe – Soil – Earth Under Test

For each soil under test and from natural stray potential curves and equations, it can easily observe that the general equation of the natural stray potential from pipe segment to the earth during humidity change is a 4^{th} degree polynomial equation which is function of the soil factor, $V_{n\ stray} = f\ (X = S_f)$. For each soil under test, the general stray potential equation is function of the measured soil factor $V_{n\ stray} = f(X{=}S_f)$, 4^{th} degree polynomial. The stray potential general equation is given by Eq.2:

$$V_{n\ stray} = A_{4vn}\mathbf{X}^4 + A_{3vn}\mathbf{X}^3 + A_{2vn}\mathbf{X}^2 + A_{1vn}\mathbf{X} + A_{0vn} \quad (2)$$

Where:
A's: = $A_{(\ )V}$ are the natural stray potential print constants of the pipe soil under test
X = is the value of the soil factor at certain humidity

5.4 Stray Capacitance General Equation For Pipe – Soil – Earth Under Test

For each kind of soil under test and from stray capacitance curves and equations, it can easily observe that the general equation of the stray capacitance, at natural condition without applying cathodic protection, to the earth during humidity change is a 4^{th} degree polynomial equation which is function of the soil factor, $C_{n\ stray}$ = f(soil factor **X**)
For each soil under test, the general stray capacitance equation is function of the measured soil factor, $C_{stray} = f(X{=}S_f)$, 4^{th} degree polynomial. The stray capacitance general equation is equal to Eq. 3:

$$C_{n\ stray} = A_{4cn}\mathbf{X}^4 + A_{3cn}\mathbf{X}^3 + A_{2cn}\mathbf{X}^2 + A_{1cn}\mathbf{X} + A_{0cn} \quad (3)$$

Where:
A's: = $A_{(\ )CN}$ are the stray capacitance print constants of the pipe soil under test
X = is the value of the soil factor at certain humidity

5.5 Surface Total Charge General Equation For Pipe – Soil – Earth Under Test

For each kind of soil under test and from the natural surface charge curves and equations, it can easily observe that the general equation of the surface charge, at natural condition without applying cathodic protection, is a 4^{th} degree polynomial equation which is function of the soil factor Q_N = f (X = soil factor). For each soil under test, the general surface natural charge equation is function of the measured soil factor, $Q_N = f(X{=}S_f)$, 4^{th} degree polynomial. The surface natural charge general equation is equal to Eq. 4:

$$\mathbf{Q}_{N} = A_{4qn}\mathbf{X}^4 + A_{3qn}\mathbf{X}^3 + A_{2qn}\mathbf{X}^2 + A_{1qn}\mathbf{X} + A_{0qn} \quad (4)$$

Where:
A's: = A ( ) q are the surface natural charge print constants of the pipe - soil under test
X = is the value of the soil factor at certain humidity

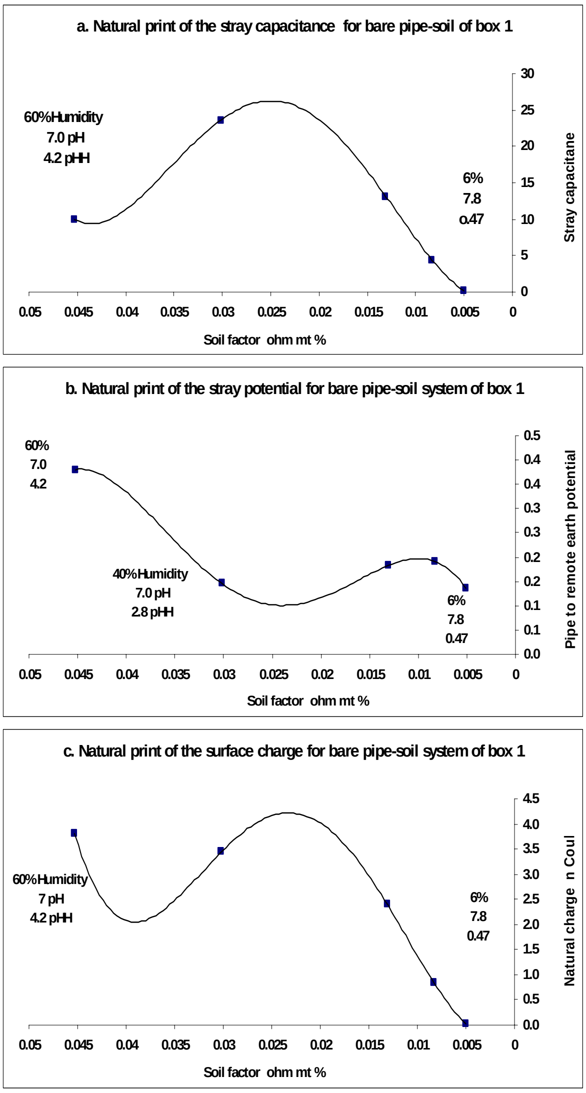

Figure 5: Natural prints of the electrical parameters for buried bare pipe-soil-earth of box 1

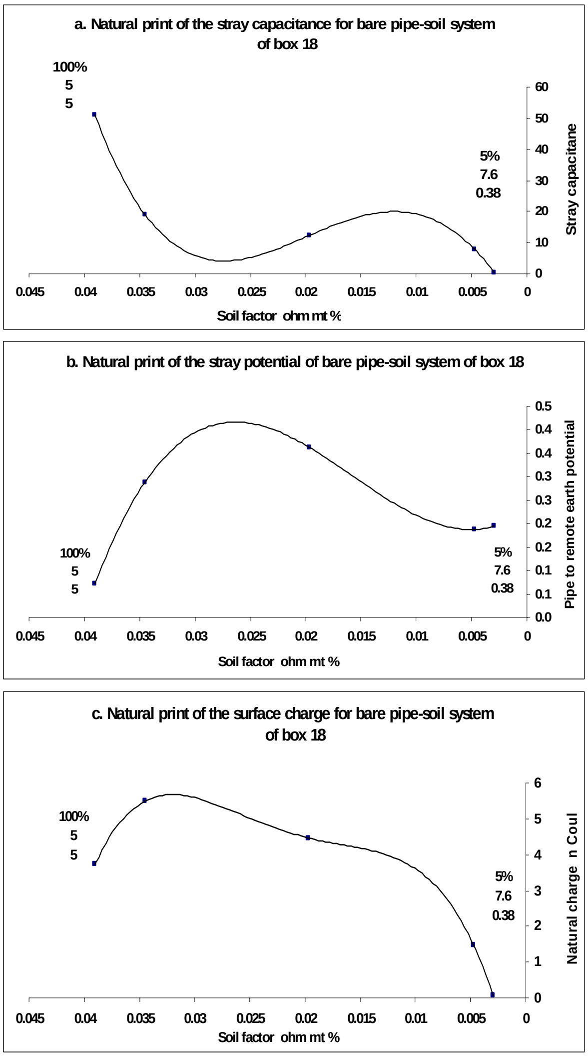

Figure 6: Natural prints of the electrical parameters for buried bare pipe-soil-earth of box 18.

5.6 The Electrical Parameter General Equation Of Pipe-Soil-Earth System At Natural Condition Without Applying CP System

We can observe clearly that the general form of any electrical parameter equation is function of the measured soil factor, 4th degree polynomial but the A's print constants are different. From equations 2, 3 and 4, we can easily summarize the natural electrical parameters equations for the pipe-soil-earth under test, without applying cathodic protection system, as follow:

$$\mathbf{C}_{n\ stray} = A_{4cn}\mathbf{X}^4 + A_{3cn}\mathbf{X}^3 + A_{2cn}\mathbf{X}^2 + A_{1cn}\mathbf{X} + A_{0cn}$$
$$\mathbf{V}_{n\ stray} = A_{4vn}\mathbf{X}^4 + A_{3vn}\mathbf{X}^3 + A_{2vn}\mathbf{X}^2 + A_{1vn}\mathbf{X} + A_{0vn}$$
$$\mathbf{Q}_{n\ stray} = A_{4qn}\mathbf{X}^4 + A_{3qn}\mathbf{X}^3 + A_{2qn}\mathbf{X}^2 + A_{1qn}\mathbf{X} + A_{0qn}$$

We can observe clearly that the general form of any electrical parameter equation, at natural condition without applying cathodic protection, is function of the measured soil factor, 4^{th} degree polynomial but the A's PRINT constants are different. Then, the general form of any electrical parameters equation of the pipe-soil-earth system under test at natural condition without applying cathodic protection with the same amount of soil volume will be as shown by the following equation :

Natural electrical parameter of pipe-soil-earth system under test

$$= A_4 \mathbf{X}^4 + A_3 \mathbf{X}^3 + A_2 \mathbf{X}^2 + A_1 \mathbf{X} + A_0$$

The A's are obtained from the correspondent print tables and **X** is the measured soil factor

The natural electric parameters general equation and PRINT curves show the following important results:

a) Buried pipe in a soil which generates the minimum natural created charge at bare pipe surface at normal steady humidity is defining the most suitable choice of soil to be around the pipe.

b) In case of space or vacuum is the medium which is surrounding the pipeline instead of soil medium, the value of the soil factor will be zero as $K_S = 1$, H = 0% , ρ = infinity. That's to say that the natural created charge will equal to zero (A_O will equal to zero for pipe-vacuum system) which is the ideal case of corrosion prevention.

c) In case of air is the medium which is surrounding the pipeline instead of soil medium, the value of the soil factor will be smaller than that of the soil at same humidity as $K_S \approx 1$ (it is not almost that $K_S \approx 1$ if the humidity exists in air), H = 10% up to 60% or more, pH = 7 & ρ = value according to H%. Consequently, the natural created charge exists in air but with smaller amount than that of soil at same humidity. That's to say that air is most proper surrounding medium for a pipe than soil at same humidity condition.

5.7 Natural Stray Potential Print Constants For Pipe-Soil-Earth Under Test

Now, the natural stray potential print constants of the pipe-soil-earth system under test are A_{4VN}, A_{3VN}, A_{2VN}, A_{1VN} and A_{0VN}. This means that these print values are valid for these pipe-soil systems under test at any time at the correspondent electrochemical properties (soil factor). Table 3 shows result example of the natural stray potential print.

Table 3: PRINT constants of the stray potential for 10 different soil under test

Soil	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
Error	0	±30%	0	0	0	0	0	0	0	0
A_{4VN}	-2.E+06	0	321339	5620	8822.1	0	118.12	140960	0	546856
A_{3VN}	202688	698.68	-78007	-3154.1	-3710.9	-48181	-153.09	-37414	-110.64	-110280
A_{2VN}	-6782.5	-157.71	6025.9	599.26	407.17	2278.7	54.029	3218.8	100.61	7753.7
A_{1VN}	82.539	9.8253	-159.72	-44.958	-3.3452	-19.695	-3.1804	-99.254	-24.97	-215.37
A_{0VN}	-0.133	0.0009	1.377	1.412	0.0954	0.2352	0.1245	0.9629	1.2357	1.8678

5.8 Natural Stray Capacitance Print Constants For Pipe-Soil-Earth Under Test

Now, the stray capacitance print constants of the pipe-soil-earth system under test are A_{4CN}, A_{3CN}, A_{2CN}, A_{1CN} and A_{0CN}. This means that these print values are valid for these pipe-soil systems under test at any time at the correspondent electrochemical properties (the soil factor). Table 4 shows the natural stray capacitance print constants.

Table 4: PRINT constants of natural stray capacitance for 10 different soils under test

Soil	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
Error	0	±30%	0	0	±30%	0	0	0	0	0
A_{4CN}	1.E+08	0	-4.E+06	1.E+06	0	6.E+07	26675	-9.E+06	21770	1.E+07
A_{3CN}	-1.E+07	262166	1.E+06	-620109	-269270	4.E+06	-35297	2.E+06	-16925	-1.E+06
A_{2CN}	322980	-47807	-88692	99288	69267	-379156	13424	-203776	3178	21862
A_{1CN}	-1549	2428	2780	-5207	-1953	6969	-1209	6766	120	874
A_{0CN}	1.27	-24.8	-15.55	84	12.77	-17	31	-58	-6	-6.8

5.9 Surface Natural Charge Print Constants For Pipe-Soil-Earth Under Test

Now, the surface natural charge print constants of the pipe-soil-earth system under test are A_{4q}, A_{3q}, A_{2q}, A_{1q} and A_{0q}. This means that these print values are valid for these pipe-soil systems under test at any time at the correspondent electrochemical properties (soil factor). Table 5 shows surface natural charge print constants.

Table 5: Natural charge PRINT at the pipe surface for 10 different soils under test

Soil	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
Error	0	± 50%	0	0	±25%	0	0	0	0	0
A_{4qn}	3.E+07	0	-919280	526631	0	-4.E+07	9205.4	-376311	-9566.4	-715518
A_{3qn}	-2.E+06	45298	242778	-267958	-26967	4.E+06	-12309	101374	9162.1	157730
A_{2qn}	60696	-8408	-20512	43238	6411	-110112	4771.1	-9536	-2632	-10306
A_{1qn}	-261	432.74	622.04	-2329	-41.27	1486.5	-461.4	360.12	227.38	253
A_{0qn}	0.1	-4.46	-3.368	38.55	-1.36	-3.463	12.625	-3.27	-4.63	-1.168

6. Case 2:

6.1 Pipe – Soil – Earth System With applying Cathodic Protection System

6.1.1The Experiment

At natural condition system without any influence of any external systems such as cathodic protection systems, pipe crossing.... (only bare pipe + soil + impressed current system + point earth), the experiment is consisting of a system with bare pipe segment (2.1cm diameter, 1mm thickness and 31.1cm length), buried in a soil with humidity equal to 10% and the soil have soil resistivity equal to ρ Ω.m, soil power of hydrogen pH and soil relative permittivity K_S. The impressed current system is consisting of a nail as an anode which is connected to the positive terminal of variable d-c source while the negative terminal is connected to the bare pipe segment. Table 1 shows the different kind of soils used in this experiment and the range of humidity.

When considering the system pipe-soil-earth for ten different kind of soil as shown in table 1, the test procedures are as follow:

1) Calculate the value of the soil factor according to the Eq.1 :
2) Measure both the stray potential V_{P-PE}, the stray capacitance C_{P-PE}, the protection current I_P and the correspondent pipe to soil potential V_{H-C} by using $Cu/CuSO_4$ half cell. Calculate total surface charge Q = $V_{P-PE} * C_{P-PE}$
3) Increase the c.p protection current I_P
4) Repeat step 2&3 up to V_{H-C} = -2 volt
5) Increase the Humidity and calculate the new value of the soil factor.
6) Repeat steps 2, 3&4 until humidity around the pipe segment reaches its max. as shown in table 1.
7) Change this type of soil by another kind of soil and repeat all the steps done before.
8) Repeat again the steps for 10 different kind of soil as shown in table 1.
9) Build up the results table.

6.1.2 Analysis

If we plot the measured electric quantity (stray potential $V_{P-PE,}$ stray capacitance C_{P-PE}, surface total charge Q and protection current I_P) individually as y axis in terms of the correspondent measured soil factor as x axis at the correspondent different levels of pipe to soil potential V_{H-C} by using $Cu/CuSO_4$ half cell from -0.2 v to -2 volt, we will obtain such following curves as shown in figures 7, 8 & 9. Except box 4 and box 24, the curves and equations of the electrical parameters show eight boxes which could be expressed by a 4^{th} degree polynomial equation with an error equal to zero percent. Table 6 shows the error table for the 10 different soil resistivity under test.

Table 6: Average error table for 10 different kinds of soil and operating range of Humidity

Soil		ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
Box under test		1	4	9	10	13	18	19	24	27	28
Polynomial degree		4^{th}	4^{th}	4^{th}	4^{th}	4^{th}	4^{th}	4^{th}	4^{th}	4^{th}	4^{th}
V_{P-PE} Error %		0	± 30	0	0	0	0	0	± 30	0	0
C_{P-PE} Error %		0	± 30	0	0	0	0	0	± 30	0	0
$Q_{TOT.}$ Error %		0	± 30	0	0	0	0	0	± 30	0	0
I_P Error %		0	± 30	0	0	0	0	0	± 30	0	0
Humidity %	Start	6	8	5	10	6	5	5	5	5	10
	End	60	85	100	100	100	100	96	80	100	100

6.2 Stray Potential For Pipe-Soil-Earth Under Test

From the stray potential PRINT curves and trend lines equations, as shown in figures 7b, 8b and 9b, it can easily observe that the general equation of the stray potential of a cathodically protected bare pipe segment during humidity change under multi level of cathodic protection levels is a 4th degree polynomial equation which is function of the soil factor $V_{Str.} = f$ (X = soil factor). For each soil under test, the general stray potential equation is function of the measured soil factor, $V_{Str.} = f(X=S_f)$, 4th degree polynomial. The stray potential general equation is equal to Eq. 5:

$$V_{Str.} = A_{4V}\mathbf{X}^4 + A_{3V}\mathbf{X}^3 + A_{2V}\mathbf{X}^2 + A_{1V}\mathbf{X} + A_{0V} \quad (5)$$

Where:
A's: = $A_{()V}$ are the stray potential print constants of the pipe - soil under test
X = is the value of the soil factor at certain humidity

6.3 Stray Capacitance For Pipe-Soil-Earth Under Test

From the stray capacitance PRINT curves and trend lines equations, as shown in figures 7a, 8a and 9a, it can easily observe that the general equation of the stray capacitance of a cathodically protected bare pipe segment during humidity change under multi level of cathodic protection levels is a 4th degree polynomial equation which is function of the soil factor $V_{Str.} = f$ (X = soil factor), the same equation as that of pipe – soil – earth system without applying cathodic protection. For each soil under test, the general stray capacitance equation is function of the measured soil factor,

$C_{Str.} = f(X=S_f)$, 4th degree polynomial. The stray potential general equation is equal to Eq. 6:

$$C_{Str.} = C_{n\ stray} = A_{4cn}\mathbf{X}^4 + A_{3cn}\mathbf{X}^3 + A_{2cn}\mathbf{X}^2 + A_{1cn}\mathbf{X} + A_{0cn} \quad (6)$$

Where:
A's: = $A_{()cn}$ are the stray capacitance print constants of the pipe - soil under test
X = is the value of the soil factor at certain humidity

6.4 Surface Total Charge For Pipe-Soil-Earth Under Test

From the surface total charge PRINT curves and trend lines equations, as shown in figures 7c, 8c and 9c it can easily observe that the general equation of the surface total charge of a cathodically protected bare pipe - segment during humidity change under multi level of cathodic protection levels is a 4th degree polynomial equation which is function of the soil factor $Q_{tot.} = f$ (X = soil factor).

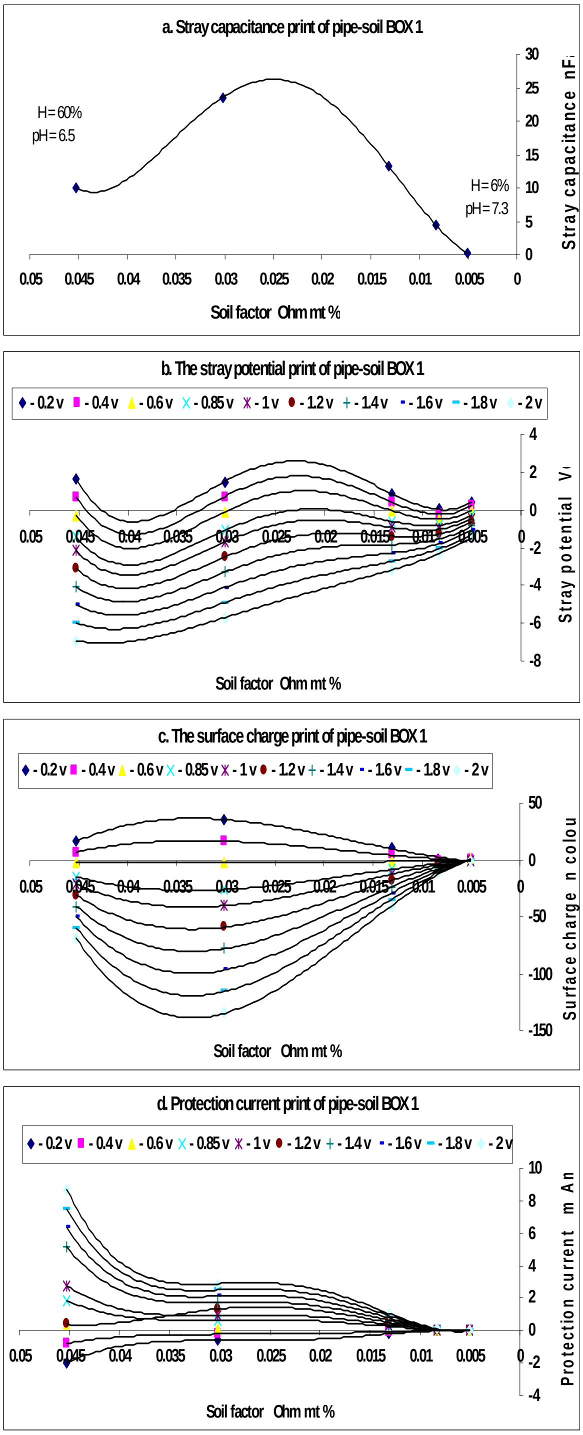

Figure 7: Electrical Parameters PRINT curves of pipe-soil-earth of BOX 1

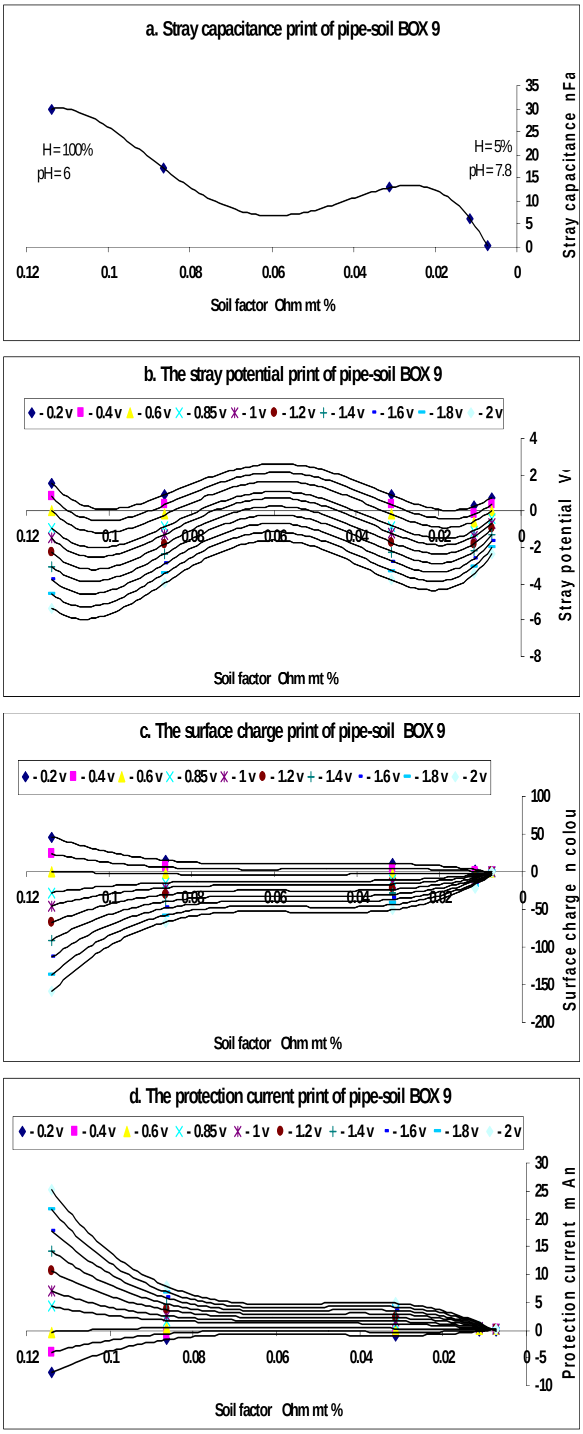

Figure 8: Electrical Parameters PRINT curves of pipe-soil-earth of BOX 9

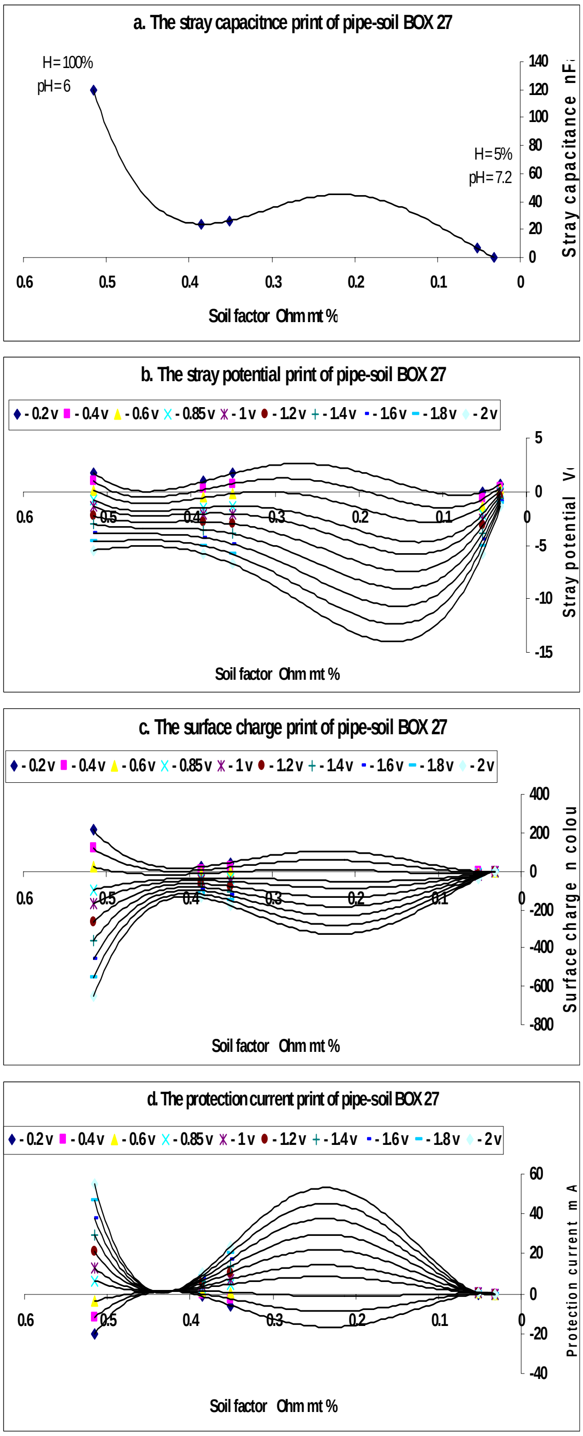

Figure 9: Electrical Parameters PRINT curves of pipe-soil-earth of BOX 27

For each soil under test, the general surface total charge equation is function of the measured soil factor, $Q_{tot.}$= f(X=S_f), 4th degree polynomial. The surface total charge general equation is equal to Eq.7:

$$\mathbf{Q_{tot.}} = A_{4q}\mathbf{X}^4 + A_{3q}\mathbf{X}^3 + A_{2q}\mathbf{X}^2 + A_{1q}\mathbf{X} + A_{0q} \quad (7)$$

Where:
A's: = A ( ) q are the surface total charge print constants of the pipe - soil under test
X = is the value of the soil factor at certain humidity

6.5 Protection Current General Equation For Pipe – Soil – Earth Under Test

Definition: "The ONION curves are the curves of the protection current I_P in terms of the soil factor S_f at different half cell voltage $V_{H.C}$ levels". From the PRINT ONION curves, , as shown in figures 7d, 8d and 9d and trend lines equations, it can easily observe that the general equation of the protection current of a cathodically protected bare pipe segment during humidity change under multi level of cathodic protection levels is a 4th degree polynomial equation which is function of the soil factor, I_P = f (X = soil factor)

For each soil under test, the general protection current equation is function of the measured soil factor I_P = f(X=S_f), 4th degree polynomial. The protection current general equation is equal to Eq. 8:

$$\mathbf{I_P} = A_{4I}\mathbf{X}^4 + A_{3I}\mathbf{X}^3 + A_{2I}\mathbf{X}^2 + A_{1I}\mathbf{X} + A_{0I} \quad (8)$$

Where:
A's: = $A_{(\,)I}$ are the protection current print constants of the pipe soil under test
X = is the value of the soil factor at certain humidity

6.6 The Electrical Parameter General Equation Of Pipe-Soil-Earth System With Applying C.P System

We can observe clearly that the general form of any electrical parameter equation is function of the measured soil factor, 4th degree polynomial but the A's constants are different and are dependant on the pipe to soil potential except the stray capacitance which is independent of the pipe to soil potential . From equations 5, 6, 7 and 8, we can easily summarize the electrical parameters trend lines equations for the pipe-soil-earth under test, with applying c.p system, are in the form as follow:

$$\mathbf{C}_{\mathbf{stray}} = A_{4cn}\mathbf{X}^4 + A_{3cn}\mathbf{X}^3 + A_{2cn}\mathbf{X}^2 + A_{1cn}\mathbf{X} + A_{0cn}$$
$$\mathbf{V}_{\mathbf{stray}} = A_{4v}\mathbf{X}^4 + A_{3v}\mathbf{X}^3 + A_{2v}\mathbf{X}^2 + A_{1v}\mathbf{X} + A_{0v}$$
$$\mathbf{Q}_{\mathbf{tot.}} = A_{4q}\mathbf{X}^4 + A_{3q}\mathbf{X}^3 + A_{2q}\mathbf{X}^2 + A_{1q}\mathbf{X} + A_{0q}$$
$$\mathbf{I_P} = A_{4IP}\mathbf{X}^4 + A_{3IP}\mathbf{X}^3 + A_{2IP}\mathbf{X}^2 + A_{1IP}\mathbf{X} + A_{0IP}$$

Then, the general form of any electrical parameters equation of the pipe-soil-earth system under test, with applying cathodic protection, will be as shown in the following general equation which is the same as that of the system without applying cathodic protection:

$$\mathbf{EP} = A_4\mathbf{X}^4 + A_3\mathbf{X}^3 + A_2\mathbf{X}^2 + A_1\mathbf{X} + A_0$$

The A's are obtained from the print constant tables and the **X** is the measured soil factor.

6.7 Stray Potential Print Constants For Pipe-Soil-Earth Under Test

Now, the stray potential PRINT constants of the pipe-soil-earth systems under test are A_{4V}, A_{3V}, A_{2V}, A_{1V} and A_{0V} at a definite cathodic protection level. This means that these print values are valid for these CP levels for these pipe soil systems under test at any time at the correspondent electrochemical properties (the soil factor). Table 7 shows result example of the stray potential print constants at CP level equal to -0.85 volt.

Table 7: Stray potential print constants at pipe to soil potential equal to -0.85 volt

BOX	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
	1	4	9	10	13	18	19	24	27	28
$\mathbf{A_{4V}}$	3.00E+07	0	925051	17354	1149.5	7.00E+07	861.17	0	2228.7	1.00E+06
$\mathbf{A_{3V}}$	-3.00E+06	-1858.9	-223313	-9862.3	-4002.1	-7.00E+06	-1531.8	61.62	-2755.3	-194014
$\mathbf{A_{2V}}$	91780	507.49	16975	1905.4	1569.6	211211	926.56	-232.3	1155.8	12478
$\mathbf{A_{1V}}$	-1023	-37.7	-428	-143	-176.7	-2389.4	-204.8	35.484	-179.3	-321.02
$\mathbf{A_{0V}}$	2.9327	-0.61	1.9	2.6	2.37	4.66	7.154	-2.19	4.49	1.6
Error	0	±30%	0	0	0	0	0	±30%	0	0

6.8 Stray Capacitance Print Constants For Pipe-Soil-earth Under Test

The stray capacitance PRINT constants of the pipe-soil-earth systems under test are A_{4C}, A_{3C}, A_{2C}, A_{1C} and A_{0C} at any cathodic protection level. This means that these print values are valid at any CP levels for these pipe-soil systems under test at any time at the correspondent electrochemical properties (the soil factor). Table 8 shows the stray capacitance print constants at all CP levels.

Table 8: Stray capacitance print constants at any pipe to soil potential

	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
BOX	1	4	9	10	13	18	19	24	27	28
A_{4C}	1E+08	0	-4E+06	1E+06	0	6E+07	26675	-9E+06	21770	1E+07
A_{3C}	-1E+07	262166	1E+06	-620109	-269270	4E+06	-35297	2E+06	-16925	-1E+06
A_{2C}	322980	-47807	-88692	99288	69267	-379156	13424	-203776	3178	21862
A_{1C}	-1549	2428	2781	-5207	-1953	6970	-1209	6766	120.2	874.8
A_{0C}	1.27	-24.8	-15.5	84.15	12.77	-17.1	31.27	-58.51	-6	-6.82
Error	0	±30%	0	0	±30%	0	0	0	0	0

6.9 Surface Total Charge Print Constants For Pipe-Soil Under Test

The surface total charge PRINT constants of the pipe-soil-earth systems under test are A_{4q}, A_{3q}, A_{2q}, A_{1q} and A_{0q} at a definite cathodic protection level. This means that these print values are valid for these CP levels for these pipe soil systems under test at any time at the correspondent electrochemical properties (the soil factor). Table 9 shows result example of the surface total charge print constants at CP level equal to -0.85 volt.

Table 9: Print constants of the surface total charge at pipe to soil potential equal to -0.85 volt

	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
BOX	1	4	9	10	13	18	19	24	27	28
A_{4q}	0	0	6E+06	50596	0	5E+08	-11047	0	-5597	-9E+06
A_{3q}	1E+06	- 303338	-1E+06	-36942	57793	-6E+07	12317	-22910	135.97	980353
A_{2q}	-70717	57990	119052	8379	-9785	2E+06	-2698	3326.1	2662	-12884
A_{1q}	-84.36	-3046	-3394	-846	-857	-24242	-460	-120	-881.7	-922.4
A_{0q}	1.71	31.3	18.7	19.6	18.61	55.6	28.1	-6.62	25	7
Error	0	50%	0	0	15%	0	0	50%	0	0

6.10 Protection current Print Constants For Pipe-Soil Under Test

The protection current PRINT constants of the pipe-soil-earth systems under test are A_{4I}, A_{3I}, A_{2I}, A_{1I} and A_{0I} at a definite cathodic protection level. This means that these print values are valid for these CP levels for these pipe-soil systems under test at any time at the correspondent electrochemical properties (the soil factor). Table 10 shows result example of the protection current print constants at CP level equal to -0.85 volt.

Table 10: The PRINT constants of the pipe current at pipe to soil potential equal to -0.85 volt

	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
BOX	1	4	9	10	13	18	19	24	27	28
A_{4I}	7E+06	0	14928	32198	-452755	-1E+07	-206.1	23296	4596.1	4.00E+06
A_{3I}	-636953	-6223	9231	-16158	216364	906336	296.1	1329	-4409	-617139
A_{2I}	17742	1138.7	-1749	2569	-30555	-25814	-118	-596.9	1202	26816
A_{1I}	-148.8	-25.2	99.9	-129	1139	371	12.56	47.3	-66.9	-345.4
A_{0I}	0.4	0.2	-0.62	2	-11.77	-0.88	-0.37	-0.5	1.1	1.34
Error	0	30%	0	0	0	0	0	0	0	0

B. The Proposed Electric Circuit Diagram Of The Buried Bare Pipe Segment- Soil - Earth System With And Without Applying Cathodic Protection System

7. Case 1:

7.1 Proposed Electrical Analogue Circuit of The Pipe Segment – Soil - Earth System Without CP System [1] [2]

In a corrosion process, the metal pipe could be considered as a current source (stray corrosion current) to the surrounding medium (stray capacitor to the remote earth). The electrical analogue circuit of the pipe line segment with the surrounding medium effect could be represented as a current source connected in series with the stray capacitance between metal o.s.a and the remote earth. Consequently, the corrosion process could be electrically simulated for both bare pipe and at bad condition of coating material as shown in Fig.10.

The general electrical analogue circuit of pipe segment-soil-earth system will consists of current source in series with an equivalent impedance $Z_{eq.}$ correlated to humidity (R_{eq} in parallel with C_{eq}) which is connected from pipe to the remote earth as shown in Fig.11. The importance of this proposed electrical circuit is that it converts both the corrosion and/or cathodic protection process into an electric problem. This is as we obtained before the electric parameters C, V and Q of the bare pipe segment-soil-earth system in terms of the electrochemical properties of the soil i.e. the general equations of the natural stray capacitance [3],[10], the natural stray potential [4][10], the surface natural created charge[5][10]. All electrical parameters are deduced in terms of the soil factor, 4th degree polynomial equations with an average error less than ± 5%. In this paper, we will continue and use the results obtained before to deduce the electric analogue circuit of the natural condition pipe-soil-earth system without applying cathodic protection system.

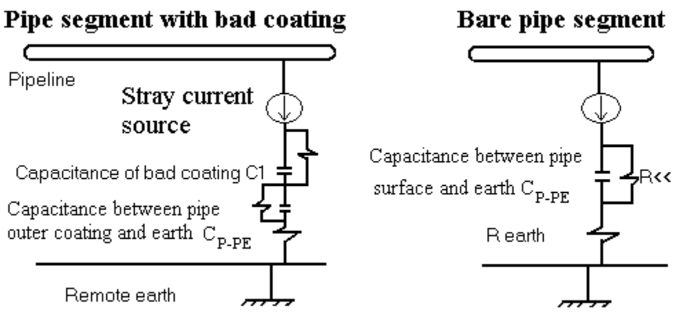

Figure 10: Proposed electrical analogue circuit of the pipe segment – soil system at the corrosion process

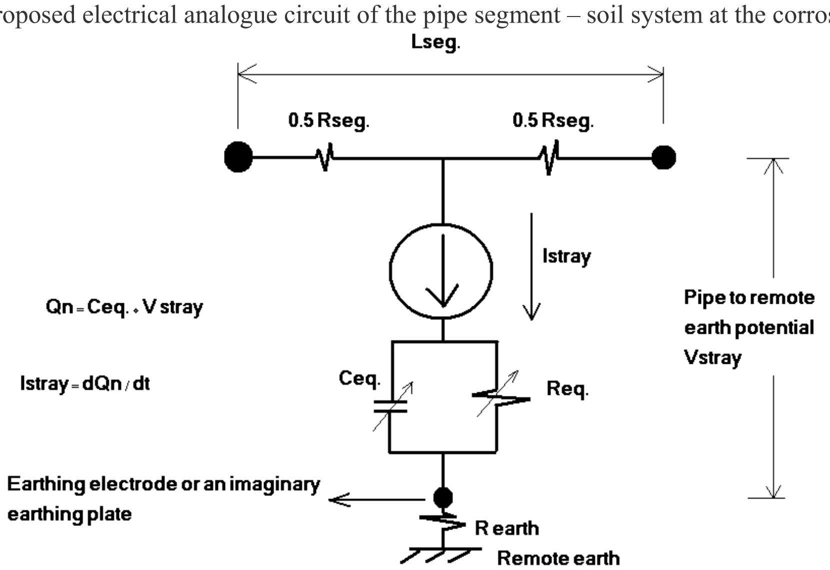

Figure 11: The proposed general electrical analogue circuit of pipe-soil system

7.2 Calculations Of The Electrical Parameters Of The Pipe-Soil-Earth system Without Applying CP System

Now, to obtain the pipe segment natural electric parameters without applying cathodic protection system, we have for the pipe-soil-earth system the following results:

7.2.1 General Equation Of The Natural Stray Electrolytic Capacitor [3],[10]

This is equal to Eq. 3:

$$C_{n\,stray} = A_{4cn}\mathbf{X}^4 + A_{3cn}\mathbf{X}^3 + A_{2cn}\mathbf{X}^2 + A_{1cn}\mathbf{X} + A_{0cn} \quad (3)$$

Where:

A's = $A_{(\ )CN}$ are the stray capacitance PRINT constants of the pipe soil under test

X = instantaneous value of the electrochemical value of the soil, the soil factor

7.2.2 General Equation Of The Natural Stray Potential [4],[10]
This is equal to Eq. 2:

$$V_{n\,stray} = A_{4vn}\mathbf{X}^4 + A_{3vn}\mathbf{X}^3 + A_{2vn}\mathbf{X}^2 + A_{1vn}\mathbf{X} + A_{0vn} \quad (2)$$

Where:
A's: = $A_{(\ )V}$ are the natural stray potential print constants of the pipe soil under test
X = instantaneous value of the electrochemical value of the soil, the soil factor

7.2.3 General Equation Of The Natural Surface Charge [5],[10]
This is equal to Eq. 4:

$$Q_N = A_{4qn}\mathbf{X}^4 + A_{3qn}\mathbf{X}^3 + A_{2qn}\mathbf{X}^2 + A_{1qn}\mathbf{X} + A_{0qn} \quad (4)$$

Where:

A's: = $A_{(\ )qn}$ are the surface natural charge print constants of the pipe - soil under test
X = instantaneous value of the electrochemical value of the soil, the soil factor

7.2.4 General Equation Of The Protection Current:
As we consider the natural condition without applying cathodic protection system, then the rectifier output will equal to zero.

$$I_P = 0 \quad (5)$$

7.2.5 The Earthing Resistance
The earthing resistance R_E could be easily measured from the field by the use of earth tester.

$$R_E = \text{Measured from the field} \quad (9)$$

7.2.6 The Pipe Segment resistance
The resistance of the pipe segment will equal to:

$$R_{SEG.} = (\rho_{IRON} \times L_{SEG})/a \quad (10)$$

Where:
$a = ¼\,\pi\,(D_O^2 - D_I^2)$
D_O = Outer diameter of the pipe segment
D_I = Inner diameter of the pipe segment
L_{SEG} = Length of the pipe segment
ρ_{IRON} = Iron Resistivity (pipe material)

7.2.7 The Natural Stray Corrosion Current Calculation
As per Eq. 4:

$$Q_N = A_{4qn}\mathbf{X}^4 + A_{3qn}\mathbf{X}^3 + A_{2qn}\mathbf{X}^2 + A_{1qn}\mathbf{X} + A_{0qn}$$

Then, rate of discharge **dQ_N/dt** will equal to the corrosion current

$$dQ_n/dt = \dot{X}\,[(4A_{4qn}\mathbf{X}^3 + 3A_{3qn}\mathbf{X}^2 + 2A_{2qn}\mathbf{X}) + A_{1qn} \quad (11)$$

As **X** = soil factor as per Eq.1, applying in Eq.11,then:

$$dQ_n/dt = \dot{X}\,[4A_{4qn}((1/K_S)\log\rho)^3_{H=10\%}\,(\mathbf{pH.H})^3 + 3A_{3qn}((1/K_S)\log\rho)^2_{H=10\%}\,(\mathbf{pH.H})^2 + 2A_{2qn}((1/K_S)\log\rho)_{H=10\%}\,(\mathbf{pH.H}) + A_{1qn}]$$

Now, for bare pipe segment-soil-earth system under test, without applying any c.p system, without any external interference, at room temperature, with soil volume under test and by neglecting CO_2 effect, the natural corrosion current from pipe surface to the surrounding medium could be obtained from an electrical concept of the corrosion and will equal to third order polynomial equation function of measured humidity and pH of the soil as shown in equation 12.

Natural corrosion current of the bare pipe segment to the surrounding medium I_{STRAY} will equal to:

$$I_{STRAY} = \dot{X}[B_{3qn}(\mathbf{pH.H})^3 + B_{2qn}(\mathbf{pH.H})^2 + B_{1qn}(\mathbf{pH.H}) + A_{1qn}] \quad (12)$$

Where:

pH.H = Variable quantity equal to (pH *Humidity) measured around the pipe segment
$\dot{X}$ = Rate of soil factor change by time dx/dt = $d(S_f)/dt$
B_{3qn} = Cons. print equal to $4A_{4qn}((1/K_S)\log\rho)^3_{at\ H=10\%}$
B_{2qn} = Cons. print equal to $3A_{3qn}((1/K_S)\log\rho)^2_{at\ H=10\%}$
B_{1qn} = Cons. print equal to $2A_{2qn}((1/K_S)\log\rho)_{at\ H=10\%}$
A_{1qn} = Constant print from natural charge equation
A_{2qn} = Constant print from natural charge equation
A_{3qn} = Constant print from natural charge equation
A_{4qn} = Constant print from natural charge equation
K_S = Constant equal to the dielectric constant of the soil at H = 10%
ρ = Constant equal to the soil resistivity in Ω.m at H = 10%

Referring to the proposed electrical circuit of bare pipe segment-soil-earth system in figure 11, the stray current source may be represented by equation 12. Then, the final proposed electric circuit of such system may be as the circuit diagram shows in figure 12 taking into account that the pipe-soil-earth system is without applying cathodic protection system and without any external interference i.e. natural condition.

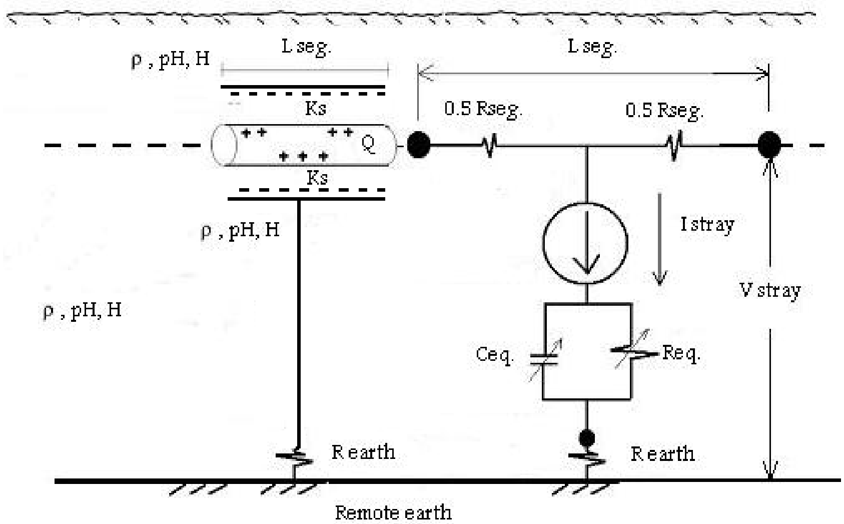

Figure 12: Final proposed electric circuit diagram of bare pipe segment-soil-earth system at natural condition without applying CP system

8. Case 2:

8.1 Proposed Electrical Analogue Circuit Of The Pipe Segment – Soil - Earth System With CP System [1] [2]

In case of cathodic protection process, the protection current either it is greater than the stray current (net current will flow through the pipe) or less than the stray current (net current will flow through the stray capacitor to the remote earth). The c.p level of the pipe line segment could be determined if the protection current before and after the pipe line segment is measured by using the proposed voltage drop canister pigged with an intelligent pig tool [1] [2]. For well coated pipe line segment, the electrical analogue circuit is as in Fig.13a. Also, Fig.13b shows the electric analogue circuit of the pipe segment which is cathodically protected by galvanic system or impressed current system Fig.13c.

The general electrical analogue circuit of pipe segment-soil-earth system will consist of current source in series with an equivalent impedance $Z_{eq.}$ correlated to humidity (R_{eq} in parallel with C_{eq}) which is connected from pipe to the remote earth as shown in figure 14. The importance of this proposed electrical circuit is that it converts both the corrosion and/or cathodic protection process into an electric problem. This is as we obtained before the electric parameters C, V and Q of the bare pipe segment-soil-earth system in terms of the electrochemical properties of the soil i.e. the general equations of the stray capacitance at many CP levels [6][10], the stray potential at many CP levels [7],[10], the surface total charge at many CP levels [8],[10] and finally the amount of the protection current at many CP levels [9],[10]. All electrical parameters deduced in terms of the soil factor, 4th degree polynomial equations with an average error less than ± 5%. In this paper, we will continue and use the results obtained before to deduce the electric analogue circuit at the natural condition pipe-soil-earth system with applying cathodic protection system.

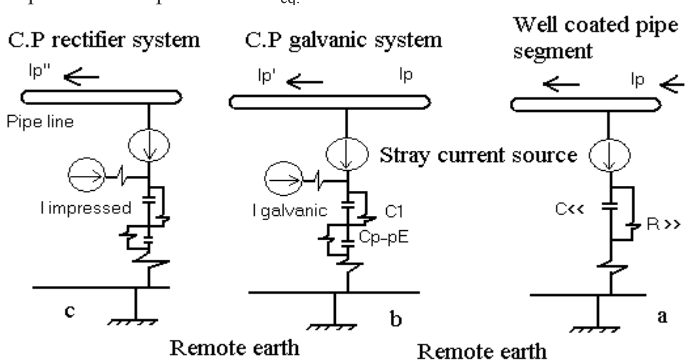

Figure 13: Proposed electrical analogue circuit of the pipe segment-soil system at the cathodic protection process (a) By well coating material (b) By galvanic system (c) By using impressed current system

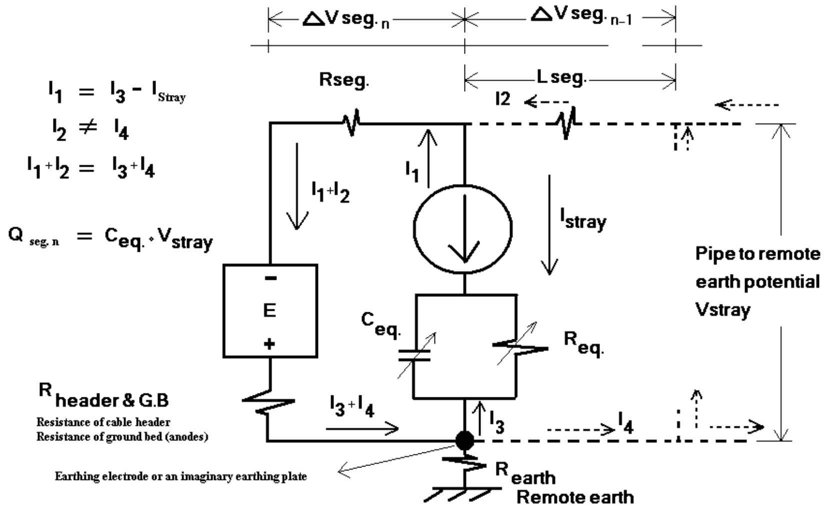

Figure 14: The proposed general electrical analogue circuit of pipe-soil system

8.2 Calculations of The Electrical Parameters Of The Pipe-Soil-Earth system With Applying CP System

Now, to obtain the pipe segment natural electric parameters with applying cathodic protection system, we have for the pipe-soil-earth system the following results:

8.2.1 General Equation Of The Electrolytic Capacitance [6][10]

This is equal to Eq. 10:

$$C_{stray} = A_{4C}\mathbf{X}^4 + A_{3C}\mathbf{X}^3 + A_{2C}\mathbf{X}^2 + A_{1C}\mathbf{X} + A_{0C} \quad (6)$$

Where:
A's: = $A_{(\,)C}$ are the stray capacitance print constants of the pipe soil under test
X = instantaneous value of the electrochemical value of the soil, the soil factor

8.2.2 General Equation Of The Stray Potential [7][11]

This is equal to Eq. 11:

$$V_{stray} = A_{4V}\mathbf{X}^4 + A_{3V}\mathbf{X}^3 + A_{2V}\mathbf{X}^2 + A_{1V}\mathbf{X} + A_{0V} \quad (5)$$

Where:
A's = $A_{(\,)V}$ are the natural stray potential print constants of the pipe soil under test
X = instantaneous value of the electrochemical value of the soil, the soil factor

8.2.3 General Equation Of The Surface Charge [9],[10]

This is equal to Eq. 12:

$$\mathbf{Q} = A_{4q}\mathbf{X}^4 + A_{3q}\mathbf{X}^3 + A_{2q}\mathbf{X}^2 + A_{1q}\mathbf{X} + A_{0q} \quad (7)$$

Where:
A's: = $A_{(\,)q}$ are the surface charge print constants of the pipe - soil under test
X = instantaneous value of the electrochemical value of the soil, the soil factor

8.2.4 General Equation Of The Protection Current Flow To The Pipe Segment (I_1) [10]

This is equal to Eq. 13:

$$\mathbf{I_1 = I_P} = A_{4I}\mathbf{X}^4 + A_{3I}\mathbf{X}^3 + A_{2I}\mathbf{X}^2 + A_{1I}\mathbf{X} + A_{0I} \quad (8)$$

Where:
A's: = $A_{(\,)I}$ are the protection current print constants of the pipe soil under test
X = instantaneous value of the electrochemical value of the soil, the soil factor

8.2.5 Natural Stray Corrosion Current I_{STRAY} [10]

This is equal to Eq. 12:

$$\mathbf{dQ_n\ /dt} = \dot{\mathbf{X}}\ [\ B_{3qn}(\mathbf{pH.H})^3 + B_{2qn}(\mathbf{pH.H})^2 + B_{1qn}(\mathbf{pH.H}) + A_{1qn}\ ] \quad (12)$$

Where:
pH.H = Variable quantity equal to (pH* Humidity) measured around the pipe segment
$\dot{\mathbf{X}}$ = Rate of soil factor change by time = $d(S_f)/dt$
B_{3qn} = Cons. print equal to $4A_{4qn}((1/Ks)\log\rho)^3_{at\ H=10\%}$
B_{2qn} = Cons. print equal to $3A_{3qn}((1/Ks)\log\rho)^2_{at\ H=10\%}$
B_{1qn} = Cons. print equal to $2A_{2qn}((1/Ks)\log\rho)_{at\ H=10\%}$
A_{1qn} = Constant print from natural charge equation
A_{2qn} = Constant print from natural charge equation

A_{3qn} = Constant print from natural charge equation
A_{4qn} = Constant print from natural charge equation
Ks = Dielectric constant of the soil at H = 10%
ρ = Soil resistivity in Ω.m at H = 10%

8.2.6 Earthing Resistance

The earthing resistance R_E could be easily measured from the field by the use of earth tester.

R_E = Measured from the field (9)

8.2.7 Pipe Segment Resistance

The resistance of the pipe segment will equal to:

$$R_{SEG.} = (\rho_{IRON} \times L_{SEG}) / a \quad (10)$$

Where:
$a = \frac{1}{4} \pi (D_O^2 - D_I^2)$
D_O = Outer diameter of the pipe segment
D_I = Inner diameter of the pipe segment
L_{SEG} = Length of the pipe segment
ρ_{IRON} = Iron Resistivity (pipe material)

8.2.8 Calculation Of The Net Current Flow Through The Pipe Segment ($I_1 + I_2$) [9]

5.2.8.1Calculation of Pipe Segment Flow Current

As total surface charge is equal to;

$$Q_{surface} = A_{4q} \mathbf{X}^4 + A_{3q} \mathbf{X}^3 + A_{2q} \mathbf{X}^2 + A_{1q} \mathbf{X} + A_{0q}$$

Then, the pipe segment flow current, ($I_1 + I_2$) components as shown in Fig.14 is equal to:

$$dQ_{surface}/dt = \dot{X} [\, 4A_{4q} \mathbf{X}^3 + 3A_{3q} \mathbf{X}^2 + 2A_{2q} \mathbf{X} + A_{1q} \,]$$

From Eq. 1, applying the value of the soil factor as X = S_f= (1 / K_S) pH H log ρ. Then: **$dQ_{surface}/dt$ =**

$$\dot{X}[\, 4A_{4q} ((1/Ks) \log \rho)^3_{at\ H=10\%} (\mathbf{pH.H})^3 + 3A_{3q} ((1/Ks) \log \rho)^2_{at\ H=10\%} (\mathbf{pH.H})^2 + 2A_{2q} ((1/Ks) \log \rho)_{at\ H=10\%} (\mathbf{pH.H}) + A_{1q} \,]$$

$$dQ_{surface}/dt = \dot{X} [\, C_{3q}(\mathbf{pH.H})^3 + C_{2q}(\mathbf{pH.H})^2 + C_{1q}(\mathbf{pH.H}) + A_{1q} \,] \quad (13)$$

Now, for bare pipe segment-soil-earth system under test which applying c.p system, without any external interference, at room temperature, with soil volume under test and by neglecting CO_2 effect, the flow current of the pipe segment-soil under test could be obtained from an electrical concept of the corrosion and will equal to third order polynomial equation function of the measured (pH*humidity) as shown in equation 14.

Flow current of the pipe segment under test

$$I_1 + I_2 = \dot{X} [C_{3q}(\mathbf{pH.H})^3 + C_{2q}(\mathbf{pH.H})^2 + C_{1q}(\mathbf{pH.H}) + A_{1q}] \quad (14)$$

Where:
pH.H = Variable quantity equal to (pH*Humidity) measured around the pipe segment
$\dot{X}$ = Rate of soil factor change by time dx/dt = $d(S_f)/dt$
C_{3q} = Cons. print equal to $4A_{4q} ((1/Ks) \log \rho)^3_{at\ H=10\%}$
C_{2q} = Cons. print equal to $3A_{3q} ((1/Ks) \log \rho)^2_{at\ H=10\%}$
C_{1q} = Cons. print equal to $2A_{2q} ((1/Ks) \log \rho)_{at\ H=10\%}$
A_{1q} = Constant print from surface charge equation
A_{2q} = Constant print from surface charge equation
A_{3q} = Constant print from surface charge equation
A_{4q} = Constant print from surface charge equation
Ks = Dielectric constant of the soil at H = 10%
ρ = Soil resistivity in Ω.m at H = 10%

8.2.8.1Calculation of the Current Reaches the Pipe Segment from d-c Source (I_3)

We have: Total surface charge **$Q_{surface}$** = charge supplied by cathodic protection **$Q_{C.P}$** – natural charge i.e **$Q_{surface} = Q_{C.P} - Q_n$** , then:

$$dQ_{CP}/dt = dQ_{surface}/dt + dQ_n/dt$$

As:

$$dQ_n/dt = \dot{X} [\, B_{3qn}(\mathbf{pH.H})^3 + B_{2qn}(\mathbf{pH.H})^2 + B_{1qn}(\mathbf{pH.H}) + A_{1qn} \,] = I_{stray} \quad \text{from Eq.(12)}$$

$$dQ_{surface}/dt = \dot{X} [\, C_{3q}(\mathbf{pH.H})^3 + C_{2q}(\mathbf{pH.H})^2 + C_{1q}(\mathbf{pH.H}) + A_{1q} \,] = I_1 + I_2 \quad \text{from Eq.(13)}$$

$$I_1 = I_3 - I_{stray}$$
$$I_{DC} = I_3 + I_4$$

In our case of pipe segment study, $I_4 = 0$ & $I_2 = 0$
Then **I_{DC}** will equal to:

$$dQ_{CP}/dt = \dot{X} [\, (B_{3qn}+C_{3q}) (\mathbf{pH.H})^3 + (B_{2qn}+C_{2q}) (\mathbf{pH.H})^2 + (B_{1qn}+C_{1q}) (\mathbf{pH.H}) + (A_{1qn} + A_{1q}) \,]$$

$$dQ_{CP}/dt = \dot{X}[D_3(\mathbf{pH.H})^3+D_2(\mathbf{pH.H})^2+D_1(\mathbf{pH.H}) +D_0\,] \quad (15)$$

Now, for bare pipe segment-soil-earth system under test which applying c.p system, without any external interference, at room temperature, with soil volume under test and by neglecting CO_2 effect, the amount of rectifier current reaches the pipe – soil system under test could be obtained from an electrical concept of the corrosion and will equal to third order polynomial equation function of the measured (pH*humidity) as shown in Eq.16. **Amount of rectifier current reaches the pipe segment under test**

$$I_{DC} = \dot{X}[D_3(\mathbf{pH.H})^3+D_2(\mathbf{pH.H})^2+D_1(\mathbf{pH.H})+D_0] \quad (16)$$

Where:
pH.H = Variable quantity equal to (pH* Humidity) measured around the pipe segment
$\dot{X}$ = Rate of soil factor change by time = $d(S_f)/dt$
D_3 = Constant equal to $(B_{3qn}+C_{3q}) = 4(A_{4q}+A_{4qn})((1/Ks)\log\rho)^3{}_{\text{at H=10\%}}$
D_2 = Constant equal to $(B_{2qn}+C_{2q}) = 3(A_{3q}+A_{2qn})((1/Ks)\log\rho)^2{}_{\text{at H=10\%}}$
D_1 = Constant equal to $(B_{1qn}+C_{1q}) = 2(A_{2q}+A_{2qn})((1/Ks)\log\rho)_{\text{at H=10\%}}$
D_0 = Constant equal to $(A_{1qn}+A_{1q})$
Ks = Dielectric constant of the soil at H = 10%
ρ = Soil resistivity in Ω.m at H = 10%

Referring to the proposed electrical circuit of the bare pipe segment-soil-earth system in figure 14, all current values are now determined for the pipe segment-soil-earth system under test. Also the values of the equivalent stray electrolytic capacitor, the potential across it, the natural stray current source from the pipe segment, pipe segment net current flow and finally the amount of DC current share for the pipe segment are determined. Then, the final proposed electric circuit of such system may be as the electrical circuit diagram shown in figure 15a & 15b. **The electrical parameters of the bare pipe segment-soil-earth system under test with applying CP system are as follow:**

$C_{eq.} = C_{stray} = A_{4cn}\mathbf{X}^4 + A_{3cn}\mathbf{X}^3 + A_{2cn}\mathbf{X}^2 + A_{1cn}\mathbf{X} + A_{0cn}$
$V_{stray} = A_{4v}\mathbf{X}^4 + A_{3v}\mathbf{X}^3 + A_{2v}\mathbf{X}^2 + A_{1v}\mathbf{X} + A_{0v}$
$I_{stray} = \dot{\mathbf{X}}[B_{3qn}(\mathbf{pH.H})^3 + B_{2qn}(\mathbf{pH.H})^2 + B_{1qn}(\mathbf{pH.H}) + A_{1qn}]$
$I_1 + I_2 = \dot{\mathbf{X}}[C_{3q}(\mathbf{pH.H})^3 + C_{2q}(\mathbf{pH.H})^2 + C_{1q}(\mathbf{pH.H}) + A_{1q}]$
$I_{DC} = I_3 + I_4 = \dot{\mathbf{X}}[D_3(\mathbf{pH.H})^3 + D_2(\mathbf{pH.H})^2 + D_1(\mathbf{pH.H}) + D_0]$
$I_2 = I_4 = 0$ for pipe segment under test

Where:
A's, B's, C's and D's: are the PRINT constants of the bare pipe-soil-earth system
X : instantaneous value of the electrochemical value of the soil, the soil factor (Eq.1)
$\dot{\mathbf{X}}$ = Rate of soil factor change by time $d\mathbf{x}/dt = d(S_f)/dt$
H: is the measured humidity
pH: is the measured power of hydrogen

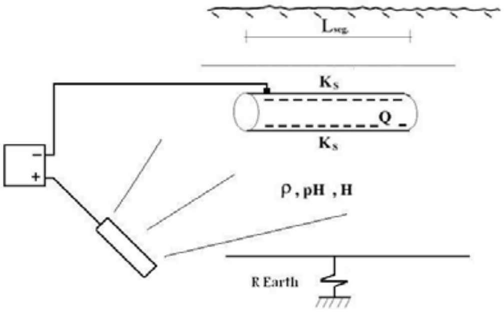

Figure 15a: schematic diagram of buried bare pipe segment with applying cathodic protection

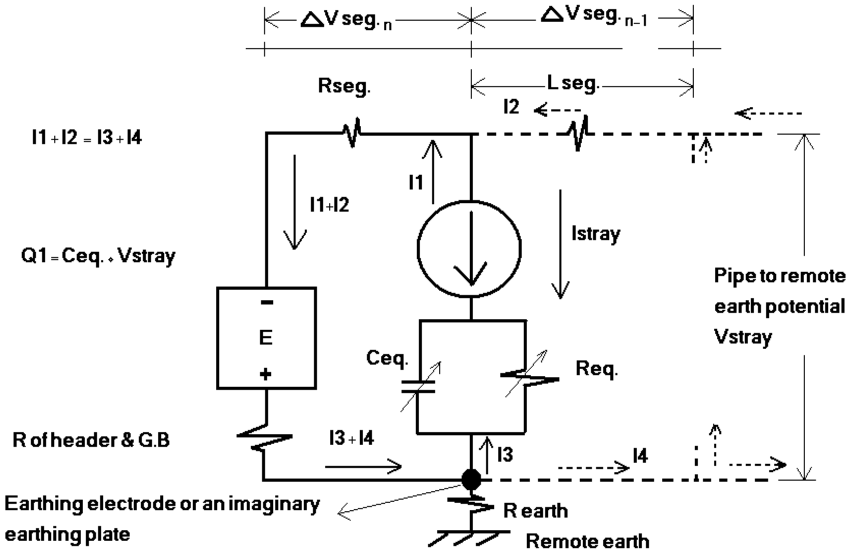

Figure 15b: The final proposed electric circuit diagram of bare pipe segment – soil – earth system with cathodic protection system

Now, by the use of the voltage drop canister which pigged with the intelligent pig and by the use of GPS system, each segment flow current I_P could be measured. Then by measuring the humidity around this pipe segment, the soil factor could be determined. Finally, from the ONION curves obtained before [9] (which correlate I_P, S_F and $V_{H.C}$), the equivalent pipe to soil potential of this buried pipe segment could be determined without the need of test point and without the need of $Cu/CuSO_4$ half cell. The most important result is that: the pipe to soil potential of any buried pipeline could be obtained segmental along its route without the need of any test points.

C. The General Equation Of Pipe To Soil Potential During Humidity Change By The Use Of Both Soil Factor and Protection Current For Pipe – Soil – Earth System

9. Analysis

As we said before, the print A's of the protection current passed through the pipe segment could be obtained from the general equation of the protection current (8) and easily we can construct the print of the protection current A's table for all boxes under test at pipe to soil potential, by the use of $Cu/CuSO_4$ half cell, from -0.2V up to -2V as per tables 10 as an example. The question now is: is it possible to rearrange the table results such that to be as the protection current A's for each box against the pipe to soil potential? This is as per table 11 as an example for the protection current A's against pipe to soil potential for box 19. What would be the results for all boxes under test?

Table 11: Protection current print constants of box 19 at pipe to soil potential equal to -0.2 volt to -2 volt

	Box 19 ρ_7									
$V_{H.C}$ Volt	-0.2	-0.4	-0.6	-0.85	-1	-1.2	-1.4	-1.6	-1.8	-2
A_{4I}	-2919.6	-2084.6	-1249.7	-206.05	420.24	1255.3	2.09E+03	2925.2	3760.1	4595.1
A_{3I}	3825.4	2739.4	1653.4	296.05	-518.53	-1604.6	-2.69E+03	-3776.5	-4862.5	-5948.5
A_{2I}	-1481.1	-1061.6	-642.13	-117.82	196.83	616.33	1.04E+03	1455.3	1874.8	2294.3
A_{1I}	150.62	108.14	65.66	12.562	-19.303	-61.787	-1.04E+02	-146.75	-189.23	-231.71
A_{0I}	-4.2838	-3.0782	-1.8728	-0.366	0.5383	1.7439	2.95E+00	4.1549	5.3604	6.5659
% error	0	0	0	0	0	0	0	0	0	0

9.1 A_{0I} print constant

The protection current A_{0I} print constant is linearly proportional to the pipe to soil potential V_{H-C} measured by $Cu/CuSO_4$ half cell. Figures 16 and 17 shows boxes 4&19 as an example and the correlation between them is governed by equation 17 for all boxes under test as follow:

$$A_{0I} = B_{1A0I} V_{H-C} + B_{0A0I} \quad (17)$$

9.2 A_{1I} print constant

The protection current A_{1I} print constant is linearly proportional to the pipe to soil potential V_{H-C} measured by $Cu/CuSO_4$ half cell. Figures 16 and 17 shows boxes 4&19 as an example and the correlation between them is governed by equation 18 as follow:

$$A_{1I} = B_{1A1I} V_{H-C} + B_{0A1I} \quad (18)$$

9.3 A_{2I} print constant

The protection current A_{2I} print constant is linearly proportional to the pipe to soil potential V_{H-C} measured by $Cu/CuSO_4$ half cell. Figures 16 and 17 shows boxes 4&19 as an example and the correlation between them is governed by equation 19 as follow:

$$A_{2I} = B_{1A2I} V_{H-C} + B_{0A2I} \quad (19)$$

9.4 A_{3I} print constant

The protection current A_{3I} print constant is linearly proportional to the pipe to soil potential V_{H-C} measured by $Cu/CuSO_4$ half cell. Figures 16 and 17 shows boxes 4&19 as an example and the correlation between them is governed by equation 20 as follow:

$$A_{3I} = B_{1A3I} V_{H-C} + B_{0A3I} \quad (20)$$

9.5 A_{4I} print constant

The protection current A_{4I} print constant is linearly proportional to the pipe to soil potential V_{H-C} measured by $Cu/CuSO_4$ half cell. Figures 16 and 17 shows boxes 4&19 as an example and the correlation between them is governed by equation 21 as follow:

$$A_{4I} = B_{1A4I} V_{H-C} + B_{0A4I} \quad (21)$$

Table 12 shows the result table of protection current print constants (A's) in terms of pipe to soil potential for all boxes under test.

9.6 The deduction of the general equation of the pipe to soil potential

We have the protection current general equation from equation 8 as follow:

$$I_P = A_{4I} X^4 + A_{3I} X^3 + A_{2I} X^2 + A_{1I} X + A_{0I} \qquad (8)$$

Where:

A's: = $A_{(\,)I}$ are the protection current print constants of the pipe soil under test

X = is the value of the soil factor at certain humidity

By substituting the values of A's from equations 17, 18, 19, 20 and 21 in equation 8 , the general equation of the pipe to soil potential will equal to equation 22 as follow:

$$V_{H.C} = \frac{I_P - [B_{0A4I} X^4 + B_{0A3I} X^3 + B_{0A2I} X^2 + B_{0A1I} X + B_{0A0I}]}{[B_{1A4I} X^4 + B_{1A3I} X^3 + B_{1A2I} X^2 + B_{1A1I} X + B_{1A0I}]} \qquad (22)$$

Where:

$V_{H.C}$: The equivalent value of the pipe to soil potential in volt measured by $Cu/CuSO_4$ half cell.

I_P: Segmental protection current in m Amp measured by the voltage drop canister of the intelligent pig.

X: Segmental soil factor in Ω.m%.

B's: New print constants of pipe-soil-earth system

Table 13 shows the error for all boxes under test while tables 14 & 15 are showing the detailed comparison between the pipe to soil potential obtained by equation 22 and the pipe to soil potential obtained by direct measurement by the use of $Cu/CuSO_4$ half cell for boxes 4 & 19 respectively during humidity change.

Table 12: The protection current print constants (A's) in terms of pipe to soil potential for all boxes under test

		ρ_1 Box 1	ρ_2 Box 4	ρ_3 Box 9	ρ_4 Box 10	ρ_5 Box 13	ρ_6 Box 18	ρ_7 Box 19	ρ_8 Box 24	ρ_9 Box 27	ρ_{10} Box 28
A_{4I}	**B_{1A4I}**	-2.00E+07	0.00E+00	-7.23E+04	-3.34E+04	-1.00E+06	-1.00E+08	-4.17E+03	-3.52E+04	-2.64E+04	-2.00E+07
	B_{0A4I}	-1.00E+07	0.00E+00	-4.79E+04	-2.53E+04	-2.00E+06	-1.00E+08	-3.75E+03	-2.76E+04	-1.78E+04	-1.00E+07
	error	H	H	H	0%	H	0%	0%	0%	0%	H
A_{3I}	**B_{1A3I}**	2.00E+06	7.24E+03	1.57E+04	1.70E+04	6.59E+04	7.00E+06	5.43E+03	5.63E+04	2.49E+04	3.00E+06
	B_{0A3I}	1.00E+06	-6.99E+01	1.43E+04	1.29E+04	1.00E+06	8.00E+06	4.91E+03	4.92E+04	1.67E+04	2.00E+06
	error	H	0%	0%	0%	H	H	0%	0%	0%	H
A_{2I}	**B_{1A2I}**	-5.53E+04	-1.99E+03	-7.41E+03	-2.75E+04	-9.94E+04	-1.22E+04	-2.10E+03	-2.77E+03	-6.75E+03	-1.21E+04
	B_{0A2I}	-2.97E+04	-5.54E+02	-8.04E+03	-2.09E+04	-1.48E+04	-1.33E+04	-1.90E+03	-2.95E+03	-4.54E+03	-8.30E+04
	error	0%	0%	0%	0%	H	H	0%	0%	0%	H
A_{1I}	**B_{1I}**	4.81E+02	4.11E+01	-1.23E+01	1.52E+03	3.70E+03	4.01E+02	2.12E+02	5.25E+00	4.22E+02	1.53E+03
	B_{0I}	2.63E+02	9.69E+00	8.94E+01	1.17E+03	5.49E+03	7.27E+02	1.93E+02	5.17E+01	2.92E+02	9.79E+02
	error	0%	0%	0%	0%	H	0%	0%	0%	0%	0%
A_{0I}	**B_{1A0I}**	-1.26E+00	-2.00E-01	3.93E-01	-2.57E+01	-3.79E+01	-3.07E-01	-6.03E+00	2.59E-01	-7.33E+00	-6.15E+00
	B_{0A0I}	-7.00E-01	-1.20E-02	-2.85E-01	-1.99E+01	-5.63E+01	-1.17E+00	-5.49E+00	-2.80E-01	-5.17E+00	-3.97E+00
	error	5%	0%	0%	0%	30%	5%	0%	0%	0%	0%

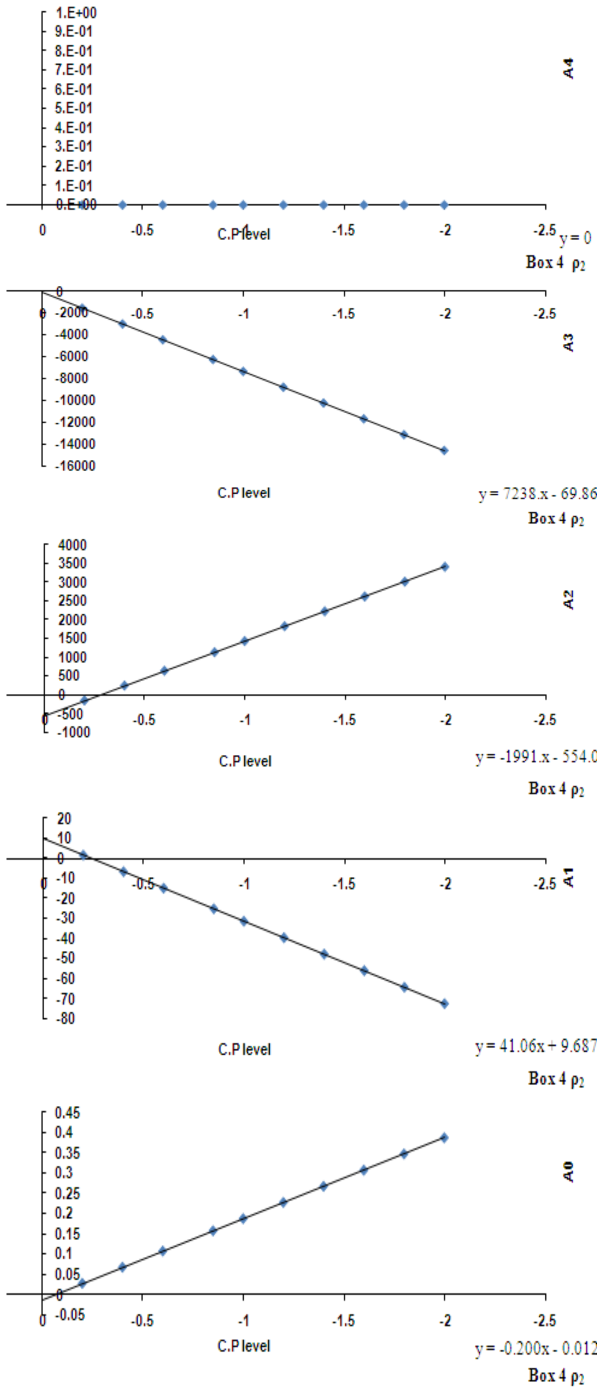

Figure 16: The protection current print constants against pipe to soil potential for box 4

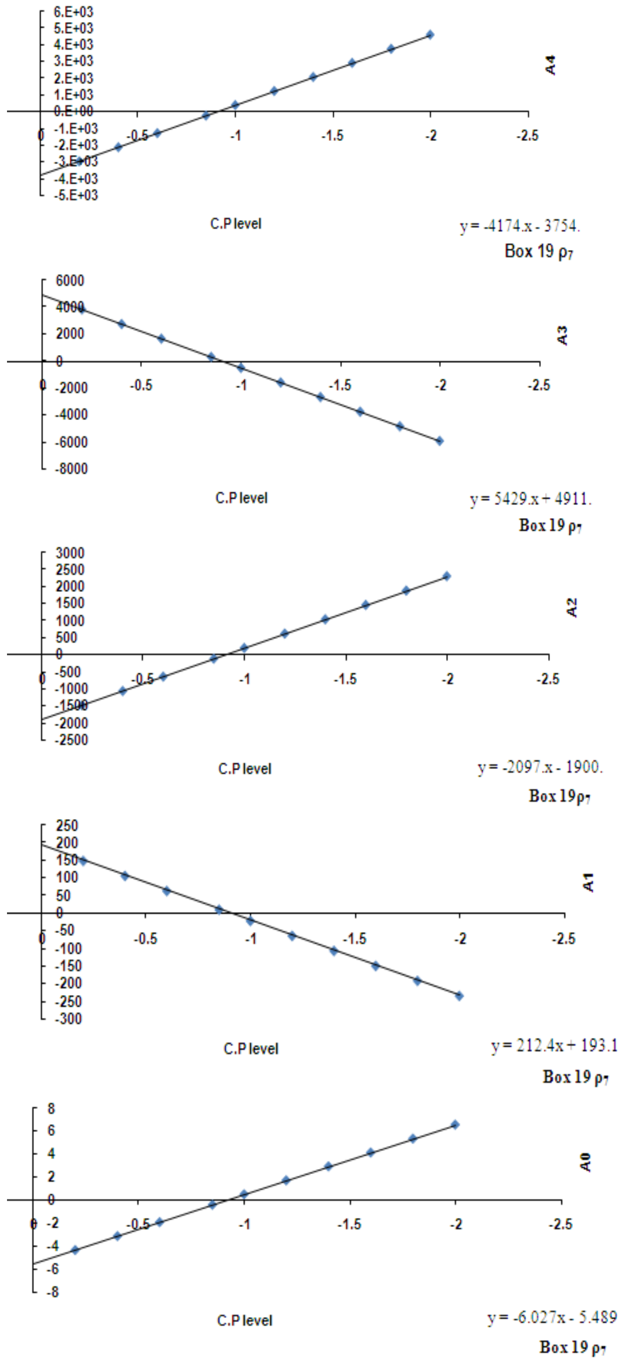

Figure 17: The protection current print constants against pipe to soil potential for box 4

Table 13: Error table between theoretical and experimental values of pipe to soil potential for all boxes under test during humidity change

Resistivity	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
Box No.	1	4	9	10	13	18	19	24	27	28
Av. Error	H	± 10 %	± 15 %	± 35 %	H	± 35 %	± 5 %	H	± 10 %	H

Table 14: Comparison between theoretical and experimental values of pipe to soil potential of box 4 during humidity change

Box	Electrical Parameters V_{P-PE} Volt	C_{P-PE} nF	I mA	PH	H %	Pipe to Soil Potential Theoretical V_{HC} - Volt	Experimental V_{HC} - Volt	Error %
4	0.1480	-0.570	0.0002	7.0	45%	-0.476829528	-0.4910	2.8860432
4	-0.2710	-0.570	0.4000	7.0	45%	-0.557774389	-0.5640	1.103831794
4	-3.7100	-0.570	5.1000	7.0	45%	-1.509352292	-1.3700	-10.17170015
4	-6.3900	-0.570	8.6000	7.0	45%	-2.217974135	-2.1110	-5.067462573
4	-9.3800	-0.570	11.1000	7.0	45%	-2.724132594	-2.6400	-3.186840686
4	-11.4400	-0.570	13.0000	7.0	45%	-3.108813023	-3.0000	-3.627100771
4	0.1000	45.600	0.0010	6.9	80%	-0.663867462	-0.5190	-27.91280574
4	-0.2050	45.600	0.3300	6.9	80%	-0.690445272	-0.5520	-25.08066515
4	-4.2800	45.600	7.9000	6.9	80%	-1.301977249	-1.3400	2.837518756
4	-6.3700	45.600	11.2200	6.9	80%	-1.570178856	-1.7000	7.636537911
4	-10.1500	45.600	15.9000	6.9	80%	-1.948246181	-2.2600	13.79441678
4	0.1930	70.000	0.0033	6.5	85%	-0.664663193	-0.6020	-10.40916827
4	-0.2140	70.000	0.1530	6.5	85%	-0.676743878	-0.8800	23.09728664
4	-2.9500	70.000	16.0000	6.5	85%	-1.955585621	-1.7800	-9.864360757
4	-4.9000	70.000	29.6000	6.5	85%	-3.053096047	-2.5500	-19.72925675
4	-6.8000	70.000	40.0000	6.5	85%	-3.892368726	-3.2300	-20.5067717
4	-8.5500	70.000	47.8000	6.5	85%	-4.521823235	-3.7700	-19.94226087

Table 15: Comparison between theoretical and experimental values of pipe to soil potential of box 19 during humidity change

Box	Electrical Parameters V_{P-PE} Volt	C_{P-PE} nF	I mA	PH	H %	Pipe to Soil Potential Theoretical V_{HC} - Volt	Experimental V_{HC} - Volt	Error %
19	0.1276	8.000	-0.0002	7.0	55%	-0.591185741	-0.5520	-7.098866132
19	-0.2490	8.000	0.3000	7.0	55%	-0.6986547	-0.6230	-12.14361155
19	-3.6500	8.000	3.0000	7.0	55%	-1.665230946	-1.4060	-18.43747837
19	-6.3200	8.000	5.2000	7.0	55%	-2.452811591	-2.0600	-19.06852382
19	-9.3000	8.000	7.7000	7.0	55%	-3.347789596	-2.8400	-17.87991536
19	0.0340	13.900	-0.0008	6.5	75%	-0.68121396	-0.6650	-2.438189508
19	-0.1920	13.900	0.1900	6.5	75%	-0.694328432	-0.6950	0.096628523
19	-4.0000	13.900	9.1000	6.5	75%	-1.306749508	-1.2500	-4.539960668
19	-6.6300	13.900	15.7000	6.5	75%	-1.76039475	-1.7300	-1.756921981
19	-9.8300	13.900	24.5000	6.5	75%	-2.365255073	-2.2800	-3.73925758
19	0.2700	72.000	0.0062	5.3	96%	-0.75561634	-0.7070	-6.876427114
19	-0.4400	72.000	0.1506	5.3	96%	-0.761007335	-0.7370	-3.25744026
19	-3.1300	72.000	14.0000	5.3	96%	-1.278057518	-1.2900	0.925773821
19	-4.7500	72.000	24.7000	5.3	96%	-1.677528755	-1.7000	1.321837922
19	-6.6900	72.000	35.8000	5.3	96%	-2.091933497	-2.0800	-0.573725824
19	-8.2000	72.000	46.2000	5.3	96%	-2.480204607	-2.4400	-1.647729778
19	-1.0700	72.000	57.4000	5.3	96%	-2.898342724	-2.8000	-3.512240159

D. The General Equation Of The Pipe To Soil Potential At All Humidity Conditions By The Use Of Both Soil Factor and Stray Potential Of The Pipe-Soil-Earthing Grid System

10. Analysis

As we said before, the print A's of the stray potential of the pipe segment to the earthing grid could be obtained from the general equation of the stray potential (5) and easily we can construct the print of the stray potential A's table for all boxes under test at pipe to soil potential, by the use of $Cu/CuSO_4$ half cell, from -0.2V up to -2V as per table 7 as an example. The question now is: is it possible to rearrange the table results such that to be as stray potential A's for each box against the pipe to soil potential? This is as per tables 16 & 17 as an example for the stray potential A's against pipe to soil potential for boxes 10 & 13 respectively. What would be the results for all boxes under test?

Table 16: Stray potential print constants of box10 at pipe to soil potential equal to -0.2 volt to -2 volt

	Box 10 ρ_4									
	-0.2	-0.4	-0.6	-0.85	-1	-1.2	-1.4	-1.6	-1.8	-2
A_{4V}	2.43E+04	22128	20006	17354	15762	13640	11518	9395.4	7273.2	5151
A_{3V}	-1.32E+04	-12146	-11131	-9862.3	-9100.9	-8085.8	-7070.7	-6055.6	-5040.4	-4025.3
A_{2V}	2.37E+03	2224.1	2082.5	1905.4	1799.2	1657.6	1515.9	1374.3	1232.7	1091
A_{1V}	-1.56E+02	-152.17	-148.12	-143.05	-140.02	-135.97	-131.91	-127.86	-123.81	-119.76
A_{0V}	3.64E+00	3.3314	3.0217	2.6345	2.4023	2.0926	1.7828	1.4731	1.1634	0.8537
error	0	0	0	0	0	0	0	0	0	0

Table 17: Stray potential print constants of box 13 at pipe to soil potential equal to -0.2 volt to -2 volt

	Box 13 ρ_5									
	-0.2	-0.4	-0.6	-0.85	-1	-1.2	-1.4	-1.6	-1.8	-2
A_{4V}	-2.52E+04	-17108	-8993.3	1149.5	7235.1	15349	23464	31578	39692	47806
A_{3V}	8.50E+03	4654	806.87	-4002.1	-6887.5	-10735	-14582	-18429	-22276	-26123
A_{2V}	-2.73E+02	293.88	860.87	1569.6	1994.9	2561.9	3128.8	3695.8	4262.8	4829.8
A_{1V}	-8.76E+01	-115.06	-142.47	-176.73	-197.29	-224.7	-252.11	-279.52	-306.93	-334.45
A_{0V}	2.14E+00	2.2143	2.2855	2.3745	2.4278	2.499	2.5702	2.6413	2.7125	2.7837
error	0	0	0	0	0	0	0	0	0	0

10.1 A_{0V} print constant

The stray potential from the pipe segment to the earthing grid, A_{0V} print constant is linearly proportional to the pipe to soil potential V_{H-C} measured by $Cu/CuSO_4$ half cell. Figures 18 & 19 show boxes 10 & 13 as an example and the correlation between them is governed by equation 23 for all boxes under test as follow:

$$A_{0V} = B_{1A0V}\, \mathbf{V}_{H-C} + B_{0A0V} \quad (23)$$

10.2 A_{1V} print constant

The stray potential from the pipe segment to the earthing grid, A_{1V} print constant is linearly proportional to the pipe to soil potential V_{H-C} measured by $Cu/CuSO_4$ half cell. Figures 18 & 19

show boxes 10 & 13 as an example and the correlation between them is governed by equation 24 as follow:

$$A_{1V} = B_{1A1V}\, \mathbf{V}_{H-C} + B_{0A1V} \quad (24)$$

10.3 A_{2I} print constant

The stray potential from the pipe segment to the earthing grid, A_{2V} print constant is linearly proportional to the pipe to soil potential V_{H-C} measured by $Cu/CuSO_4$ half cell. Figures 18 & 19 show boxes 10 & 13 as an example and the correlation between them is governed by equation 25 as follow:

$$A_{2V} = B_{1A2V}\,\mathbf{V}_{H\text{-}C} + B_{0A2V} \qquad (25)$$

10.4 A_{3V} print constant

The stray potential from the pipe segment to the earthing grid, A_{3V} print constant is linearly proportional to the pipe to soil potential $V_{H\text{-}C}$ measured by $Cu/CuSO_4$ half cell. Figures 18 & 19 show boxes 10 & 13 as an example and the correlation between them is governed by equation 26 as follow:

$$A_{3V} = B_{1A3V}\mathbf{V}_{H\text{-}C} + B_{0A3V} \qquad (26)$$

10.5 A_{4V} print constant

The stray potential from the pipe segment to the earthing grid, A_{4V} print constant is linearly proportional to the pipe to soil potential $V_{H\text{-}C}$ measured by $Cu/CuSO_4$ half cell. Figures 18 & 19 show boxes 10 & 13 as an example and the correlation between them is governed by equation 27 as follow:

$$A_{4V} = B_{1A4V}\,\mathbf{V}_{H\text{-}C} + B_{0A4V} \qquad (27)$$

Table 18 shows the result table of protection current print constants (A's) in terms of pipe to soil potential for all boxes under test

Table 18: Stray potential print constants (A's) in terms of pipe to soil potential for all boxes under test

		ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
		Box 1	Box 4	Box 9	Box 10	Box 13	Box 18	Box 19	Box 24	Box 27	Box 28
A_{0V}	**B_{1A0V}**	2.19E+00	1.567	0.911	1.548	-0.355	-2.09E+00	-7.671	2.437	-2.635	1.1
	B_{0A0V}	4.80E+00	0.724	2.688	3.95	2.072	2.88E+00	0.632	-0.117	2.302	2.535
	error	0%	0	0	0	0	3%	0	0	1%	0%
A_{1V}	**B_{1A1V}**	-468.88	-8.6912	141.17	-20.257	137.08	1660.1	237.32	28.372	135.56	82.588
	B_{0A1V}	-1421.8	-45.09	-308.35	160.27	-60.217	-978.29	-3.0607	59.6	-67.017	-250.82
	error	0	0	0	0	0	0	0	0	1%	0
A_{2V}	**B_{1A2V}**	58664	865.2	-3960	708.1	-2834	-13567	-1225	-857.8	-493.2	-2781
	B_{0A2V}	14164	1020	13609	2507	-840	95891	-115.2	-961.4	747.3	10114
	error	0	± 70%	0	0	0	0	0	0	0	0
A_{3V}	**B_{1A3V}**	-2.00E+06	-7698	41703	-5075	19236	4.00E+06	2301	5996	428.4	55331
	B_{0A3V}	-5.00E+06	-8402	-18786	-14176	12348	-4.00E+06	424.3	5158	-2400	-14698
	error	±10%	0	0	0	0	±5%	0	0	±1%	0
A_{4V}	**B_{1A4V}**	2.00E+07	0	-99143	10611	-40571	-3.00E+07	-1424	0	129	-36192
	B_{0A4V}	5.00E+07	0	83364	26373	-33336	4.00E+07	-349.5	0	2335	66349
	error	10%		0	0	0	3%	0		1%	20%

10.6 The deduction of the general equation of the pipe to soil potential

We have the stray potential general equation from equation 5 as follow:

$$V_{Str.} = A_{4V}\mathbf{X}^{4} + A_{3V}\mathbf{X}^{3} + A_{2V}\mathbf{X}^{2} + A_{1V}\mathbf{X} + A_{0V} \qquad (5)$$

By substituting the values of A's from equations 23, 24, 25, 26 and 27 in equation 5 , the general equation of the pipe to soil potential will equal to equation 28 as follow:

$$V_{H.C} = \frac{V_{Stray} - [B_{0A4V}\mathbf{X}^4 + B_{0A3V}\mathbf{X}^3 + B_{0A2V}\mathbf{X}^2 + B_{0A1V}\mathbf{X} + B_{0A0V}]}{[B_{1A4V}\mathbf{X}^4 + B_{1A3V}\mathbf{X}^3 + B_{1A2V}\mathbf{X}^2 + B_{1A1V}\mathbf{X} + B_{1A0V}]} \qquad (28)$$

Where:

$V_{H.C}$: The equivalent value of the pipe to soil potential in volt measured by $Cu/CuSO_4$ half cell.

$V_{Str.}$: Stray potential of the pipe segment in Volt.

X: Segmental soil factor in Ω.m%.

B's: New print constants of pipe-soil-earth system Table 19 shows the error for all boxes under test while tables 20 & 21 are showing the detailed comparison between the pipe to soil potential obtained by equation 28 and the pipe to soil potential obtained by direct measurement by the use of Cu/$CuSO_4$ half cell

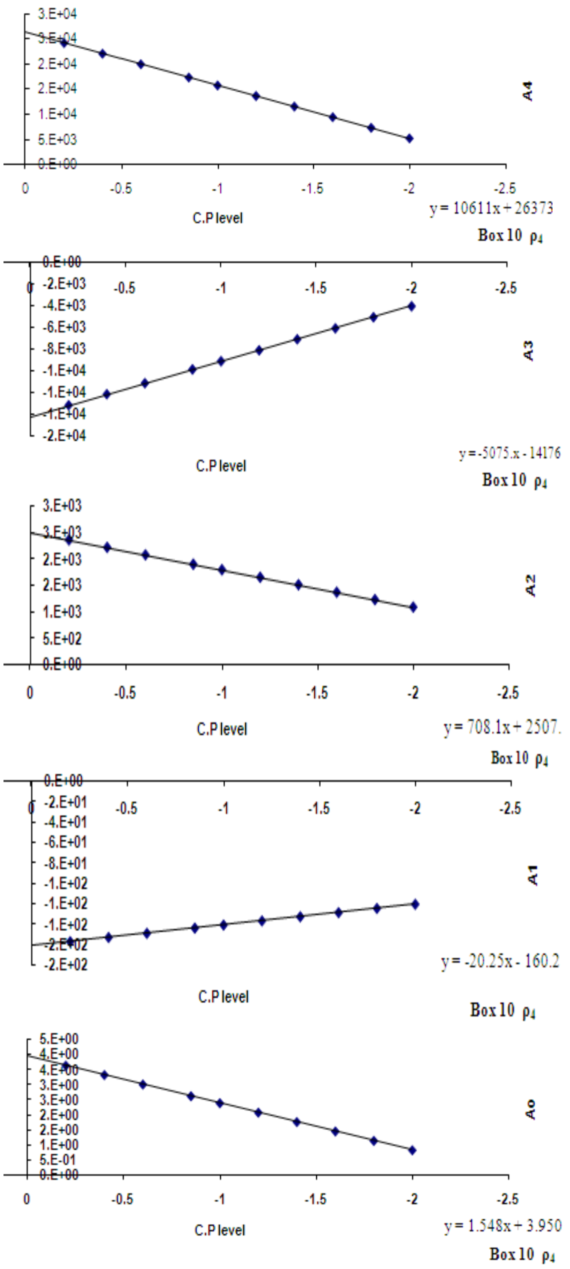

Figure 18: The stray potential print constants against pipe to soil potential for box 10

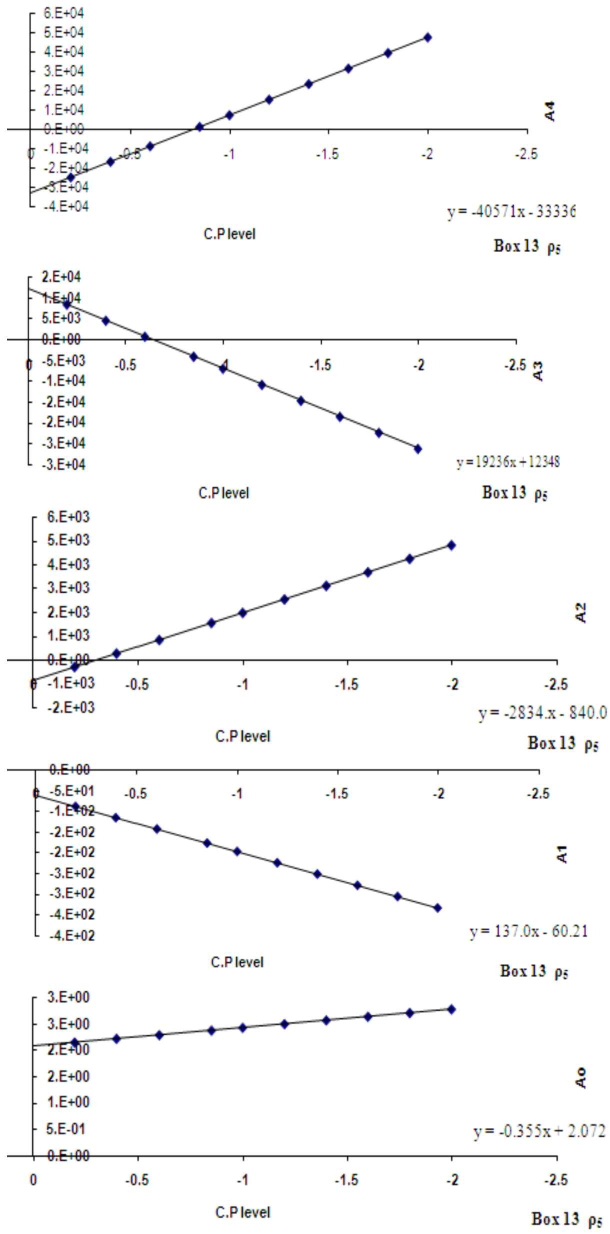

Figure 19: The stray potential print constants against pipe to soil potential for box 13

Table 19: Error table between theoretical and experimental values of pipe to soil potential for all boxes under test

Resistivity	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}
Box No.	1	4	9	10	13	18	19	24	27	28
Av. Error	H	± 5 %	± 40 %	± 5 %	± 5 %	H	± 5 %	± 40 %	± 5 %	± 5 %

Table 20: Comparison between theoretical and experimental values of pipe to soil potential of box 10

Box	Electrical Parameters			pH	H	Pipe to Soil Potential		Error
	V_{P-PE}	C_{P-PE}	I		H	Theoretical	Experimental	Error
	Volt	nF	mA		%	V_{HC} - Volt	V_{HC} - Volt	%
10	0.49	0.172	0.0015	7.8	10%	-0.314839657	-0.3000	4.7134014
10	-0.461	0.172	0.0060	7.8	10%	-0.9620273	-0.9600	0.2107321
10	-4.33	0.172	0.0175	7.8	10%	-3.595012572	-3.6000	-0.1387319
10	-5.07	0.172	0.0220	7.8	10%	-4.098607584	-4.1400	-1.0099141
10	-8.06	0.172	0.0335	7.8	10%	-6.133403645	-6.1000	0.5446184
10	0.2723	7.900	0.0046	7.7	18%	-0.182218469	-0.3063	-68.094926
10	-0.1923	7.900	0.1000	7.7	18%	-0.431641808	-0.4550	-5.4114757
10	-4.37	7.900	1.2600	7.7	18%	-2.674465499	-2.4960	6.6729408
10	-6.79	7.900	1.9600	7.7	18%	-3.973657238	-3.8500	3.1119251
10	-9.38	7.900	2.7500	7.7	18%	-5.364114513	-5.3500	0.2631285
10	-10.5	7.900	3.1400	7.7	18%	-5.965393335	-6.1300	-2.7593598
10	0.21	33.400	0.0023	7.0	65%	-0.43028885	-0.5010	-16.433414
10	-0.315	33.400	0.5000	7.0	65%	-0.657031363	-0.6600	-0.4518258
10	-3.38	33.400	5.5400	7.0	65%	-1.980775742	-1.8600	6.0973961
10	-6.1	33.400	11.2100	7.0	65%	-3.1555179	-3.2000	-1.4096608
10	-9.5	33.400	17.0000	7.0	65%	-4.623945597	-4.6500	-0.5634669
10	0.145	49.600	0.0018	6.5	88%	-0.432519024	-0.5380	-24.387592
10	-0.29	49.600	0.1850	6.5	88%	-0.615311165	-0.6400	-4.0124146
10	-3.93	49.600	10.6000	6.5	88%	-2.144882184	-1.9900	7.2210112
10	-6.31	49.600	17.6000	6.5	88%	-3.144986311	-3.0900	1.74838
10	-9.6	49.600	30.0000	6.5	88%	-4.527483193	-4.6500	-2.7060687
10	0.244	89.000	0.0048	6.0	100%	-0.564233649	-0.6350	-12.542029
10	-0.006	89.000	0.1530	6.0	100%	-0.656040154	-0.6700	-2.1278951
10	-3.56	89.000	18.8000	6.0	100%	-1.961161418	-1.9000	3.1186325
10	-5.42	89.000	34.2000	6.0	100%	-2.64420181	-2.5300	4.3189521
10	-6.72	89.000	44.0000	6.0	100%	-3.121595632	-3.1800	-1.870978
10	-8.45	89.000	55.0000	6.0	100%	-3.756896641	-3.8400	-2.2120214

Table 21: Comparison between theoretical and experimental values of pipe to soil potential of box 13

Box	Electrical Parameters			pH	H	Pipe to Soil Potential		Error
	V_{P-PE}	C_{P-PE}	I		H	Theoretical	Experimental	Error
	Volt	nF	mA		%	V_{HC} - Volt	V_{HC} - Volt	%
13	0.145	0.000	0.0019	7.3	6%	-0.505960215	-0.4730	6.5143887
13	-0.705	0.000	0.0067	7.3	6%	-1.163633299	-1.1390	2.1169297
13	-4.06	0.000	0.0224	7.3	6%	-3.759507649	-3.9000	-3.736988
13	-4.9	0.000	0.0275	7.3	6%	-4.409443403	-4.4100	-0.0126228
13	-7.13	0.000	0.0394	7.3	6%	-6.134868083	-6.0700	1.0573672
13	0.2796	8.700	0.0044	7.6	10%	0.315257985	-0.2900	191.98815
13	-2.575	8.700	0.0800	7.6	10%	-1.358426955	-0.4860	64.223325
13	-3.81	8.700	0.7000	7.6	10%	-2.082521715	-2.1100	-1.3194717
13	-5.66	8.700	1.0100	7.6	10%	-3.167198076	-3.2220	-1.7302967
13	-8.49	8.700	1.5900	7.6	10%	-4.826459752	-4.8500	-0.4877332
13	-10.79	8.700	2.0200	7.6	10%	-6.174976309	-6.3600	-2.9963466
13	0.288	31.900	0.0024	6.9	80%	-0.441743481	-0.4960	-12.282359

Table 21 Cont.

Box	Electrical Parameters					Pipe to Soil Potential		
	V_{P-PE}	C_{P-PE}	I	pH	H	Theoretical	Experimental	Error
	Volt	nF	mA		%	V_{HC} - Volt	V_{HC} - Volt	%
13	-0.211	31.900	0.9200	6.9	80%	-0.670961813	-0.6590	1.782786
13	-3.77	31.900	10.8000	6.9	80%	-2.305807595	-2.2900	0.6855557
13	-6.44	31.900	18.8000	6.9	80%	-3.532286449	-3.7100	-5.0311195
13	-9.11	31.900	27.4000	6.9	80%	-4.758765302	-4.8600	-2.1273312
13	0.146	109.200	0.0019	5.2	100%	-0.648122287	-0.6880	-6.1528069
13	-0.244	109.200	1.0800	5.2	100%	-0.793995223	-0.7700	3.0220866
13	-3.4	109.200	30.0000	5.2	100%	-1.974443905	-2.0000	-1.2943439
13	-6	109.200	56.0000	5.2	100%	-2.946930144	-3.0400	-3.1581969
13	-9.5	109.200	85.0000	5.2	100%	-4.256046236	-4.3200	-1.5026567
13	0.133	243.000	0.0014	5.0	100%	-0.660302144	-0.7010	-6.1635202
13	-0.14	243.000	0.1870	5.0	100%	-0.761080019	-0.7840	-3.0115074
13	-2.87	243.000	19.1000	5.0	100%	-1.768858767	-1.7500	1.0661545
13	-4.6	243.000	60.5000	5.0	100%	-2.407487791	-2.4200	-0.5197206
13	-6.3	243.000	87.0000	5.0	100%	-3.035042323	-3.0800	-1.4812867
13	-7.55	243.000	108.0000	5.0	100%	-3.496479478	-3.6000	-2.9607073

11. Conclusion

The behavior of the electrical parameters of the pipe-soil-earth system during the change of the electrochemical properties of the soil could be plotted in electrical parameters PRINT which will be always valid in all times as the pipe-soil system is maintained and without any external interference. Once the system is changed by replacement another pipe with different dimension and/or the replacement of the soil, there will be another new electrical parameters PRINT for the new pipe-soil-earth system. Also, the buried pipe line segment with soil surrounding medium could be simulated electrically by an electric circuit where the system is subjected to the law: (charge = capacitance × volt) between the pipe surface and the remote earth. This is where each of circuit electric parameter could be obtained by an equation as a function of the measured electrochemical properties of the soil (soil factor), 4th degree polynomial at room temperature but the A's constants are different for each electric quantity .The constants of each equation (A's) considered to be as a PRINT of such pipe-soil-earth system and valid until pipe and/or soil is changed with of course new print values. For buried bare pipe segments in different kind of soils at different cathodic protection level, the PRINTS of the electrolytic stray capacitor between pipe & earth, the stray potential across the stray capacitance, surface charge and the protection current of the cathodic protection system passed through the pipe segment were obtained in terms of the new parameter, the soil factor. The useful of these prints is to obtain complete electrical data correlated with many cathodic protection levels which help, after complete erection of the pipeline, in defining the c.p level (pipe to soil potential) of any pipe line segment through it's length by measuring the protection current and calculating the soil factor at the pipe segment from direct field measurements. Not only has that but also to define the most suitable route of the pipe line, before the erection process, which generates the minimum surface charge. The error of electric parameters equations reduced to be less than ± 5%. The most important advantage of such electrical analogue circuit of pipe segment-soil-earth system is the possibility to simulate a complete pipeline – soil system by an electric circuit and to convert both the corrosion and cathodic protection problems of the pipeline to an electric problem. This will help in corrosion monitoring and the maintenance of c.p systems. The most important result is that: the pipe to soil potential of any buried pipeline could be obtained segmental along its route without the need of any test points. This is by the use of the new electric concept of pipe-soil-earth system.

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