Cathodic Protection Design for Buried Steel Pipes

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Chemical Engineering

by

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Certification

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Abstract

Iraq has a huge network of pipelines, transport crude oil and final hydrocarbon products as well as portable water. These networks are exposed to extensive damage due to the underground corrosion processes unless suitable protection techniques are used. Information of cathodic protection has been collected for pipeline in practical fields, to obtain data base for understanding and optimizing the design which is made by simulation using MATLAB software for the environmental factors and cathodic protection variables.

The first part concerns with field work and simulation Simulink which is enables the designer to build cathodic protection for buried structure and predicting the numbers of anode and its operating voltages and currents under various operational conditions, and compare it with those in practices. In this work a comparison has been made between the field and simulation results which include anode numbers, rectifier voltage and current; it was found that as the number of anode increase the resistance of the anode ground bed decrease and vice versa with some exceptions. The current depends on the length of the section to be protected while the applied voltage depends on the soil resistivity beside the length of the structure. The second concerns about the anode position effect on the cathodic protection system as well as the coating effect and the soil resistivity effect.In cathodic protection system the design of anode ground bed plays very important role since the current distribution and pipe potential will be affected by anode position with respect to the structure position. A comparison have been made between different positions in different soil conditions for coated and uncoated pipe; contours maps for potential distribution are also obtained. The work shows that coated pipe need less voltage to protect than if it is uncoated, dry soil needs more voltage than moisture soil, as the anode distance increase the pipe potential decrease.

In the field work the most economical design for the first pipeline was at station no. 2 which need 2.5 A for protection of the pipeline for that specific length and for second pipeline station no. 4 which need 12 A for protection of the pipeline for that specific length. And the best anode positions was from 50-150 m away from pipeline to give a better protection for the pipeline, and the anode grounded resistance decrease as the number of anodes increases.

In the experimental work the best distance between the anode and the cathode was 30cm away from pipe, and the best depth was at apposition below the pipe surface rather than at the same level.

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Nomenclature

Symbol	Meaning	Units
E	Electrode potential	Volt
IR	Potential drop	Volt
L	Length of protected structure at specified zone	ft
D	Pipe diameter	in
CE	Coating efficiency	dimensionless
I	Required current density	mA/m^2
A	Total structure surface area	ft^2
A1	Corrosion current density	ft^2/anode
I1	Recommended maximum current density out put	mA
N	Number of anodes	dimensionless
l	life	years
W	Weight of anode	lb
La	Length of anode backfill column	ft
K	Anode shape factor	dimensionless
S	Center to center spacing between anode backfill column	ft
Ra	Anode resistance	Ohm
Rw	The ground bed header cable resistance	Ohm

d	Anode /backfill diameter	in
L_{eff}	Effective anode length	ft
Rc	structure to Electrolyte resistance	Ohm
L_{deep}	Anode length in deep anodes ground bed	m
d_{deep}	Anode diameter in deep anode ground bed	m
$Rt_{.}$	Total resistance	Ohm
V	Voltage	Volt
R	Coating resistance	Ohm

Greek symbols

Symbol	Meaning	Units
ρ	Soil Resistivity	Ohm.cm

Abbreviations

Abbreviation	Meaning
NACE	National Association of Corrosion Engineers
CP	Cathodic protection
DC	Direct current /power supply
RE	Reference electrode
HSCI	High silicon cast iron
CSE	Copper sulfate electrode

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Chapter One

Introduction

1.1 Introduction:

In the modern age of Industrial world, the oil refineries, petroleum products, and petrochemicals form the major part of the industrial set-up all over the world. It is often economical and practical to carry the liquid and gaseous products through pipe-lines rather than by tankers over long distance. Passing through land, rivers, sea, mountains crossing other services like roads, railways, transmission lines, underground Pipes/Cables etc. This pipelines passing through soils which can be considered as corrosive environment; therefore it suffers from underground corrosion. According to a recent study made by the National Association of Corrosion Engineers NACE, the estimated loss due to corrosion in the United States during 2012 would be of an approximate amount of $1 trillion [1].

The transporting of oil in Iraq is so important for the country economy; revenue potential of approximately $14.8 billion has been lost to the Iraqi government due to unavailability of increased capacity for moving oil.

Therefore; attention focuses on protection from corrosion. There are different methods to provide protection against corrosion one of them is cathodic protection. Cathodic protection is unique amongst all methods of corrosion control in its ability to stop corrosion completely, but it remains within the choice of the operator to accept a lesser, but quantifiable, level of protection. It is an important and versatile technique cathodic protection is the utilization of the electrical properties of corrosion of metallic substances to provide a system for the protection of steel piping or any other buried metallic structure, to extend their useful life [2].

Corrosion is the destructive attack of a metal by chemical or electrochemical reaction with its environment**.** Rusting applies to the corrosion of iron or iron - base alloys with formation of corrosion products consisting largely of hydrous ferric oxides. Nonferrous metals, therefore, corrode, but do not rust. Corrosion can compromise the safety of operating equipment by causing failure**.** For example, pressure vessels, boilers, metallic containers for toxic chemicals nuclear power plants and for disposal of nuclear wastes [3]. if the current is considered to flow from (+) to (-), as conventional electrical theory, then a structure is protected if current enters it from the electrolyte [4].

The ideal design for a cathodic protection system is the one which will provide the desired degree of protection at the minimum total annual cost over the projected life of the protected structure.

The prevention of corrosion with cathodic protection is not new; the technology has existed for over 189years. In 1824, Sir Humphrey Davy used cathodic protection to prevent corrosion of British naval ships. Humphrey's role in the application of cathodic protection should not be ignored. In 1824, Davy presented a series of papers to the Royal Society in London, in which he described how zinc and iron anodes could be used to prevent the corrosion of copper sheathing on the wooden hulls of British naval vessels [2, 3].

1.2 Objectives of the Study:

The objectives of this study are:

1. Obtain data based to understand and optimize with the design results which is made by simulation for the environmental factors and cathodic protection variables.
2. Modeling to build cathodic protection for buried structure and predicting the positions of anodes, number of anodes used and its operating voltages and currents under various operational conditions, and compare it with those in practices.
3. Studying the effect of anode position and comparison have been made with different positions
4. Investigating the benefit coating to reduce cathodic protection current density as compared with bare pipe.

5. Study (measurement) distribution potential along the pipe at similar and dissimilar soils.
6. Contours maps for potential distribution also obtained.

Chapter Two

Literature Review

2.1 Literature Review:

Iraq has the world's second largest proven oil reserves. Iraq's oilfields are distributed between two distinct production areas: the southern fields and the northern fields. The map of these fields is shown in fig. 2-1.

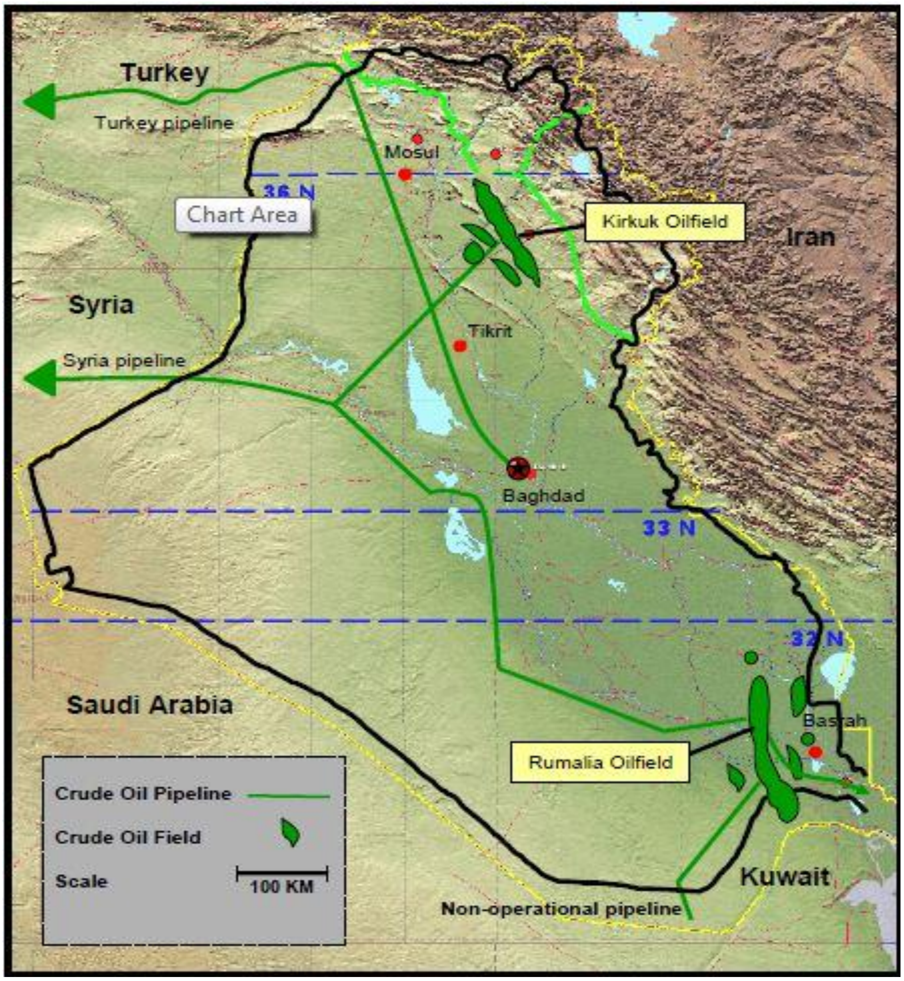


Figure 2-1 Crude oil field

The principle oilfields in northern Iraq extend from the town of Kirkuk some 70 miles northwards toward Mousl. Kirkuk oil fields provide all crude oil for the Baiji refinery, 40 to 45 % of the crude oil for the Doura refinery and export of crude oil to Turkey. The ideal design for a cathodic protection system is the one which will provide the desired degree of protection at the minimum total annual cost over the projected life of the protected structure.

2.2 Corrosion:

Corrosion cell (electrochemical cell, galvanic cell) a circuit consisting of an anode and a cathode in electrical contact in an electrolyte, and metallic path.

The most common methods to prevent corrosion are:

1. Preventing access of electrolyte.

Coating possesses the following properties; high resistance coatings are used on most pipelines to reduce the amount of current necessary to protect the pipeline. However, the introduction of nicks and scrapes which expose bare steel cannot be avoided during installation. It is therefore absolutely necessary to use cathodic protection CP on coated pipes since experience has shown that not using CP results in accelerated failure [5]. The coating defects represent a low resistance path, and therefore a preferred route, to the structure, for the cathodic protection current. The function of external coatings is to control corrosion by isolating the external surface of the underground or submerged piping from the environment, to reduce cathodic protection current requirements, and to improve current distribution [6]. When a high resistance coating is used, the current passing directly through the coating will be negligible compared with that flowing to coating defects unless the number and size of the defects are usually small [7].

2. Reversing the flow of electrons this is done by cathodic protection.
3. The use of corrosion resistance alloys such as stainless steel.
4. Corrosion allowance.

In the case of a tank or pipeline, this can be the tank or pipe itself, or it can be a metallic bond to different metallic structure [8].

The aqueous corrosion of iron under conditions of air access can be written as:

$$2Fe \rightarrow 2Fe^{2+} + 4e^{-} \qquad E^{o}=0.45\ V \quad \text{Oxidation} \qquad \ldots(1)$$

The product, ferrous hydroxide, is commonly further oxidized to magnetite (Fe_3O_4) or a hydrated ferric oxide (FeOOH), that is, rust.

It is convenient to consider separately the metallic and nonmetallic reactions in equation 1: [9]

$$O_2+2H_2O+4e^- \rightarrow 4OH^- \quad E^o=0.4\ \text{V} \quad \text{Reduction} \quad \ldots(2)$$

$$2Fe+O_2+2H_2O \rightarrow 2Fe(OH)_2 \quad E^o=0.85\ \text{V} \quad \text{Total} \quad \ldots(3)$$

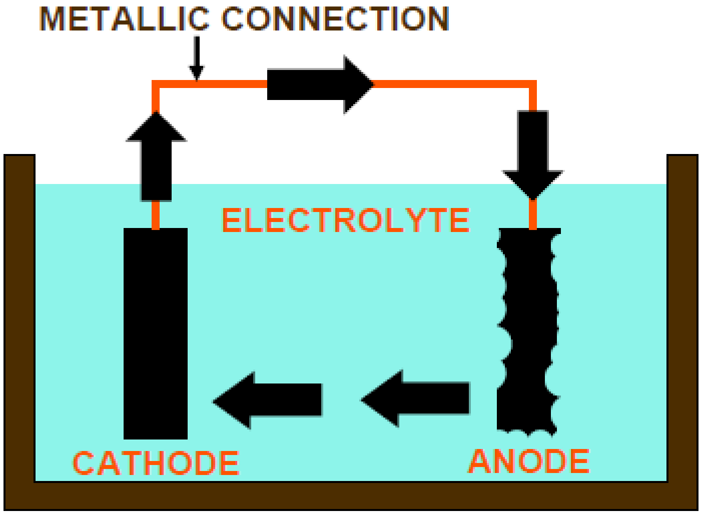


Figure 2-2 Corrosion cell [10]

2.3 Cathodic Protection:

It is an electrical method of mitigating corrosion on structures that are exposed to electrolytes such as soils and waters [11].

Cathodic protection is a method to reduce corrosion by minimizing the difference in potential between anode and cathode [12] which means corrosion of the structure is completely eliminated when the open-circuit potentials of the cathodic sites are polarized to the open-circuit potentials of the anodic sites [11].

Cathodic protection is primarily feasible when the surfaces to be protected are buried or submerged. External surfaces of buried metallic structures, surfaces of metal waterfront structures such as sheet pilings or bearing piles, and the internal surfaces of tanks containing electrolytes such as water are applications where cathodic protection is usually technically feasible and is commonly utilized in protecting such structures. Cathodic protection has limited applicability on internal surfaces of small diameter pipelines and other areas where ion flow in the electrolyte is restricted by electrolyte resistance [13].

2.3.1 Types of Cathodic Protection:

There are two types of cathodic protection namely, sacrificial anodes and impressed current cathodic protection.

A- Sacrificial anode

Sacrificial anode techniques cathodic protection systems provide cathodic current by galvanic corrosion. The current is generated by metallically connecting the structure to be protected to a metal/alloy that is electrochemically more active than the material to be protected. Both the structure and the anode must be in contact with the electrolyte. Current discharges from the expendable anode, to the electrolyte, and onto the structure to be protected [14].

Zinc or magnesium anodes are connecting to the pipe at recorded intervals along it. The anodes are regularly lifted for inspection and replaced when necessary. To minimize anode consumption, the pipework is given primary protection by a coating such as a tarred wrap. One of the most effective and inexpensive methods of protecting steel sheet in near neutral aqueous environments is to coat it with a thin layer of zinc, either by hot-dipping, i.e., *galvanizing* , or more usually by electrode position.

In near-neutral aqueous media, the zinc coating resists corrosion by forming a passive surface of $Zn(OH)_2$. At defects in the coating caused by abrasion and at cut edges, the exposed iron is cathodically protected by corrosion of the newly exposed zinc, producing $Zn(OH)_2$, which covers the exposed iron, stifling further attack.

It may seem surprising that tin coatings can galvanically protect steel food cans [15]. Cathodic protection in the sacrificial anode system is essentially a controlled electrochemical cell. Anode life is dependent upon the amount of current emitted by the anodes and their size [11].

A galvanic cathodic protection system makes use of the corrosive potentials for different metals. Without cathodic protection, one area of the structure exists at a more negative potential than another, and corrosion results. If however, a much less inert object (that is, with much more negative potential, such as magnesium anode) is placed adjacent to the structure to be protected, such as pipeline, and a metallic connection (insulated wire) is installed between the object and the structure, the object will become the anode and the entire structure will become the cathode. That is, the new object corrodes sacrificially to protect the structure as shown in Fig. 2-3. Thus the galvanic cathodic protection system is called a *sacrificial anode cathodic protection system* because the anode corrodes sacrificially to protect the structure. Galvanic anodes are usually made of either magnesium or zinc because of the more negative potentials of these metals compared to steel structures.

Tests should not be attempted on lines which are electrically protected with sacrificial anodes spaced at close intervals unless they are disconnected [16].

In practice, pure metals are never used as sacrificial anodes. There are a variety of reasons for this, which includes the need for [17, 2]:

- A reliable, reproducible and negative operating potential for the anode;
- A high and reproducible capacity (A h^{-1} kg^{-1}) for the anode;
- Uniform dissolution of the anode so that all metal is consumed usefully in providing cathodic protection and not wastefully by mechanical loss;
- Freedom from any loss of activity by the anode due to passivation

B- Impressed current

Impressed current type cathodic protection systems provide cathodic current from an external power source. A DC power forces current to discharge from expendable anodes, to the electrolyte, and onto the structure to be protected. Although the current is generated by a corrosion reaction at the auxiliary anode, the energized materials used for the auxiliary anodes either do not corrode or corrode very slowly because corrosion resistant materials and alloys are used [14]. Impressed current cathodic protection systems use the same elements as the galvanic protection system; only the structure is protected by applying a current to it from an anode. The anode and the structure are connected by an insulated wire, as for the galvanic system. Current flows from the anode through the electrolyte onto the structure, just as in the galvanic system. The main difference between galvanic system relies on the difference in potential between the anode and the structure, whereas the impressed current system uses an external power source to derive the current, the external power source is usually a rectifier that changes input AC power to the proper DC power level the rectifier can be adjusted, so that proper output can be maintained during the systems life. Impressed current cathodic protection system anodes typically are high-silicon cast iron or graphite**.**

The principle advantage of impressed current cathodic protection is its much greater output capacity as compared to galvanic anode system. Therefore, whenever corrosion protection is desired for very large, poorly coated, or bare structures, impressed current is often the system choice [18].

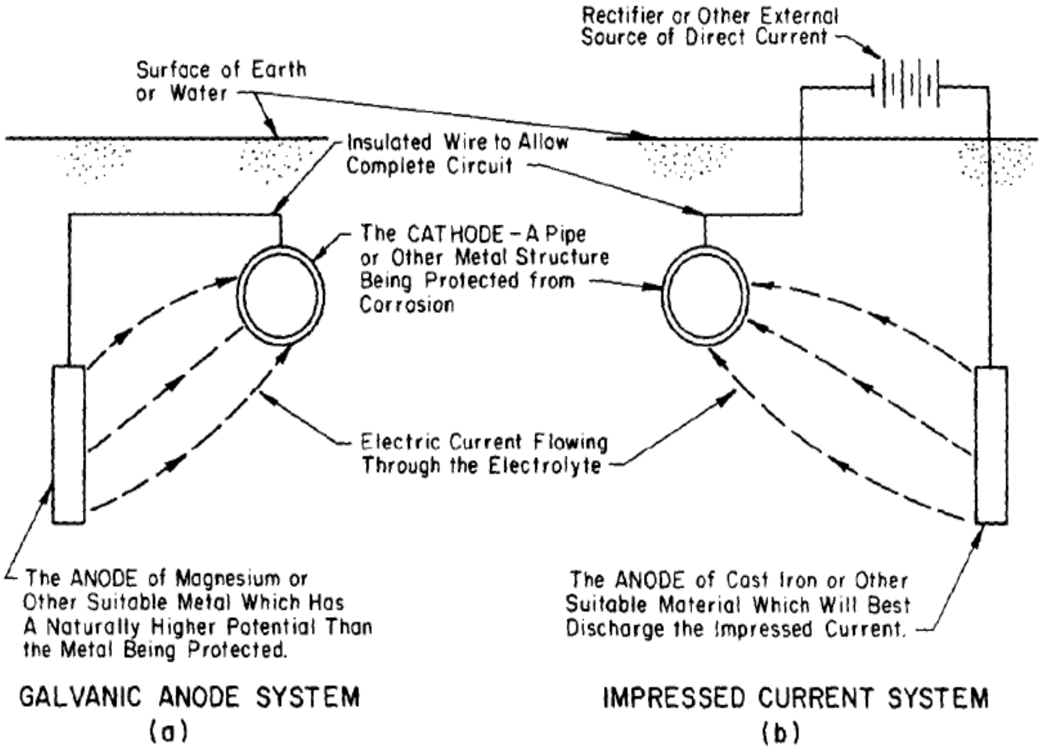


Figure 2-3 Types of cathodic protection [11]

2.4 Determining Type and Design of Cathodic Protection System:

In cathodic protection design there is a sequence for choosing the best design; Figure 2-4 shows that sequence.

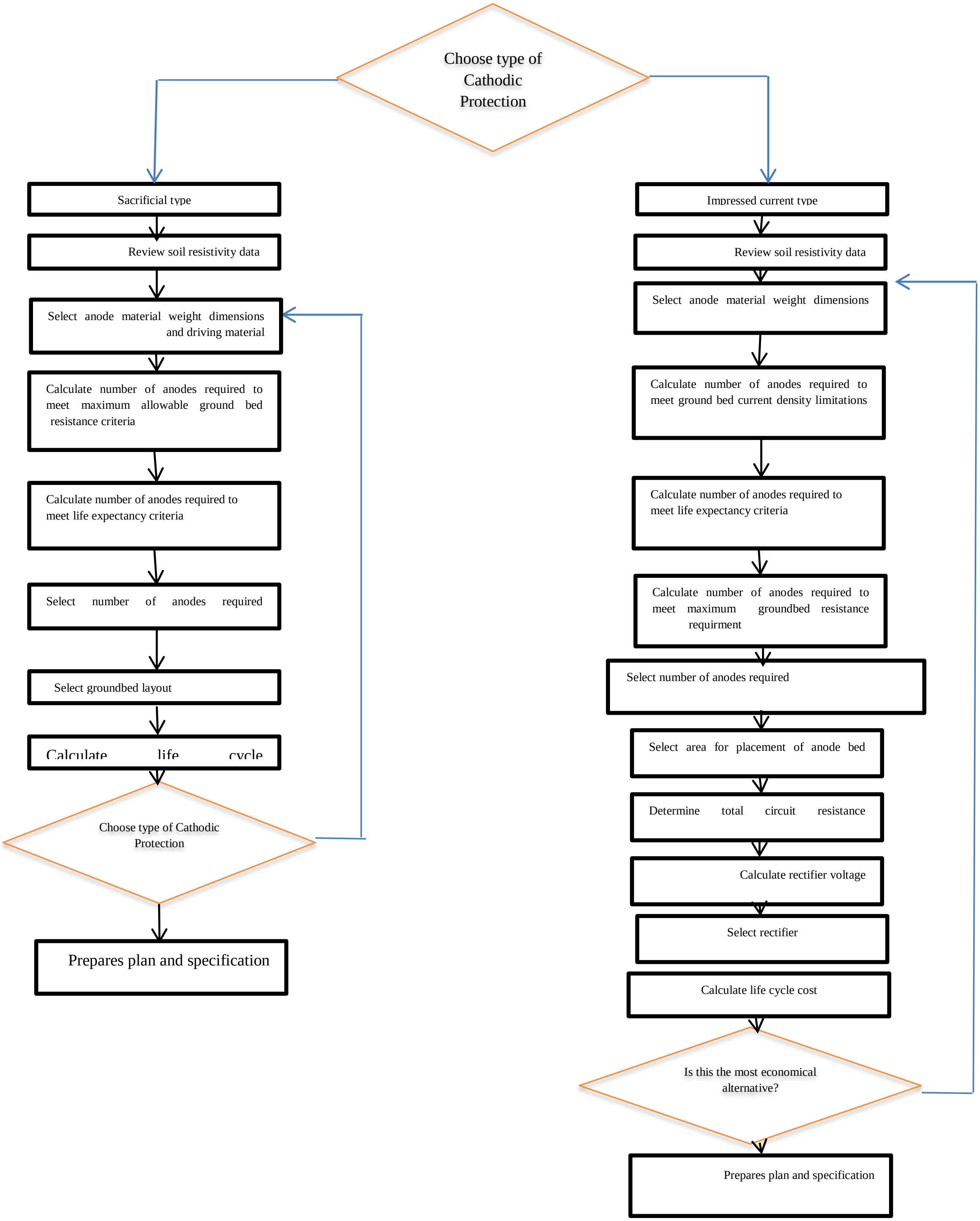


Figure 2-4 Design sequence of cathodic protection system. [11]

2.5 Factors Affecting Cathodic Protection System:

2.5.1 Soil:

There are over 50 general types of soil that have been characterized for corrosion properties. Each soil has specific resistivity. Soil resistivity is the lowest and the electrical potential difference is the greatest. Examples of corrosive soils are Merced (alkali) silt loam, Montezuma (alkali) clay adobe, Muck, and Fargo clay loam. Pipelines or tanks that are exposed to an electrolyte that is not homogeneous exhibit different electrical potentials in the different components of the soil. The area(s) with the higher potential becomes the anode in this electrochemical corrosion cell.

In general buried steel pipelines suffer from soil corrosion because one or more of the following conditions [19].

1. Moisture Content in soil, if a pipe is buried in two types of soil having different moisture contents, the area of the pipe in contact with wet soil (high moisture) would corrode, whereas the pipe in contact with the dry soil would not corrode. The area of the pipe in contact with the dry soil becomes the cathode and the area in contact with the wet soil, the anode [13, 8].

2. pH value, the pH of the soil or water electrolyte in an electrochemical corrosion cell affects the rate of the corrosion by speeding or slowing the chemical reactions at the anode and/or the cathode. The pH of an electrolyte is basically referred to the concentration of hydrogen ions. A corrosion rate of mild steel increases for pH below 4, and it will be increases tremendously at pH of 3 [8].

The generation of OH^- ions raises the pH of the electrolyte at the metal surface, producing some important incidental effects. The rise in alkalinity is protective to the metal because it tends to passivate the steel and also promotes precipitation of a protective carbonate scale on the metal surface [15].

Iron in air free soils at pH of 9.0 has a negligible corrosion rate at a potential of

-0.78 V versus KCl electrode this equivalent to -0.85 V measured against a Cu/$CuSO_4$ [20, 21].

3. Soil Resistivity, the resistivity essentially represents the electrical resistance of a standardized cube of material [22]. Resistivity variations in the electrolyte between the anode and cathode also have a strong influence on the current distribution. Areas of low resistivity will “attract” a higher current density, with current flowing preferentially along the path of least resistance this is shown in Fig. 2-5.

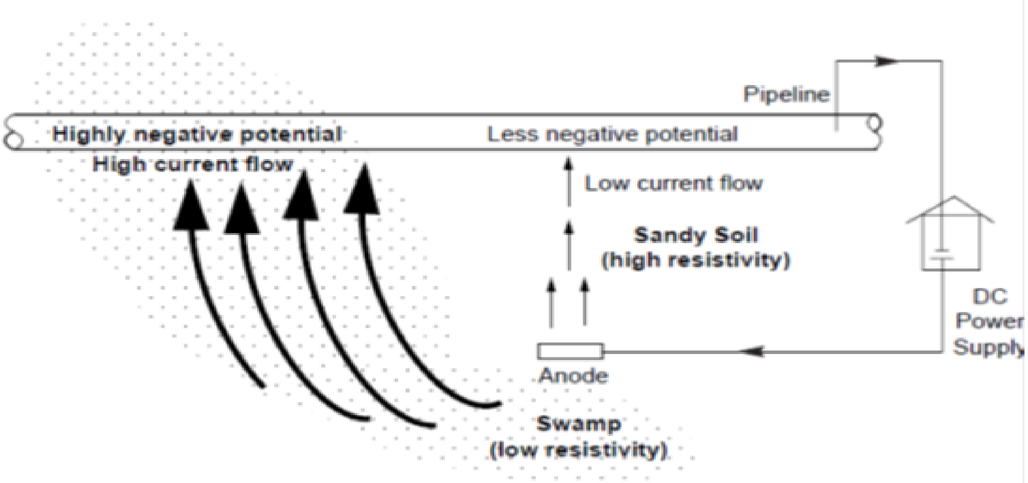


Figure 2-5 Relation between soil moisture content and current distribution [20].

The lower the soil resistivity, the more current will flow from the anodic areas to the cathodic areas, and resulting corrosion rate will be higher. If the soil resistivity varies from higher to lower values in a short distance localized accelerated corrosion can occurred [23].

There is definite a relationship between the corrosivity of the soil in various areas and surface elevation, it has been found the lower the elevation the more corrosive is the soil [23].

The resistivity is inversely proportional to current, and therefore to corrosion, if it is double and all other factors remain the same the amount of corrosion is reduced to half. [8]

4. Degree of aeration, a pipeline is buried in a completely uniform soil and that some areas of the line have a free supply of oxygen and other areas have a restricted supply. The part of the pipe buried in the soil with free supply of oxygen (high oxygen content) would form the cathode and the part with a less supply of oxygen or poorly aerated forms that anode this is commonly called a differential aeration cell.

5. Presence chlorides, sulfates microorganisms [13, 8].

2.5.2 Interference:

The following is a summary of preventive methods which could be used to minimize the interference: [18]

- The current output of the main rectifier may be reduced.
- The groundbed may be re-sited, if necessary. This is applicable if a foreign pipeline passes close to the groundbed.
- Installation of a crossing bond between the pipes. A bond between the two points of crossing is installed and the amount of current flow is controlled by a resistor.
- Installation of magnesium anodes on the corroding structure.
- Isolation of the anodic section of the structures and installation of continuity bonds across the anodic section.
- Coating the metal/ electrolyte interface, or the contact surfaces. In cases of foreign line, the foreign line must be coated.

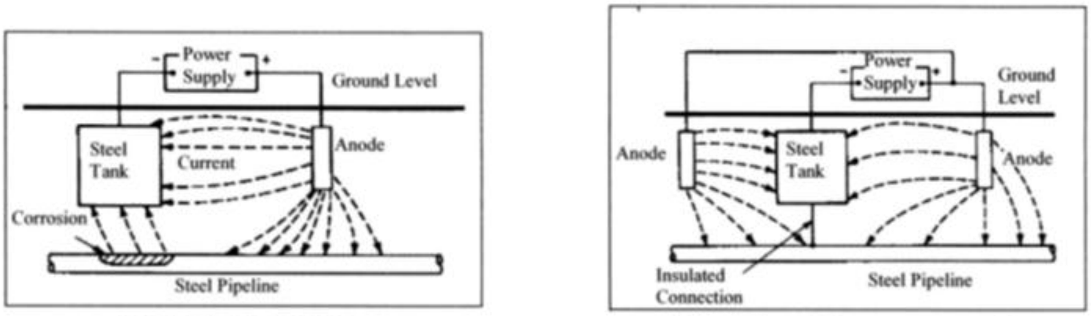
2.5.3 Stray Currents: [13]

In a cathodic protection system, the conventional current, for example Zn^{++} ions, flows from the groundbed through the earth towards the metallic structure. If a current encounters a metallic structure on its way it is picked up by the metallic structure, transmitted to other parts of the structure and finally discharged from the structure through the earth and retunes to the cathode. The point at which the current is discharged from the metallic structure to the ground becomes the anode and, therefore, corrodes (forming Fe^{++} ions). The undesired currents which enter the metallic structure on its way to the cathode is called stray currents and the corrosion caused by stray current is called stray current corrosion.

There are two main categories of stray currents:

- Static type, cathodic protection rectifier, railroad signal batteries.
- Dynamic type, DC Equipment in mines, electric railway generating equipment.

If the cathodically protect metallic object is buried near the path of the stray current, the current may “jump-on” the protected structure because it offers a lower resistance path for the current to flow. The affected structure will be cathodic where the stray current enters but will be highly anodic where the stray current returns to the earth. At the point where the current discharges, rapid corrosion of the structure intended to be protected will occur. If unsteady readings are observed on the protected structure and you have determined that it is not because of a bad electrical connection, you should suspect that stray current is affecting the protected structure [24].



a) Stray-current corrosion

b) Prevention of Stray-current corrosion

Figure 2-6 Stray currents corrosion and prevention technique [4].

A- Influence:

It is the inherent tendency of a cathodic protection installation to produce stray currents; it depends on the amount of current used, the location of the anodes or groundbeds, their configuration and resistance to earth, and the type of structure being protected. For any fixed anode arrangement, and type of structure, and soil resistivity, the influence is directly proportional to the current [10].

B- Susceptivness:

It is the inherent ability of an unprotected structure to pick up stray current and discharge it in manner likely to cause corrosion, the most susceptive structure is an uncoated one, and the least susceptive is a structure with a highly insulated coating a pipe line with poor coating [10].

C- Coupling:

It is the change in potential of a particular unprotected structure when protective current is applied to a nearby structure. Assuming a constant influence and susceptiveness, the tendency of a cathodically protected structure and its anode to cause the flow of current in a nearby structure depends upon the earth resistivity and the physical separation between the structures [10].

D- Telluric Currents:

Disturbances in the earth’s magnetic field sometimes cause induced current in metallic structures. Where this current leaves the structure to enter into the earth, corrosion occurs [10].

2.5.4 Anode/Cathode Ratio:

The relative area between the anode and cathode of a corrosion cell greatly affects the rate at which the anode corrodes. If the anodic area is small in relation to that of cathode for example a steel rivet in a copper plate, the anode (steel rivet) will corrode rapidly. This is because the corrosion current is concentrated in a small area (large current density). Also, the large cathode may not polarize easily, thus maintaining a high rate of corrosion.

When a small cathode is connected to a large anode (copper rivet in a steel plate), the corrosion current density on the anode (steel) is much less than in the opposite case discussed above, and the anode corrodes more slowly. Polarization may play an important role here, too. The small cathode may polarize rapidly, reducing the rate of corrosion current flow [25].

2.6 Impressed Current Cathodic Protection System:

The site for the installation of impressed current systems should be selected taking in consedaration the following factors: [26]

- Availability of low-voltage power supply;
- Level of protective current requirement;
- Lowest possible soil resistivity in the area of the groundbed;
- Minimum impact on third party interests;
- Good access to installations;
- Sufficient distance between groundbeds and foreign installations to minimize interference;
- Sufficient distance between groundbeds and the structure to be protected;
- Hazardous areas.

2.6.1 Components of Impressed Cathodic Protection System and Design Information:

- **Structure:**

Physical dimensions of structure to be protected one important element in designing a cathodic protection system is the structure's physical dimensions drawing of structure to be protected, Corrosion history of structures in the area [12].

The most common uses for carbon steel are for structures, Oil country tubular goods (OCTGs), and piping and process equipment. The term “carbon steel” is applied to any alloy consisting of iron plus carbon. Other elements may be added for deoxidation or machinability purposes. The term “killed steel” is applied to steels where the dissolved gases have been removed by the addition of either silicon or aluminum. It is common to have minimum residual content requirements for these elements to insure that most of the dissolved gases have been removed. Most carbon steels used in the oil field are killed [25].

- **Anode groundbed:**

The term groundbed usually refers to a group of anodes interconnected and operated as a unit [10].

They are two types of groundbed remote groundbed, close groundbed (represented by distributed anode system). The terms, close and remote, are related to the area of influence in the electrolyte around the anode.

In the case of remote anode groundbed surrounding the pipe, the pipeline is negative with respect to the remote earth as opposed to the close groundbed system, where the local earth is made positive with respect to the pipe [13].

Groundbed consists of a carbonaceous extender generally coke breeze and graphite, silicon-iron scrap steel, platinized titanium or niobium anodes [27]. Identified the following desirable properties of an “ideal” impressed current anode material: [22]

- Low consumption rate, irrespective of environment and reaction products
- Low polarization levels, irrespective of the different anode reactions
- High electrical conductivity and low resistance at the anode-electrolyte interface. The lowest grounding resistance practically possible should be designed for in order to keep down the electric power and therefore the operating costs [26].
- High reliability

- High mechanical integrity to minimize mechanical damage during installation, maintenance, and service use
- High resistance to abrasion and erosion
- Ease of fabrication into different forms
- Low cost, relative to the overall corrosion protection scheme

To minimize stray currents in congested areas, they can be installed vertically in tandem down deep holes called "deep anode beds" [18].

One of the characteristics of deep well anode systems is that they typically operate at relatively high outputs – they are designed to supply lots of current over a broad area. One of the potential reactions that occur at the anode is the generation of chlorine gas from the dissolution of naturally occurring salts in the soil. The amount of chlorine gas generated is a function of the current density – the higher the current discharged the more chlorine gas that can be generated. Chlorine gas attacks cable insulation and eventually will aggressively react with the copper in the cabling system rendering the deep well inoperable. For this reason, deep well anode systems typically have a vent pipe assembly, which is centered in the active area coke column and allows any chlorine gas formed at the anode to vent to atmosphere. Without a properly functioning vent pipe, chlorine gas can form and attack the cabling resulting in a premature system failure [27].

Materials currently popular for use as anode material include graphite, high silicon cast iron, mixed metal oxide, platinum, and steel.

Graphite anodes

Graphite anodes are consumed at no more than two pounds per ampere per year when discharging current into an electrolyte. When used with carbonaceous backfill by direct electrical contact, most of the material consumed is backfill material rather than the anode itself [10].

These anodes have the advantages of long life corrosion protection, low maintenance cost and high efficiency. The typical anode current density is between

10.8 and 40.0 A/m^2. The rate of consumption is between 0.225 and 0.45 kg per year per ampere [13].

Both diameter and length of the anode directly affect the anodes resistance in the earth. Increasing the anode diameter slightly reduces this resistance, where as increasing the anode length and number of anodes has much more dramatic effect in reducing this resistance [18].

High silicon cast iron anodes [10]

Hi-Silicon Cast Iron HSCI anodes were first developed by the Duririon Company of Dayton, Ohio in the late 1950's and early 1960's, The alloy soon gained market acceptance and became the dominate alloy until the 1970's when the development of Hi-Silicon Cast Iron Anodes gained dominant market acceptance [12].

A typical analysis of silicon cast iron anode is (Silicon 14.35 min, Carbon 0.85 max, Manganese 0.65 max, Iron remainder) [11]. Silicon alloy behaves differently from ordinary cast iron when discharging current. Ordinary cast iron loses approximately 20 lbs of its iron content per ampere per year. High silicon cast iron, on the other hand, loses material at a much lower rate. A common size used in impressed current groundbeds is 2-in. diameter by 60-in. length.

High-silicon chromium cast iron anodes rely on the formation of a protective oxide film (mainly hydrated SiO_2) for corrosion resistance. The chromium alloying additions are made for use in chloride containing environments to reduce the risk of pitting damage [21]. These anodes can be used with or without carbonaceous backfill which absorbs most of the consumption resulting from current discharge [7]. In the latter case the resistance to ground is increased (particularly under dry conditions) as are the consumption rates. Consumption rates have been reported to typically range between 0.1 to 1 kg A^{-1} y^{-1}. The castings are relatively brittle and thus susceptible to fracture under shock loading [28].

Consumption rate is between 90- 250 g/A year. The maximum current output is 50A/m^2 [13]

Chemical Composition (Nominal), Percent by Weight Element Grade 2,Silicon 14.20-14.75,Manganese 1.50 Max, Carbon 0.75-2.15, Chromium 3.25-5.00, Iron Balance

Electrical Resistivity, 72 microhm-centimeter at minus 7 degrees C 20 degrees F.

Density 7.0 grams per cubic centimeter [29]

Scrap steel and iron

Scrap steel and iron represent consumable anode material and have been used in the form of abandoned pipes, railroad or well casings, as well as any other scrap steel beams or tubes. These anodes found application particularly in the early years of impressed current CP installations. Because the dominant anode reaction is iron dissolution, gas production is restricted at the anode. The use of carbonaceous backfill assists in reducing the electrical resistance to ground associated with the buildup of corrosion products. Periodic flooding with water can also alleviate resistance problems in dry soils [28].

It has the advantage of being cheap and abundantly available, the rate of consumption of mild steel scrap is 6.6-9.0 kg/A year, and for cast iron the rate is 0.9-9.0 kg/A year, the rate of consumption of steel scrap is generally uniform. The material is mostly available in the form of long or thin sections and depending whether these sections are installed horizontally or vertically, they may encounter soil strata with different resistivities resulting in non-uniform corrosion [13].

When soil resistance is low and current requirements are small, steel rods driven vertically into the earth can be used [10].

Mixed-metal anodes

Mixed-metal anodes also utilize titanium, niobium, and tantalum as substrate materials. A film of oxides is formed on these substrates, with protective properties similar to the passive film forming on the substrate materials. The important difference is that whereas the “natural” passive film is an effective electrical insulator, the mixed metal oxide surface film passes anodic current.

The product forms are similar to those of the platinized anodes. These anodes are typically used with carbonaceous backfill. Electrode consumption is usually not the critical factor in determining anode life; rather the formation of nonconductive oxides between the substrate and the conductive surface film limits effective functioning. Excessive current densities accelerate the buildup of these insulating oxides to unacceptable levels [29].

Mixed metal oxide coated titanium anodes are based on electrode technology developed in the early 1960s for production of chlorine and caustic soda. Usually the mixed metal oxide films are thermally applied to precious metal such as titanium or niobium cores. These oxide coatings have excellent conductivity, are resistant to acidic environments, are chemically stable, and have relatively low consumption rates [10].

Polymeric anodes

Polymeric anodes are flexible wire anodes with a copper core surrounded by a polymeric material that is impregnated with carbon. The impregnated carbon is gradually consumed in the conversion to carbon dioxide, with ultimate subsequent failure by perforation of the copper strand. The anodes are typically used in combination with carbonaceous backfill, which reportedly increases their lifetime substantially. Because these anodes are typically installed over long lengths, premature failures are possible when soil resistivity varies widely [7].

Lead anodes

Lead anodes are made of various lead alloys, such as Pb-1Ag-5Sb-1Sn. The density of lead anode is around 11.0 to 12.2 g/cm^3. Pb-1Ag-6Sb has capacity of 160-220A/m^2 and a consumption rate of 90g/A year at acurrent density of 108 A/m^2. The other anode containing 10 % Sn and 5 % abtimony has acapacity of 500A/dm^{2}and the rate of consumption 0.3 to 0.8 kg/year. This alloy has good mechanical properties, and can be extended to any shape [13].

The backfill material for impressed current anode is coke; it should be installed very dry around the anodes except in desert conditions. The coke breeze provides a low resistance between anode and earth and a longer life for the impressed current anode. Because the greater part of the current passes from the anode to the backfill particles, the anode is consumed at a slower rate [13]. Backfill Impurities is similar to the non-homogeneous soil concentration cells, except that the "backfill impurities" are materials that do not normally occur in the soil, but are foreign materials mixed into the electrolyte during or between the excavation and the backfill process. This can be any material that forms anodic or Cathodic areas on the structure. It can also be an isolating material that forms different conditions in the electrolyte [8].

The term "carbonaceous backfill" used earlier describes the backfill surrounding groundbed anodes. There are three common materials that fit this description: Coal coke breeze, calcined petroleum coke breeze, and natural or man-made graphite particles.

All are basically carbon in a low resistivity form. "Breeze" is a loose term indicating a finely divided material. Originally it referred to the fine screenings left over after coal coke was graded for sale as fuel. For backfill purposes, however, specific particle sizes may be obtained. Carbonaceous backfill serves two purposes when surrounding impressed current anodes:

- To increase the size of the anode to obtain lower resistance to earth
- To bear the consumption resulting from current discharge.

Consumption rate of the backfill should not exceed two pounds per ampere per year. Natural or manufactured graphite both have low resistivity [10].

Good groundbed being very low in electrical resistance to earth having the characteristics of evenly distributing the current into the earth [23].

Theoretically the most economical anode installation is one in which the annual cost of power is equal to annual interest charge on the investment of the protective system [30].

There are three interrelated key performance issues when designing/evaluating a deep well groundbed:

1. Groundbed resistance – deep well anode systems are commonly designed to produce 1 Ω or less resistance. Several factors influence groundbed resistance including soil resistivity, active area length, coke column quality, and anode consumption. Groundbed resistance often changes over time.

2. Groundbed output – current output is a function of the power available as applied

Voltage and circuit resistance (Ohm’s law V=IR). Over time, as the resistance of the groundbed changes, the current output decreases unless more voltage is applied.

3. System life – deep well groundbeds have a design life and they have an actual operating life. The design life is typically a calculated value based on the quantity of anode installed and the time required to consume the available anode at the design current. Actual system life can exceed the design life in some cases or may be much less than the design life as a result of poor design, premature component failure improper installation or from operating the system beyond its original design parameters [27].

2.6.2 Test Station:

Test points are the best means of electrically examining a buried pipeline to determine whether or not it is cathodically protected as well as to make other tests associated with corrosion control work. [7].

The test station provides a connection between the anode lead wire and the structure via the test panel. The surface box is sometimes buried below the ground level. The anodes are connected to the pipe via a central control test panel [13]. Test stations for potential, current, or resistance measurements should be provided at sufficient locations to facilitate cathodic protection testing. Such locations may include, but not be limited to, the following: [7]

- Pipe casing installations
- Metallic structure crossings

- Isolating joints
- Waterway crossings
- Bridge crossings
- Valve stations
- Galvanic anode installations
- Road crossings
- Stray-current areas
- Rectifier installations

Test point types by function are illustrated in Fig. 2-6. A color code is shown to illustrate a system whereby leads may be identified. Whatever color code is adopted should be made standard throughout your pipeline system.

The two-wire potential test point is the one used most frequently. Two wires make it Possible to check pipe-to-earth potential with one while test current is being applied to the line (if desired) using the other [7].

The four-wire insulated joint test point permits measuring pipe-to-earth potentials on each side of an insulated joint. The second pair of heavier gauge wires is available for inserting a resistance or solid bond across the insulated joint if necessary.

The six-wire combination insulated joint and line current test point is useful, particularly at terminal insulated flanges, because it permits positive measurement of current flow through an insulated flange should the flange become totally or partially shorted for any reason. Likewise, it will measure the current flowing through a solid or resistance bond should such measurement be necessary. One heavier gauge wire is provided on each side of the insulated joint for bonding purposes (if required).

An indicating voltmeter test point is installed at key points on some systems. These meters may be read by operating personnel on a routine basis and the indicated values recorded and reported to the corrosion engineer. As shown in Fig.

2-6 a voltmeter may be connected between the pipe and a reference electrode suitable for underground service.

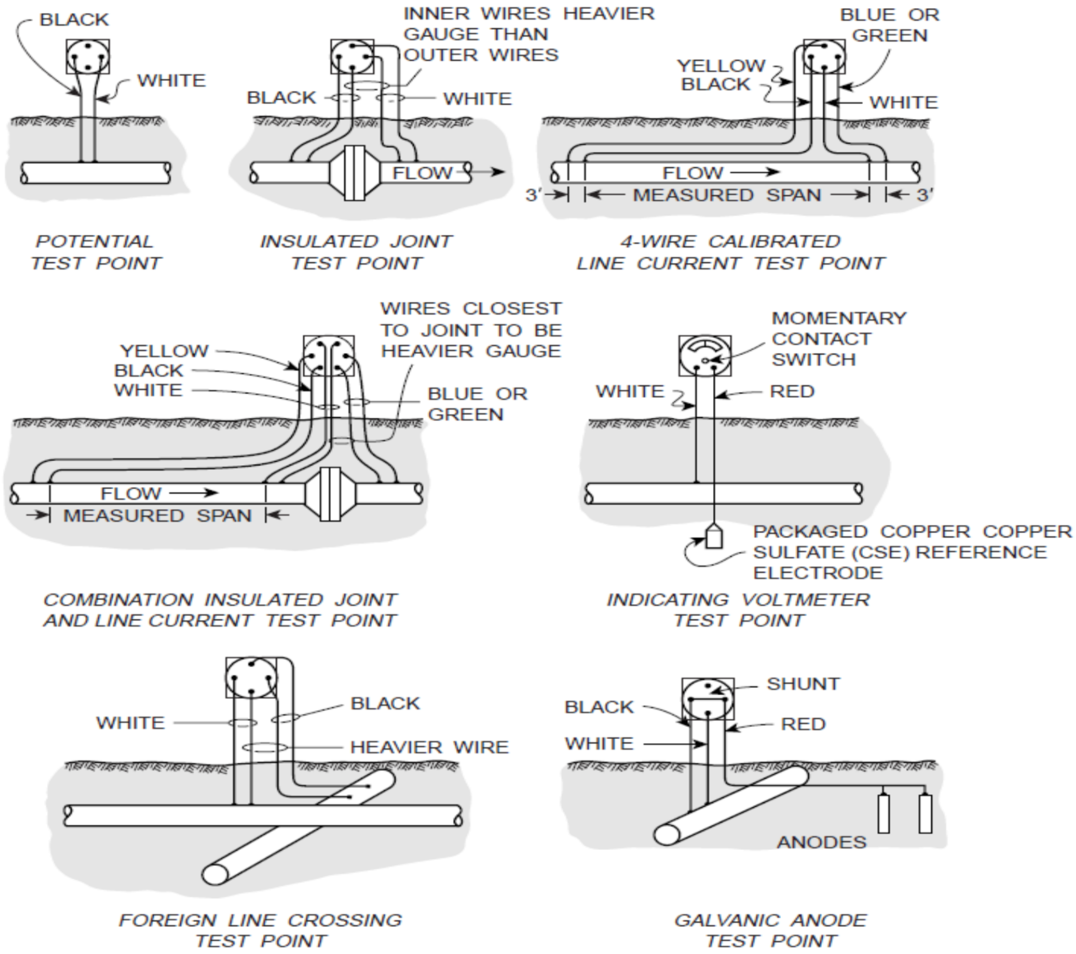


Figure 2-7 Typical types of test station

2.6.3 Reference Electrode:

It is used primarily in field measurements where the electrode must be resistant to shock and where its usual large size minimizes polarization errors [3].

A standard copper/copper sulfate reference electrode (also known as a half cell or reference cell) must be utilized in order to obtain structure-to-soil potentials. The reference electrode must be maintained in good working condition and must be placed in the soil in a vertical position when conducting a test [31]. Figure 2-7 shows a reference electrode.

Figure 2-8 Copper/copper sulfate electrode

Cu/CuSO$_4$, electrode is suitable for use in soil, but should never be used in seawater or on concrete. Contamination of the electrode can occur which will produce serious changes in the reference potential [2].

Some engineers prefer to locate the electrode a distance away from the structure equal to the depth of its burial [10].

Another group proposed that as the electrolyte resistivity increases, the smaller the anode the closer the reference electrode is placed to the structure [32].

Pearason has shown that the length of pipe affecting a reference electrode is roughly four times the distance between the electrode and the pipe. This being the case the electrode over pipe 3 feet deep observes the average potential of roughly twelve of of pipe while the electrode 200ft away observes the average potential of 800 feet of pipe [33].

A- Photovoltaic Effect

It is known that sunlight striking the viewing window of a reference electrode can have an effect (as much as 50 mV) on the voltages observed when conducting testing. It is important that the viewing window of the reference electrode is kept out of direct sunlight. As an alternative, the viewing window can be covered with black electrical tape in order to prevent any sunlight from reaching the copper-copper sulfate solution [25, 33].

B- Temperature

The temperature of the reference electrode affects the voltages that are observed when conducting cathodic protection testing. A correction has been made to the observed potential in some extreme and/or marginal cases. The “standard” temperature is considered to be 77^{o} F. A potential of 0.5 mV must be added to the observed voltage for every degree less than $77\ ^{o}$ F and conversely 0.5 mV must be subtracted to observe the voltage for every degree above $77\ ^{o}$ F [24].

2.6.6 Power Source:

Rectifier:

Cathodic Protection (CP) rectifiers have the following major components. These typically include a transformer to step down AC line voltage to low voltage, AC on the secondary with a tap arrangement to permit selecting a range of voltage, a rectifying element (usually full wave silicon diodes for rectification), and a housing for outdoor mounting. Alternating current sources such as a power line may be used if a rectifier is used to convert the current to direct current. Alternating current will not provide any protection since the pipeline would be anodic or cathodic depending on the direction of the current. (Connections.GI-01(1994))

These components are supplemented by an AC circuit breaker and DC outputs. Both single-phase and three-phase units are in common use [6].

Some experimental data indicated that three rectifier installations per mile would be required to obtain optimum current distribution necessary for raising pipe to soil potential of approximately 0.3 V (negative to soil) [34].

2.7 Cathodic Protection Requirements:

2.7.1 A Negative Voltage of at Least minus 850 millivolts

Nearly 25 years ago Kuhn indicated the optimum protective potential of steel pipe to a $Cu/CuSO_4$ reference electrode is -0.85 V [35].

This potential shall be obtained over 95 percent of the total metallic area without the "instant off" potential exceeding 1200 millivolts [29].

The current required for CP can increase by a factor of two for every 10± ^{o} C (18± ^{o} F) increase in temperature of the pipe. Typically, a potential of -950 mV CSE is used for hot pipelines. The general consensus in the industry is to avoid polarized (instant off) potentials more negative than -1.05 to -2.1 V (CSE) to avoid coating damage and minimize hydrogen damage in these steels [7].

In some situations, such as the presence of sulfides, bacteria, elevated temperatures, acid environments, and dissimilar metals, this criteria may not be sufficient [6].

2.7.2 100 millivolt Polarization Shift Wee1 and Cast Iron

The cathodic protection currents react with the electrolyte around the pipe and the resultant products produce a shift in the negative direction of the structure to electrolyte potential. A minimum value of 100 millivolts is a positive indication that the pipeline is reacting as a cathode and that corrosion is substantially reduced or eliminated [36].

Factors affecting validity of criteria

- Temperature
- Sulphate reducing bacteria
- AC Current density
- Type of metal
- Mixed metals
- Stress Corrosion Cracking (SCC)

100 mV polarization one of the three criteria that are commonly accepted as indicating adequate cathodic protection has been achieved. It is typically measured by interrupting the protective current on an impressed current system. When the current is interrupted, an “instant off” potential is recorded and the structure under cathodic protection is then allowed to depolarize until a change of at least 100 mV

in potential is observed. Not more than 24 hours should be allowed for the depolarization to occur when conducting this test.

2.7.3 850 millivolt Off - One of the three criteria that are commonly accepted as indicating adequate cathodic protection has been achieved. It is measured with the protective current interrupted, either the power is cut off to the rectifier or the sacrificial anodes are disconnected. This criterion is considered by most to be the best indicator that adequate cathodic protection has been provided [32].

2.8 Pipe to Soil Potential:

Potentials can vary seasonally as a result of variation in the soil moisture content. Some pipeline companies perform annual surveys at the same time each year, so that trends in the behavior of a pipeline can be properly interpreted [10].

Pipe to soil potential shall not be more negative than - 1.5V ON or - 2.18V off with respect to Cu-CuSO4 RE [33].

The protection potential for a given metal is numerically different according to the reference electrode used. Thus the protection potential for iron in aerobic environments is:

-*0.85* V VS. Cu/CuSO$_4$
-0.77 V VS. Ag/AgC1/1 M KCI
-0.84 V VS. Ag/AgCI/0.1 M KCI
-*0.80* V VS. Ag/AgCl/seawater
-*0.55* V VS. Standard hydrogen electrode

IR voltage drops are more prevalent in the vicinity of an anode bed or in areas where stray currents are present and generally increase with increasing soil resistivity. The difference between the on- and the off-potential indicates the magnitude of the IR voltage drop error when the measurement is made with the protective current applied [7].

In long structures such as pipelines the electrical resistance of the structure itself becomes significant. The resistance of the structure causes the current to decrease nonlinearly as a function of distance from a drain point. A drain point refers to the point on the structure where its electrical connection to the anode is made. This characteristic decrease in current (and also in potential), shown in fig. 2-.

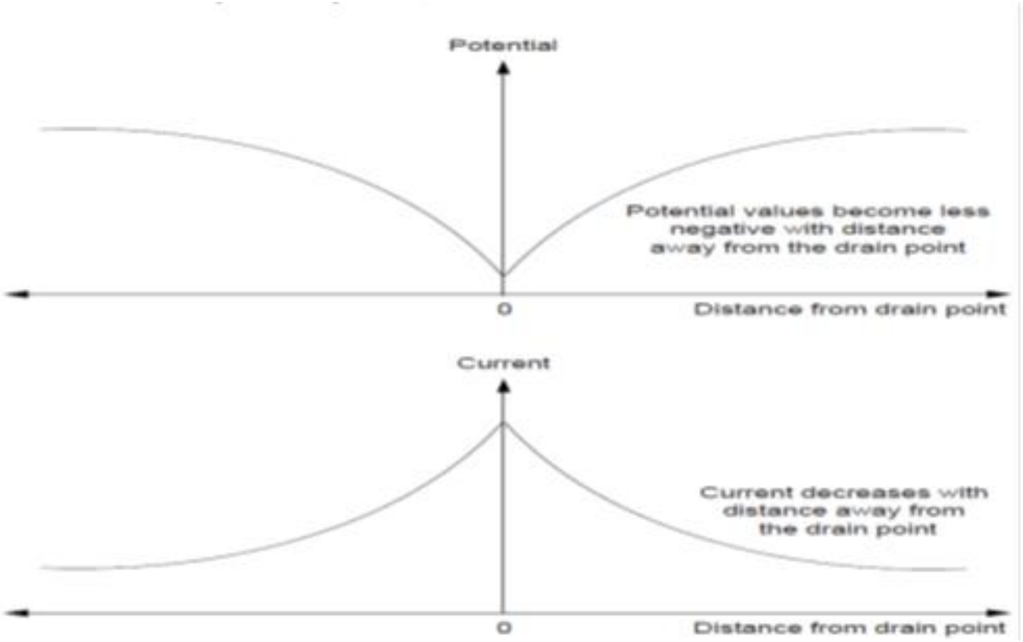


Figure 2-9 Potential and current attenuation as a function of distance from the drain point. [19]

It is not always possible to place the reference electrode close to the structure to minimize the IR error but it can be achieved using the so-called instant-off technique. The technique relies on the fact that when the current is interrupted, the IR effect, being ohmic, dissipates immediately but the polarization decays much more slowly. Thus, if the current is switched off and the potential is measured immediately, the IR-free polarized potential (which can be defined as the potential across the structure to electrolyte boundary (interface); this is the sum of corrosion potential and the cahtodic polarization [25] of the structure can be measured. Where the cathodic protection system uses multiple power sources, it is necessary to switch off all the units simultaneously if true IR-free conditions are to be achieved [2].

Methods suggested for determining IR drop involve one or more of the following:
[36, 7]

1. Contacting the pipe close to the point of measurement to reduce metal IR drop.
2. Placing the reference cell close to the pipe surface to reduce electrolyte IR drop.
3. Interrupt the protective current to eliminate IR drop.
4. Calculate IR drop from a step-wise current reduction or increase.
5. Estimate IR drops as a function of distance from the pipeline and extrapolate.

An ammeter that has a very low internal resistance is necessary when testing impressed current systems in order to accurately determine the current output of the rectifier and/or individual circuits in the system [24].

Voltmeters that have a variable input resistance can be utilized to ensure that contact resistance between the reference electrode and the electrolyte has been evaluated as a source of error (voltage drop) in the observed structure-to-soil potential. This is accomplished by changing the input resistance and noting whether or not the voltage observed changes significantly. If no voltage change is observed when the input resistance is changed, it can be assumed that contact resistance is not causing an error in the structure-to-soil potential measurement [24].

2.9 Review of the Previous Work:

Glass (1951) designed a cathodic protection including a 2300 V overhead distribution line which was constructed parallel and adjacent to the pipeline (142.3 km). Soil resistivity was 1638 ohm.cm, anodes used carbon anodes, and performance data on rectifiers which are placed three per mile of pipeline protected, experience with groundbeds (6-10) anodes for each station, current requirements to maintain protection, bonding procedures with parallel and/or crossing foreign structures. An economic study is made of the system based upon investment charges, operating and maintenance costs, and actual power costs [34].

Logan (1954) compared the results of cathodic potential tests including and excluding IR drop and with the reference electrode both over and remote from the pipe. Results using the break in the current potential curve as a criterion for protection were compared with lowering the pipe potential -0.3 volt and to -0.85 volt. The criteria do not agree. Results of increasing the test current in equal steps are compared with those obtained by increasing the current by 50 percent increments. Equal current increments gave smoother curves, the potential of the pipe with respect to a reference electrode over the pipe may or may not be the same as that referred to a remote electrode [37].

Toedtman (1971) the life of a sacrificial anode is extended by providing an insulating barrier in bottom of open bottom housing. Since the barrier was an electrical insulator, it increased the resistance to any stray current path to the outside of the housing. Thus the barrier significantly prolongs the life of the sacrificial anode by reducing wasteful or stray currents, to the outside of the housing, which tend to erode the anode. [38]

Townesend (1975) A cathodically protected metal article, such as a pipeline, tank, or vessel, is covered with a first coating of chlorinated rubber, and a second, outer coating of a bituminous material wherein either or both coatings contained dispersion of not less than 5 percent by weight of calcium carbonate. Thus coated article exhibited improved corrosion resistance [39].

Robinson and Doniguian, (1999) found that since E/R probe corrosion rates tend to stifle when connected to pipeline components under CP protection, the adequacy of CP levels and protection criteria can be assessed with probe corrosion monitoring. Pulse cathodic protection can be used in conjunction with conventional CP to improve protection levels for buried pipelines in remote area where conventional systems were limited [40].

AL- Jawary (2005) study impressed current method in which, two different auxiliary electrodes, high silicon iron and graphite were used to estimate the impressed current density furthermore they studied sacrificial anode method, in which three electrodes (Mg, Zn and Al) were used. Protection level of and the effect of distance between cathode and anode investigated. Carbon steel pipe of (100cm) length and (5cm) outside diameter, the pipe was painted with multi-layers of chemical paint and coated (insulated) perfectly .for a same soil resistivity cathodic protection current density increased with increasing distance between cathode and anode, while it decreased in sacrificial anodes system. Impressed current density for high silicon iron auxiliray anode was higher than the impressed current density for graphite anode [41].

Al-kelaby (2002) designed an impresses current cathodic protection system to prevent corrosion on metal specimen using graphite electrode as anode CP four major factors that affect the performance of CP process length, the distance, the impressed current and concentration had been tested. His results showed that the cathode length did not affect limiting current density, cathodic protection current density and free corrosion rate [42].

Gurrappa (2004) studied the types of cathodic protection and anodes available apart from a brief review on sacrificial and impressed current cathodic protection. The necessatiy of desiging of an effective cathodic protection system for cooling waters pipelines had been emphasized. In addition, the economics of cathodic protection has been highlighted with an example. After installation of CP system, opearation and maintenance part had also been mentioned [43].

Riemer and Orazem (2004) developed a mathematical model for predicting the cathodic protection of pipeline networks and extend it to treat cathodic protection of bottoms of cylindrical from above ground storage tanks. A single tank was modeled for which protection was provided by an anode located infinitely far from the tank bottom, by a series of anodes distributed around the circumference of the tank, and by an anode grid laid underneath the tank bottom. The influence of an insulating barrier associated with secondary spill containment was also modeled for the arrangements in which anodes are placed adjacent to the tank bottom. The performance predictions were strongly dependent on anode placement, the oxygen content of the soil, and the presence of insulating barriers associated with secondary spill containment [44].

William et al. (2005) developed a CP design protocol to deep water petroleum production compliant risers. This was accomplished by focusing both existing and newly developed pipeline CP principles and concepts of the specific geometric and operational aspects of these risers [45].

Salih (2005) studied the effect NaCl concentration, distance between cathode and anode and the temperature on the cathodic protection current density in order to protect submerged pipelines from corrosion. The structure used is carbon steel metal pipe. The carbon steel results showed that the cathodic protection current density increases with increasing the above studied variables. Also icp showed sharp increasing when the fluid was stirred. The corrosion potential became more negative as temperature increases so that cathodic protection criterion was investigated to be more negative to some extent in order to make adequate protection [46].

Luiz (2005) presented a boundary element methodology coupled to genetic algorithms for inverse problems in corrosion engineering. The problems studied include the identification of parameters characterizing the polarization curve, the identification of coating holidays (defects) and the optimization of anode positioning and their impressed current. Several results of applications are discussed, including CP studies of practical three dimensional engineering problems [47].

Hafiz (2006) studied the cathodic protection for carbon steel, a length of the cathode was placed horizontally 3, 6, 9,100 and 224 cm. 2.65 cm outside diameter, and variable coating quality, the pipeline will pick up relatively more current from the environment in the areas of poor coating. This resulted in larger potential drops in the environment adjacent to the poorly coated section and the pipe to environment potential in these areas will be lower than in nearby areas of good coating. When pipelines are partly bare, this effect is even more pronounced; the pipe to environment potential at a bare area will normally be much lower than that in an adjacent coated area, even though the coated area may be more remote from the drain-point [48].

Ajeel and Ghalib (2007) found that cathodic protection current density increases with increasing temperature and concentration. The current density also slightly increases with increase distance between cathode and anode. The effective sequence of these parameters on cathodic current density was as follows: [49]

Temperature > concentration > pH of solution > cathode – anode distance

Abd AL-Rahman (2009) studied the cathodic protection system for anode graphite, 1.3cm diameter, and 30cm length. Pipe 10cm length, 2 cm inside diameter and 2.5 cm outside diameter, various soil resistivities, cathodic protection current density (required current) increased with decreasing environment resistivity. Cathodic protection current density increased with increasing of distance between anode and cathode. CP current density for coated pipe was very low compared with cathodic protection current density for bare pipe. CP current density for coated pipe increased with decreasing environment resistivity and increasing number of defects in the coating [50].

Laoun B., K. Niboucha and L. Serir (2009) designed a cathodic protection system by impressed current supplied with solar energy panels applied to a pipeline, The output current was high enough to protect the pipeline with low costs [51].

Al-Haidary et al. (2011) Found that the anode current is able to reach a proper distance from the anode center and meet the requirements for cathodic protection with this region. Cathodic protection was actually achieved by a counter electromotive force that forces cathodic protection reactions to occur at the protected surface. Current was not the cause of corrosion but an effect of the corrosion process. The potential increases in the negative direction when increasing time to approach fix potential, in region 25 and 50, Ω.cm the potential is a provide protection to steel pipe because the potential was less than – 800 mV, while the regions 600, 1000 and 5000 Ω.cm the potential does not provide protection to steel pipe because the potential was more than – 800 mV. The parameters solution resistivity, distance between cathode and anode, and different alloys (sacrificial anodes) and their interactions have significant effect on the cathodic protection current. The best selected sacrificial anode was the alloy (Al - 10 wt % Zn) because it gave higher capacity and life with protection potential less than -800 mV to protect steel pipe as compared with other alloys. Current density output from the sacrificial anodes in sacrificial cathodic protection system decreased with increased the distance between sacrificial anode and protected pipe from 40 to 60 cm, and increases with decreasing the solutions resistivity from 5000 for 25 Ω.cm [52].

Chapter Three

Experimental and Field Work

The experimental work consists of two parts the first part is the field work that collecting of more comprehensive data, which will provide a technical basis for the design, and optimization of cathodic protection requirements for buried structures, in particular pipelines .The second part deals with the effect of anode position on the protection level of the structure at different conditions.

3.1 Field Work:

3.1.1 Pipelines:

The field work concerns about two pipelines with specifications shown in table 3-1 which provides the required data that for simulation design. The Pipelines used were isolated from the pump house with an insulating joint on the main line inside the pump house. These pipelines coated with coal tar with properties listedin table 3-2 . These pipelines are connected togather no insulating joint are used.

The connection between the negative cable and the structure can be made by thermit welding or by a mechanical connection. The procedures and precautions are referred to the section on “wire attachment” in cathodic protection tester course manual by nace [23].

Figure 3-1 shows different pipelines with coating followed by tape and shows how the corrosion lead to leakage in the pipe.

Figure 3-1 Pipelines carrying crude oil

Table 3-1 The coal tar characteristics

Oxygen transmitted through [53] mL of O_2/m^2/day100:m film 85 % RH 23˚C, 1 atm O_2	(213±8)
Water transmitted through coating [53] g water/m^2/day 25m film, 95 %R.H.36˚C	(30± 1)
Time before overcoat [54]	24 hour
Touch dry after [54]	7 hour
Optimum dry film thickness (μm) [54]	400

Table 3-2 Pipelines specifications

characteristic	First pipeline	Second pipeline
length	52km	28 km
diameter	10 in	16 in
Coating type	Coal tar with tapping	Coal tar with taping
depth	1.2 m	1.2 m

Tables 3-3 and 3-4 show the stations of the first and the second pipelines respectively. These pipelines are describe in fig. 3-2 and 3-3 respectively.

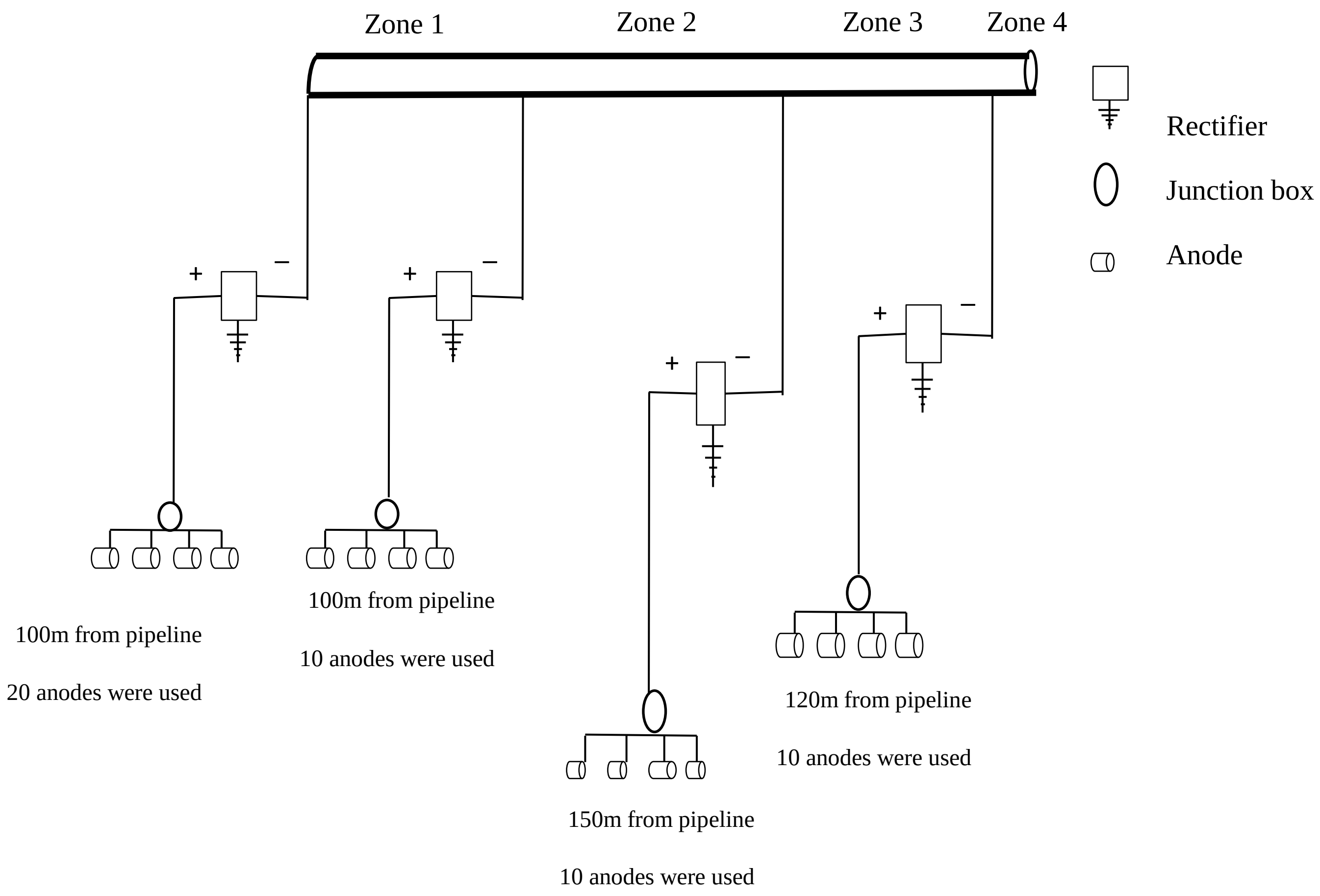


Figure 3-2 First field pipeline descriptions.

Table 3-3 First pipeline stations

Station number	Anodes number	Distance between anode and pipeline (m)	Zone length(km)
Station 1	20	100	15
Station 2	10	100	20
Station 3	10	150	15
Station 4	10	120	2

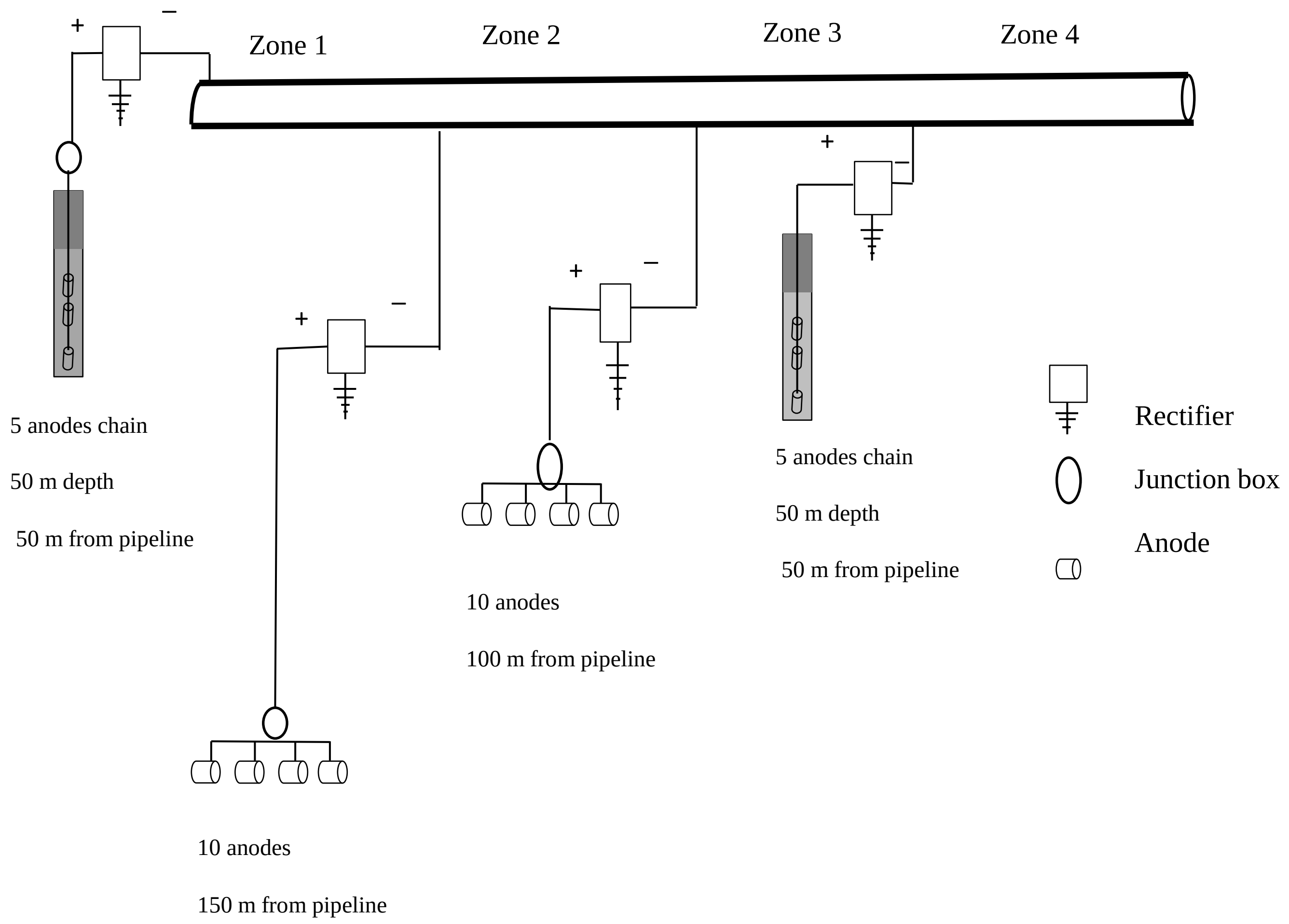


Figure 3-3 Second field pipeline descriptions.

Table 3-4 Second pipeline stations

Station number	Anodes number	Distance between anode and pipeline (m)	Zone length (km)
Station 1	5 chain 55m depth	50 deep	7
Station 2	10	150	7
Station 3	10	100	7
Station 4	5 chain 55 m depth	50 deep	7

3.1.2 Soil Specification:

There are two main types of soils in Iraq. Heavy alluvial deposits, containing a significant amount of humus and clay, as one type which are used for construction. The second type is a lighter soil composed of wind-deposited nutrients. A high saline content in some areas contaminates the otherwise rich composition of the soils [55].

Normally, soil resistivity surveys for cathodic protection studies are performed using the wenner configuration. Wenner's four terminals method is the most commonly employed methods in the field measurements. In this method, four contact rods are spaced at equal distance in straight line, and alternating current (AC) is applied between the outer two electrodes. The difference of potential between the line electrodes is observed and the resistivity then calculated from the formula or read directly on the instrument. This is based on the principle of passing an alternating current through the ground between two pins and measuring the volts drop between two other pins placed in between. Table 3-5 shows the soil resistivity survey for the two pipelines.

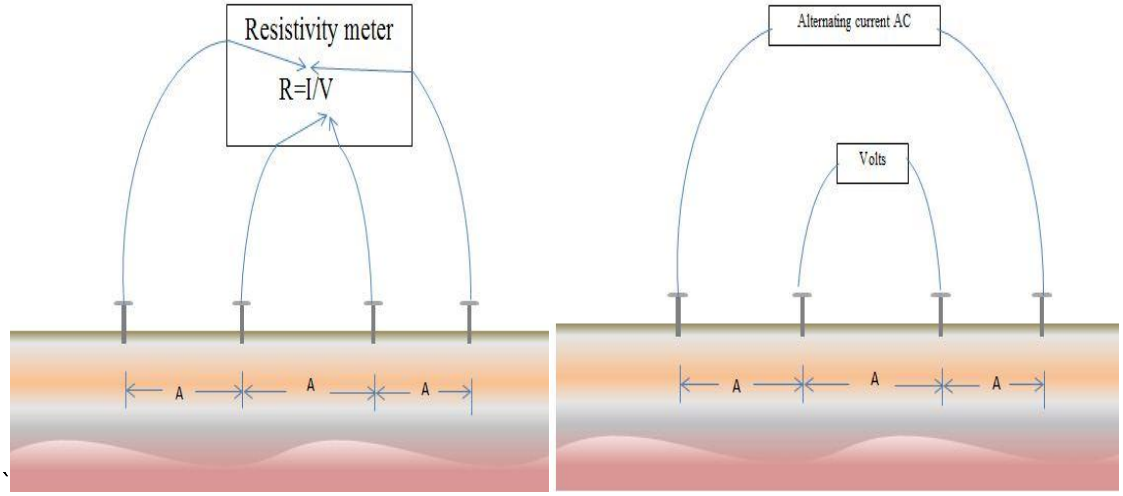


Figure 3-4 Wenner four pin

Figure 3-5 Soil resistivity measurement.

If the measured resistivity is determined from the formula, it is equal to the resistance (the ratio of the measured voltage divided by the current flowing into the ground) multiplied by the geometric factor (for a Werner array the factor is 2π). The resistivity ρ is then

$\rho = 2 \times \pi \times A \times R$

where:

ρ = resistivity in Ω.cm

A= spacing between electrodes, in cm, which represent the depth of burial

R = resistance, in Ω

In Iraq the quantity of rainfall marks a critical distinction between corrosive and more inert soils. A characteristic feature of these desert soils is their lack of homogeneity. A multiplicity of low resistivity salty patches lie scattered throughout a matrix of high resistivity ground. The typical desert soil receives insufficient annual rainfall to carry soluble salts deep into the earth. A great number of salty patches are typical features of desert country, wherever the soil is of clayey nature with some powers of water retention; where the surface consists, however, of loose sandy particles with small water-holding power. The winter rainfalls do not penetrate deeply into the ground in these desert soils afforded by search for water-bearing formations [56].

- pH of soil, the pH of soil was in the range 7-8.

Table 3-5 Soil resistivities of two pipelines stations

First pipeline		Second pipeline	
Station number	Ohm.cm	Station number	Ohm.cm
Station 1	1500	Station 1	1000
Station 2	1000	Station 2	1500
Station 3	1200	Station 3	1000
Station 4	1500		

3.1.3 Anodes Ground Bed Specifications:

Ground bed resistivity was sufficiently low and stable at a 2.5 to3 m depth. Installed approximately 150 to 250 m depending on the soil resistance at each station; away from and horizontal to the pipe or installed deeply into soil in order to obtain suitable distribution of current to the line

The depth of ground bed was between (2.5-3) m, their resistance varying from (1.88-0.675) Ohm for the first pipe, while the second pipe from (0.92-0.599) Ohm.

Fifty anodes were used for the 52 km pipeline and 25 anodes for the 22 km pipeline. In some installations where interference problems are severe, anode beds are sometimes installed deep below the surface. This causes the current flow to become more vertical and reduces interference between horizontally displaced structures. In the first station for the second pipeline the anode type was deep anodes. Deep anodes are also used where the resistivity of the soil near the surface is high. Anodes installed deeper than 15.24 m are called "deep" anodes.

The computer models are modeling the cathodic protection processes. The model provides a powerful technique for obtaining the required number of anodes and their resistances.

- **Electrical connections:**

For anode system a cable is run from the positive bus bar to the positive terminal in the rectifier follow wiring diagrams carefully to ensure that negative circuits are connected to the correct terminals in the junction box. Manholes or junction boxes shall be provided at points of change in conduit grade or size, at junctions with laterals or branches, and wherever entry for maintenance is required. Distance between points of entry shall be not more than about 91.64m for conduits with diameter smaller than 0.762 m.

Conduit alignment between entry points shall be straight, except for 0.762m and larger sizes. Each terminal is connected to the positive bus bar through a shunt so the individual anode outputs can be read. It is necessary to mark each anode lead from bottom to top so that each can be identified in the junction box; specialized equipment and skill is required for the installation of such an anode array.

Figure 3-6 The junction box

3.2 Experimental Work:

Experimental work was carried out to investigate the best cathodic protection requirements for bare and coated pipe buried in different soil resistivities. Different distances between pipe and anode where studied; attenuation potential of the pipes also obtained for each condition.

The instillation of cathodic protection system was carried out to find the voltage required to protect a carbon steel pipe segment which is buried inside the wooden box in different types of soils within a wooden box. Figure 3-7 shows the experimental system.

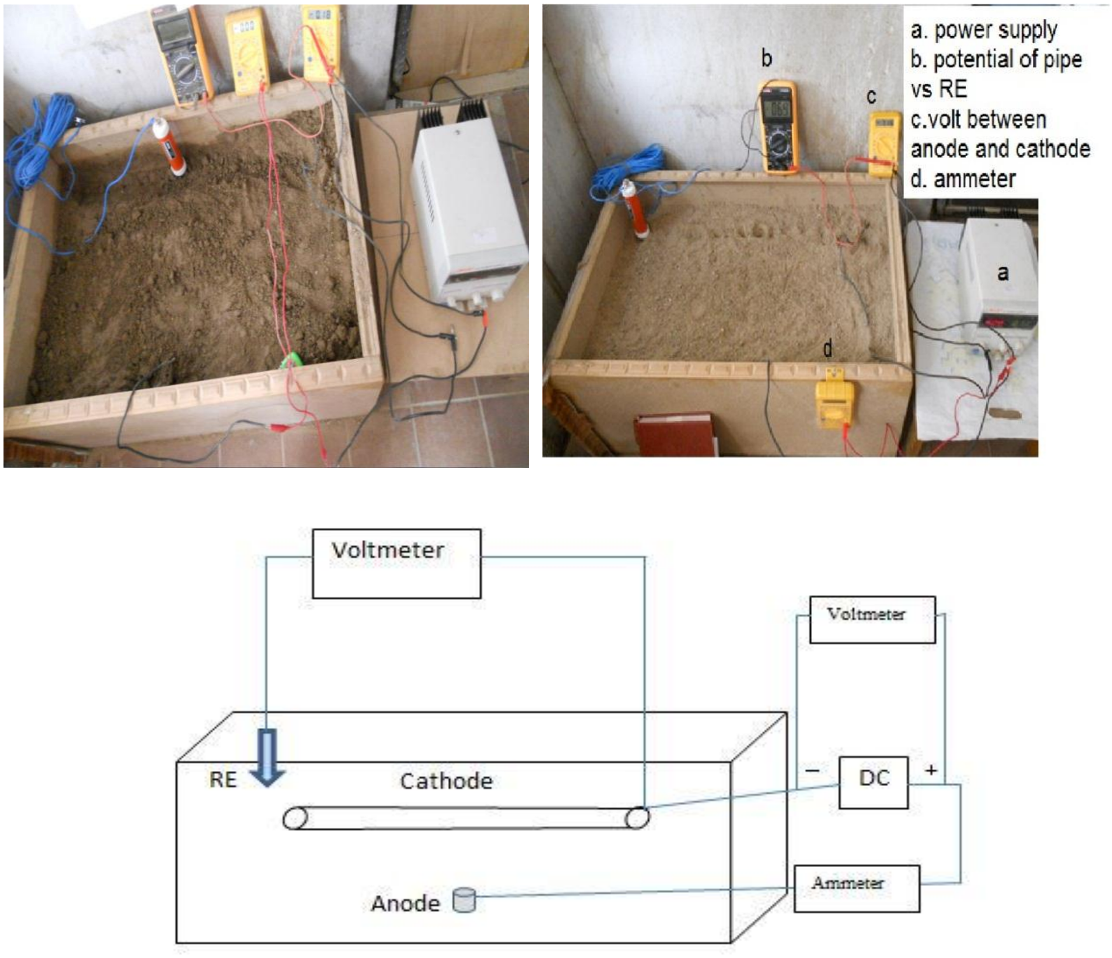


Figure 3-7 Experimental apparatus

The major parts used for the experiment are:

- **Pipe used and Rig (box):**

Carbon steel pipe consists of (carbon 0.1649 wt%, manganese 0.5027 wt% , phosphor 0.002 wt%, sulfur 0.0068 wt%, Fe rest) of length 62 cm diameter 0.5 cm and buried in wooden box of dimensions (72 × 45× 32) cm. This box was filled with soil. Figure 3-8 shows the rig filled with soil and the pipe.

Figure 3-8 Wooden box

- **Reference electrode:**

Reference electrode (copper/copper sulfate) was buried over the pipe samples. Figure 3-9 shows the reference electrode position.

Figure 3-9 Copper-copper sulfate electrode

- **Anode:**

Anode used is scrap steel of 30 cm length, 25mm outside diameter and 23mm inside diameter. Figure 3-10 shows the anode used.

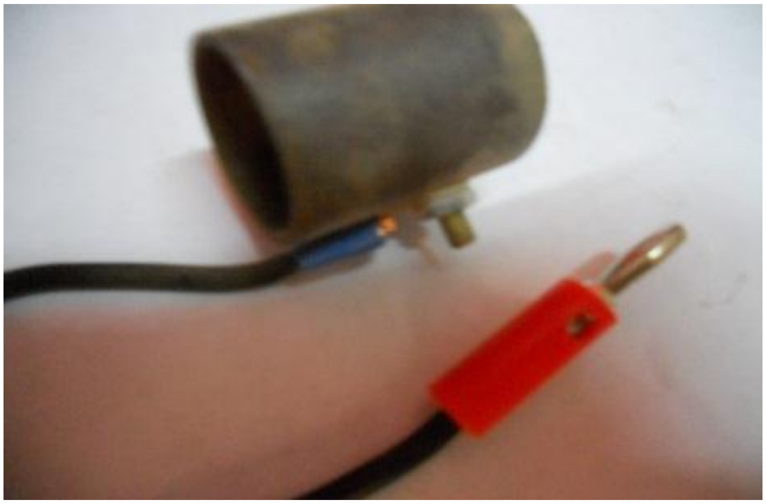


Figure 3-10 Anode

- **Enviroment:**

It is important that stones, pebbles, and root fragments are removed from the soil sample before any sort of measurements take place. Figure 3-11 shows the soil used.

A sample of soil was weight after and before drying and the amount of moisture content was calculated.

a. 2 % moisture Dry soil

b. 12 % Moisture soil

Figure3-11 Soil sample

- **Power supply:**

DC power supply type SY 3005D where used. Figure 3-12 shows the power supply.

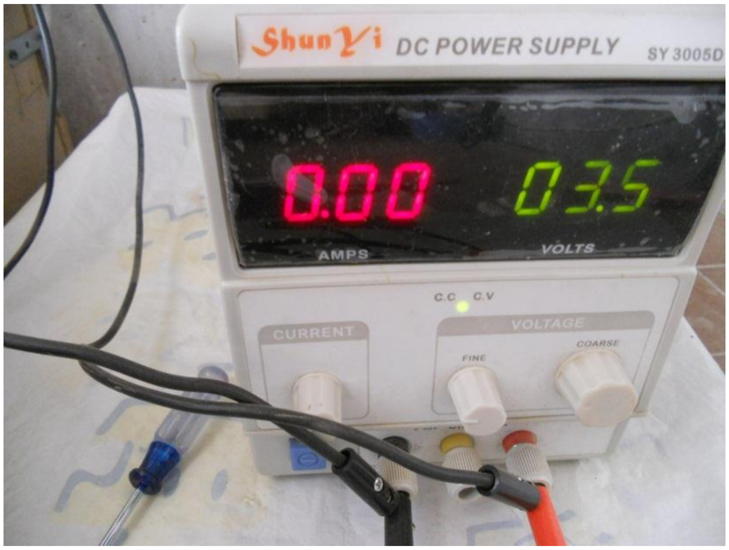


Figure 3-12 DC power supply

- **Voltmeter and ammeter:**

Two voltmeters were used; one to measure the potential of the pipe versus the RE, the second was used to measure the voltage between the pipe and the anode.

An ammeter was used to find the current of the circuit. Figure 3-13 shows the voltmeters and the ammeter.

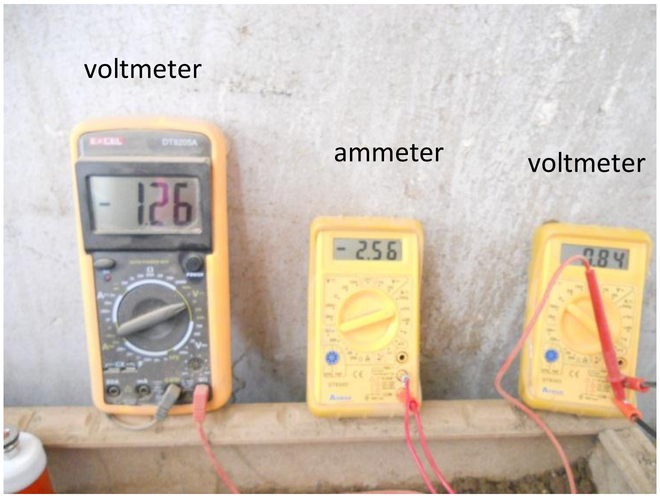


Figure 3-13 Ammeter and voltmeters used

3.2.1 Experimental Programme:

The experimental programme aimed to study the factors influencing cathodic protection process of buried steel pipe within different environments.

There are three conditions were studied with the pipe coated with poly ethylene and with uncoated pipe.

- For dry soil, the resistivity of dry soil is 1800 Ω.cm,
- Moisture anode bed.
- Different soil resistivities: water was added to the soil to decrease its resistivity; a moisture content of 5 % was used. 1100Ω.cm.

The experimental procedures to study the factors influencing cathodic protection process of steel wall with different environments are proposed. In this work, the resistivity of soil, anode and cathode distance, different depths of anodes and different applied voltages have been nominated as process parameters to be studied.

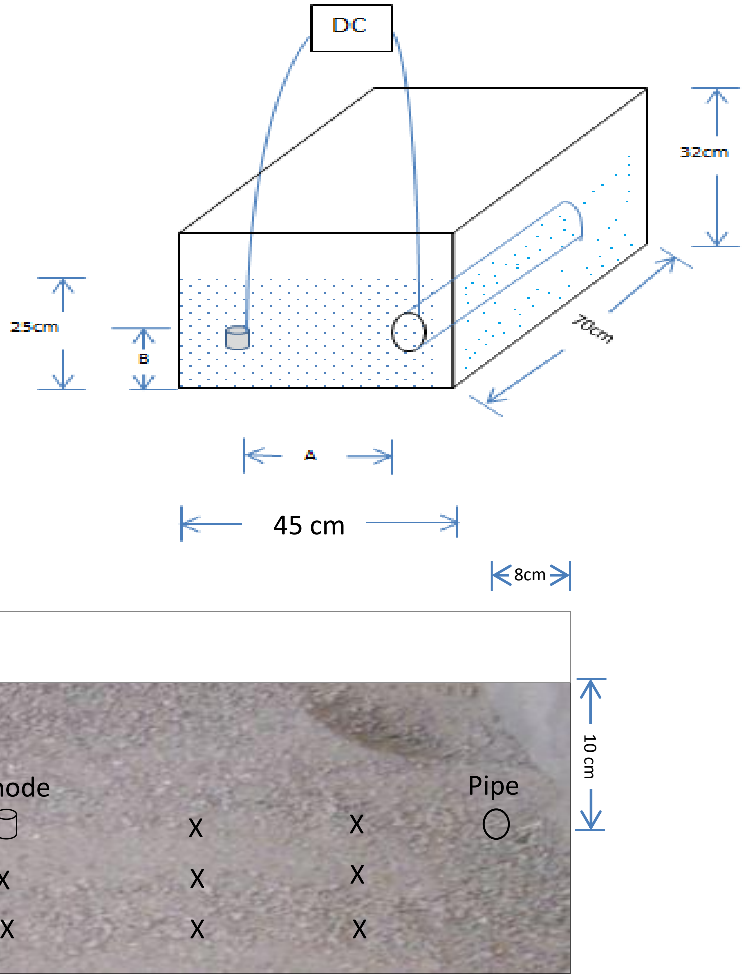
3.2.2 Evaluation of Experimental Runs:

A series of runs have been made under different conditions so that; in each run the anode position is specified. The runs conditions are tabulated in table 3-6; Figure

3-14 shows the experimental apparatus. The anode position is at the same with respect to structure (pipe) while the anode is changing the distance and the depth can be changed. The following data were obtained for each test:

- Potential versus distance for pipe. In order to estimate the amount of current required for cathodic protection system (to test cathodic protection system after installation. i.e. as monitor tool) various ways for pipe to soil potential were used.

- Contour maps for the potential distribution



Where X (s) are the positions of anode

Figure 3-14 Experimental runs

In each run the pipe position was fixed at a distance of 8 cm from wall and at 10 cm depth.

Table 3-6 Anode position with respect to pipe.

Run number	B depth cm	A distance cm	Soil condition	Insulation condition	Run number	B cm	A cm	Soil condition	Insulation condition
1	15	10	moist	coated	17	15	20	moist	coated
2	-	-	moist	uncoated	18	-	-	moist	uncoated
3	-	-	dry	coated	19	-	-	dry	coated
4	-	-	dry	uncoated	20	-	-	dry	uncoated
5	5	10	moist	coated	21	10	30	moist	coated
6	-	-	moist	uncoated	22	-	-	moist	uncoated
7	-	-	dry	coated	23	-	-	dry	coated
8	-	-	dry	uncoated	24	-	-	dry	uncoated
9	10	20	moist	coated	25	5	30	moist	coated
10	-	-	moist	uncoated	26	-	-	moist	uncoated
11	-	-	dry	coated	27	-	-	dry	coated
12	-	-	dry	uncoated	28	-	-	dry	uncoated
13	5	20	moist	coated	29	15	30	moist	coated
14	-	-	moist	uncoated	30	-	-	moist	uncoated
15	-	-	dry	coated	31	-	-	dry	coated
16	-	-	dry	uncoated	32	-	-	dry	uncoated

3.2.3 Potential Contours around Anode:

The voltage gradient between the anode and the cathode is a decent tool that helps understand the effect of soil resistivity.

Tests have been done to illustrate the potential distribution along the soil surrounded the anode ground bed. The anode gives off charges into the electrolyte which diffuse according to Kirchhoff’s laws of passing through the least line of resistance to complete their circuit. Imagine that the anode is surrounded by a shell. For the purposes of this example to visualize that the electrolyte is homogenous with an even resistance all-round the anode. Figures 3-15 through 3-17 shows anode contours measurements procedure.

Figure 3-15 Set up potential contours measurements for anode in dry soil of position 30cm away from pipe.

Figure 3-16 Set up potential contours measurements for anode in dry soil of position 20cm away from pipe.

Figure3-17 Set up potential contours measurements for anode in dry soil of position 10cm away from pipe.

3.2.4 Reference Electrode Position:

Another factor is included in this test which is the position of the reference electrode copper-copper sulfate electrode $Cu/CuSO_4$from pipe. Figures 3-18 and 3-19 show how these measurement where taken.

Figure3-18 Set up potential contours measurements procedure for different electrode depth Position.

Figure 3-19 Set up potential contours measurements procedure of moisture soil

3.2.5 Wet Anode Ground Bed

- Since this research is concerned with studying the effect of soil moisture and the design of cathodic protection system, several amounts of distilled water was added to the soil constructed box. This step was implemented during the electrochemical techniques measurements. In this experiment the pipe was buried in soil of higher moisture than the first experiment. Addition of water to the anode ground bed enhances the cathodic protection process by lowering the anode to earth resistance, thus allowing higher current output for a given voltage [23].

Figure 3-20 View for experiment with wet soil.

Chapter Four

Results and Discussion

4.1 Field Work:

Field survey gathered information necessary for designing efficient cathodic protection systems. Simulation for the factors that affect the cathodic protection system gives design information needed for pipeline external corrosion protection, which mean reach the -0.85 V potential. The simulation results include the following;

- Information needed for the numbers of anodes for adequate protection.
- Information needed for the rectifier voltage and current applied to the system.

4.1. Simulation Variables: [57, 58, 59]

Mathematical models were developed to predict cathodic protection (CP) requirements for coated pipelines protected by parallel anodes. This work was motivated by the need to estimate current and voltage of the rectifier as well as the numbers of anodes used for each situation when anodes are placed nearby.

Simulink accomplished by using the size and geometry of the structure to be protected, coating efficiency, design life for anode, soil resistivity, anode dimensions current density required, etc. should be take into account to find the voltage and current output from the rectifier so as one can reveal the origin of weak points in the system and, hence, make efforts to improve the CPS efficiency.

Mathematical equations used for the simulation are:

1. Pipe surface area=$\pi \times D \times L$
2. Current requirement= $A \times I \times (1-CE)$

Where

I *required current density*

A *total structure surface area*

3. number of anodes to meet the anode supplier current density $= \frac{I}{A1 \times I1}$

A1 *anode surface area*

I1 *recommended maximum current density out put*

4. number of anodes to meet the design life requirement $= \frac{l*I}{1000\times W}$

N *number of anodes*

l *life*

W *weight of anode*

5. Maximam number of anodes required to meet the groundbed requirements

$$= \frac{\rho \times K}{La \times (Ra - \frac{\rho \times P}{S})}$$

K *anode shape factor*

S *center to center spacing between anode backfill column*

P *paralleling factor*

La *length of anode backfill column*

6. Ra(anode ground bed resistance)= $\frac{\rho\times K}{L\times N} + \frac{\rho\times P}{S}$
7. Rw(the groundbed header cable)= *(Ohm/ft)(L)*
8. Deep anode groundbed $= \frac{0.00521\times\rho}{\text{Ldeep}} (ln\frac{8\text{Ldeep}}{d} - 1)$
9. Rc (structure to Electrolyte resistance)= $\frac{R}{A}$
10. Total resistance (Rt) =Rc+Rw+Ra
11. Rectifier voltage= I × Rt × 150 %

Required informations for the simulation inputs are:

1. Average soil resistivity
2. Effective coating resistance at 20 years is estimated at 2500 Ohm /ft^2.
3. Pipe outside diameter.
4. Pipe length for the specified station.
5. Design life.

6. Design current density per square foot of bare pipe was chosen for each station according to soil resistivity as shown in table 4-4.
7. Design for 80 to 90 percent coating efficiency based on experience.
8. The pipeline must be isolated from the pump house with an insulating joint on the main line inside the pump house.
9. High silicon cast iron anodes must be used with carbonaceous backfill. Specification about these anodes is tabulated in tables 4-1 through 4-3.
10. Anode bed resistance must not exceed 2 Ohm.
11. Electric power is available at 240 V AC single phase 50 Hz or three phases from a nearby overhead distribution System.
12. Current requirement test indicates that 2.36 A are needed for adequate cathodic protection.

Table 4-1 Shape functions (K) for impressed current cathodic protection anodes where L_{eff} is the effective anode length, d is anode/backfill diameter. [60]

L_{eff}/d	K	L_{eff}/d	K
5	0.014	28	0.0207
6	0.015	20	0.0213
7	0.0158	25	0.0224
8	0.0165	30	0.0234
9	0.0171	35	0.0242
10	0.0177	40	0.0249
12	0.0186	45	0.0255
14	0.0194	50	0.0261
16	0.0201	55	0.0266

Table 4-2 Weights and dimensions of high silicon chromium-bearing cast iron anodes. [61]

Anode weight (lb.)	Anode dimensions (in)	Anode surface size (in)	Package area (sq. ft.)
12	1×60	1.4	10×84
44	2×60	2.6	10×84
60	2×60	2.8	10×84
110	3×60	4.0	10×84

Table 4-3 Anode paralleling factors (P) for various numbers of anodes (N) installed in parallel [61].

N	P	N	P
2	0.00261	14	0.00168
3	0.00289	16	0.00155
4	0.00283	18	0.00145
5	0.00268	20	0.00135
6	0.00252	22	0.00128
7	0.00237	24	0.00121
8	0.0024	26	0.00114
9	0.00212	28	0.00109
10	0.00201	30	0.00104
12	0.00182		

Table 4-4 Current density and types of environment. [62]

Environment	Current density (mA/m^2)
Soil 50 to 500 ohm.cm	20 to 40
Soil 500 to 1500 ohm.cm	10 to 20
Soil 1500 to 5000 ohm.cm	5 to 10
Soil over 5000 ohm.cm	5
Fresh water	10 to 30
Moving fresh water	30 to 65
Brackish water	50 to 100
Sea mud zone	20 to 30

Table 4-5 Simulation results for zone 1 for the first pipeline.

Simulation input		Simulation output	
Coating resistance ohm	2500	Pipe area m^2	11972.5
Pipe length m	15000	Current requirement mA	11973
Pipe OD m	0.254	No. of anodes to meet the anode supplier current density	4.2759
Current density mA/ m^2	9.999	No. of anodes need to meet the design life requirement	3.3523
Coating effecincy	0.9	Maximum no. of anodes required to meet the ground bed requirements	2.216
At m^2/anode	0.2602	Ra	1.109
It mA/ m^2	10758	Rw	1.208
W kg	11.36	Rc	0.0194
Life in yaer	20	Rt	1.2306
Soil resistivity ohm.cm	1500	Rectifier voltage V	17.35
Amp. Needs for adequate cp	2.36		
L effective anode length m	2.13		

Table 4-6 Simulation results for zone 2 of the first pipeline

Simulation input		Simulation output	
Coating resistance ohm	2500	Pipe area m^2	15963.34
Pipe length m	20000	Current requirement mA	7981.7
Pipe OD m	0.254	No. of anodes to meet the anode supplier current density	2.8506
Current density mA/ m^2	4.999	No. of anodes need to meet the design life requirement	6.3854
Coating effecincy	0.9	Maximum no. of anodes required to meet the ground bed requirements	2.15
At m^2/anode	0.2602	Ra	0.86
It mA/ m^2	10758	Rw	0.0795
W kg	11.36	Rc	0.0146
Life in yaer	20	Rt	0.954
Soil resistivity ohm.cm	1500	Rectifier voltage V	9.13
Amp. Needs for adequate cp	2.36		
	2.13		

Table 4-7 Simulation results for zone 3 of the first pipeline

Simulation input		Simulation output	
Coating resistance ohm	2500	Pipe area m^2	11972.50
Pipe length m	15000	Current requirement mA	11973
Pipe OD m	0.254	No. of anodes to meet the anode supplier current density	4.2759
Current density mA/ m^2	9.999	No. of anodes need to meet the design life requirement	9.578
Coating effecincy	0.9	Maximum no. of anodes required to meet the ground bed requirements	1.68
At m^2/anode	0.2602	Ra	0.524
It mA/ m^2	10758	Rw	0.0795
W kg	11.36	Rc	0.0194
Life in yaer	20	Rt	0.623
Soil resistivity ohm.cm	1200	Rectifier voltage V	11.18
Amp. Needs for adequate cp	2.36		
L effective anode length m	2.13		

Table 4-8 Simulation results for zone 4 of the first pipeline.

Simulation input		Simulation output	
Coating resistance ohm	2500	Pipe area m^2	17174
Pipe length m	2000	Current requirement mA	1596.3
Pipe OD m	0.254	No. of anodes to meet the anode supplier current density	0.5701
Current density mA/ m^2	9.999	No. of anodes need to meet the design life requirement	0.1507
Coating effecincy	0.9	Maximum no. of anodes required to meet the ground bed requirements	2.257
At m^2/anode	0.2602	Ra	1.612
It mA/ m^2	10758	Rw	0.0795
W kg	11.36	Rc	0.1456
Life in yaer	20	Rt	1.83
Soil resistivity ohm.cm	1500	Rectifier voltage V	4.3
Amp. Needs for adequate cp	2.36		
L effective anode length m	2.13		

. **Table 4-9** Simulation results for zone 1 of the second pipeline

Simulation input		Simulation output	
Coating resistance ohm	2500	Pipe area m^2	8939.48
Pipe length m	7000	Current requirement mA	16091.1
Pipe OD m	0.406	No. of anodes to meet the anode supplier current density	5.74682
Current density mA/m^2	17.99	No. of anodes need to meet the design life requirement	1.519
Coating effecincy	0.9	Maximum no. of anodes required to meet the ground bed requirements	0.972
At m^2/anode	0.260	Resistance for deep anode	0.48
It mA/m^2	10758	Rw	0.0795
W kg	11.36	Rc	0.02599
Life in yaer	25	Rt	0.5832
Soil resistivity ohm.cm	1200	Rectifier voltage V	14.077
Amp. Needs for adequate cp	2.36		
L effective anode length m	2.13		

Table 4-10 Simulation results for zone 2 of the second pipeline

Simulation input		Simulation output	
Coating resistance ohm	2500	Pipe area m^2	8939.5
Pipe length m	7000	Current requirement mA	17879
Pipe OD m	0.406	No. of anodes to meet the anode supplier current density	6.3854
Current density mA/m^2	19.99	No. of anodes need to meet the design life requirement	10.727
Coating effecincy	0.9	Maximum no. of anodes required to meet the ground bed requirements	2.081
At m^2t/anode	0.2602	Ra	0.6229
It mA/m^2	10758.4	Rw	0.0795
W kg	11.363	Rc	0.026
Life in yaer	15	Rt	0.7284
Soil resistivity ohm.cm	1200	Rectifier voltage	15.62
Amp. Needs for adequate cp	2.36		
L effective anode length m	2.13		

Table 4-11 Simulation results for zone 3 of the second pipeline

Simulation input		Simulation output	
Coating resistance ohm	2500	Pipe area m^2	8939.48
Pipe length m	7000	Current requirement mA	13409
Pipe OD m	0.406	No. of anodes to meet the anode supplier current density	4.789
Current density mA/m^2	14.999	No. of anodes need to meet the design life requirement	1.2658
Coating effecincy	0.9	Maximum no. of anodes required to meet the ground bed requirements	1.3609
At m^2/anode	0.2602	Ra	0.7394
It mA/m^2	10758	Rw	0.0795
W kg	11.36	Rc	0.026
Life in yaer	25	Rt	0.844
Soil resistivity ohm.cm	1000	Rectifier voltage V	16.99
Amp. Needs for adequate cp	2.36		
L effective anode length m	2.13		

Table 4-12 Simulation results for zone 4 of the second pipeline

Simulation input		Simulation output	
Coating resistance ohm	2500	Pipe area m^2	8939.48
Pipe length m	7000	Current requirement mA	8939.49
Pipe OD m	0.406	No. of anodes to meet the anode supplier current density	3.1926
Current density mA/m^2	9.999	No. of anodes need to meet the design life requirement	0.84389
Coating effecincy	0.9	Maximum no. of anodes required to meet the ground bed requirements	1.3728
At m^2/anode	0.260	Ra	0.68
It mA/m^2	10758.4	Rw	0.0795
W kg	11.36	Rc	0.21186
Life in yaer	25	Rt	0.97387
Soil resistivity ohm.cm	3000	Rectifier voltage V	13.0588
Amp. Needs for adequate cp	2.36		
L effective anode length m	2.13		

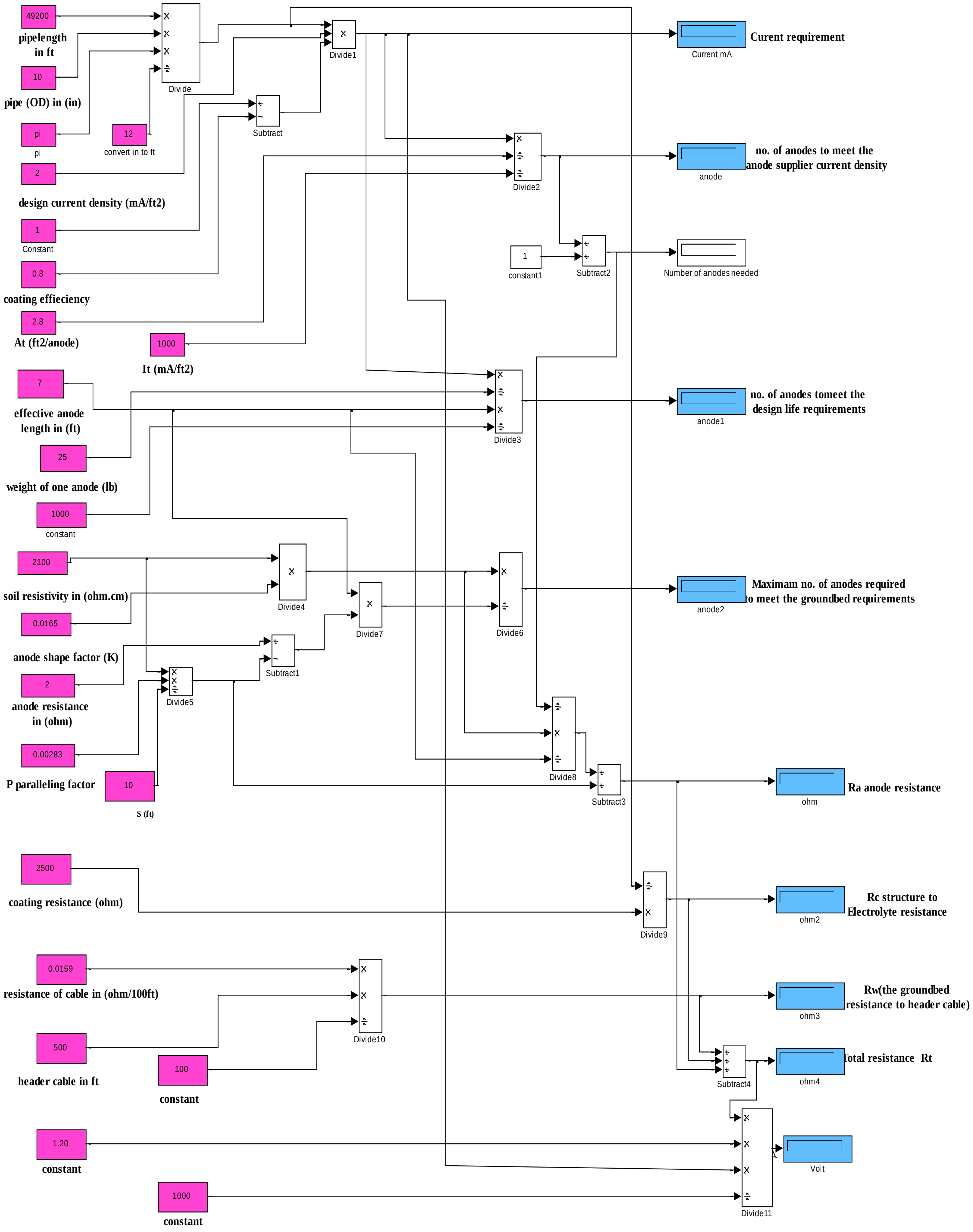


Figure 4-1 The simulation work of field variables.

4.1.2 Comparison between Field Work and Simulation

Based on the results obtained from the simulation and field survey, comprehensive calculations were performed for a well-defined model of cathodic protection system to control the external corrosion of buried pipeline. This model is designed to simulate the behavior of corrosion problems and cathodic protection systems. The comparison between the calculated and measured data has been employed.

Table 4-13 The first pipe stations current requirement, voltage; number of anodes used and need.

Station no.	Soil resistivity (Ohm.cm)	Real (field)	Simulation results	Ra (Ohm)
Station 4	1500	5A	1.59A	1.6
		7.5V	4.3V	
		10anodes	3anodes	
Station3	1200	4V	11.88 V	0.524
		5A	11.9A	
		10anodes	10anodes	
Station2	1500	2.5A	7.9A	0.8606
		7V	9.1V	
		10anodes	7anodes	
Station 1	1500	59A	11.9A	1.1091
		48V	17.35V	
		10anodes	5anodes	

Table 4-14 The second pipe stations current requirement, voltage; number of anodes used and need.

Station no.	Soil resistivity (Ohm.cm)	Real (field)	mulation results	Ra(Ohm)
Station 4	3000	5V	13V	0.68 (deep anode)
		12A	8.9 A	
		5anodes	4 anodes	
Station3	1000	14V	16.99V	0.739
		24A	13.4A	
		10anodes	5anodes	
Station2	1500	13A	17A	0.6229
		25V	15V	
		10anodes	11anodes	
Station 1	1200	19A	16A	0.48 (deep anode)
		14V	14V	
		5anodes	6anodes	

- A rectifier with a relatively high voltage output is required to buck the rail to earth potential.
- A transformer is used to increase or decrease voltage or to isolate an incoming voltage source from the outgoing voltage.
- No metallic connection to other lines in the section being tested which permit current entry other than through the coating [30].

1. It is clear that the applied current increase as the soil resistivity decrease (except for the deep anode system). The total current calculated from the software was less or higher than the current applied and measured in the field in some stations. This was recorded when the soil resistivity, the anode resistance, anode numbers values change these three factors
2. As the number of anodes increase the total resistance of anodes decrease, just like if the amount of moisture around the anode increase the resistance of anode ground bed decrease this lead to an increase of current discharge by an anode. Anode location; moisture or wet location good for ground bed. The resistance of the anode bed can be lowered by adding additional anodes, using longer anodes, or by increasing the spacing

of the anodes [9]. This is obvious in the first pipeline with some exception in the second pipeline.

3. The arrangement of anodes is parallel so the current of more than one anode is greater than for one anode for the same rectifier (applied) voltage.
4. As the anode distance between anode and the pipeline increase the region of pipe to be protected will increase.
5. Current density should be kept low to prevent undue drying out of the soil around the anode [58].

The used of HSCI anode is related to the formation of a silicon oxide (SiO_2) film that forms on the anode surface reducing the rate of oxidation, and retarding the consumption rate [19]. It have been seen that when increasing the impressed current densities the consumption of anodes were increased also and that is in agreement with AL-Jawary [42]. As Ra increase the applied voltage of the rectifier is increased which is obvious in the second pipeline with some exception in the first pipeline stations (3, 4).

Horizontal Remote anode type systems are:

1. Commonly used for pipelines in remote areas where a rock stratum is located near the surface or where other soil conditions would require horizontal installation to ensure the anode is in a uniform environment.
2. This is usually the most economical choice when there are no other utilities in the area, there is sufficient room to locate the anodes remote from the structure, and there is a rock strata near the surface.
3. Horizontal placement of the anodes in the earth tends to raise the total resistance to earth of the system (versus vertical). The distance to remote earth varies according to the resistivity of the earth, usually 91 to 213 meters (300 to 700 feet).
4. Care must be taken to ensure that the low resistance area is not continuous to the protected structure. Poor current distribution may occur if this condition occurs. In some cases, the best location for an anode bed may be in higher resistivity earth.

The anodes may have individual leads connected to a header cable or they may be installed on a continuous cable [9].

- Ground bed were designed for locations remote from the cathode, allowing low current density transmission across long distances with moderate soil to pipe voltage at the line. Greater importance than the total current density applied is the way that current is distributed. The optimum current distribution requirement should be assessed from the underground structure arrangement, the extent of corrosion spread, and the level of activity
- The use of a deep anode:

1. These systems are commonly used to protect large structures in built up areas.
2. This is usually the most economical choice when the structure is large, in an area with many other utilities, or the anodes cannot be placed near the surface.
3. This type of anode bed is used to protect pipeline distribution systems, above ground tank farms, and pipelines in built-up areas.

- In the field casing must be electrically isolated from the carrier pipe, wires on both the pipe line and the casing, the vent can be used instead, there should be different of anywhere from 0.25 to 1.0 V or more between pipe to soil potential of the casing and the pipeline if the casing has anodes connected to it, the pick up or resistance tests between the casing and the pipeline may be required [24].
- For structures that are not buried deeply in the earth, advantage is taken of the fact that all stray currents near the surface must of necessity flow parallel to the surface. Thus placing the observing half-cell directly over the structure being observed, the IR drops of stray currents are at right angles to the observing circuit, and their effects are usually negligible.
- Some cathodic protection design has more than one negative circuit. This usually occurs when two or more facilities are being protected by single rectifier. In order to control the current flowing to each structure, negative cables may be run to junction box in which resistors can be placed; damage to the insulation is not critical as it is on the positive cable, because the negative cable is on the cathodic side of the circuit. Still precautions need to be taken in handling the negative cable.

- Coal tar has a good property that’s why it is still used nowadays for coatings. These properties are; minimum holidays susceptibility, low current requirements good resistance to cathodic disbondment and good adhesion to steel [63]. Coal tar coatings have been used for many centuries because of their resistance to water and biological organisms.
- Computer modeling can be used to secure optimal anode numbers. 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. 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.

4.2 Results of Experimental Work:

Great care and consideration were given about the proper location and selection of anode systems for cathodic units in order secures an even distribution of anodes on a symmetrical structure.

The experimental studied include soil moisture content, coating effect, anode depth, anode distance, applied voltage, reference electrode position and moisture anode ground bed.

4.2.1 Soil Moisture Content:

The effect of the soil moisture content on the applied voltage need for protection of the structure for coated and uncoated pipe was investigated. It was found that as the soil resistivity decrease the applied voltage decrease. This result is agreed with previous study by Hafiz [49] who found that cathodic protection current density increases especially in the higher environment resistivity. Figures 4-3 through 4-9 show the soil resistivity effect on the protection of the pipe. Table 4-15 show the result for each condition.

The attenuation in potential of uncoated pipe that occurs in moisture soil rather than in dry soil is related to the current that passes through the least resistance medium. It is worthy to mention that soil resistivity is higher in dry soil. Nonuniform current distribution over a pipeline resulting from differences in the electrolyte (soil) resistivity (schematic). The main current flow will be along the path of least resistance this is agreed with opinion given by Roberge as shown in fig. 2-5. Moisture soil has less resistance than the dry soil because of salt in the soil would dissolved as a result of the addition of water, so the current would pass through this soil rather than in dry soil.

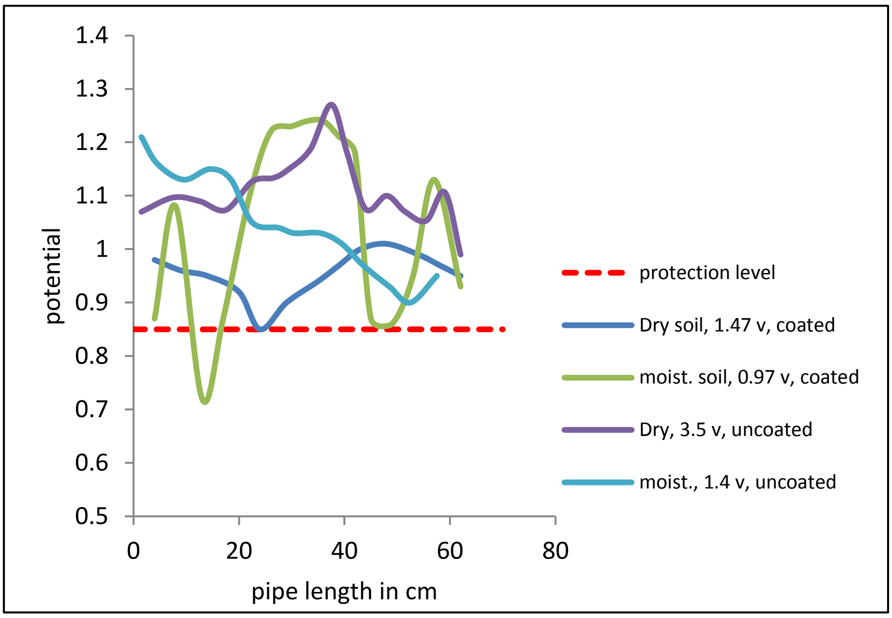


Figure 4-3 The effect of moisture content of soil for the protection of pipe with anode position of 30cm away from pipe at 20 cm depth.

Figure 4-3 shows the variation of the potential of the coated pipe with distance for anode position of 30 cm away from the pipe and at 20 cm depth. It illustrates that as the soil resistivity decrease from 1800 Ohm.cm to 1100 Ohm.cm (63.63 %) the applied voltage decrease from 1.47 v to 0.97 v (51.5 %). The complex trends of the two curves was due to the soil resistivity, as the soil resistivity decrease the distribution of current is more uniform than in higher resistivity soil (dry soil).

The potential of the pipe buried in dry soil was in the range 1.24V to 0.72 V (72 %) while for the pipe buried in moisture soil was 1.01 V to 0.85 V (18.82 %). The lowest potential value was at point 13 cm and 46 cm this was due to coating defect, while the highest value was at the center of the pipe (the area that faced the anode).

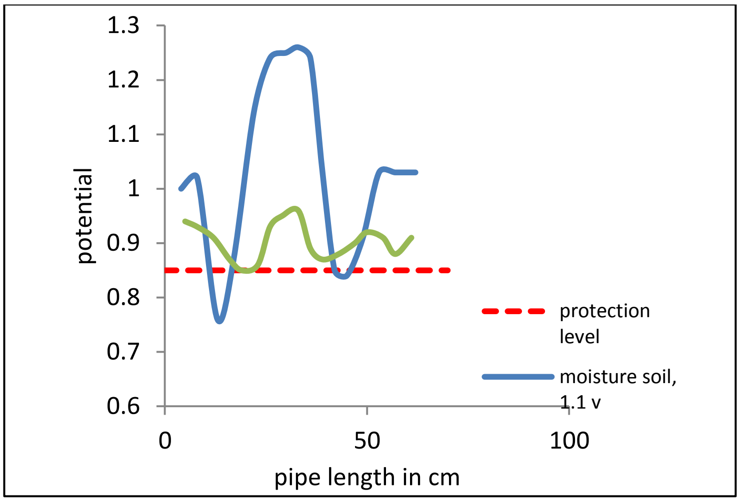


Figure 4-4 The effect of moisture content of soil for the protection of coated pipe with anode position of 30 cm away from pipe and 15 cm depth.

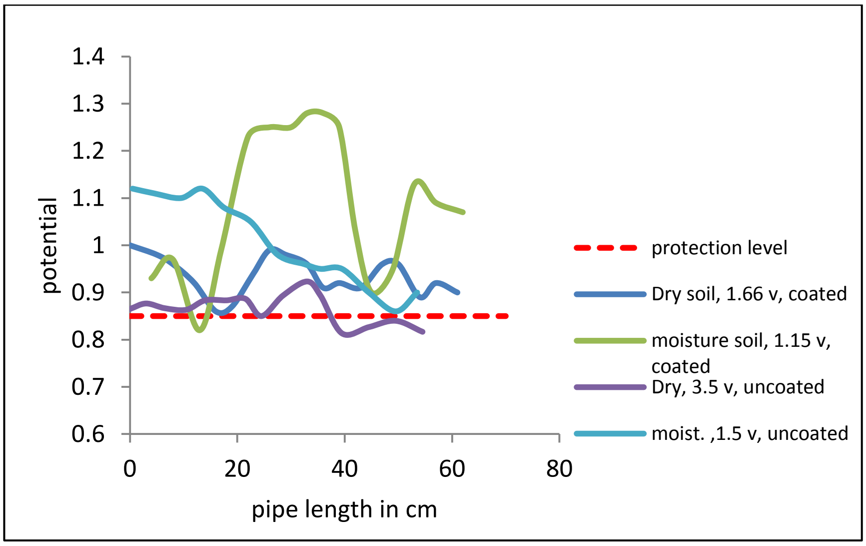


Figure 4-5 The effect of moisture content of soil for the protection of pipe with anode position of 20cm away from pipe and 15 cm depth.

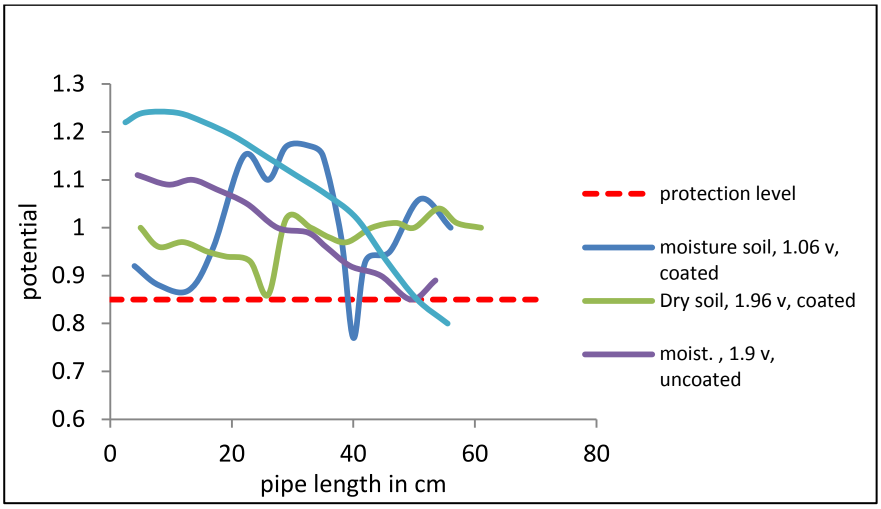


Figure 4-6 The effect of moisture content of soil for the protection of pipe with anode position of 10cm away from pipe and 15 cm depth.

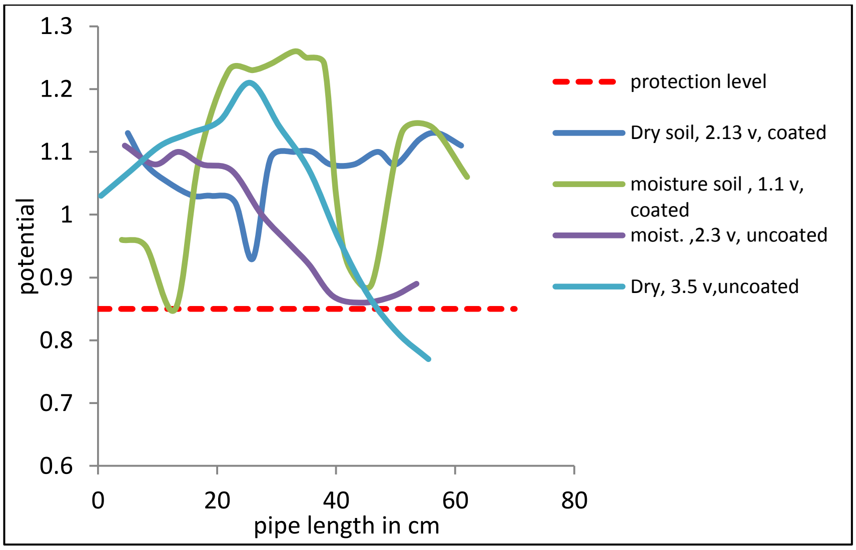


Figure 4-7 The effect of moisture content of soil for the protection of pipe with anode position of 10cm away from pipe and 20 cm depth.

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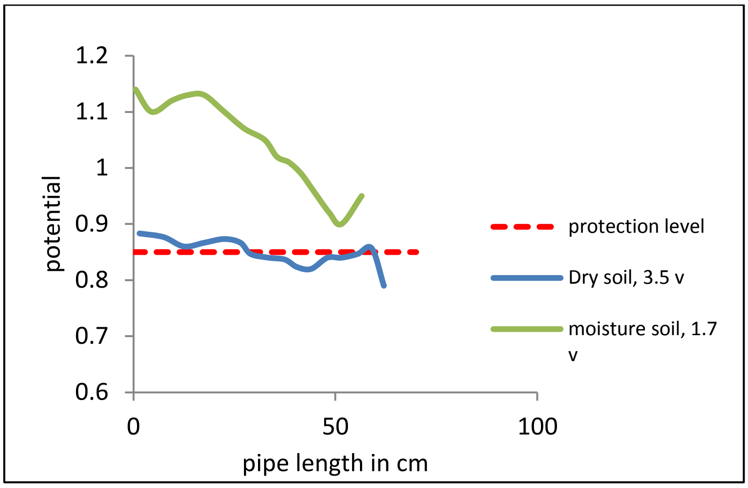

Figure 4-8 The effect of moisture content of soil for the protection of pipe with anode position of 30cm away from pipe and 10 cm depth.

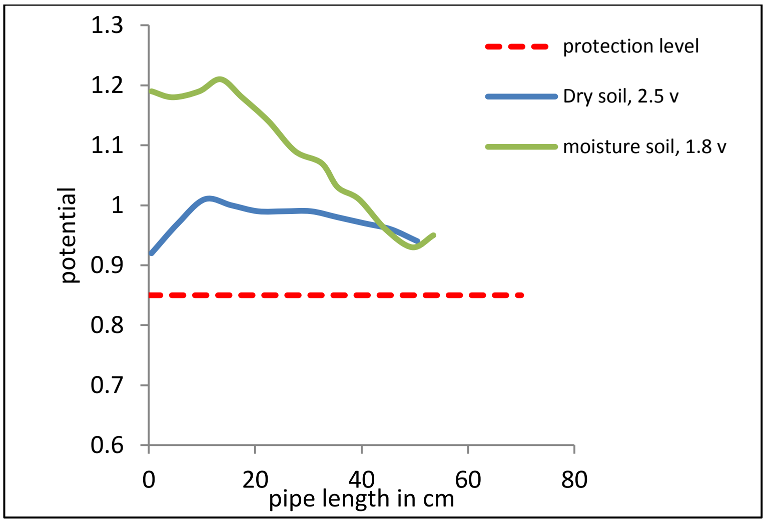

Figure 4-9 The effect of moisture content of soil for the protection of pipe with anode position of 20cm away from pipe and 20 cm depth.

Table 4-15 The results of the effect of moisture soil content.

Anode position distance cm-depth cm	$V_{appl.}$ Dry soil	V_{appl} Moist. soil	Decreasing in V_{appl} %	Potential range (dry soil)	Decreasing in potential %	Potential range (moist soil)	Decreasing in potential %
30-10	1.66	1.1	51	0.96-0.85	12.9	1.26-0.76	65.7
20-10	1.66	1.15	44.34	1-0.86	16.27	1.28-0.82	56.09
10-10	1.96	1.06	84.9	1.04-0.86	20.93	1.77-0.71	149
10-20	2.13	1.1	93.6	1.13-0.93	21.50	1.26-0.85	48.23
30-15	3.5	1.7	105	0.88-.79	11.3	1.14-0.9	26.67
30-20	3.5	1.4	150	1.27-0.99	28.28	1.21-0.9	34
20-10	3.5	1.5	133	1.01-0.87	16.09	1.12-0.86	30.23
20-20	2.5	1.8	38.89	1.01-0.92	9.7	1.21-0.93	30.1
10-10	3.5	1.9	84.2	1.24-0.8	55	1.11-0.85	26
10-20	3.5	2.3	52.17	1.21-0.77	57.14	1.11-0.86	29.06

4.2.2 Coating Effect:

As the power supply on a closed circuit occurs the bare metal is in contact with the soil, current flows through it and through the electrolyte (soil) and this experience of an IR drop. Depending on the pipe and anode mutual positions, the R could change with the position inside the pipe, and the current could be lower with the distance from the connection point as a physical analogue, this visualize water flowing in a pipe with a series of holes, the pressure of the water and the flow out of the holes will lower with the distance of each hole from the injection point. When coated, the flow of current can be only from coating holidays, but the difference in potential could be also due to local variations in the soil.

Figures 4.10 through 4.13 show the coating effect on the applied voltage. It is obvious that the applied voltage decrease for coated pipe rather than uncoated. For bare and coated pipe, cathodic current density increases as environment resistivity decreases due to increasing the conductivity, result in agreement with the observation of Hafiz [49]. The results of each condition were tabulated in table 4-16.

In the case of a power-impressed system, a single cathodic-protection system may supply efficient protection to as much as 150 km of extremely well coated pipeline, whereas for similar sizes of bare (uncoated) pipelines it may be necessary to have installations at only 2 km intervals. The decrease in a potential and current density along buried or immersed pipeline from the drainage point is called attenuation as schematically illustrated in Fig. 2-9 observed the effect of attenuation. This attenuation should increase with time as anodes expire (current output per anode decreases) or the coating deteriorates (or both); and eventually the current demand of the pipeline exceeds the anode output capability [24], furthermore, the current attenuation is indicative of the coating quality and integrity [64].

The current density CP for coated pipe is very low compared with cathodic protection current density for bare pipe which is in agreement with the result of Al-Rahman [50]. If a bare pipeline is buried in an environment of uniform resistivity, the potential along the pipeline will almost vary in the same manner as of a uniformly coated pipeline. However, if a bare pipeline passes through environment where the resistivity widely varies from point to point, current pickup will be largely concentrated in the areas of low environment resistivity, resulting in large potential drops in the environment and low pipe to environment potential in these areas. It should be observed that in the coated pipe the potential distribution is uniform and the areas in the middle of the pipe where it faced the anode ground bed the potential is higher than the other sides of the pipe. On the other hand, different distribution of potential is shown with uncoated pipe due to the attenuation. This is mean that as the distance from the drainage point increase the potential decrease and this attenuation is more obvious when the uncoated pipe buried in moisture soil than when it buried in dry soil [19]. The coating playing very important rule for the current distribution as the amount of the current that leave the pipe is smaller than the that of uncoated one, also the reference electrode reading for the coated one the only resistance that will be active is the coating resistance.

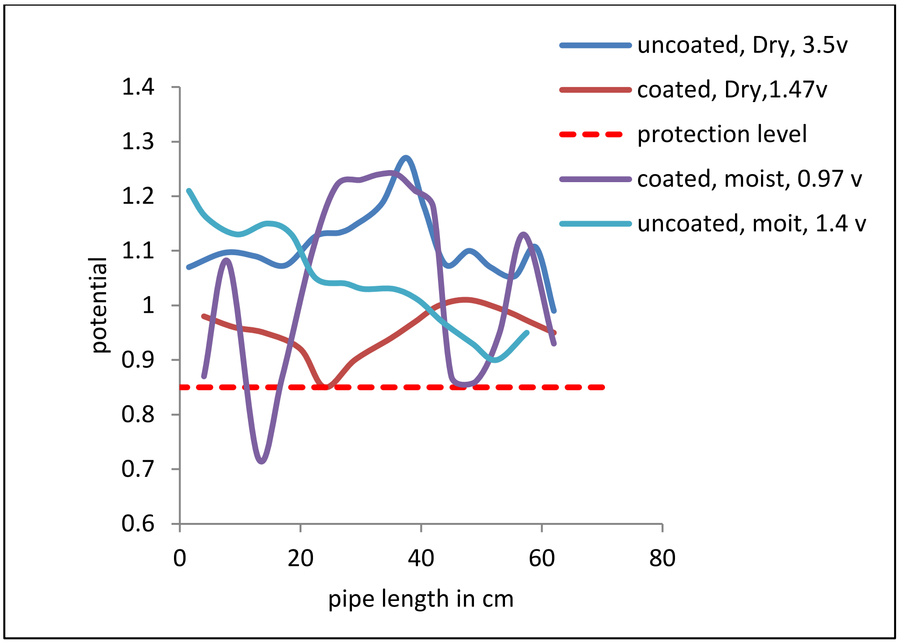

Figure 4-10 The effect of the coating on the protection of the pipe buried in different soil for anode position 30cm away from pipe at a depth 20 cm.

Figure 4-10 shows the variation of the potential of pipe with distance for anode position 30 cm away from pipe and at 20 cm depth. Curves indicate that the coated pipe needs less voltage than that of the uncoated one. The coated pipe buried in dry soil needed only 1.47 V to reach the protection level while the uncoated pipe needed 3.5 V. While for the pipe buried in moisture soil curves illustrated that the coated pipe needed only 0.97 v to reach the protection level while the uncoated pipe needed 1.4 v. it is observed that the attenuation of the potential occur in the uncoated pipe rather than the coated one this was due to the coating resistance which restrict the current from leaving the pipe the decreasing in potential was (34.4 %).

Table 4-16 Results of soil moisture content on cathodic protection of the pipe for different anode position.

Anode position	App. V coated	App. V uncoated	Decreasing in potential %	Soil condition
20-15	1.66	3.5	6	dry
10-15	1.96	3.5	55	dry
10-20	2.13	3.5	26	dry
30-20	0.97	1.4	34.4	moist
30-15	1.17	1.1	23.65	moist
30-10	0.98	1.7	24	moist
20-15	1.15	1.5	30.23	moist
20-20	1.14	1.8	30.1	moist
10-20	1.1	2.3	29	moist
10-15	1.06	1.9	29	moist

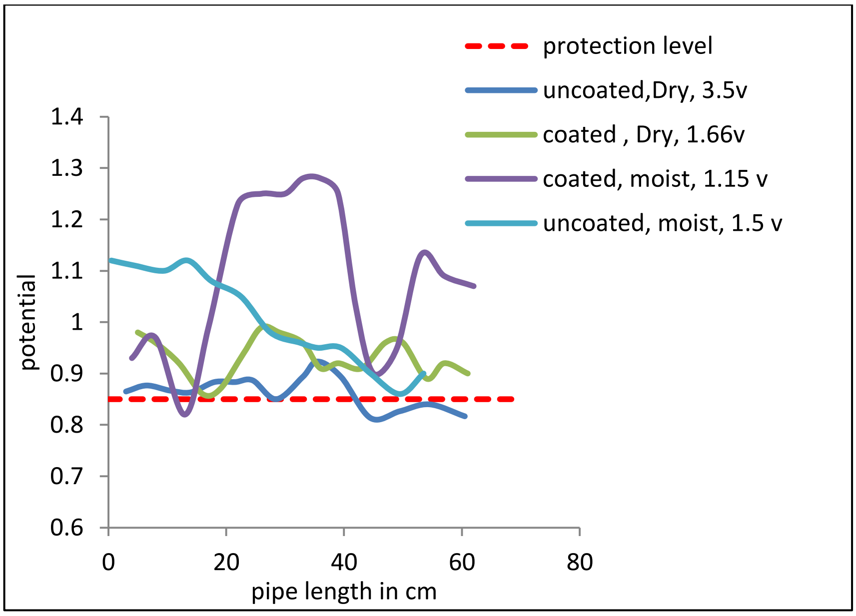

Figure 4-11 The effect of the coating on the protection of the pipe in different soil for anode position 20cm away from pipe at a depth 15 cm.

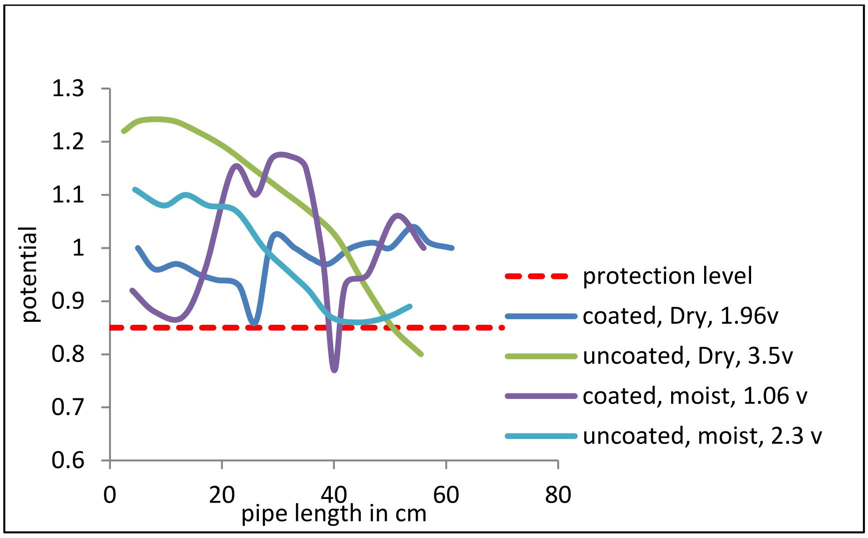

Figure 4-12 The effect of the coating on the protection of the pipe buried in different soil for anode position 10cm away from pipe at a depth 15 cm.

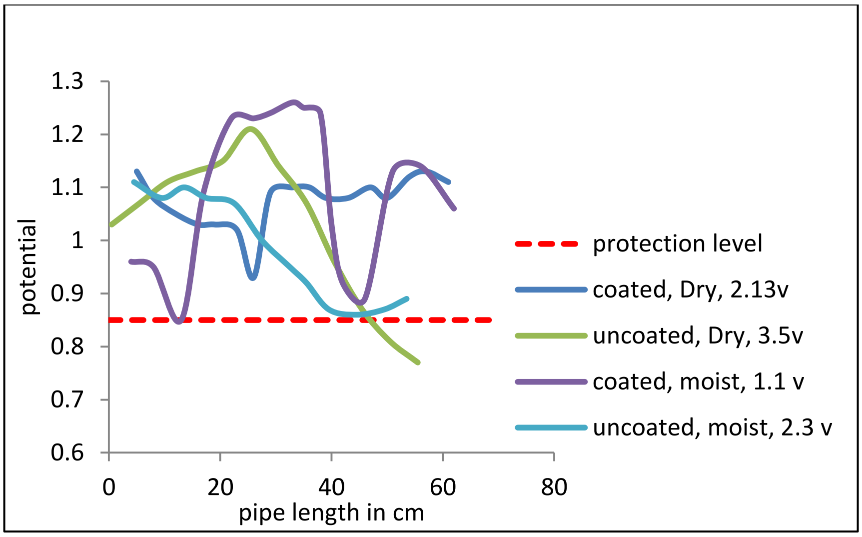

Figure 4-13 The effect of the coating on the protection of the pipe buried in different soil for anode position 10cm away from pipe at a depth 20cm.

4.2.3 Anode Depth

The effect of the depth of the anode for the same anode distance from pipe has been made. The anode is above the pipe, it may be in dry soil and unable to discharge adequate current at the same time the pipe is in wet, low resistivity, soil. If the anode is below the pipe, the anode will be actively corroding every time the water table rises to the pipe depth. For coated pipe the best depth was 20 cm while for the uncoated pipe it is varied between 20 cm and 15 cm depth.

If the anode is on the surface then these resistances will form a hemisphere and not a globe, the atmosphere being virtually nonconductive. At various depths the resulting shells of resistance at various depths will take the form of the limits if the measurable potential gradient in the ground. That charges radiate out so the deeper the anodes the less resistance according to the inverse square law of radiation and the number of resistances in parallel. If the anode is above the pipe, it may be in dry soil and unable to discharge adequate current at the same time the pipe is in wet, low resistivity soil; this is because the distance between particles in mud soil are pressed tightly together while the distance between particles in sandy soil are more separated and air pass through it and this reduce electrical conductivity of soil.

It should emphasized that the data in Fig. 4-15 through 4-44 show the effect of anode depth when all other factors remain constant. A conclusion can be made from these figures that as the anode become on the same surface with respect to the buried the pipeline, the protection became minimum instead of where the anodes position below the pipeline depth. This is because of the current distribution way in to the pipe surface. It is observed from these anode contours that distribution of potential varies from side to another and the potential decreases with increasing the anode depth and vice versa.

Figure 4-14 shows the potential contour figure and where the anode position as well as the pipe.

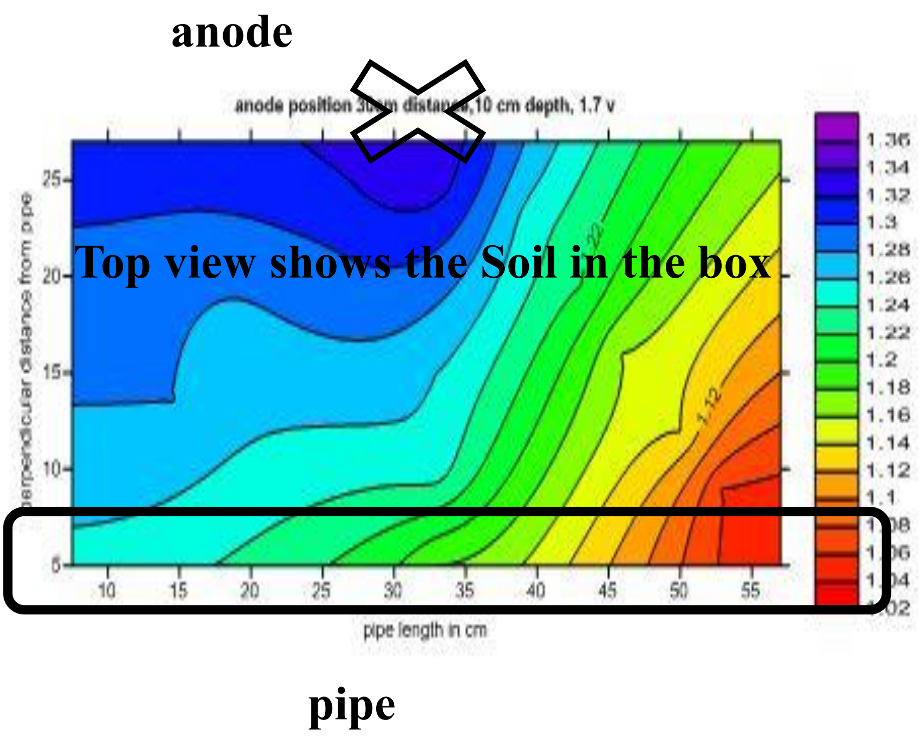

Figure 4-14 Position of the anode and pipe in a potential contour.

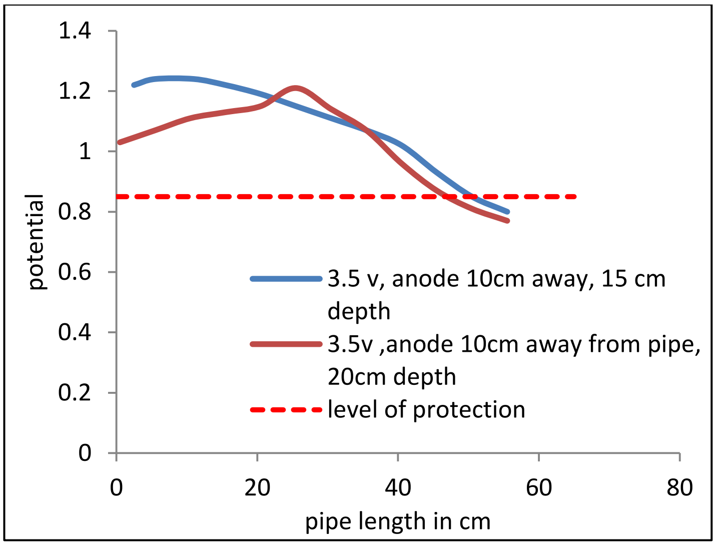

Figure 4-15 The effect of the anode depth for 10 cm distance from uncoated pipe buried in dry soil

Figure 4-15 shows the variation of potential of the pipe with distance. Both curves indicate no significant change in the protection level for anode depths for the 10 cm distance from uncoated pipe buried in dry soil.

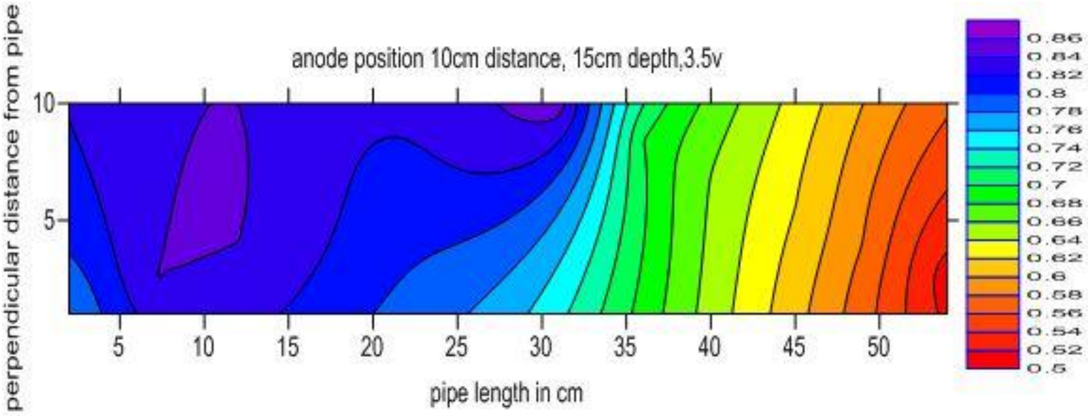

Figure 4-16 Potential contours for anode location 10 cm distance and 15 cm depth from uncoated pipe buried in dry soil, (RE on surface)

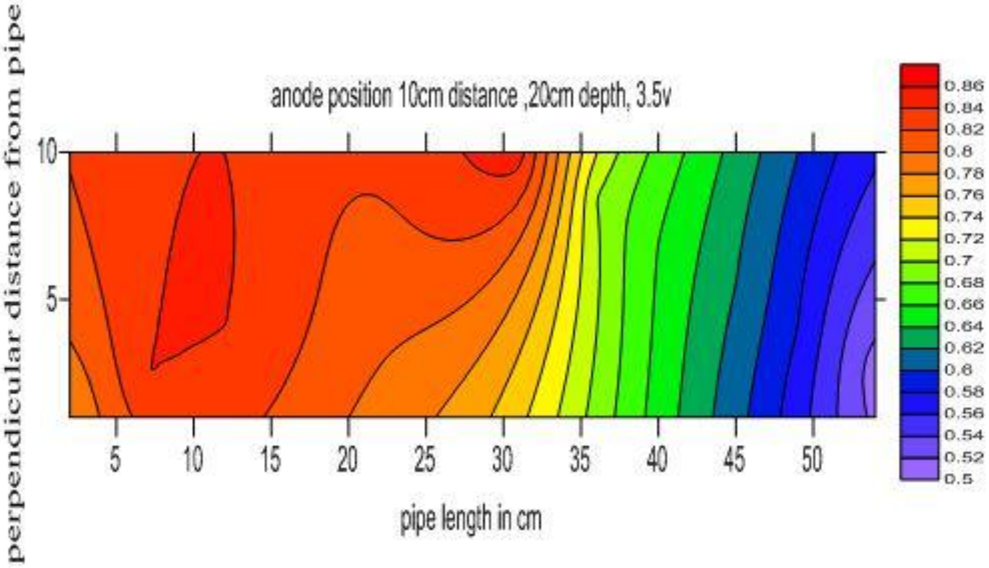

Figure 4-17 Potential contours for anode location 10 cm distance and 20 cm depth from uncoated pipe buried in dry soil, (RE on surface).

Figure 4-16 and 4-17 show that as the anode depth increase the potential range increase.

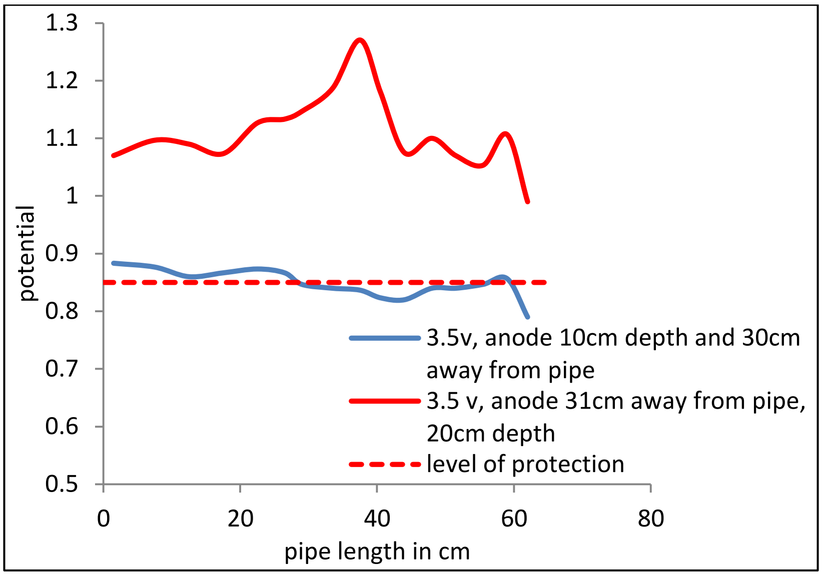

Figure 4-18 The effect of anode depth for anode position 30 cm away from uncoated pipe buried in dry soil.

It is obvious in fig. 4-18 that the best depth for anode was 20 cm at 30 cm distance from uncoated pipe buried in dry soil; as the depth increase from 10 cm to 20 cm the protection level increase by 21.6 %. If the anode is buried very deep then extends to a zone where there are so many resistances in parallel that there are an infinite number of resistances and therefore infinite conductance.

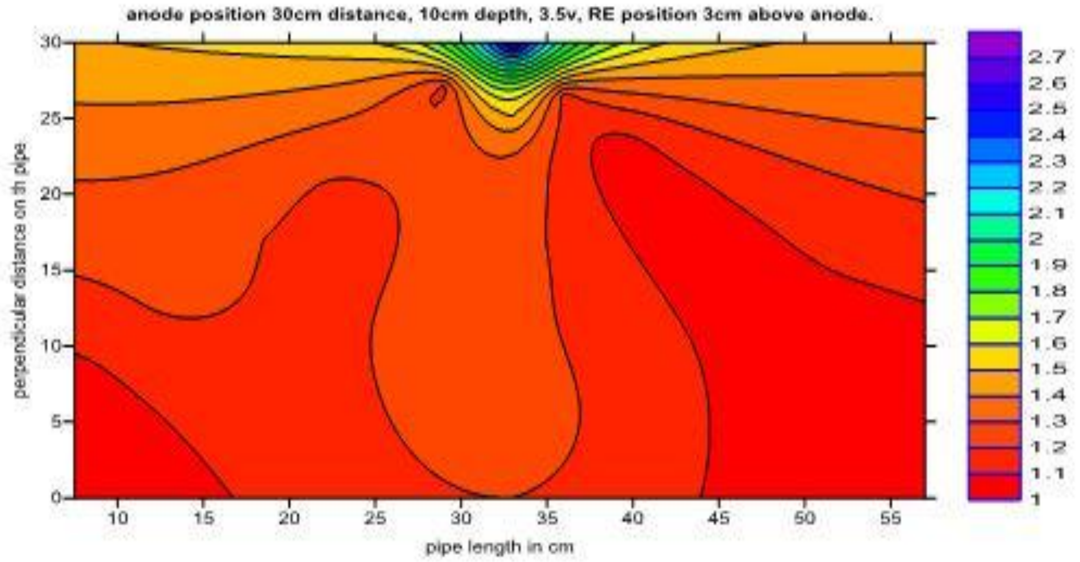

Figure 4-19 Potential contours for anode position 30 cm distance at 10 cm depth from pipe in dry soil for applied voltage of 3.5 v

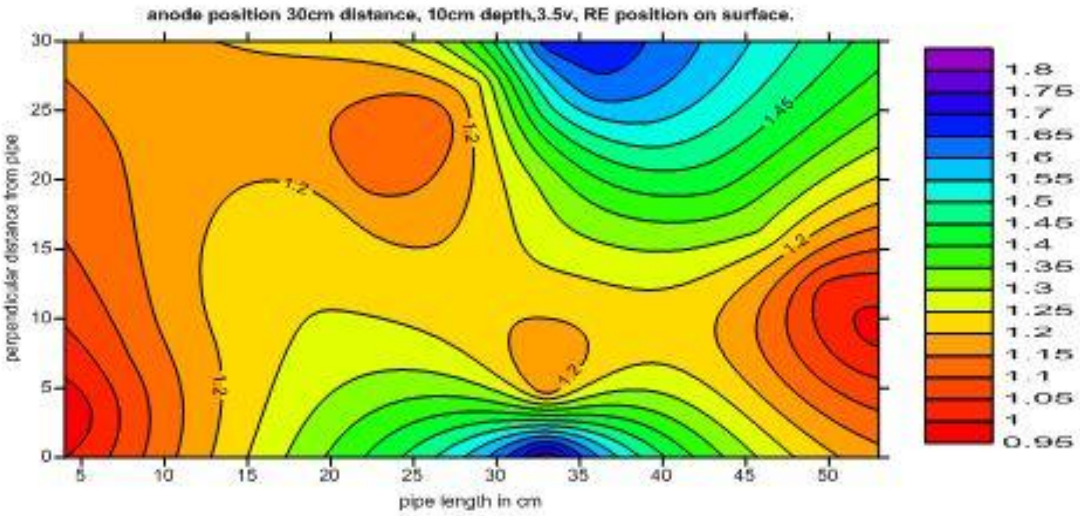

Figure 4-20 Potential contours for anode position 30 cm distance and depth of 10 cm from uncoated pipe buried in dry soil.

Figure 4-19 and 4-20 show that as the reference electrode became near the anode the potential range increase.

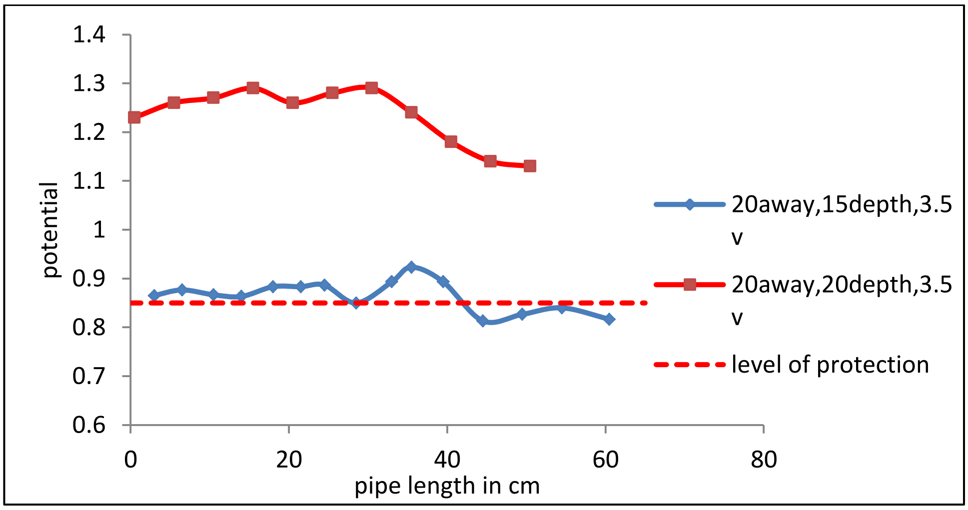

Figure 4-21 The effect of the anode depth for the distance of 20 cm away from uncoated pipe buried in dry soil.

Figure 4-21 shows that the best depth for anode was 20 cm at 20 cm distance from uncoated pipe buried in dry soil; as the changed from 15 cm to 20 cm the protection level increase by 48.2 %. If the anode is buried very deep then extends to a zone where there are so many resistances in parallel that there are an infinite number of resistances and therefore infinite conductance.

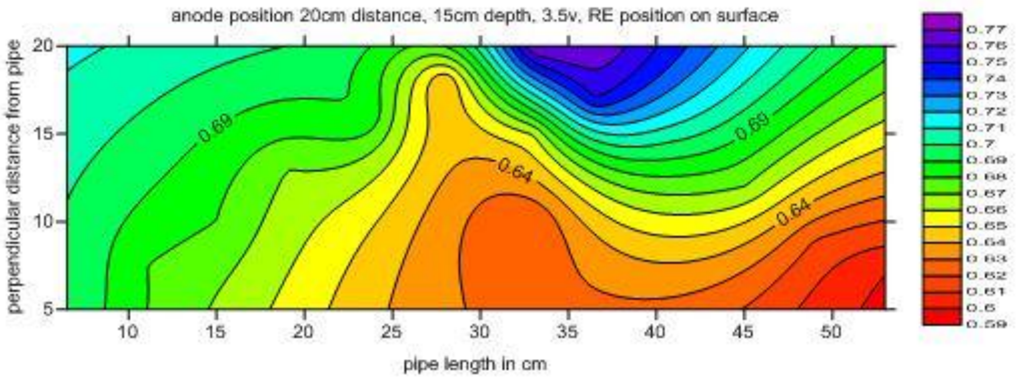

Figure 4-22 Potential contours for anode position 20 cm distance and15 cm depth from uncoated pipe buried in dry soil, RE position on surface.

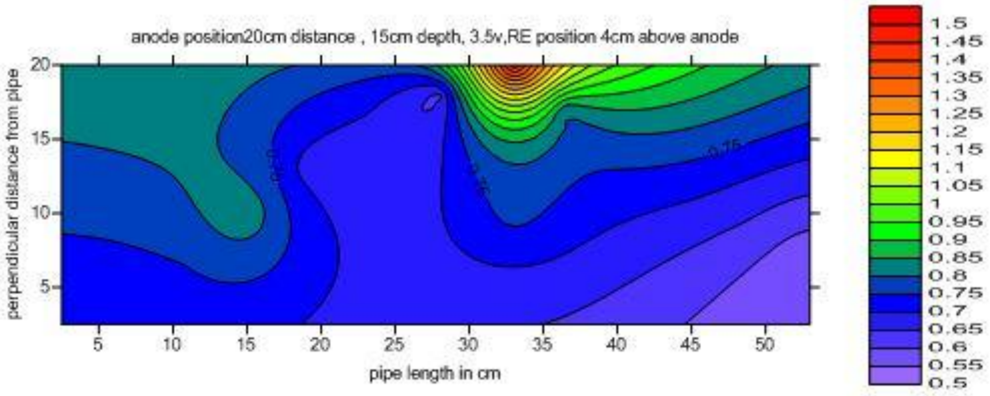

Figure 4-23 Potential contours for anode position 20 cm distance and15 cm depth from uncoated pipe buried in dry soil, RE position 4 cm above the anode.

Figure 4-22 and 4-23 show that as the reference electrode became near the anode the potential range increase.

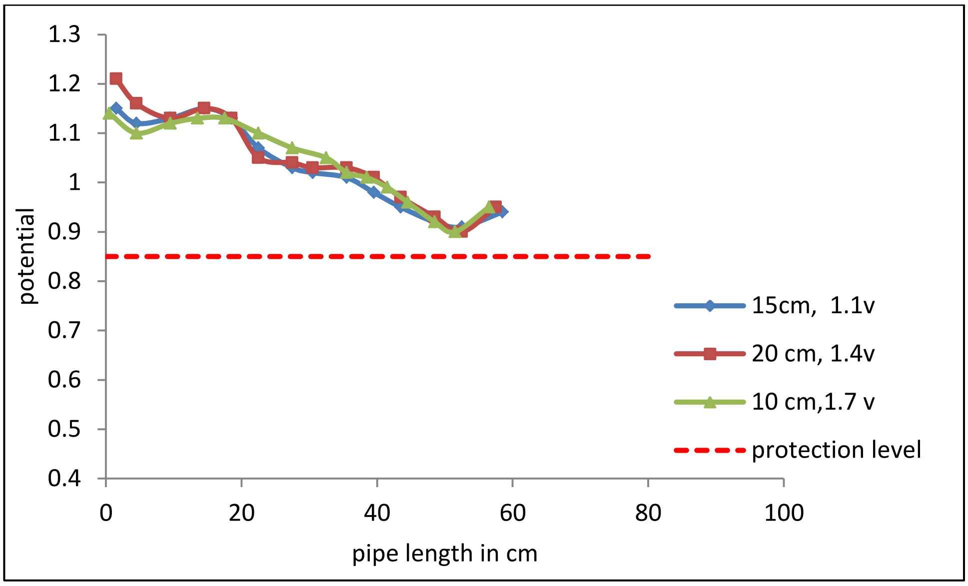

Figure 4-24 The variation in the applied voltage to give the protection for the same anode distance 30 cm from uncoated pipe buried in moisture soil and variable depth.

In fig. 4-24 it was obvious that the 15 cm depth was the best depth for anode at 30 cm distance from uncoated pipe buried in moisture soil; this is obvious in the applied voltage since this position need the lowest applied voltage (low cost).

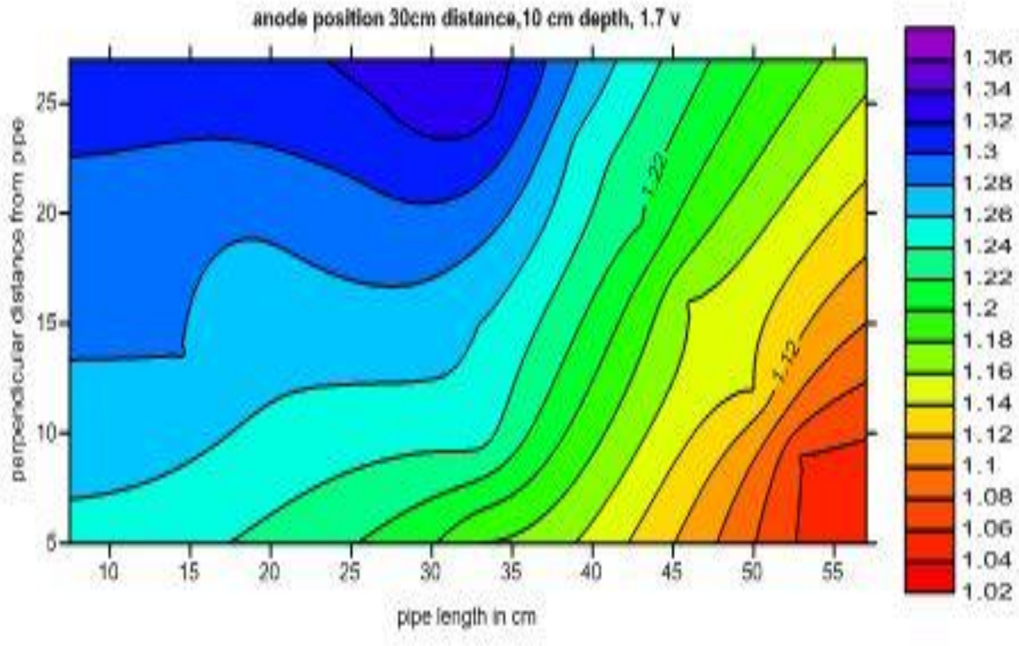

Figure4-25 Potential contours for anode position 30 cm distance and 10 cm depth from uncoated pipe buried in moisture soil.

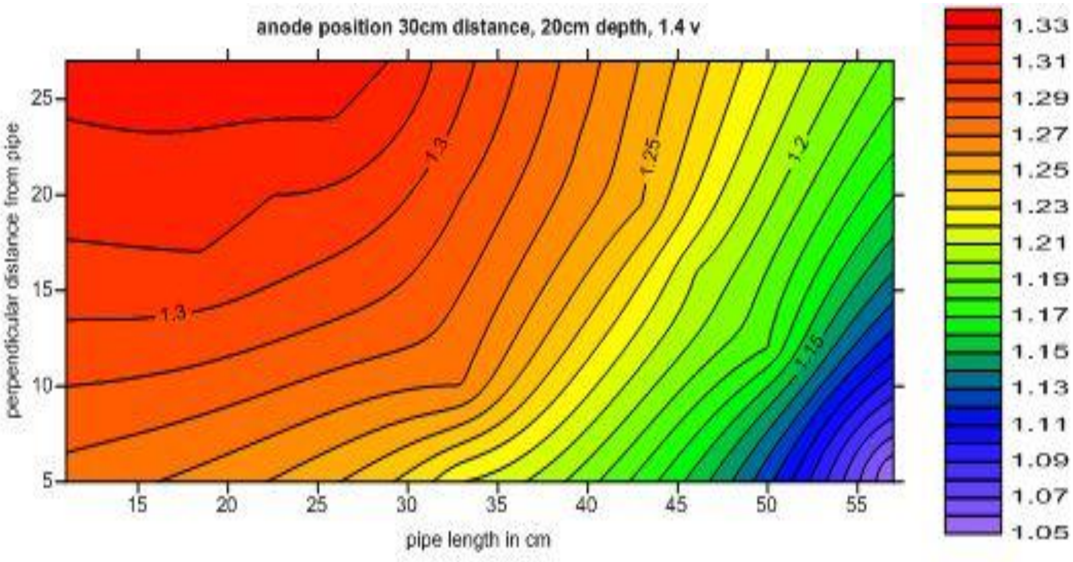

Figure 4-26 Potential contours for anode position 30 cm distance and 20 cm depth from uncoated pipe buried in moisture soil.

Figure 4-25 and 4-26 show that as the anode depth increase the potential range increase.

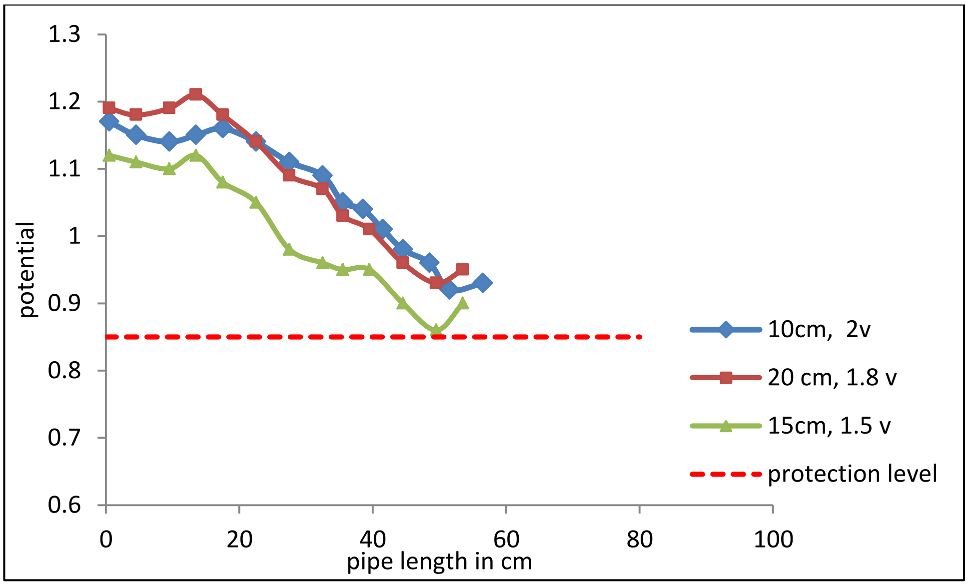

Figure 4-27 The difference of the voltage for the anode position at the same distance of 20 cm away from uncoated pipe buried in moisture soil and different depth.

Figure 4-27 shows that the depth of anode has no effect on the protection level for anode distance 20 cm from uncoated pipe buried in moisture soil.

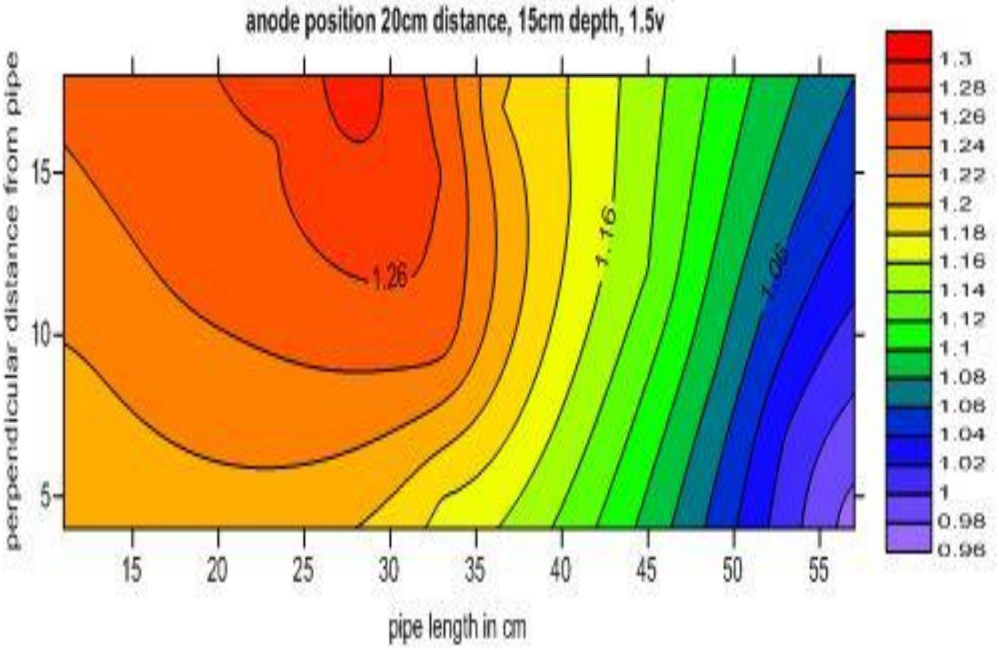

Figure 4-28 Potential contours for anode position 20 cm distance and 15 cm depth from uncoated pipe buried in moisture soil.

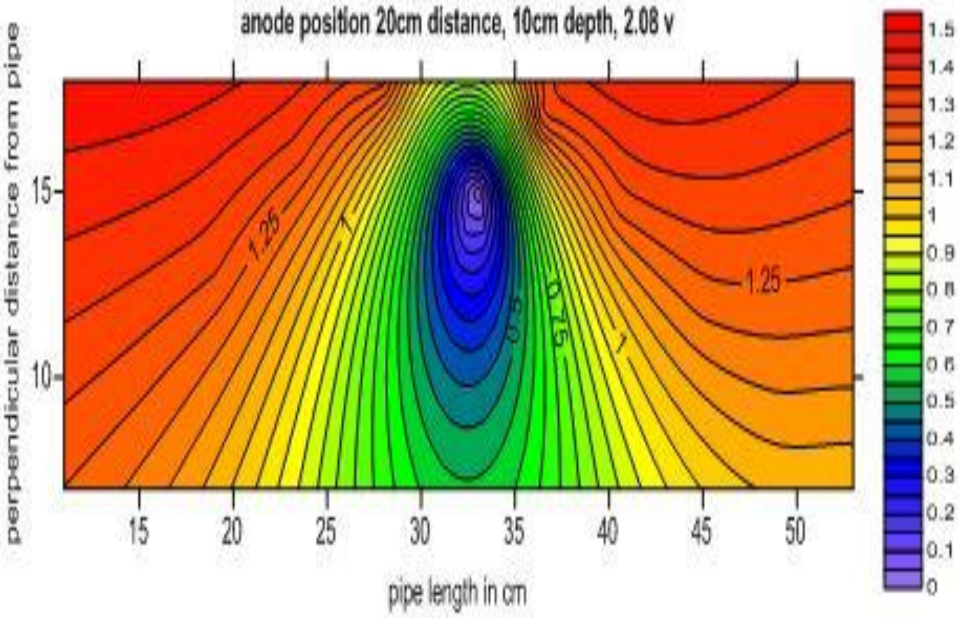

Figure 4-29 Potential contours for anode position 20 cm distance and10 cm depth from uncoated pipe buried in moisture soil.

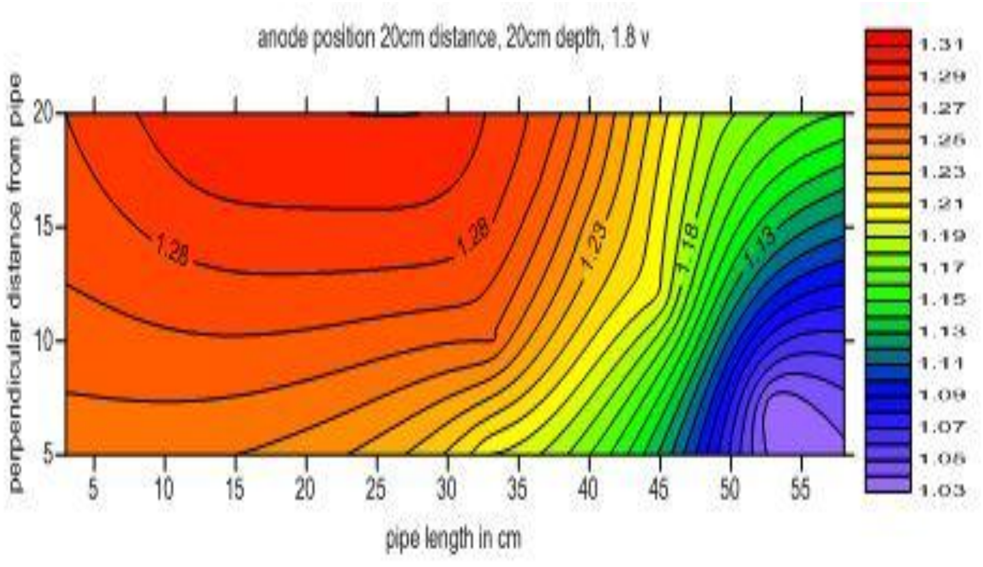

Figure 4-30 Potential contours for anode position 20 cm distance and 20 cm depth from uncoated pipe buried in moisture soil.

Figure 4-28 and 4-30 show that as the anode depth increase the potential range increase; and figure 4-29 show that as the pipe was at the same level of the anode the current distribution was not uniform to protect the pipe.

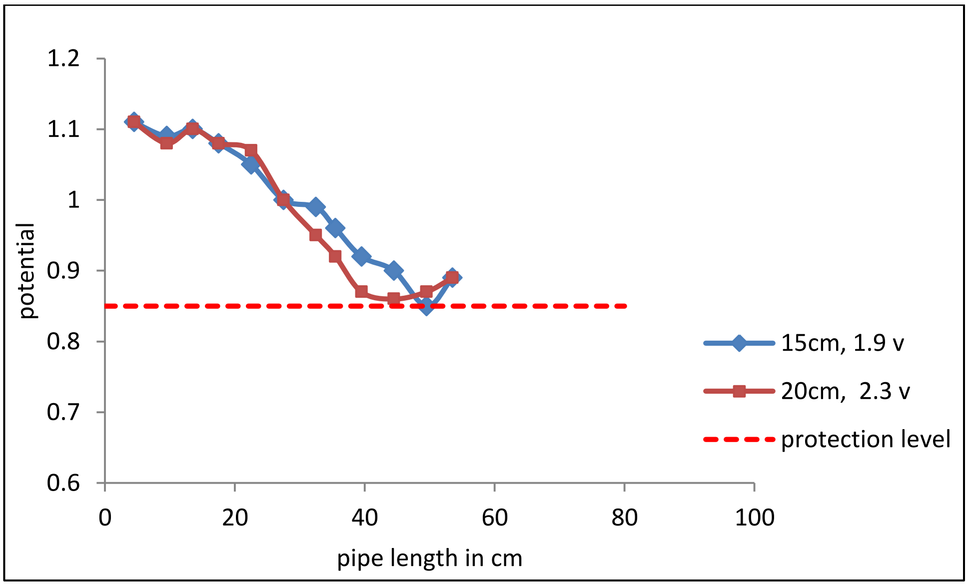

Figure 4-31 The difference of the voltage for the anode position at the same distance of 10 cm distance from uncoated pipe buried in moisture soil at different depth.

The best depth of anode was 15 cm for 10 cm distance from uncoated pipe buried in moisture soil this is shown in fig. 4-31; this is obvious in the applied voltage (low cost).

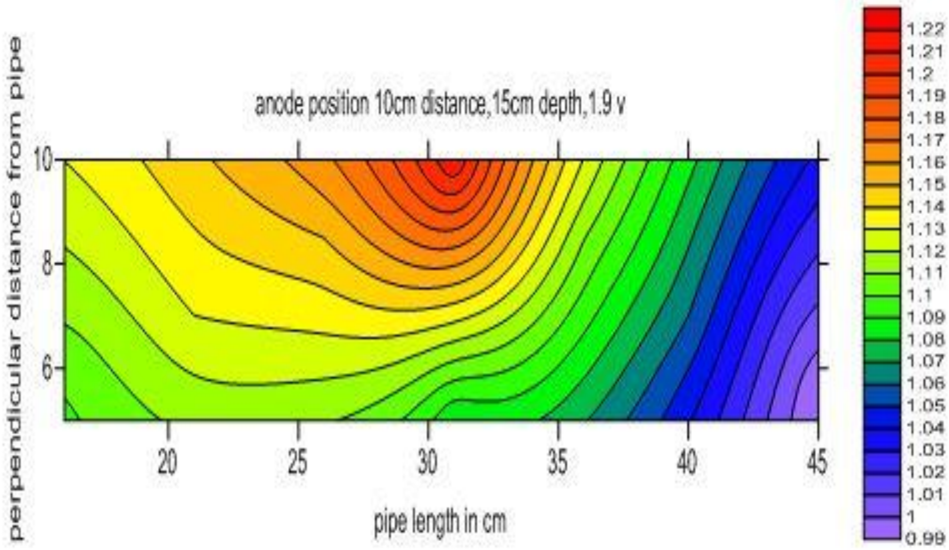

Figure 4-32 Potential contours for anode position 10 cm distance at 15 cm depth from uncoated pipe buried in moisture soil.

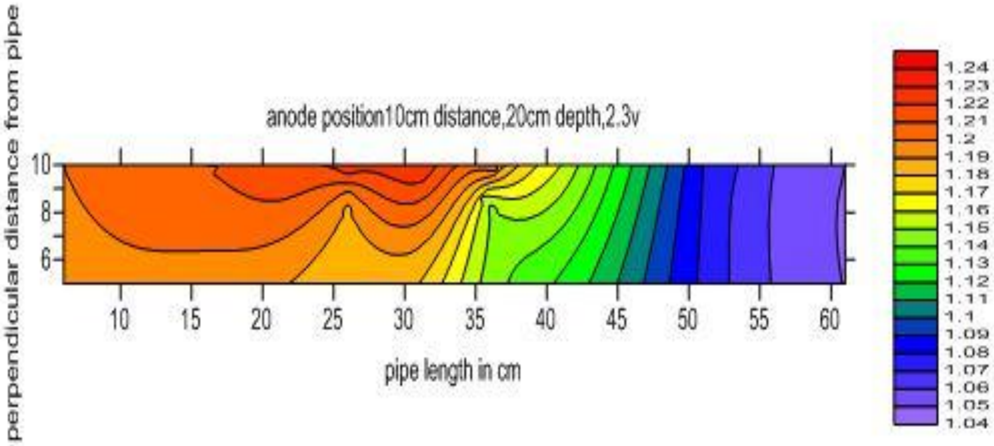

Figure 4-33 Potential contours for anode position 10cm distance and depth of 20cm from uncoated pipe buried in moisture soil.

Figure 4-32 and 4-33 show that as the anode depth increase the potential range increase.

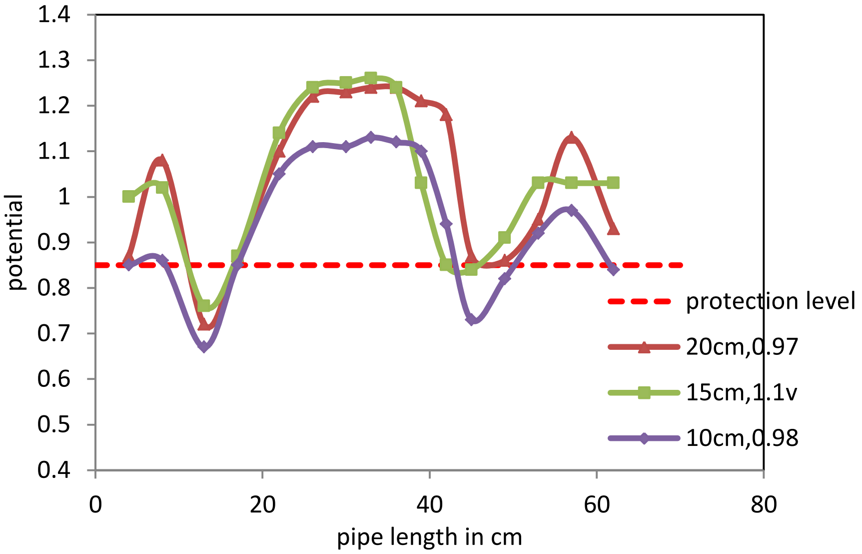

Figure 4-34 The effect of anode depth for the same distance 30 cm from coated pipe buried in moisture soil.

Figure 4-34 revealed that the anode depth has no effect on the protection level when the anode was at 30 cm distance from coated pipe buried in moisture soil.

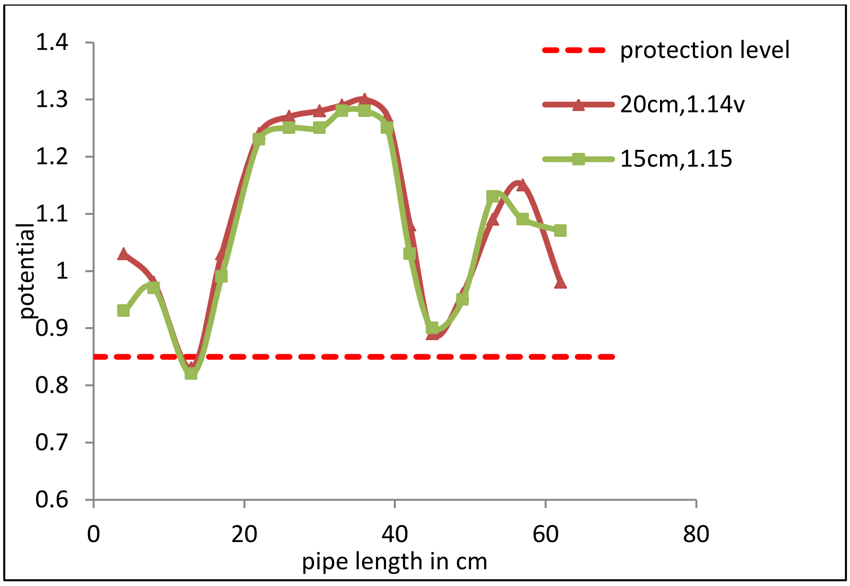

Figure 4-35 The effect of anode depth for the same distance 20 cm from coated pipe buried in moisture soil.

Figure 4-35 revealed that the anode depth has no effect on the protection level when the anode was at 20 cm distance from coated pipe buried in moisture soil.

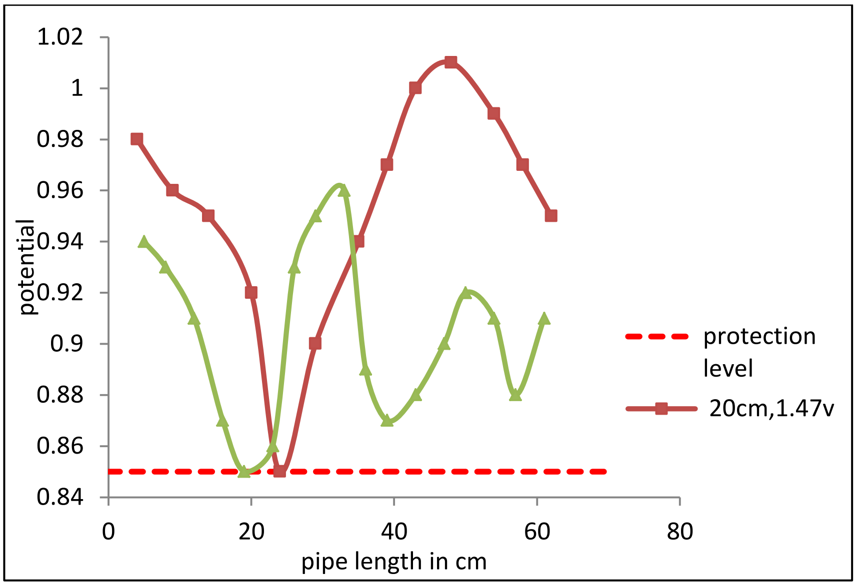

Figure 4-36 Effect of the depth of anode for the same distance 30 cm from coated pipe buried in dry soil.

Figure 4-36 illustrated that the best depth for anode was 20 cm for 30 cm distance from coated pipe buried in dry soil. If the anode is buried very deep then extends to a zone where there are so many resistances in parallel that there are an infinite number of resistances and therefore infinite conductance.

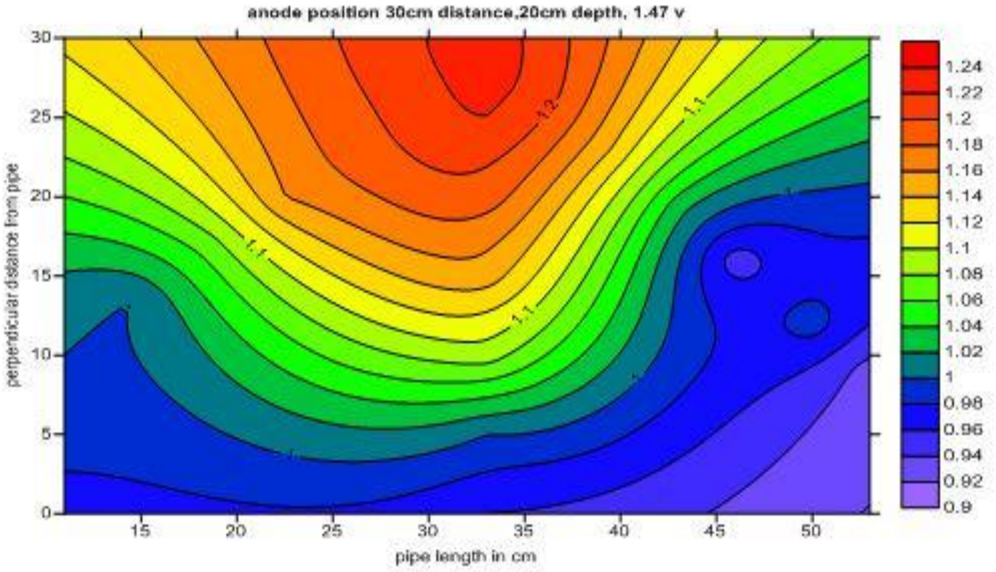

Figure 4-37 Potential contours for anode position 30 cm distance and 20 cm depth from coated pipe buried in dry soil.

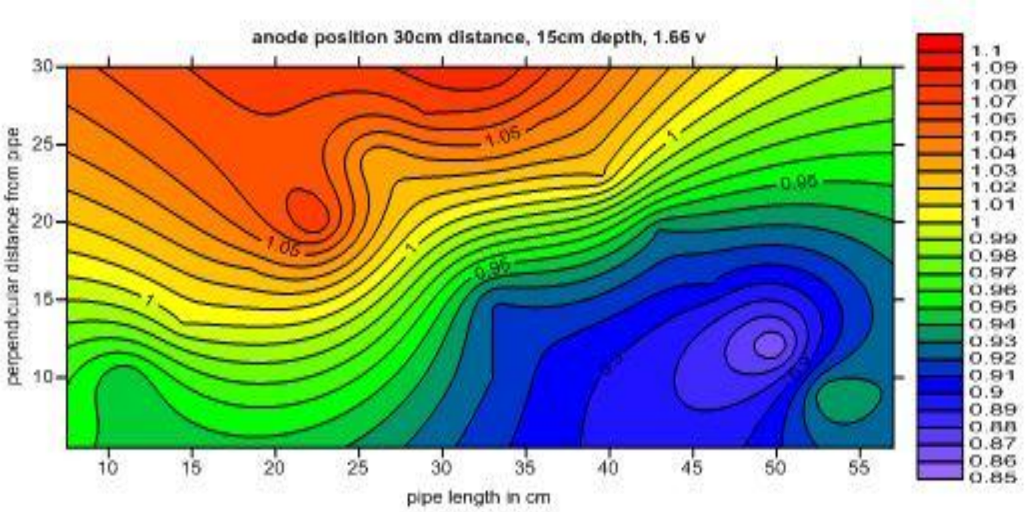

Figure 4-38 Potential contours for anode position 30 cm distance and 15 cm depth from coated pipe buried in dry soil

Figure 4-37 and 4-38 show that as the anode depth increase the potential range increase.

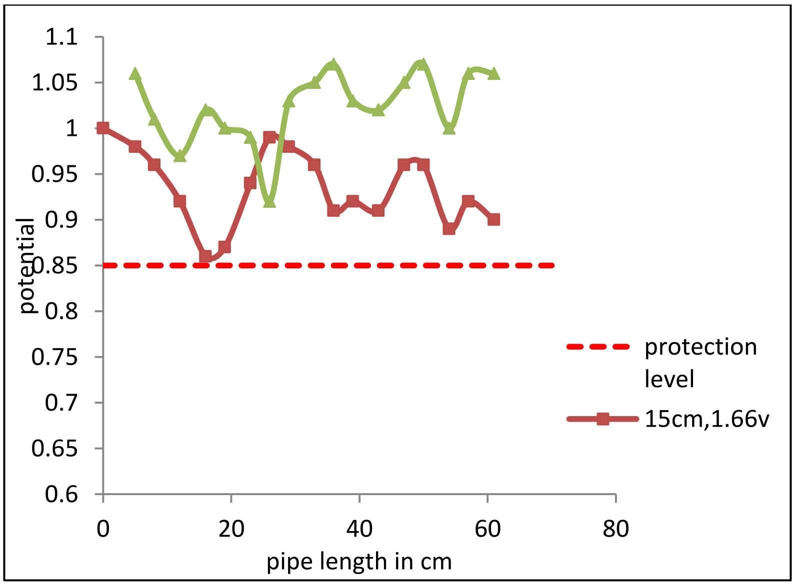

Figure 4-39 The effect of the depth of anode for the same distance 20 cm from coated pipe buried in dry soil.

Figure 4-39 shows that at anode position 20 cm no significant change in the protection level for different anode distances from coated pipe buried in dry soil.

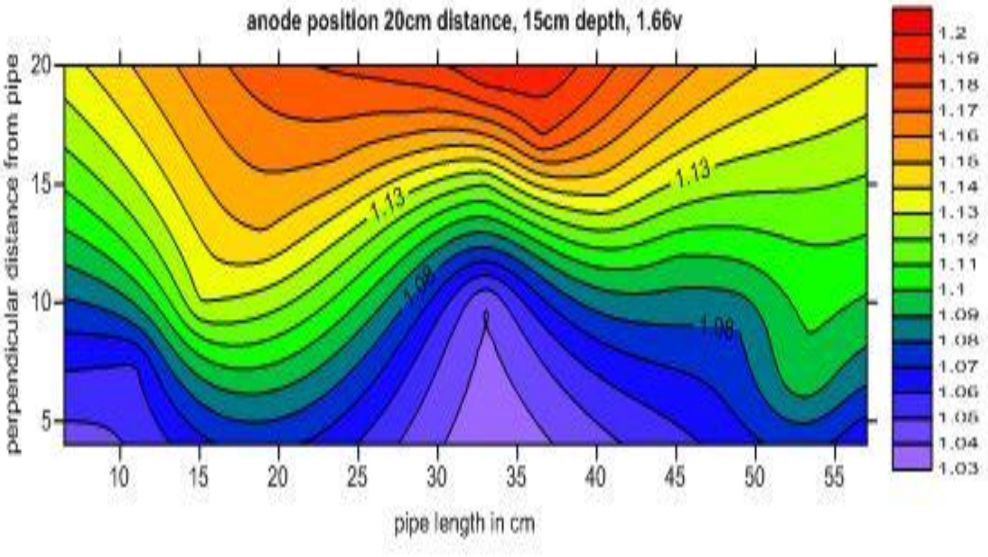

Figure 4-40 Potential contours for anode position 20 cm away and 15 cm depth from coated pipe buried in dry soil.

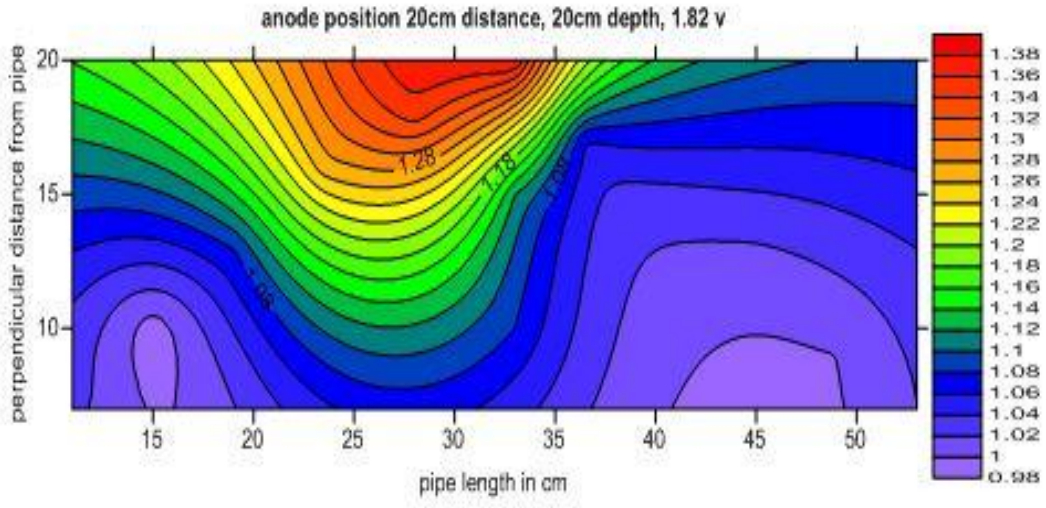

Figure 4-41 Potential contours for anode position 20 cm away and 20 cm depth from coated pipe buried in dry soil.

Figure 4-40 and 4-41 show that as the anode depth increase the potential range increase.

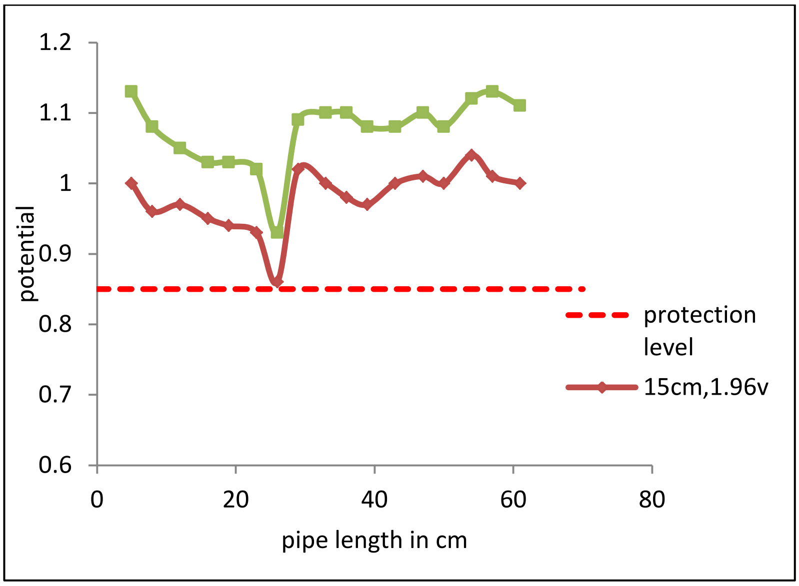

Figure 4-42 The effect of the depth of anode for the same distance 10 cm from coated pipe buried in dry soil

There is no significant change in protection level for anode position for 10 cm distance from coated pipe buried in dry soil as shown in fig. 4-42.

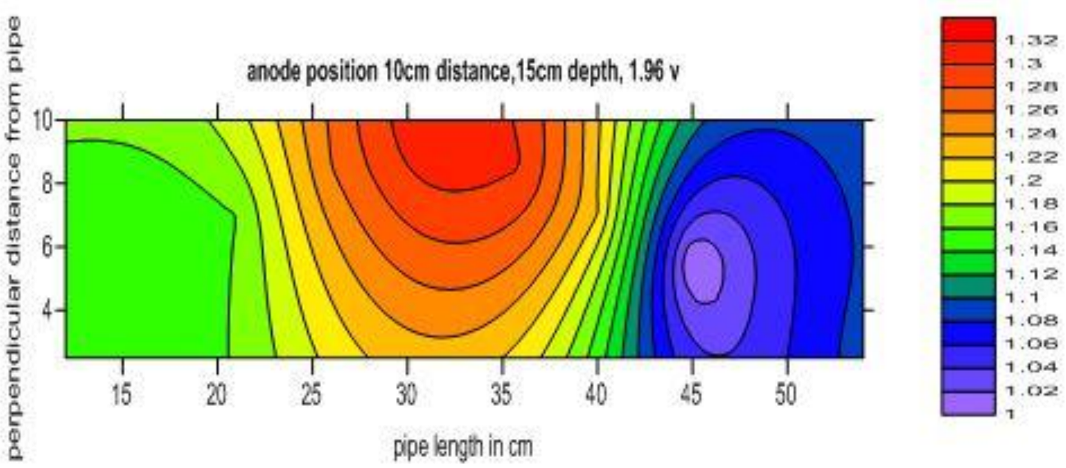

Figure 4-43 Potential contours for anode position 10 cm away and depth of 15 cm from coated pipe buried in dry soil

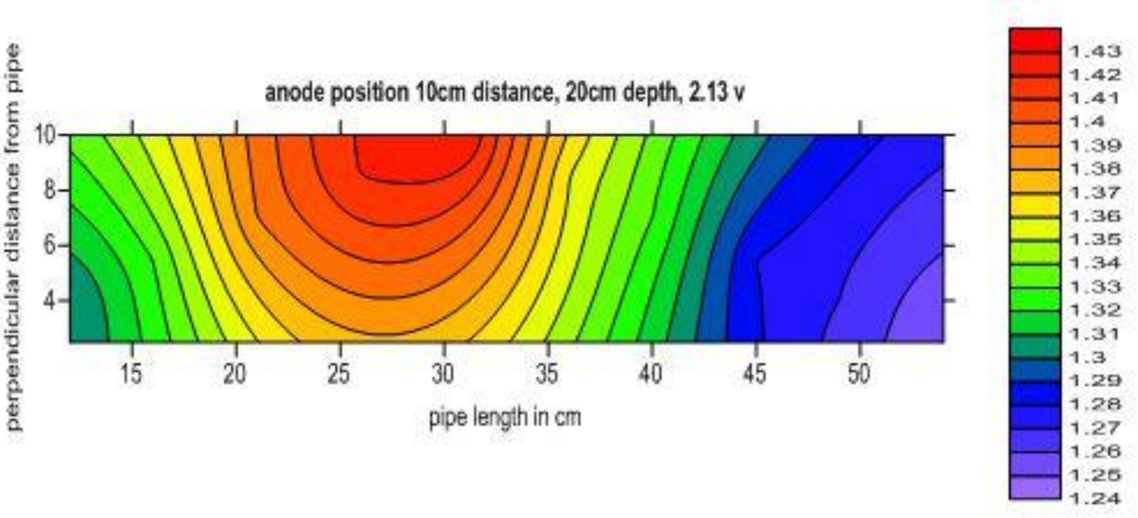

Figure 4-44 Potential contours for anode position 10 cm away and 20 cm depth from coated pipe buried in dry soil.

Figure 4-43 and 4-44 show that as the anode depth increase the potential range increase.

4.2.4Anode Distance:

As the distance between the anode and structure decrease the protection increase in such a way not to reach over protection degree, this is governed by the current distribution that influenced by the soil resistivity of the soil, the pipe surface, and the resistance of the ground bed. Figure 4-56 through 4-71 show that effect. For coated and uncoated pipe the best distance from the pipe that result a better distribution for current was 30 cm from pipe.

A conclusion from the Anode contours figures that when a buried anode is connected to the positive terminal of DC source, the potential of the earth surrounding the anode raised, the magnitude of increase depending up on the distance from the anode [35]. The maximum increase is in the earth immediately adjacent to the anode and as the distance from the anode increase the potential decrease [30]. The pipe is most polarized immediate to the anodes; and potential attenuates with increasing distance therefrom. Four factors affect the magnitude of this potential attenuation, as listed below [65]:

- Anode resistance. This resistance is encountered as current leaves the anode and enters the electrolyte. It is a consequence of the geometrical confinement in the vicinity of the anode. Accordingly, attenuation from this cause is greatest immediate to the anode and decreases with increasing distance. Anode resistance is higher the greater the electrolyte resistivity and the smaller the anode.
- Coating resistance
- Metallic resistance. Although resistivity of steel is orders of magnitude less than that of sea water, the confined pipeline cross section combined with the relatively long distance that current may have to travel in returning to electrical ground results in this term being influential.

Because of the high soil resistivity, the loss of current will be restricted. However, the corrosion risk at such an undetected defect will be reduced since the corrosion current would also be restricted by the high soil resistivity.

With increasing distance between pipe and anode for different environment resistivities, too close separation distance results in poor distribution Hafiz, M. H. [49]. The region of the protected pipe is increased with increasing distance between cathode (pipe) and anode. That is because increasing the distance between anode and cathode increase the distribution of current density on the pipe, so i.e increasing the protective surface area of the pipe (cathode).

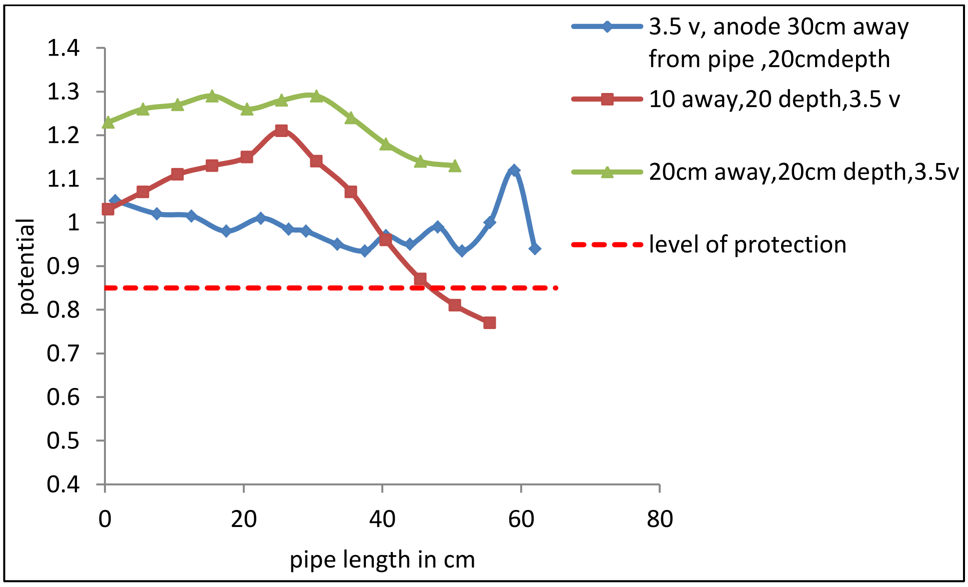

Figure 4-45 The effect of anode distance at depth of 20 cm from uncoated pipe buried in dry soil

Figure 4-45shows that the 20 cm distance from the uncoated pipe buried in dry soil gives the best protection level than the other positions for the 20 cm depth.

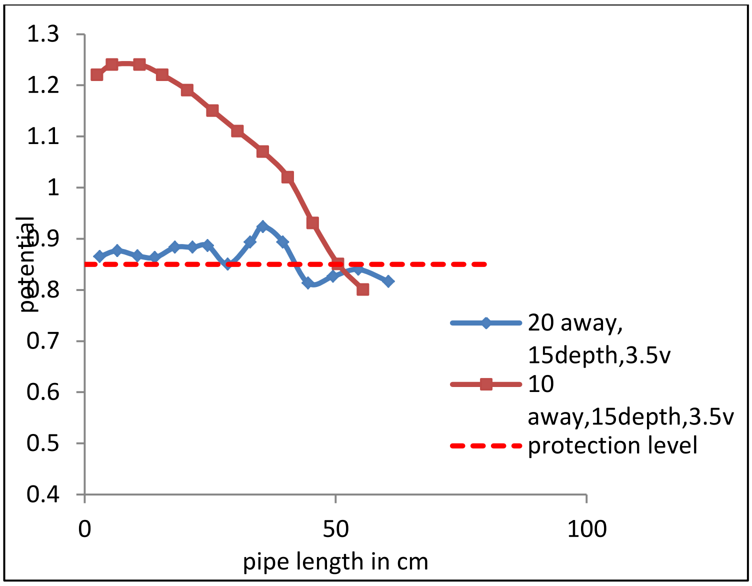

Figure 4-46 The effect of anode distance at a depth of 15 cm from uncoated pipe buried dry soil

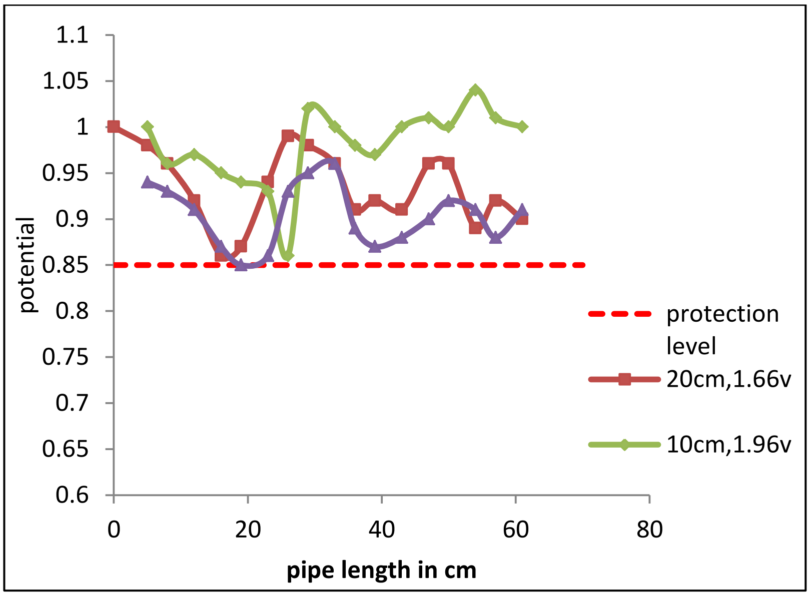

Figure 4-47 The effect of the anode distance at depth 15 cm from the coated pipe buried in dry soil.

Figure 4-47 revealed that the distance of the anode from coated pipe buried in dry soil has no effect on the protection level at a depth of 15 cm.

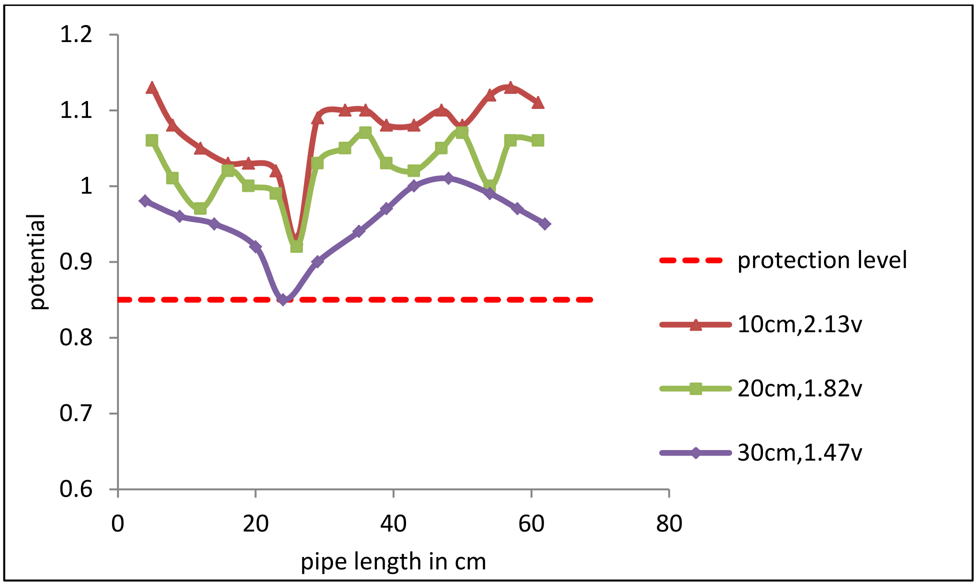

Figure 4-48 The effect of the anode distance at depth 20 cm from the coated pipe buried in dry soil

Figure 4-48 revealed that the distance of the anode from coated pipe buried in dry soil has no effect on the protection level at a depth of 20 cm.

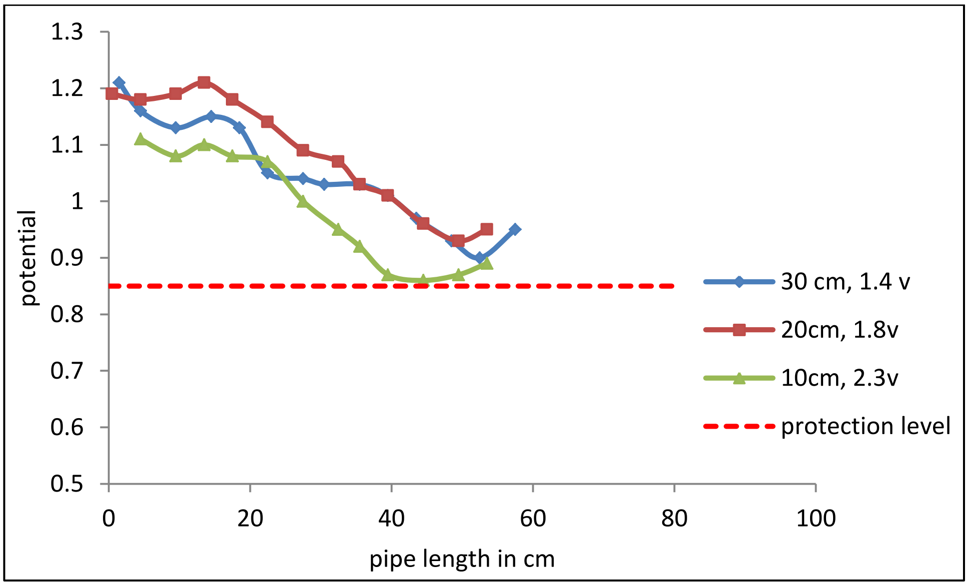

Figure 4-49 The effect of the distance of anode at depth of 20 cm from uncoated pipe buried in moisture soil.

The best distance for anode from the uncoated pipe buried in moisture soil was 30 cm at 20 cm depth because it needed the lowest value of the applied voltage (low cost).

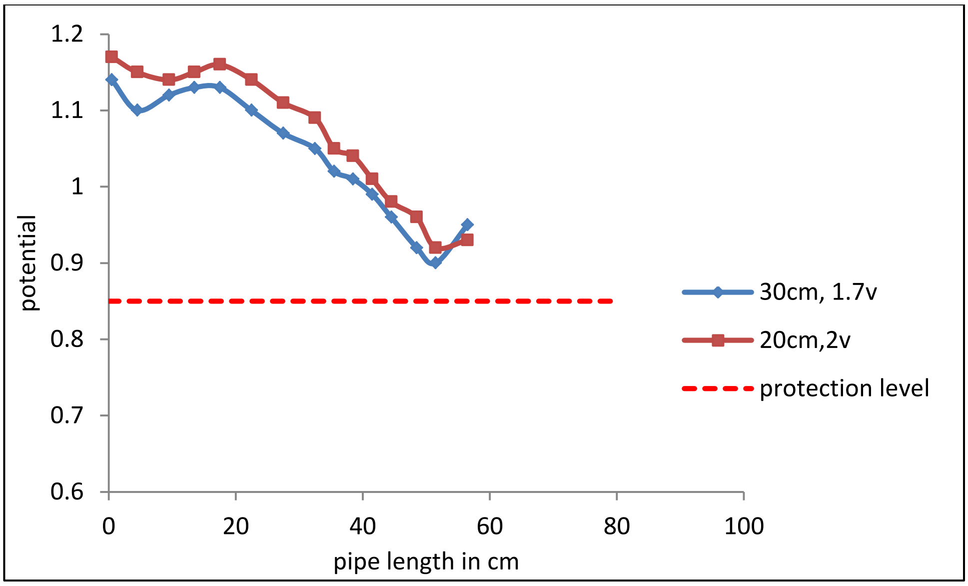

Figure 4-50 The effect of the distance of anode at depth of 10 cm from uncoated pipe buried in moisture soil.

No significant change in the protection level for the anode position is found at 10 cm depth when changing the distance of anode from uncoated pipe buried in moisture soil as shown in fig. 4-50.

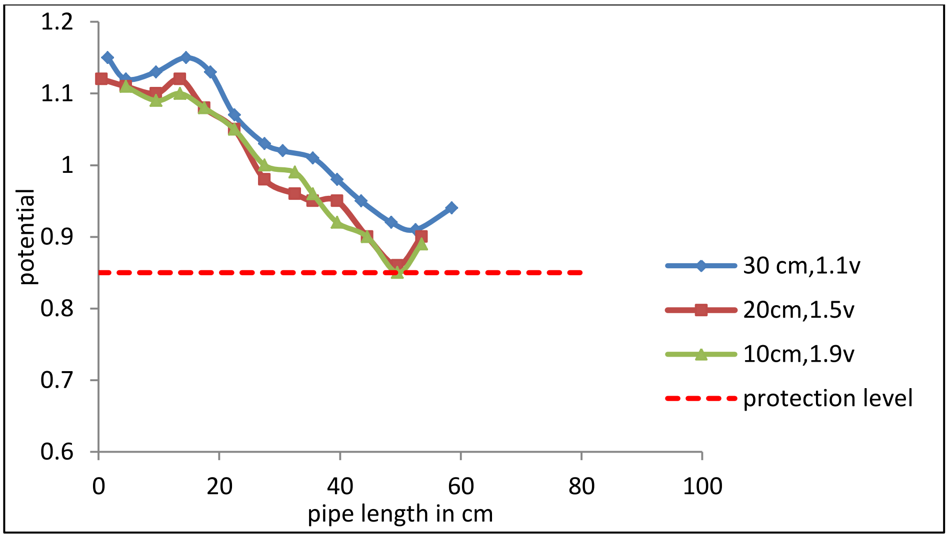

Figure 4-51 The effect of the distance of anode at depth of 15 cm from the uncoated pipe buried in moisture soil.

Figures 4-51 illustrates that the distance of the anode from the uncoated pipe buried in moisture soil has no change in protection level at 15cm depth .

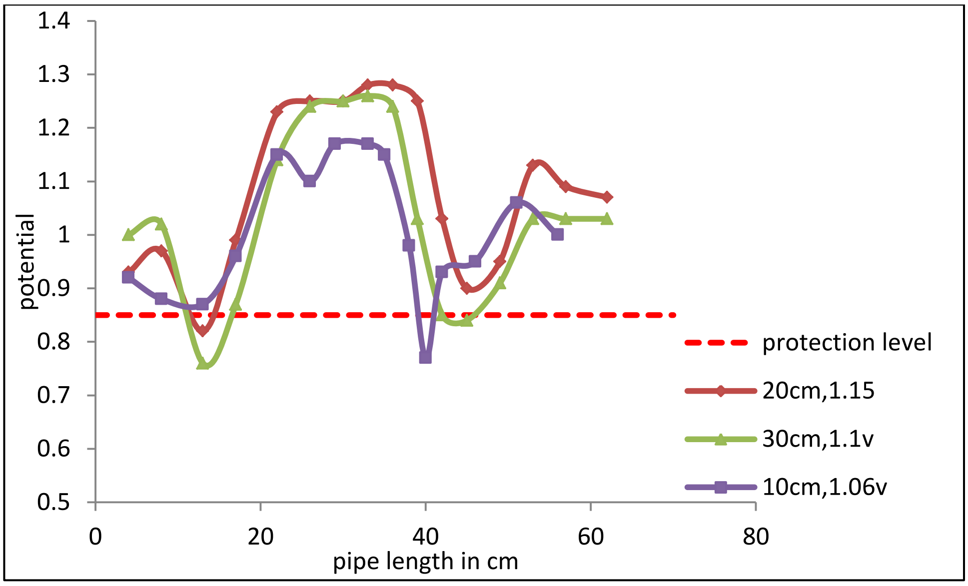

Figure 4-52 The effect of anode distance at depth of 15 cm from coated pipe buried in moisture soil

Figure 4-52 shows that the distance of anode from coated pipe buried in moisture soil has no effect on the protection level at 15 cm depth.

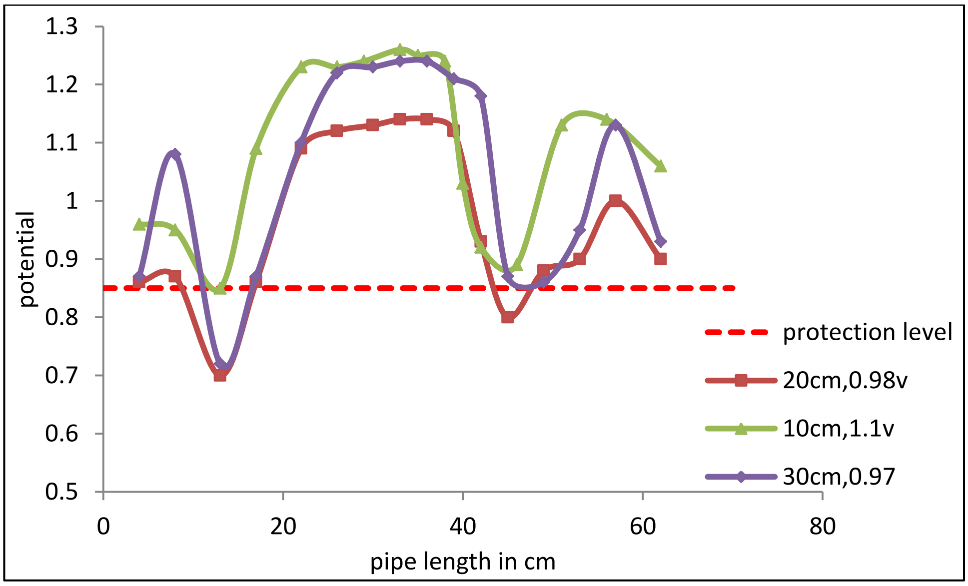

Figure 4-53 The effect of distance soil at depth of 20 cm from coated pipe buried in moisture

It is clear that there is no significant change in the protection level for the anode position at 20 cm depth when changing the distance of anodes from coated pipe buried in moisture soil.

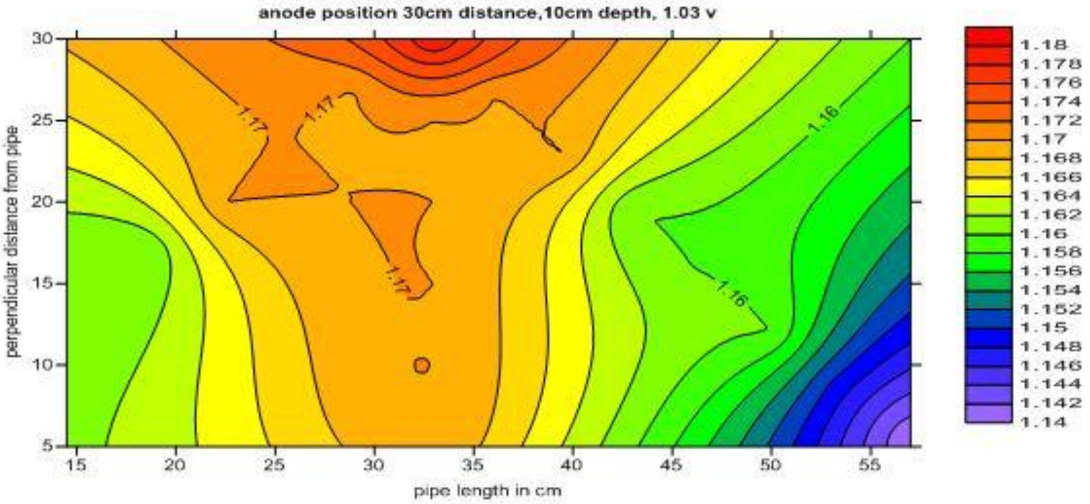

Figure 4-54 Potential contours for the anode position 30 cm distance at depth of 10 cm from coated pipe buried in moisture soil.

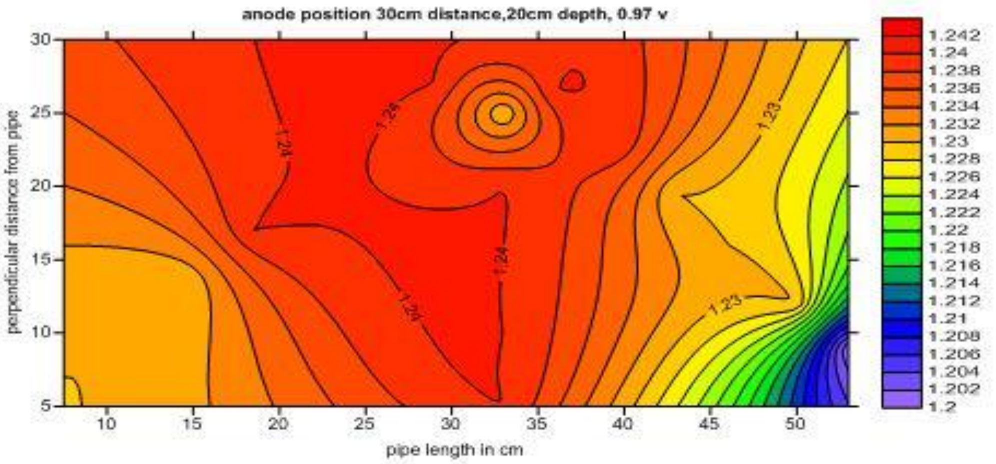

Figure 4-55 Potential contours for the anode position 30 cm distance at depth of 20 cm from coated pipe buried in moisture soil.

Figure 4-54 and 4-55 show that as the anode depth increase the potential range increase.

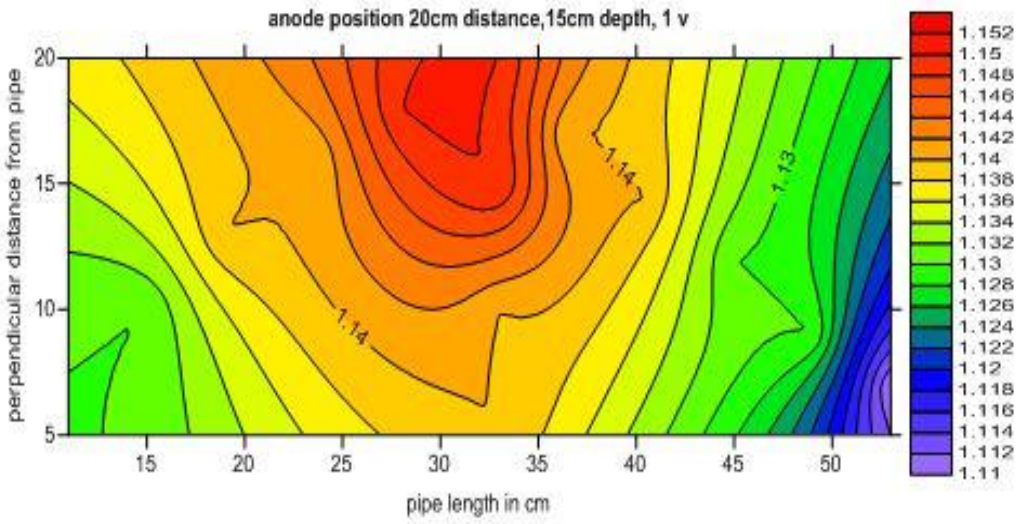

Figure 4-56 Potential contours for the anode position 20 cm distance at depth of 15 cm from coated pipe buried in moisture soil.

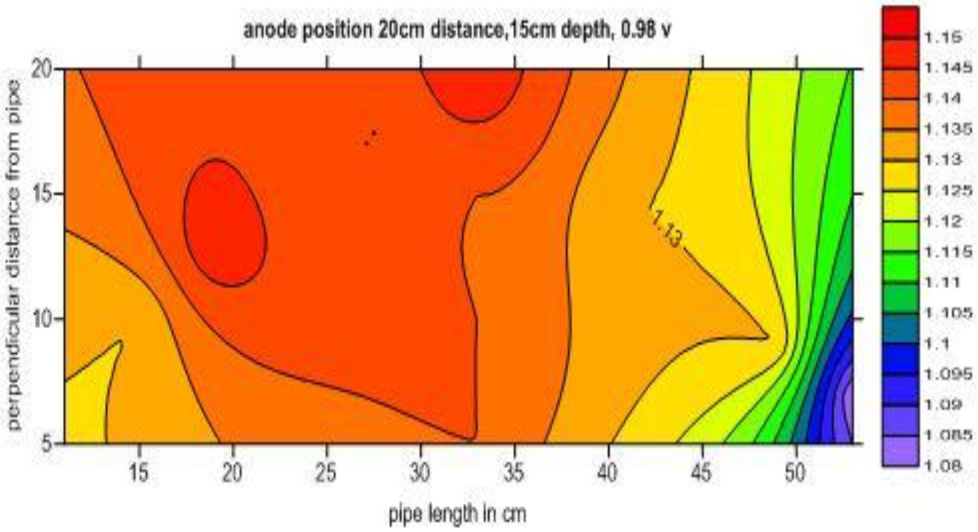

Figure 4-57 Potential contours for the anode position 20 cm distance at depth of 15 cm from coated pipe buried in moisture soil.

Figure 4-56 and 4-57 show that as the applied voltage increase the potential range increase.

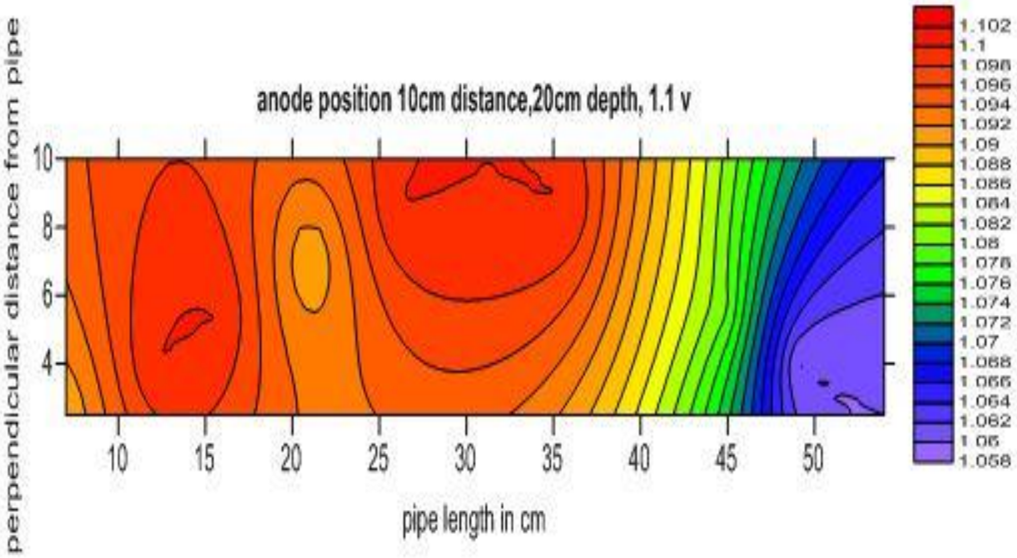

Figure 4-58 Potential contours for the anode position 10 cm distance at depth of 20 cm from coated pipe buried in moisture soil.

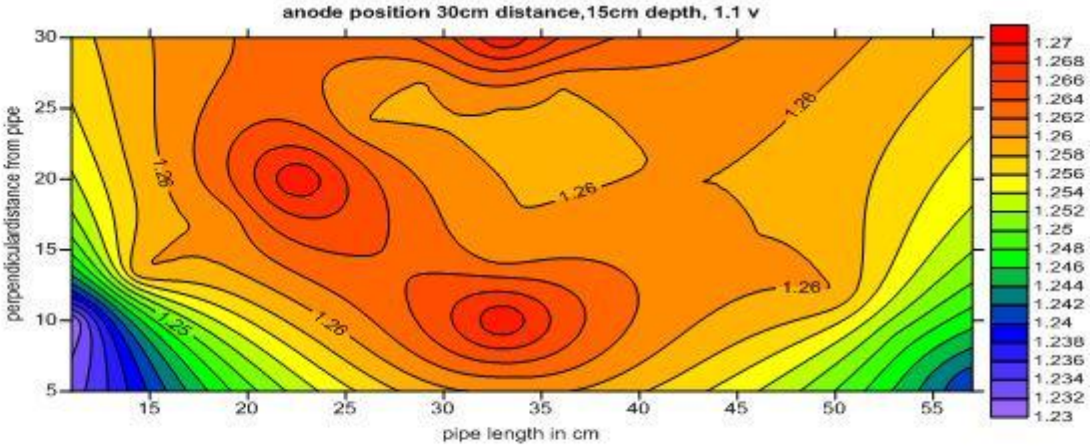

Figure 4-59 Potential contours for the anode position 30 cm distance at depth of 15 cm from coated pipe buried in moisture soil.

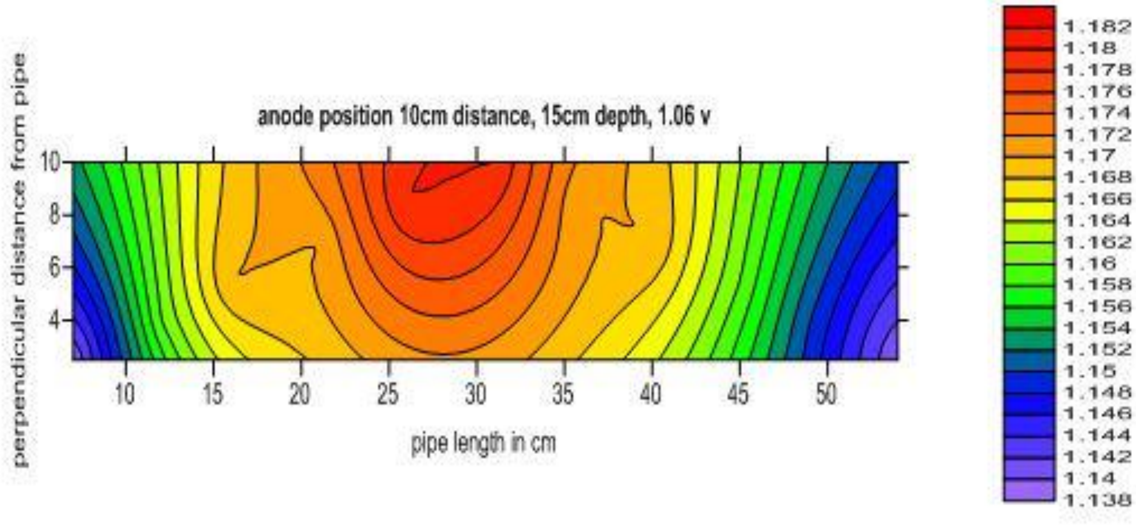

Figure 4-60 Potential contours for the anode position 10 cm distance at depth of 15 cm from coated pipe buried in moisture soil.

From figure 4-59 and 4-60 it is clear that as the distance between the anode and the cathode increase the potential range increased. And from fig. 4-58 and fig. 4-60 it is clear that as the anode depth increase the potential increased.

It should be observed from these anode contours that the distribution of potential different from side to another we can see that as the distance from the anode increase the potential decrease and vice versa. This variation in potential is called the cone shape curve for the voltage distribution which is called the voltage cone of the anode bed. The height of the voltage cone depends on the anode voltage and its shape depends on the arrangement of the anode [66].

4.2.5 Applied Voltage: Uncoated Pipe

The effect of the applied voltage for the same anode position, figure 4-61 through 4-63 illustrated that as the applied voltage (rectifier voltage) increased the protection level increase, but caution must be taken into account so that the pipeline should not be over protected, because the following reasons:

- Coating damage according to hydrogen evolution
- Power wasting (cost factor).

When cathodic protection is applied to a coated line, there is an upper limit to the potential to which the pipe can be raised, in order to avoid damage to the coating and excessiveness over protection at the drain point. This is usually considered to be -2.5volts to a copper sulfate electrode.

This sets a limit to the amount of current which can be drained from a single point, a limit which depends on the pipe size, the completeness and effectiveness of the coating, and the electrical resistivity of the soil. When this maximum current is drained from a point, the pipe to soil potential is a maximum current at the drain point, and decreases exponentially along the pipe in both directions [67].

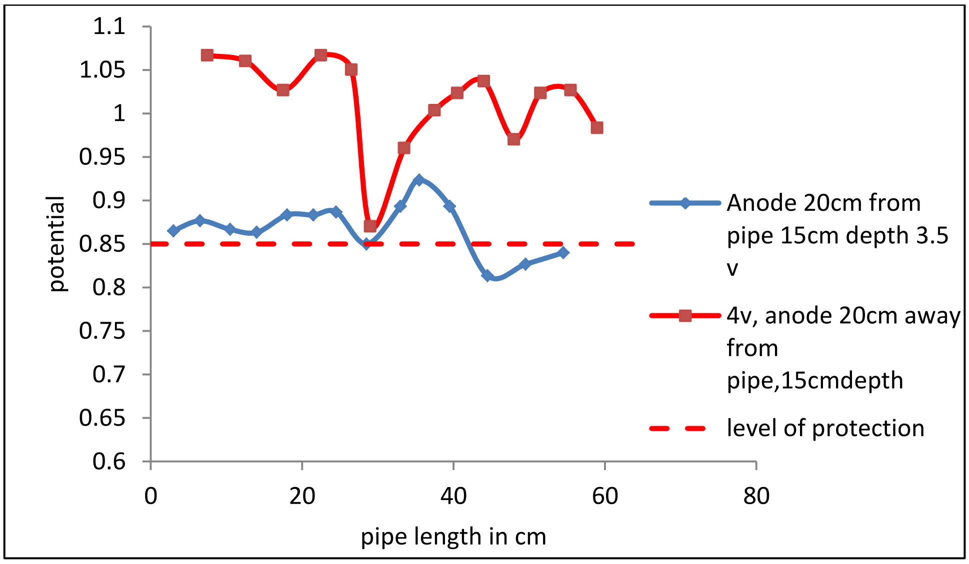

Figure 4-61 The applied voltage effect on cathodic protection for anode distance 20 cm distance and 15 cm depth from uncoated pipe.

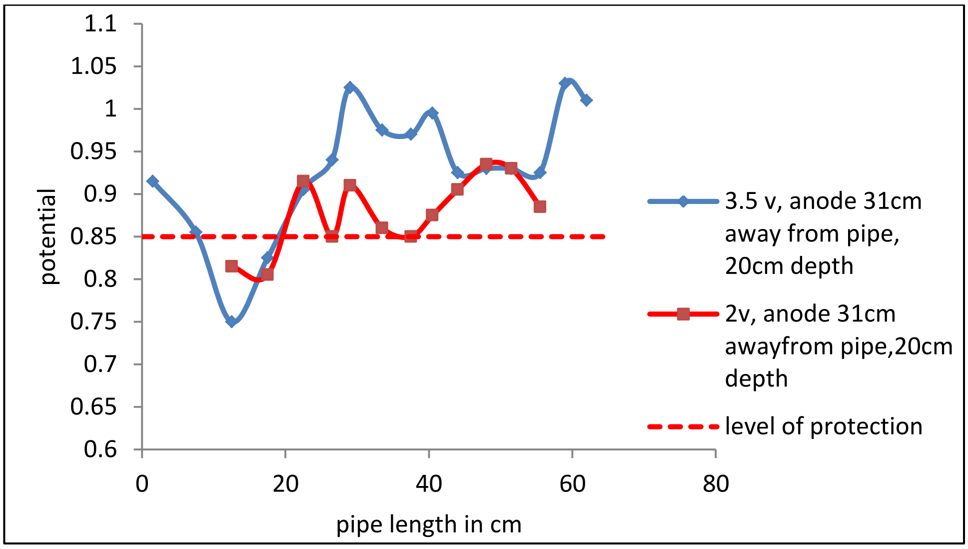

Figure 4-62 The applied voltage effect on cathodic protection for anode distance 30 cm distance and 20 cm depth from uncoated pipe

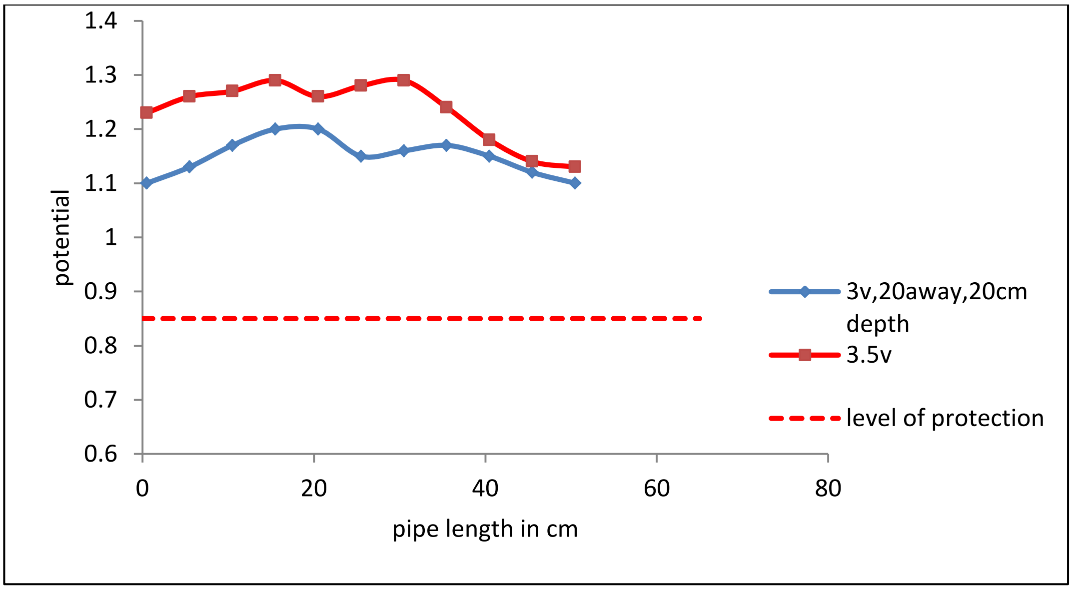

Figure 4-63 The effect of applied voltage for anode 20 cm distance and 20 cm depth from uncoated pipe.

1.2.6 Reference Electrode Position:

-850 mV criterion with CP applied, is probably the most widely used for determining if a buried or submerged steel or cast iron structure has attained an acceptable level of CP.

In the case of a buried steel or cast iron structure, an acceptable level of protection is achieved, based on this criterion, if the potential difference between the structure and a CSE contacting the soil directly above and as close as possible to the structure is equal to or more negative than (larger in absolute value) -850 mV. As described above, voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement. These voltage drops are a result of current flow in the electrolyte (soil) and are generally referred to as ohmic or IR voltage drops. IR voltage drops are more prevalent in the vicinity of an anode bed or in areas where stray currents are present and generally increase with increasing soil resistivity. For bare or very poorly coated structures, IR voltage drops can be reduced by placing the reference electrode as close as possible to the structure [6].

For the majority of coated structures, most of the IR voltage drop is across the coating, and the measurement is less affected by reference electrode placement.

Relocate the reference electrode; moving it around the voltage gradient near the pipe surface. As bring it closer to the surface the result is decreasing the IR drop error.

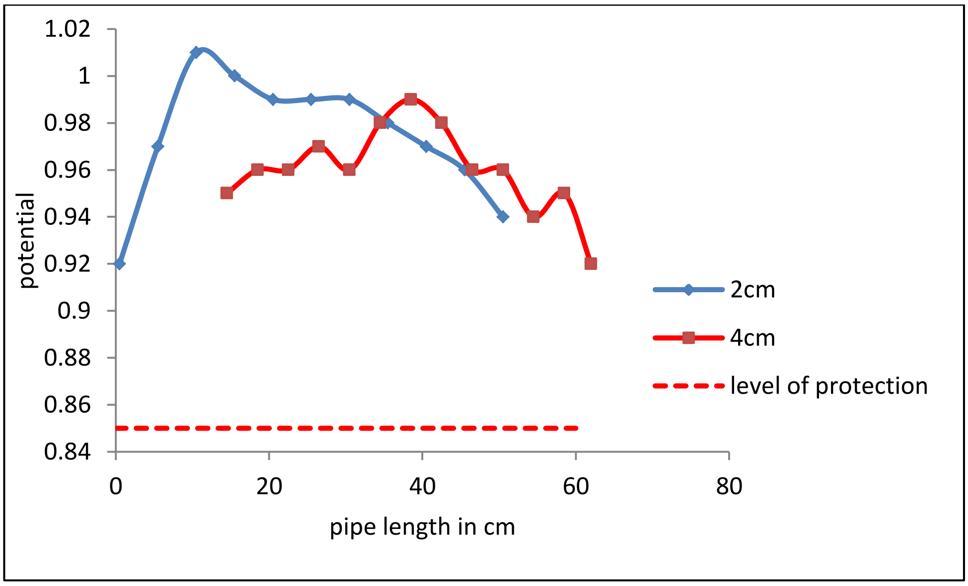

Figure 4-64 The effect of reference electrode position from uncoated pipe for 20 cm distance and 20 cm depth from uncoated pipe, 2.5v

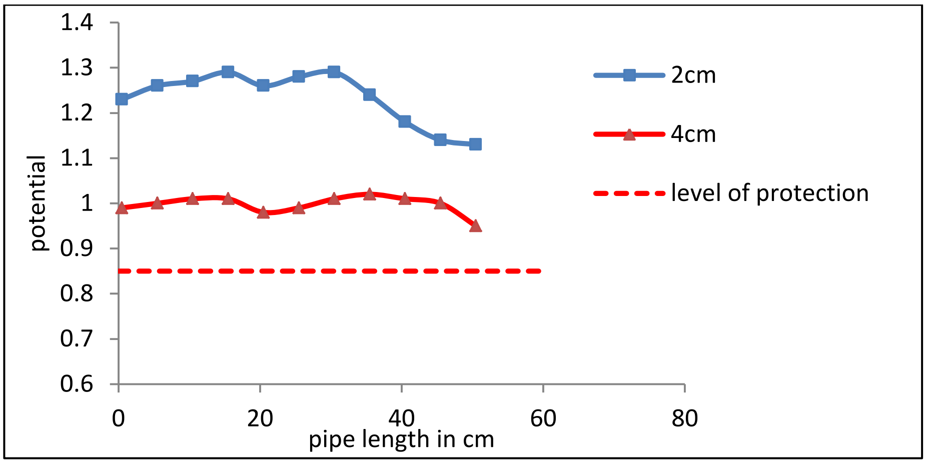

Figure 4-65 The effect of reference electrode position from pipe for 20 cm distance and 20 cm depth from uncoated pipe.3.5 v

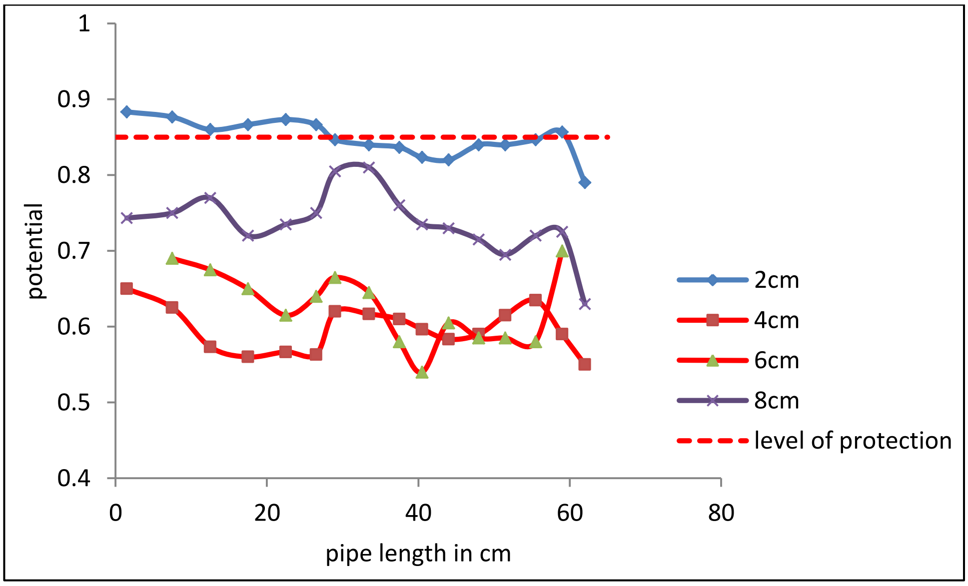

Figure 4-66 The effect of reference electrode position from uncoated pipe for 30 cm distance and 10 cm depth from uncoated pipe, 3.5v.

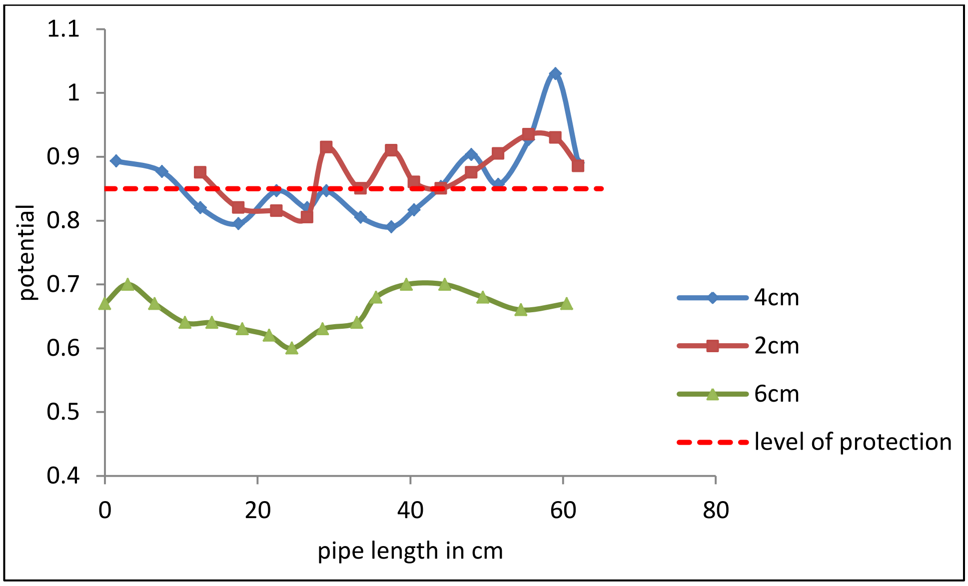

Figure 4-67 The effect of reference electrode position from uncoated pipe for 30 cm distance and 20 cm depth from uncoated pipe, 2v.

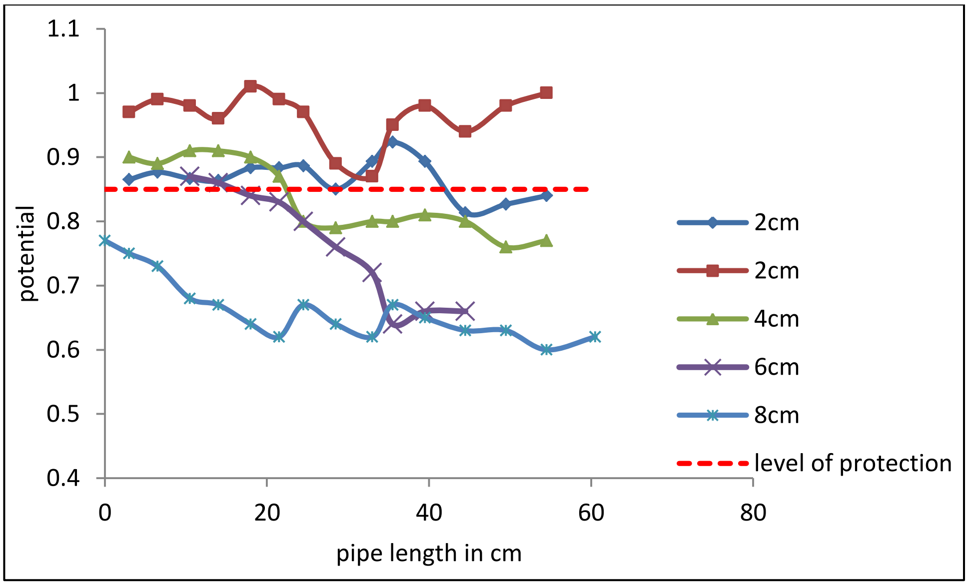

Figure 4-68 The effect of reference electrode position from uncoated pipe for 20 cm distance and 15 cm depth from uncoated pipe, 3.5v

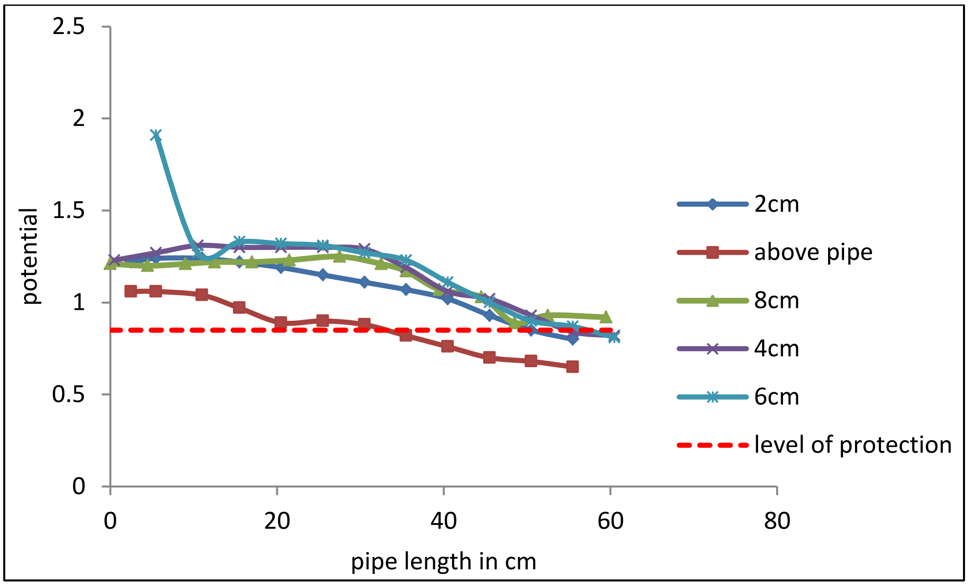

Figure 4-69 The effect of reference electrode position from uncoated pipe for 10 cm distance and 15 cm depth from uncoated pipe, 3.5v

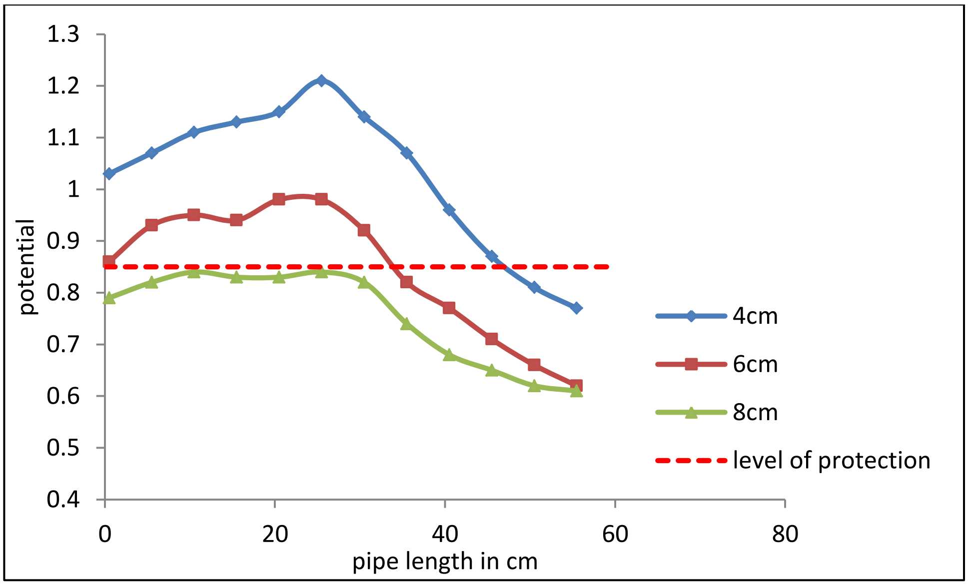

Figure 4-70 The effect of reference electrode position from uncoated pipe for 10 cm distance and 20 cm depth from uncoated pipe, 3.5v

There are different methods for the location of reference electrode to find the pipe to soil potential, each method interested with the same thing that the other method interested with; to find the actual potential of the pipe that can be reach by decreasing the IR drop of this potential. It is obvious that all of the factors affecting the cathodic protection design are governed by the potential of the pipe versus the reference electrode. Figure 4-64 through 4-70 show the effect of the electrode position from the protected structure (pipe) as this distance decrease the potential of pipe increase this is because of the IR drop as the result of the current distribution in the soil; concern on the position with no other current than the current pass through the coating should be occur protective current flowing from the soil to the structure to be protected causes potential gradients which depend on electrode location, soil resistance, the amount of current flow [27].In fully coated pipe near the pipe or remote it would not make any difference as the coating resistance makes up most of the resistance between the pipe and the soil[11]. The measurement of the potential procedure was moisture the soil before the contact with the reference electrode to decrease the circuit, and careful that the pipe do not reach this water. The location of the reference electrode becomes more important as the environment resistivity increase. Another group found that the smaller the anode the closer the reference electrode to the structure [38]. The Pipe to soil potential or long time potential measurement is the potential difference between the pipe and the standard reference electrode in electrical contact with the soil. A copper/copper sulfate electrode (CSE) is usually used as the reference electrode. The electrode is placed in contact with the soil directly over the pipeline, to read the potential relative to close soil [68].

In these contours it is clear that the distribution of the current around the anode is different from position to another.

In this test the current according the theoretical calculation was less than 10^{-6} A so a decision have been made to decrease the anode ground bed resistivity so as to increase the current discharge from anode and calculate the current through the experiment.

Once the pipe and anode were connected to the power supply, the cathode starts polarizing but this polarization is limited by the high resistivity of the soil. Therefore, the anode could not feed more current, and the maximum current discharged was less 1 mA.

The potential reading should be taken with the reference electrode contacting the electrolyte directly over the structure, to minimize Ohmic voltage drop errors in the measurement and to minimize the extent of averaging over large areas of the structure [19].

4.2.7 Wet Anode Ground Bed:

Adding water for the anode test shows a huge difference between the voltage need for adequate protection at 0.5 rather than the 3.5 V need for the first test because the difference in the anode resistance to earth. Figures 4-71 and 4-76 show the potential distribution for the pipe with moisture anode ground bed.

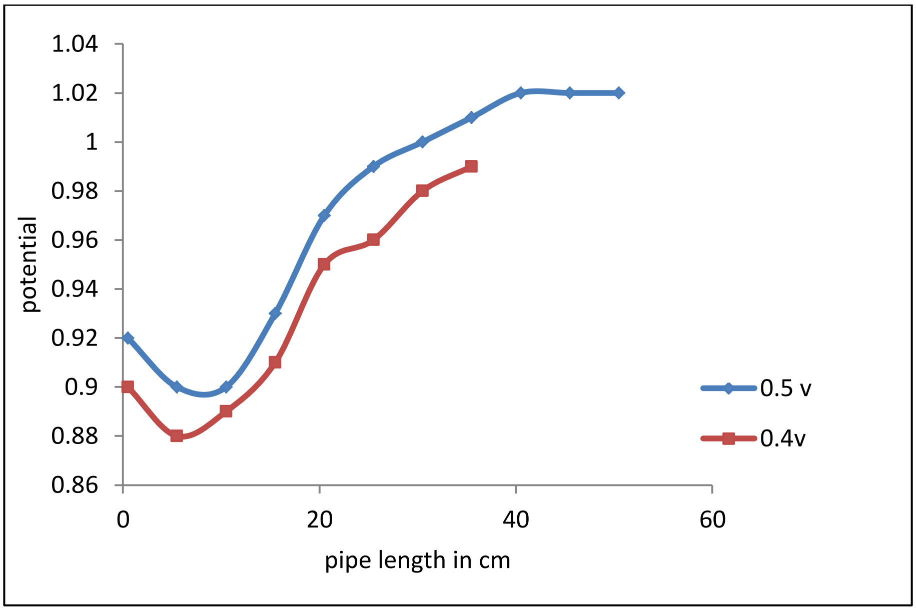

Figure 4-71 The effect of applied voltage on pipe potential for 30 cm away from uncoated pipe, 15 cm depth.

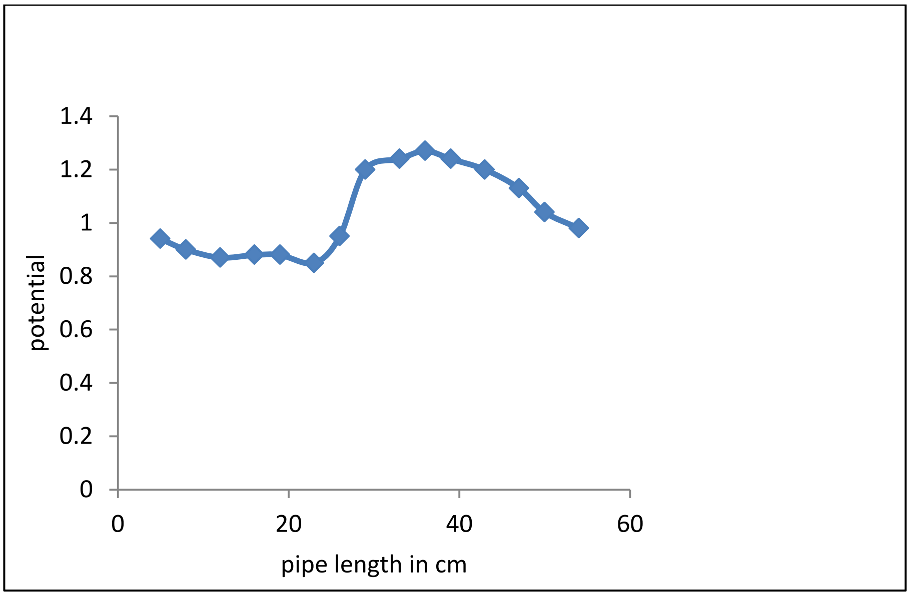

Figure 4-72 Potential of the pipe with wet anode ground bed for anode position 30 cm away from coated pipe and 10 cm depth.

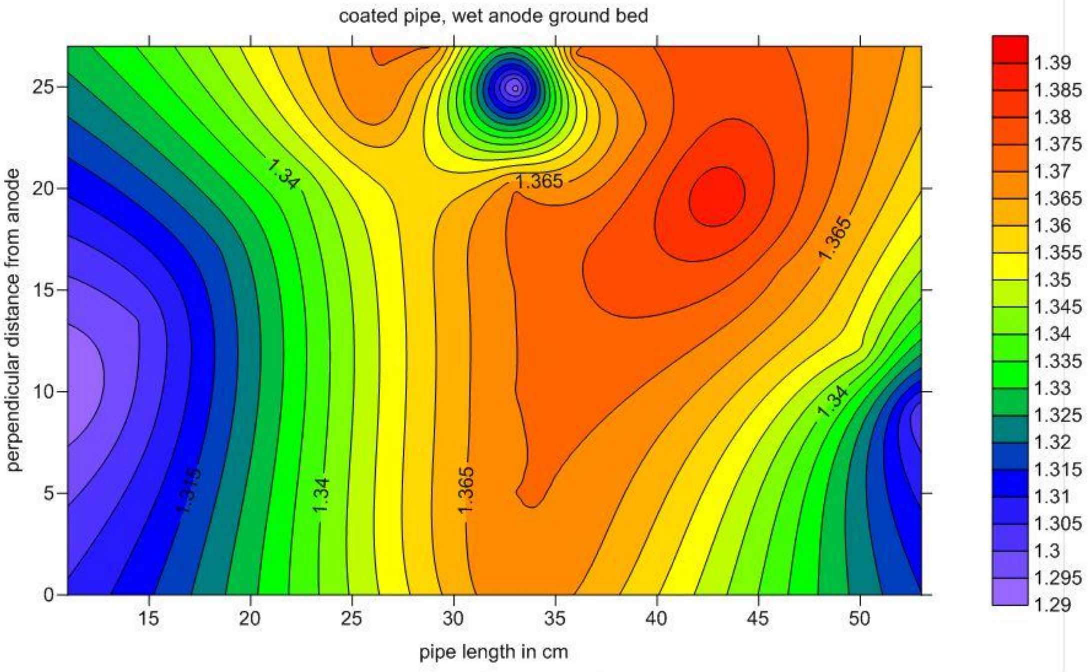

Figure 4-73 Potential contours for anode position 30 cm away from coated pipe and 10 cm depth.

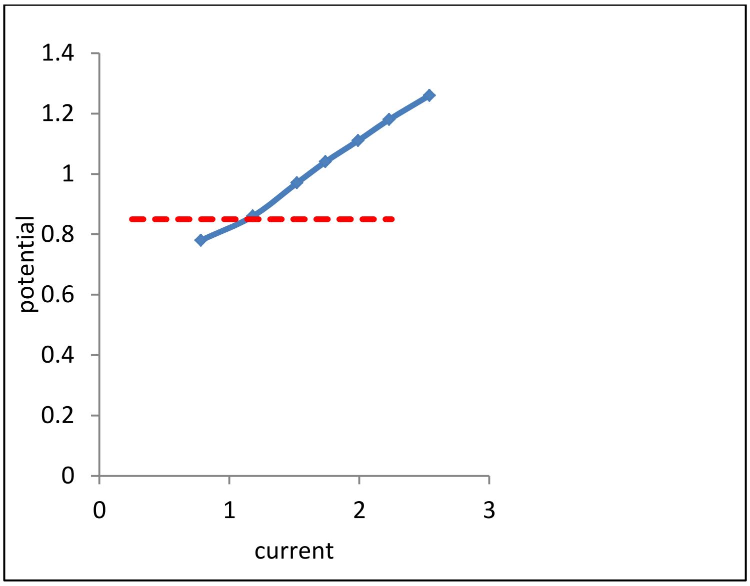

Figure 4-74 The potential along pipe versus current for anode 30 cm away from uncoated pipe, 15 cm depth, and 34.5 cm away from wall.

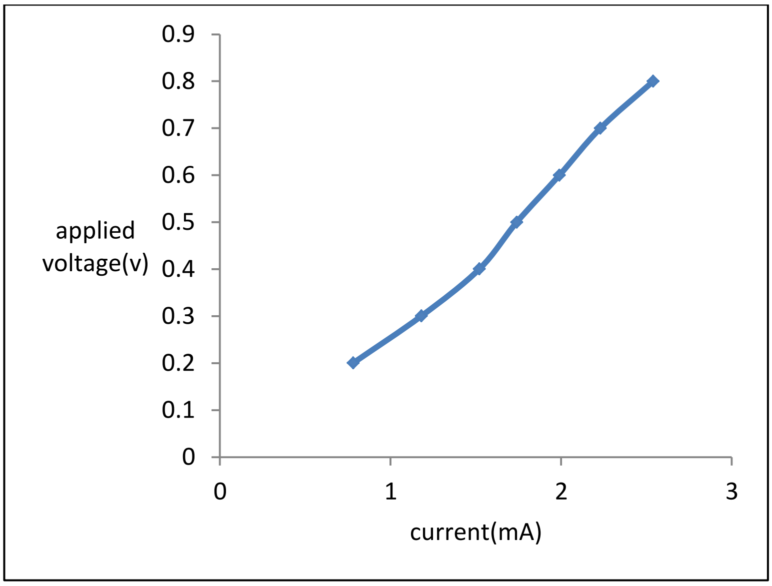

Figure 4-75 The potential along pipe versus current for anode 30 cm away from uncoated pipe, 15 cm depth, and 34.5 cm away from wall.

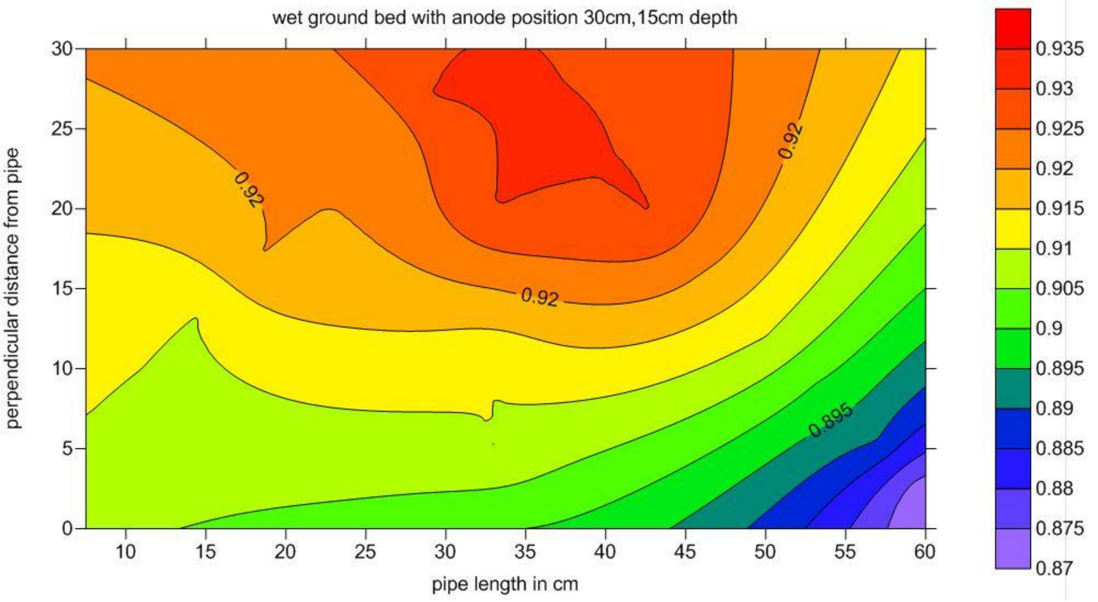

Figure 4-76 Potential contours for anode position 30 cm distance from uncoated pipe and 15 cm depth.

The maximum increases are in the earth immediately adjacent to the anode and as distance from the anode increases, the rise of earth potential decreases this change of earth potential in the area surrounding the anode is called the anode potential gradient [35]. The external circuit of this measurement is high, so a high input resistance voltmeter is required for accurate measurement [28].

If the current flow is too large, errors will be introduced owing to the voltage drop caused by the contact resistance between the reference electrode and the electrolyte. It is thus clear that the prime requirement of a potential measurement circuit is high resistance.

Once ground bed locations have been selected for either impressed current or galvanic anode systems and the effective soil resistivities for design purposes have been determined, the design process can proceed. Designs are reasonably simple when design charts are available, and many companies utilize such charts. These charts are typically based on the type of anode and construction to be employed. Determining effective soil resistivity is prerequisite to all decisions before designing the system. Because of all of the variables involved, it should be recognized that the design calculations for completed ground bed resistance may not be highly precise [9].

For instance, the lower in the soil resistivity means the higher in the current that will flow from the pipe into the soil. Soil resistivity which varies from station to another depending of the region desert or salty**.**

The charges follow the line of least resistance and will disperse according to the inverse square law of radiation through a homogenous ground condition; this appears in the anode contours. Areas of low resistivity will "attract" a higher current density, with current flowing preferentially along the path of least resistance [19].

Chapter Five

5.1 Conclusions

- In conclusion, it is believed that in design of an efficient anode system, the proper configuration should be selected, within the limitations of space and materials available. The previous statements of experiences and recommendations for establishing more efficient systems of cathodic protection.
- In practice, the current distribution in CP systems tends to be far removed from idealized uniform current profiles. It is the nature of electron current flow in structures and the nature of ionic current flow in the electrolyte between the anode and the structure that influence the overall current distribution. A number of important factors affect the current distribution, as outlined below.
- Too close a separation distance results in a poor current distribution as shown in contour figures.
- The soil resistivity effect: Cathodic protection current density (required current) increases with decreasing environment resistivity; Resistivity variations in the electrolyte between the anode and cathode also have a strong influence on the current distribution.
- Cathodic protection current for coated pipe is very low compared with cathodic protection current for bare pipe.
- Anode depth with respect to the structure; best protection level reached as the anode depth was at lower level than the pipe (when the anode was at a lower level the potential range was higher than that potential range when the anode at the same level of the pipe this is clear in contour figures).
- The position of reference electrode with respect to structure; this factor was affected by the coating; which mean that if the pipe was uncoated the RE position playing important rule while the coated pipe this factor is negligible.
- Coating effect: the coating affect the rectifier applied voltage in the first place and therefore affect the power consumption which mean the cost; Cathodic

protection current density for coated pipe increases with decreasing environment resistivity.

5.2 Recommendations for future work

1. It is well known that the effect of stray currents are widely influenced the cathodic protection efficiency. This effect was not included in the present study and it is preferred to perform future work to study that effect.
2. Extending the duration time of cathodic protection experiments to a long period. The time in sacrificial system plays important rule in the cathodic protection efficiency. This study was basically concern on the impressed current cathodic protection and the influenced of time would be included in future work.
3. Further work is preferred to build a model using BEASY software. This software is basically simulate the cathodic protection system based on the system variable .It would give the potential distribution on the structure as well as the applied voltage and number of anodes.
4. Another work can be carried out to build a model for same design by using Boundary Element Method. This method is a theoretical solution for the cathodic protection design.

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الخلاصة

لدى العراق شبكة كبيرة من خطوط الأنابيب لنقل النفط الخام والمنتجات الهيدروكربونية بالاضافة للمياه الصالحة للشرب. وتتعرض هذه الشبكات لأضرار واسعة النطاق بسبب عمليات التآكل تحت الأرض ما لم يتم استخدام تقنيات حماية مناسبة. في هذه الرسالة تم جمع المعلومات من منظومات الحماية الكاثودية لخطوط الأنابيب في المجالات الحقلية، للحصول على قاعدة بيانات لفهم وتحقيق الاستفادة المثلى من التصميم والتي تتم عن طريق المحاكاة باستخدام برنامج MATLAB للحصول على العوامل البيئية والمتغيرات المؤثرة على تصميم منظومات الحماية الكاثودية.

الرسالة تتالف من جزئين; الجزء الاول متعلق بالمجالات الحقلية اما الجزء الثاني متعلق بتاثير بعد الانود عن الهيكل المراد حمايتهفي ظل ظروف مختلة للتربة بالنسبة للانبوب المغلف وغير المغلفز

الجزء الاول:المحاكاة بالحاسبة تمكن المصمم من بناء هيكل الحماية الكاثودية لدفن الانابيب وتوقع أعداد الأنودات المستخدمة وفولتية وتيار التشغيل في ظل ظروف تشغيلية مختلفة، ومقارنتها مع مثيلاتها في الحقول الواقعية. في هذا العمل تم إجراء مقارنة بين نتائج ميدانية ونتائج المحاكاة والتي تشمل اعداد الأنودات المستخدمة; وجد أن ز يادة عدد الأنودات يؤدي الى نقصان مقاومة التربة عند حوض الأنودات والعكس بالعكس مع بعض الاستثناءات .وقد وجد ايضا ان التيار المسلط على الانبوب يعتمد على طول المقطع المراد حمايته في حين أن الفولتية المسلطة تعتمد على مقاومة التربة اضافة الى طول الموقع.

الجزء الثاني:عند تصميم نظام الحماية الكاثودية تصميم حوض الأنود يلعب دورا هاما للغاية ذلك نتيجة ان توزيع التيارات في التربة لحماية الانبوب متعلق بهذا التصميم. في هذه الأطروحة تم إجراء مقارنة بين مواقع مختلفة للانودات في ظروف مختلفة للتربة للانبوب مغلف وغير مغلف؛ خرائط لتوزيع التيارات تم رسمها أيضا. تبين أن الانابيب المغلفة تحتاج الى فولتية أقل لحماية نفس الانبوب مما لو كان غير مغلف . التربة الجافة تحتاج الى مزيد من الجهد من التربة الاكثر رطوبة. المسافة بين الأنود والانبوب زيادة زيادة حماية الانبوب.

وقد وجد أن تاثير كل عامل كما يلي:

١. عمق الأنود بالنسبة للانبوب; وكان أفضل مستوى الحماية التي تم التوصل إليها عندما يكون الانود في مستوى اكثر انخفاضا من الانبوب

٢.المسافة بين الانود والانبوب; وقد لوحظ أفضل المسافة التي هو 30 سم عن الانبوب.

٣. موقع النصف خلية بالنسبة للانبوب ; عامل التغليف يلعب دورا مهما في هذه الحالة مما يعني أنه إذا كان الأنبوب غير مغلف موقع قطب الكبريتات النحاسية يلعب دورا مهما في حين أن الأنابيب المغلفة هذا العامل لا يكاد يذكر.

٤. تأثير الطلاء ;تطبيق الطلاء يؤثر على المعدل الجهد في المقام الأول، وبالتالي تؤثر على استهلاك الطاقة مما يعني تكلفة.

٥. تأثير المقاومة التربة، بل هو جزء رئيسي التي تحكم توزيع التيارات من الأنود إلى الأنابيب وكذلك لديها تأثير هام على الفولتية المسلطة على الانبوب هذا يظهر في خرائط كنتورية.

الشكر والتقدير

ولو أنني أوتيت كل بلاغة وأفنيت بحر النطق في النظم والنثرلما كنت بعد القول إلا مقصرا ومعترفا بالعجز عن واجب الشكر .اوجه الشكر والحمد لخالق السماوات والارض الله عز وجل لهدايتي لطريق العلم ووفقني في مسيرتي الدراسية واتوجه بالشكر والتقدير للدكتور نصير الحبوبي لتوجيهاته القيمة خلال مسيرة انجاز البحث.

الشكر والتقدير للاستاذ المهندس نهاد احمد لتوجيهاته العلمية وتوفير الاجهزة الازمة لاتمام البحث.

الشكر والتقدير للمهندس حسين علي العاملي لمساعدته القيمة في اتمام البحث .

الشكر والثناء والتقدير لوالدي العزيزين الذين يعتبران السبب الرئيسي لوصولي هذه المرحلة واعتبر هذه الشهادة هي تقديرا لهم لتوفيرهم البيئة التي تكاد تكون خيالية اكثر منها مثالية للوصول لهذه المرحلة ...

الشكر والتقدير لاخواني واختي الاعزاء....

والحمد لله رب العالمين

تصميم الحماية الكاثودية لانابيب الحديد الفولاذي المدفونة

رسالة

مقدمة إلى كلية الهندسة في جامعة النهرين

و هي جزء من متطلبات نيل درجة ماجستير علوم

في الهندسة الكيمياوية

من قبل

شهد فاضل عبد

(بكالوريوس علوم في الهندسة الكيمياوية ٢٠١٠)

جمادى الاخرة ١٤٣٤
اذآر ٢٠١٣