SOIL CORROSIVITY CONDITION INDEX FOR BURIED STEEL PIPELINE

FATIMAH AQILAH BINTI MOHAMAD NAZIM

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I dedicate this to

Myself

My husband and lovely children, abang, syifa' and zayd.

My beloved family, mama, deda, aqil, afif, atifah and eira.

My family in-law, ummi, ayah and those brothers and sisters.

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RESArians.

My akhawats and murabbi.

My ummah.

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ABSTRACT

External corrosion is common threat on underground pipeline structures resulting bad impact on human, environment and financial. Researches show that the identification of soil corrosivity level may be determined by the location conditions and suitability of pipeline structures installation. Currently, there is no guideline to assess the condition of site corrosivity by rank or index system for soil conditions in Malaysia. The index system, referring to site corrosivity may provide an early indication on the potential structural damages subjected by soil corrosion prior to pipeline installation and to assess the possible failures of damaged pipeline. This research focuses on the development of soil corrosivity condition index based on soil parameters and site characteristics evaluation for pipeline structure installation and maintenance work purposes. A total of 207 carbon steel coupons originated from X-70 metal type were installed in site A, B, C, D and E located at peninsular Malaysia for a period of 18 months. The buried coupons were retrieved every 3-months to monitor the corrosion rate by metal loss product coupled with measurement of the soil parameters including Soil Resistivity (*Res*), Moisture content (*Mc*), pH, Sulphide (SO_4), Sulphate (SO_3), Chloride (*Cl*) and site characteristics information including Soil Type (*ST*), Water Access (*WA*) and Disturbance Factor (*DF*). The results of corrosion rates and soil parameters were analyzed by using statistical method through normality, hypothesis and outlier's detection test, and the corrosion rates were classified into three categories: cr_{max}, cr_{avg} and cr_{med}. The site corrosivity conditions were designed by the classification of four corrosivity percentage levels with 0% as the worst condition and 100% as the best condition namely as "not corrosive" for 76-100%, "mildly corrosive" for 51-75%, "corrosive" for 26-50% and "very corrosive" for 0-25%. A number of six (6) soil parameters and three (3) site characteristic indexes were designed within 0-10, where 0 represent the worst condition and 10 points represent the best condition. The equation model of site corrosivity condition percentage was finally designed along with the weighing factor considerations. The collected data of soil parameters and site characteristics were applied into the model equation to compare the accuracy of designed indices with the existing corrosion rate data. Based on the comparison, the results show that the soil corrosivity condition index proposed model is identical to cr_{max} data and approximately similar to cr_{avg} and cr_{med} data for every site. The results also show that site B and C are identified as the most corrosive sites compared to site A, D and E. In conclusion, the proposed index system can assist pipeline operators in selecting the most suitable sites for pipeline installation by considering the level of soil corrosivity, hence, minimising the unnecessary corrosion protection on buried pipeline.

ABSTRAK

Kakisan luar paip merupakan salah satu ancaman terhadap struktur saluran paip bawah tanah yang mengakibatkan kesan buruk kepada manusia, alam sekitar dan kos kewangan. Kajian menunjukkan bahawa pengenalpastian tahap kakisan tanah boleh ditentukan oleh keadaan lokasi dan kesesuaian pemasangan struktur saluran paip. Sehingga kini, masih tiada garis panduan untuk menilai keadaan pengaratan tanah di tapak melalui sistem indeks bagi keadaan tanah di Malaysia. Sistem indeks pengaratan di tapak boleh memberi petunjuk awal terhadap potensi kerosakan struktur tertakluk kepada kakisan tanah sebelum pemasangan saluran paip dan menilai kemungkinan kegagalan bagi saluran paip. Kajian ini memberi tumpuan kepada penghasilan sistem pengindeksan keadaan pengaratan tanah berdasarkan parameter tanah dan penilaian ciri-ciri tapak untuk pemasangan struktur saluran paip dan tujuan kerja penyelenggaraan. Sebanyak 207 kupon keluli karbon daripada jenis logam X-70 telah dipasang di tapak A, B, C, D dan E di semenanjung Malaysia untuk tempoh 18 bulan. Kupon keluli yang ditanam telah diambil pada setiap 3 bulan untuk memantau kadar pengaratan melalui kehilangan produk logam beserta pengukuran parameter tanah termasuk rintangan tanah (*Res*), kandungan lembapan (*Mc*), pH, Sulphide (SO_4), Sulphate (SO_3), Klorida (*Cl*) dan maklumat ciri tapak termasuk jenis tanah (*ST*), akses terhadap air (*WA*) dan faktor gangguan (*DF*). Keputusan kadar pengaratan dan parameter tanah dianalisis dengan menggunakan kaedah statistik melalui ujian normal, hipotesis dan pengecaman titik terpencil, dan kadar kakisan telah diklasifikasikan kepada tiga kategori: cr_{max}, cr_{avg} dan cr_{med}. Keadaan kakisan tapak telah dikelaskan melalui empat tahap peratusan pengaratan dengan 0% sebagai keadaan yang paling teruk dan 100% sebagai keadaan yang terbaik iaitu 76-100% sebagai "tidak mengkakis", 51-75% untuk "separa mengkakis", 26-50% untuk "mengkakis" dan 0-25% untuk "sangat mengkakis". Sejumlah enam (6) parameter tanah dan tiga (3) ciri tapak telah diberikan nilai 0-10, di mana 0 mewakili keadaan yang paling teruk dan 10 mewakili keadaan yang terbaik. Model persamaan peratusan markah indeks akhirnya direka dengan mengambil kira faktor pemberat. Data parameter tanah dan ciri-ciri tapak yang diperolehi di tapak telah digunakan ke dalam model persamaan untuk membandingkan ketepatan indeks yang direka dengan kadar kakisan yang sedia ada. Berdasarkan perbandingan, ia menunjukkan bahawa keputusan daripada model indeks keadaan pengaratan tanah yang dicadangkan adalah sama dengan data cr_{max} dan hampir sama dengan data cr_{avg} dan cr_{med} di setiap kawasan. Keputusan juga menunjukkan bahawa tapak B dan C dikenalpasti sebagai tapak yang paling mengkakis berbanding dengan tapak A, D dan E. Kesimpulannya, sistem indeks yang dicadangkan mampu membantu operator paip dalam menentukan kawasan yang paling sesuai bagi pemasangan paip berdasarkan tahap kakisan tanah. Seterusnya mampu mengurangkan perlindungan pengaratan yang tidak perlu kepada saluran paip dalam tanah.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

*	Asterisk marks (Significance value)
°C	Degree Celsius
Ω.cm	ohm - centimetre
±	plus - minus
%	Percentage
ρ	Resistivity
Σ_i	Total sum
A	Area (in cm^2)
a	Electrode separation (cm)
avg	Average
AWWA	American Water Work Association
C	Concentration of the standardized thiocyanate solution (in *mol/L*)
Ca^{2+}	Calcium Cation
CP	Cathodic Protection
Cl	Chloride
Cl	Chloride Content
cr_{avg}	Average corrosion rate
cr_{med}	Median corrosion rate
cr_{max}	Maximum corrosion rate
CR	corrosion rate
Corr.	Corrosion rate
df	Degree of freedom
DF	Disturbance factor
D	Density (in g/cm^3)
e-	Electron
emf	Voltage potential
Fe_2O_3nH	Hydrated crystallized ferric oxide

Fe	Iron
g	grams
GPS	Global Positioning System
H_0	null hypothesis
H_2O	water
I	Index
K	a constant (8.76 x 10^4mm/y)
K^+	Potassium ion
LCA	Linear Correlation Analysis
LNG	liquefied natural gas
m_3	mass of each test specimen used (*g*)
m_4	mass of ignited precipitate (*g*)
mm	millimetre
mL	millilitre
Mc	moisture content
Mo – Nb	Molybdenum – Niobium
max	maximum
med	median
ML	metal loss
mm/y	millimetre per year
mc	moisture content
Mc	Moisture Content
Mg^{2+}	Magnesium ion
mV	milivolts
MIC	microbiologically influenced corrosion
m.per	marks percentage
n	weighting factor
n_P	weighting factor of parameter
n_T	total summation of weighting factor
Na^+	Sodium ion
O_2	oxygen
OH^-	hydroxide ion
pH	pH content

p value	Significance value
ppm	part per million
R	resistance, Ω
Res	soil resistivity
Sig.	Significations
SM	Soil Moisture
STATSGO	State Soil Geographic Steel corrosion
SC	Soil Corrosivity
SO_4	sulphide content
SO_3	sulphate content
ST	soil type
SPSS	Statistical Package for the Social Science
SRB	Sulphate Reducing Bacteria
SCC	Soil Corrosivity Score
SR	Soil Resistivity
T	Time of exposures (in hours)
t	exposure of time
t	month
V_2	volume of the silver nitrate solution added (in *mL*)
V_3	volume of the standardized thiocyanate solution added (in *mL*)
v	volts
W	Mass loss (in grams)
WA	water excess
W_0	Initial weight

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

Pipelines play an important role as they transfer liquid, oil and gas from their sources to the ultimate consumers. The structures are commonly installed underground, under the water or at above ground. Underground pipeline structures are commonly exposed to various types of risk, such as corrosion. The corrosion process of underground pipeline structures may reduce the strength of the metal and cause structural failure. Corrosion is an issue that has to be taken seriously into consideration as it has negative impacts on the environment as well as human and economic systems. Some of the problems that can possibly occurs due to corrosion are pipeline leakages, plant shutdowns, waste of valuable resources, contaminated products, efficiency reduction, high maintenance cost, expensive over-design, serious injuries to personnel, and explosion.

Corrosion of underground pipeline structures can be categorized into two groups: external and internal corrosion. External corrosion is caused by exposure to soil environment, while internal corrosion is caused by the influence of material flow in the pipeline. In order to reduce the possibility of underground external corrosion, it is important to identify the level of soil corrosivity of the pipeline installation location.

1.2 Research Background

Many cases have been reported on the pipeline structures failure due to corrosion problems which has a devastating impact on the surrounding life and environment. Wiese (2015) reported that the probable cause of pipeline failure on the West Texas Gulf Pipeline System on February 2015 is due to external metal loss caused by corrosion. For that reason, it is important to understand and recognize the mechanism of corrosion by identifying the suitable material, design, protective system, treatment and device for pipeline structures. Generally, underground pipeline structures are designed to have a long life span by having protection system applied, such as coating and cathodic protection to preserve the external integrity. Sausville and Wu (1998) reported that metallic pipeline system has about 30 years of life expectancy as per State regulations requirement. As reported by Kiefner and Rosenfeld (2012), older pipelines in 1940s and 1950s seem to be more susceptible to external corrosion because the pipelines were installed without coating and the cathodic protection applied was lesser back then. This shows that the age pipeline structures contribute to the corrosion threat on pipeline systems.

However, Peabody (2001) suggests that corrosion damages are still a reality even though pipeline structure are protected by this kind of system as it is not certainly guaranteed as a complete anti corrosion attack system. This is because underground pipeline structures are constantly exposed to the soil environment that contains varying types of material which can damage the protection system and accelerate the corrosion process. The soil environment consists of complex measured parameters and characteristics which can determine the extent of soil corrosivity. Soil corrosivity is a multi scale process involving metal degradation reacting with soil due to the soil behaviour itself. Soil corrosivity, when compared to that of the atmosphere or seawater, corrosivity is often more difficult to categorise with regards to both pipe specific parameters and surrounding soil properties (Farreira, 2006; Pritchard *et al.,* 2013).

Pritchard *et al*. (2013) states that soil influenced corrosion is a complicated phenomenon due the complexity and heterogeneous dynamics of soil environments.

In this case, it is important to analyse and evaluate the soil corrosivity parameters in order to assess the phase of soil corrosivity. By obtaining information about the soil corrosivity phase, researches can provide useful guidance on pipeline selection, corrosion control method and the maintenance system of pipeline structures.

1.3 Research Problem

The current practices to mitigate the external corrosion on underground pipelines involve the combination of cathodic protection and pipeline coatings. Cathodic Protection (CP) is a technique used to reduce corrosion rate of a metal surface by making it the cathode of an electrochemical cell (Peabody, 2001), while coatings normally are used to form a continuous film of an electrically insulating material over the metallic surface to be protected (Peabody, 2001).

However, Fessler (2008) reported that cathodic protection application alone would not be practical to protect pipelines against corrosion as the required amount of current are highly proportional to the exposed area and will be expensive to protect a long bare pipeline. Coatings by themselves also would not be totally effective, because it is impossible to produce a perfect coating over an entire pipeline (Fessler, 2008). These protection methods are actually applied during designing the pipeline structures and after the process of pipeline installation. Hence, the methods of protection applied are not designed based on corrosion analysis on the site prior installation as per stated by Ismail and El-Shamy (2009) that risk of corrosion should be estimated prior to pipeline structures installation.

Other corrosion potential assessment practiced by industries is generally identified by examining a few variables for corrosion evidence, such as pipe-to-soil potential due to its simplicity. However, it is difficult to quantify the characteristics that may indicate high corrosion potential since corrosion is a function of many parameters. For example, the soil acts as an electrolyte which reacts within specific locations and time depending on variables such as moisture content, bacteria, ion concentrations etc. which leads to difficulties in accurate estimation.

By investigating the characteristics of soil; soil engineering properties and their chemical content of the proposed or existing pipeline installation locations, researches can provides insight on the corrosion potential experienced by the buried pipeline and the potential threats to structural integrity. The assessment of soil corrosion risk may act as an initial step that enables the circumvention of the hazardous impacts caused by pipeline corrosion. However, the study of soil corrosion risk assessment still has a certain limit and has yet to be extensively modified.

Muhlbauer (2004) suggests that, the application of corrosion index may reflect the potential for corrosion, which may or may not mean that corrosion is actually happening. The ranking or index systems referring to site corrosivity are vitally required to give an early indication on the potential of structure damage subject to soil corrosion. It can also be used prior to installation of pipelines or to assess possible failures of damaged pipelines qualitatively.

Distribution of pipeline infrastructure conveys that natural gas products from Kerteh to end-user (industry) in Malaysia are buried underground. Up until now, there are no specific guidelines that can be used and referred to in order to assess the level of soil corrosivity of potential installation sites in Malaysia. The current practice to identify the level of soil corrosivity in Malaysia is only through the soil resistivity measurements and the potential of pipe to soil on site. The detailed site conditions and information were not being studied and identified whether the site is suitable or not for pipeline installation. These will incur higher cost in the future due to the removal and reinstallation process of pipeline structures. Although previous studies on soil corrosion risk have been carried out in several European countries, there is no evidence or strong recommendation of the applicability of the findings to assess soil corrosivity in Malaysia. In fact, Malaysia is located on the equatorial zone and has a tropical climate.

Revie and Uhlig (2008) stated that a metal in some part of country may perform satisfactorily, but may not in other countries due to the specific differences of soil composition, pH, moisture content etc. Revie and Uhlig (2008) also stated that groundwater in tropical climates tends to be more acidic. Based on the requirements, soil corrosivity condition index system needs to be developed in order to facilitate the identification process of soil corrosivity condition of pipeline installation locations. Soil corrosion risk design in accordance to soil characteristics in Malaysia can be very useful to the pipeline companies in Malaysia as the installation of pipeline structures shall be more systematic and safety-ensured.

1.4 Research Aim

The aim of this research is to develop condition index of soil corrosivity based on the evaluation of soil parameters and site characteristics for pipeline installation and maintenance works. To achieve the stated research aim, the following objectives must be fulfilled as follows:

i. To measure metal mass loss of corroding X70 steel coupon exposed to the underground environment.

ii. To measure soil parameters and site characteristic data which may have strong influence towards corrosion of the X70 steel coupon

iii. To develop index values of soil parameters and soil characteristics and an empirical model to quantify soil corrosivity condition.

iv. To verify the validity of soil corrosivity condition index design by comparing the results of corrosivity condition for every site with the existing corrosion rate data.

1.5 Research Scopes

The research puts the focus on the study of parameters related to soil engineering properties and chemical content affecting soil corrosiveness, such as soil resistivity, moisture content, chlorides, sulphide, sulphate, pH and the general characteristics of site field work. The corrosion process caused by microbial activity is not considered. The metal loss products are obtained from the buried samples derived from the X70 steel pipeline section. Field work and laboratory experiments are carried out to measure the weight of metal loss, an indication of the corrosion process of steel pipelines.

The field works are carried out in five selected sites in Peninsular Malaysia, located in three states which are Pahang, Terengganu and Johor. These sites were selected based on the inspection data and maintenance records provided by PETRONAS. The environment diversity, coupon installation feasibility and safety aspect were also considered in selecting these sites. The corrosion of the steel coupon is considered under the worst case scenario whereby the steel coupon is assumed to experience a coating breakdown. Hence, corrosion can start to initiate immediately. The corrosion index system is designed by considering the type of soil in east coast only due to time and cost constraint. As the types of soil on east coast are not the same as the type of soil on the some part of west coast, the proposed procedure may be used on the recommended types of soil only.

1.6 Research Significance

Various efforts have been proposed to minimise corrosion problems on pipeline structures. However, there are some surveillance methods that are considered inefficient in terms of operational cost, such as Cathodic Protection (CP) where the current are applied to the entire pipeline structures, and pipeline coating where the entire pipeline structures are coated by the same amount of coating layer. Even with all the modern pipeline construction practices, better coatings, more extensive CP and other methods of corrosion control, the pipeline industry continues to experience corrosion (external and internal) on pipelines (Norsworthy, 2014). Thus, the system of Soil Corrosivity Condition Index is a possible solution to overcome the cost issues and benefits the pipeline industry.

The Indexing system offers preliminary information of the selected site for pipeline installation. This allows the pipeline industry parties to determine the site suitability in term of soil corrosion level prior to pipeline installation. The system is suitable to apply by the industries as it can be viewed before and after laying the pipeline structures. As natural resources are becoming more and more valuable, losses must be kept to the minimum as the industry strives to become perfect (which will not happen) in its corrosion control effort (Norsworthy, 2014). By the application of the index system, industries would be able to control the cost for the protection of the pipeline structure by having a proper control on the amount of protection applied. Soil corrosivity index system is specifically developed using parameters from local sites that has the potential to be a reliable method of controlling the corrosion on pipelines and provides the following benefits:

i. The proposed index system can be utilized by operators to detect potential threats to the existing pipeline structural integrity due to soil-corrosion by considering various types of environmental parameters.

ii. It can greatly assist the pipeline system operator in making accurate decisions on what, when and where future inspection repair and maintenance resources can be deployed.

iii. The ranking system is designed to reduce errors in selecting installation sites with low-risk of corrosion by ranking the sites according to soil corrosivity for future pipeline installation.

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