MODELLING OF EXTERNAL CORROSION GROWTH OF STEEL PIPELINE IN SOIL FOR TROPICAL CLIMATE

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My humble works and efforts I dedicate to

My beloved hubby Raizan
For earning an honest living for us and the kids Aminah & Mubashir
for supporting and encouraging me to believe in myself

My dearest parents and parents in-law
A strong and gentle soul who taught me to trust in Allah S.W.T,
believe in hardwork and that so much could be done with little

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Who has been a constant source of knowledge and inspiration
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ABSTRACT

The reliability of a buried steel pipeline is strongly influenced by external corrosion due to soil. However, the external corrosion does not affect the pipeline equally at all locations and corrosion does not grow at the same rate throughout a pipeline. Therefore, the need of reliable predictive corrosion model is of great interest among researchers and engineers. The available current models are relying on huge historical data storage; thus, massive excavation works, equipment and technical expertise are required. In addition, the feasibility of these models for practical application in different regions with different climate and soil conditions still remains unknown. Therefore, this research aims to develop a predictive model for underground corrosion with the improved multi-parameter models in which several soil characteristics are considered without the need for a return trip to the field, on-site excavation and the presence of technical expertise. Moreover, the models developed in this study are based on empirical results reflecting a wide range of exposure conditions suitable for Malaysia's site conditions through Component 1 and 2. Two predictive corrosion models based on power law equation were developed using two different approaches at two different locations namely real and simplified sites. The most common applied model used to predict corrosion loss is the power law model ($P = kt^v$), where t is exposure time, and k and v are constant regression of soil parameters. There are a total of 932 mild steel coupons being buried in soil up to 18-month period in 5 different locations and 65 soils samples were analysed for its contents and engineering properties. The results were analysed using statistical methods such as exploratory data (EDA), single linear regression (SLR), principal component analysis (PCA) and multiple linear regression (MLR), while Component 3 was conducted to verify the models using two-way ANOVA (Analysis of variance). From the analysis, the extraction of soil variables related to k and v were successfully obtained. In order to get the best fit of predictive model, the extracted variables are modelled using MLR with 20 combinations of linear equation and embedded in the power law equation. The model revealed that chloride (CL), resistivity (RE), organic (ORG), moisture content (WC) and pH were found to be the most influential variable in predicted mass loss, k while sulphate content (SO), plasticity index (PI) and clay content (CC) appear to be influential with v. The predictive corrosion models based on data from real and simplified sites have yielded reasonable prediction of metal mass loss with R^2 score of 0.89 and 0.81 respectively. This research has introduced innovative ways to model the corrosion growth for underground pipeline environment. Moreover, heavy statistical analysis has been utilised to determine the level of influence of soil contents and its engineering properties towards soil corrosivity. The model enables to predict potential metal mass loss, hence the level of soil corrosivity for Malaysia. The knowledge on soil corrosivity may assist pipeline operators in designing effective corrosion mitigation program for their underground assets.

ABSTRAK

Kebolehtahanan saluran paip keluli bawah tanah amat dipengaruhi oleh kakisan luaran yang disebabkan oleh tanah. Walaubagaimanapun, kakisan luaran ini tidak menjejaskan kakisan yang sama di semua lokasi dan ia tidak berkembang pada kadar yang sama sepanjang saluran paip. Oleh itu, keperluan model ramalan kakisan amatlah menarik minat para penyelidik dan jurutera. Model kakisan yang sedia ada kebanyakannya bergantung pada simpanan data yang banyak, ini memerlukan kerja-kerja penggalian serta peralatan yang besar dan kepakaran operator saluran paip. Tambahan pula, kesesuaian model-model tersebut bagi kegunaan di rantau yang berbeza dari segi iklim, muka bumi, dan keadaan tanah masih menjadi tanda tanya. Oleh itu, kajian ini bertujuan untuk membangunkan model kakisan yang lebih baik untuk meramal kadar kakisan dalam tanah dengan mengambilkira sifat kimia dan fizikal tanah tanpa memerlukan perjalanan balik ke tapak, penggalian di lokasi serta kehadiran kepakaran teknikal. Selain itu, model yang dibangunkan dalam kajian ini juga adalah berdasarkan kepada keputusan empirikal yang mencerminkan pelbagai keadaan pendedahan yang sesuai bagi keadaan di Malaysia melalui Komponen 1 dan 2. Dua model ramalan kakisan telah dibangunkan berdasarkan persamaan hukum kuasa dengan menggunakan dua pendekatan yang berbeza iaitu tapak sebenar dan simulasi. Model kakisan yang biasa digunakan adalah model hukum kuasa ($P = kt^{v}$), dengan t ialah masa pendedahan, dan k dan v adalah pemalar regresi tanah. Sebanyak 932 kupon keluli sederhana telah ditanam di dalam tanah selama 18 bulan di 5 lokasi yang berbeza dan 65 sampel tanah telah dianalsis kandungan kimia dan fizikalnya. Keputusan tersebut telah dianalisis dengan menggunakan kaedah statistik seperti data saringan (EDA), regresi linear tunggal (SLR), analisis komponen utama (PCA) dan regresi linear pelbagai (MLR), manakala Komponen 3 bertujuan sebagai pengesahan bagi model yang dibangunkan dengan menggunakan analisis ANOVA dua-hala. Dari analisis, pengekstrakan pembolehubah tanah yang berkaitan dengan k dan v telah berjaya diperoleh. Untuk mendapatkan model ramalan yang terbaik, pembolehubah yang telah diekstrak akan dimodelkan menggunakan MLR dengan 20 gabungan persamaan linear dan dimasukkan dalam persamaan hukum kuasa. Model ini menunjukkan bahawa, klorida, kerintangan, organik, kandungan kelembapan dan pH mempengaruhi pembolehubah k, manakala kandungan sulfat, indeks keplastikan dan kandungan tanah liat berhubungkait dengan v. Model ini telah menghasilkan ramalan degradasi keluli masing-masing sebanyak 0.89 dan 0.81 berdasarkan data dari tapak sebenar dan tapak simulasi. Kajian ini telah memperkenalkan cara yang inovatif dalam permodelan pertumbuhan kakisan paip keluli bawah tanah. Tambahan pula, analisis statistik berat telah digunakan untuk menentukan tahap pengaruh kandungan tanah dan sifat kejuruteraannya. Model ini juga mampu dalam meramal kehilangan jisim keluli dan juga tahap kakisan tanah di Malaysia. Dengan adanya pengetahuan mengenai kakisan dalam tanah, ia dapat membantu operator saluran paip dalam merekabentuk program mitigasi yang lebih berkesan dalam melindungi aset bawah tanah mereka.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

5L	-	Specification for line pipe
AFAT	-	All-factor-at-a-time
APB	-	Acid-producing bacteria
API	-	American Petroleum Institute
ANOVA	-	Analysis of variance
ASTM	-	American standard test anad materials
C	-	Constant (8760 x 10 cm/y)
C1	-	Component 1
C2	-	Component 2
CC	-	Clay content
$CaSO_4$	-	Calcium sulphate
cm^2	-	Centimetre square
cm	-	Centimetre
CL	-	Chloride content
CLR	-	Corrosion loss rate
CP	-	Cathodic protection
CR	-	Corrosion rate
Co	-	Cobalt
Cr	-	Chromium
DO	-	Dissolved oxygen
e.g.	-	For example
EDA	-	Exploratory data analysis
exp	-	exponent
E	-	East
Fe^{2+}	-	Ferrous ion
$Fe_2O_3.H_2O$	-	Hydrated ferrous oxide (brown rust)
FBE	-	Fusion bonded epoxy

Fe	-	Iron (element)
$Fe(OH)_2$	-	Ferrous hydroxide
$Fe(OH)_2$	-	Ferric hydroxide
FeS	-	Ferum sulphide
GDS	-	Glow discharge spectrometer
GPP	-	Gas processing plant
H^+	-	Hydron
H_a	-	Alternative hypothesis
HSD	-	Honestly Significant Difference
H_o	-	Null hypothesis
H_2O	-	Water oxygen
H_2S	-	Hydrogen sulphide
HCI	-	Hydrochloric acid
ICCP	-	Impressed current cathodic protection
ILI	-	In-line Inspection
K-S	-	Kolmogorov-Smirnov
ksi	-	Kilopounds per square inch
K_n	-	Constant
KMO	-	Kaiser-Meyer-Olkin
LL	-	Liquid limit
log	-	logarithma
m	-	metre
M	-	molar
Max	-	Maximum
Med	-	median
mg/kg	-	Miligram per kilogram
MIC	-	Microbiologically influenced corrosion
ml	-	mililitre
ML	-	Metal mass loss
mm/y	-	Milimetres per year
MRA	-	Multiple regression analysis
mmscf	-	Millions of standard cubic feet
Na^+	-	Sodium ion

NaCl	-	Sodium chloride/ natrium chloride
NaOH	-	Sodium hydroxide
NHE	-	Normal hydrogen electrode
Ni	-	Nickel
O_2	-	Oxygen
OFAT	-	One-factor-at-a-time
OH^-	-	Hydroxyl ion
ORG	-	Organic content
ORP	-	Oxidation-reduction potential
P/S	-	Pipe-to-soil
P-value	-	Probability value
P_c	-	Corrosion pit dimension / environmental variables
PCA	-	Principal component analysis
$P_{max,cal}$	-	Predicted value of measured pit depth
PGB	-	Petronas Gas Berhad
PGU	-	Peninsular Gas Utilisation
PI	-	Plasticity index
PIAM	-	Pipeline integrity assessment and management
PS	-	Particle size distribution
PL	-	Plastic limit
R^2	-	Coefficient of determination
RES / Re	-	Resistivity
ROW	-	Right-of-way
S-W	-	Shapiro-Wilk
S	-	Sulphide
SCC	-	Stress corrosion cracking
SL	-	Shrinkage limit
SLR	-	Single linear regression
SO_4^{2-}	-	Sulphate ion
SO	-	Sulphate
Std. dev.	-	Standard deviation
SRB	-	Sulphate-reducing bacteria
T	-	Time of exposure

Tcf	-	Trillion cubic feet
UTM	-	Universiti Teknologi Malaysia
V	-	Voltage
WC	-	Moisture content
X70	-	Pipe having a minimum yield strength of 70ksi
XLSTAT	-	Statistical software suite for Microsoft excel

LIST OF SYMBOLS

%	-	Percentage
ºC	-	Degree celcius
ρ	-	Resistivity
Ω	-	Ohm
A	-	Regression coefficient / area of exposure
$b_1, b_2, b_3 ... b_n$	-	Coefficient of predictor variables
b	-	Power coefficient
d	-	Pit depth
d	-	Steel density
D	-	Steel density in g/cm^3
d_{max}	-	Maximum pit depth
e^-	-	electron
E_h	-	Oxidation-reduction potential
k	-	Metal loss constant
l	-	length
n	-	Corrosion growth pattern constant
t	-	Exposure time / thickness
t_o	-	Initial time of exposure
v	-	Corrosion growth pattern constant
w	-	width
W_o	-	Initial weight
W_i	-	Final weight loss
x	-	Time exposure
y	-	Dependent variables

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Gas transportation via pipeline has been seen as an alternative in providing the cleanest, safest, most cost effective and reliable energy solution for the nation and consumers. For the purpose of security, safety, stability and supply continuity, all coated gas pipelines in Malaysia were buried under the ground and maintained by adequate levels of cathodic protection (CP). Although there are several forms of protection such as physical coating and CP, buried pipelines still experience corrosion attack. Without realizing it, the soil surrounding the pipe plays an important role in coating failure such as abrasion resistance, wrinkling, tearing, shifting, disbondment, blistering, etc. This implies soil corrosiveness as a form of external corrosion that poses a threat to buried pipelines.

As mentioned by Amend [2009], the basic soil corrosiveness model is relying on soil resistivity as sole indicator. However, several technical resources show that the relationship is not consistent. Further mentioned by Papavinasam *et al*. [2010], the corrosion allowance is calculated either from the predicted corrosion rate and the design life of the pipeline or determined from experience. With the help of external model, it would assist pipeline operators in designing a maintenance programme and prioritizing the locations for assessment. Furthermore, modelling results can be used as a substitute for default corrosion rates when setting the reassessment intervals.

1.2 Problem Statement

Most pipelines constructed in the last 60 years are still in operation, and most of them will continue safely operating into the future if properly maintained. In the field, one of the major mechanisms of failure of external corrosion is the soil itself. The problems are that these factors do not affect the pipeline equally at all locations and corrosion does not grow at the same rate throughout a pipeline. Currently, many established models are relying on bursting pipeline, coating failure, stress corrosion cracking and cathodic protection efficiency; therefore, huge excavation works are needed to obtain the data from the corroding pipeline that is still in operation. Most of the corrosion models from current researches demonstrated a full utilisation of historical record of metal loss measured on site during excavation. Nevertheless, not all pipeline operators keep the records since site excavation, purposely to measure the external metal loss on pipeline surface, is not a standard practice, highly costly and interruptive to the operation. Therefore, a simpler technique should be explored to record the on-site metal loss volume so as to provide valuable information to the modelling of underground external corrosion.

For this reason there is desire to predict soil corrosiveness with the improved multi-parameter models in which several soil characteristics are considered without the need for a return trip to the field, on-site excavation and the presence of technical expertise. The models developed in this work are generally based on empirical results reflecting a wide range of exposure conditions suitable for tropical climate's site conditions keeping in mind that the pipelines still are operating throughout the research duration. Even though previous researches have successfully developed a number of predictive empirical models for external condition of corroding pipelines, the feasibility of these models for practical application in different regions with different climate and soil condition is unknown. Hence, the need for a predictive corrosion model specially tailored for tropical soil condition.

The corrosion rate of mild steel pipeline depends on the soils corrosiveness. These models are expressed as a power law pattern; $d = kt^{v}$ where t is the exposure time, and k and v are metal loss constant and corrosion growth pattern over time respectively, using a multivariate regression analysis known as all-factor-at-a-time (AFAT) approach. It was conducted with *d* as the dependent variable, and the soil physical and chemical properties as independent variables. As mentioned by Ricker [2010], so many diverse factors influence corrosion rates underground that planning of proper tests and interpretation of the results are vitally needed. Hence, accurate classification of soil parameters into the right group between both constant *k* and *v* has become a major issue. The classification of parameters related to soil chemical content and soil physical properties to both constant *k* and *v* has seen inconsistent results across the globe. Therefore, it is proposed to use the one-factor-at-a-time (OFAT) approach to provide better understanding of the degree of influence of soil chemical and physical properties towards dynamic corrosion growth particularly for Malaysian region.

1.3 Research Aim

Mild steel grade API 5L X70 are frequently used in transmission gas pipelines in Peninsular and West Malaysia. Understanding the effects of dynamic corrosion growth is essential for the integrity and reliability of these pipelines. Research focusing on developing the external growth rate model by correlating the growth of external corrosion based on corrosion rate and metal loss data gathered by steel coupons buried underground, soil engineering properties and soil chemical properties as reported herein, would increase the understanding of a pipeline structure and deteriorating effects of dynamic corrosion growth on structural integrity. The predicted external model is based on statistical modelling used to support external corrosion direct assessment (ECDA) and integrity management of buried pipelines in Malaysian soil conditions. As the model is based on all-factors-at-a-time (AFAT) approach using a multivariate analysis, it requires less excavation works and is suitable for those researchers who do not have the luxury to access the historical record of metal loss data.

1.4 Research Objectives

The following objectives were identified as steps towards achieving the research aim:

a) To determine the metal mass loss and corrosion growth pattern of mild steel coupon installed in an underground environment;

b) To identify the empirical relationship between metal mass loss rate towards soil properties and soil chemical content through on-site evaluation and experimental works;

c) To classify the parameters of soil chemical content and engineering properties according to the level of influence towards power law coefficient of *k* and *v* using AFAT approach;

d) To verify the classification of soil parameters to power law coefficient of *k* and *v* using OFAT approach.

1.5 Research Scopes

A large part of this research are related to corrosion study involving extensive field and laboratory experimentation to examine the correlation between volume of metal loss and those parameters that are considered to influence metal loss such as pH, temperature, chloride content, sulphate content, sulphide content, moisture content, organic content and resistivity as well as soil physical properties such as plasticity index, clay content and soil particle size. Through this field and laboratory works, the empirical model of the external corrosion can be implemented based on the tested parameters. This model can be used to obtain the corrosion growth rate and can be used to assist pipeline operators in designing an effective Pipeline Integrity Assessment and Management (PIAM). The pipelines involved in this research are owned by Petronas Gas Berhad (PGB) and are laid all the way from Kerteh to Kangar. However this research will focus only on laid pipeline from Kerteh to Segamat due to time and allocation constraints. The steel coupons used to measure corrosion rates are prepared from actual segments of steel pipe of grade API 5L X70.

Statistical analysis and multi regression techniques were utilised to identify the relationship between soil physical and chemical properties towards dynamic corrosion growth in developing the prediction model.

1.6 Importance of Research

As an integrated part of pipeline reliability, external corrosion modelling in the buried gas pipeline has been receiving greater attention from both researchers and municipalities but modelling based on Malaysian soil conditions is not readily available. This research is significant for the following reasons:

a) The proposed model can reduce the uncertainties in the estimation of corrosion growth by incorporating multi parameters related to soil chemical content and soil engineering properties.

b) The proposed model would assist operators in making decisions on route selection for future pipeline construction and to forecast the corrosive tendency of a specific site.

c) The proposed model can assist the operators in arranging the future inspection, repair and maintenance resources, thus reducing the operating and maintenance cost of underground pipelines.

1.7 Contribution of the Research

The research was meant to develop an empirical external corrosion growth rate model suitable for Malaysian soil conditions whereby historical corrosion data from site excavation on pipeline installation site is lacking. Moreover, the model can also be used to predict the corrosion loss while the pipeline is still in operation; therefore, it would assist the pipeline operator in designing maintenance programmes and to prioritize the locations for assessment and setting reassessment intervals or future pipeline construction. The research was conducted in right-of-way (ROW) of East Peninsular Malaysia at five different locations with legal permission from

Petronas Company. Other than ROW, the research was also conducted in UTM open areas in terms of empirical model development based on soil data from a particular area at ROW. For those who are not fortunate to have an enormous yet real data field, they can use data taken from the open area to develop a model as demonstrated by this research.

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