LONG TERM PREDICTION OF PIPELINE CORROSION UNDER TROPICAL SEABED SEDIMENT

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ALHAMDULILAH

Praise be to Allaah, all glory and honor to Him who says:

“Give thanks to Me and to your parents. Unto Me is the final destination”

[Quraan, Luqmaan 31:14]

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ABSTRACT

The corrosion of pipeline steels buried under seabed sediment is not fully predictable, since there are many parameters affecting the pipeline at different degrees. In relation to that, corrosion growth predictive model based on long term experimental study is of great demand to assist in making suitable pipeline integrity decisions. Therefore, research has been conducted to investigate the metal loss behaviour and corrosion mechanism of pipeline steel under seabed sediment conditions. Then, this study developed a predictive model for corrosion under seabed sediment and highlighted corrosion parameters which presented in tropical climate. Two corrosion models were proposed; one based on the results of a long term exposure of steel coupons to the real field condition. Furthermore, another descriptive model was developed using response surface methodology. The most common applied model used to predict corrosion loss is the power law model ($P = kt^n$), where t is exposure time, and k and n are constant regression of the sediment parameters. Carbon steel coupons were buried in seabed sediment up to two years period. The sediment samples were analysed for its contents and properties. The descriptive model was constructed with aid of Statistica 6.0 software for the data obtained from the laboratory experiment. The results were analysed using statistical methods such as correlation test analysis (CTA), principal component analysis (PCA), multiple linear regression (MLR) and ANOVA (analysis of variance). From the analysis, the extraction of sediment variables related to k and n were successfully obtained. In order to get the best fit of predictive model, the extracted variables are modelled using MLR and embedded in the power law equation. Good curve fitting results are obtained between the actual test data and the proposed models. With consideration of pipelines integrity, the prediction of metal loss due to corrosion in SBS environment using the developed power-law model is considered satisfactory with R^2 score of 0.76. The corrosion model based on data from the laboratory has yielded reasonable prediction of metal mass loss with R^2 score of 0.83. Noticeably, several sediment factors play an important role in corrosion process and thus determine the corrosion severity. Corrosion growth models have been developed and proposed to predict corrosion progress for steel pipelines buried under seabed sediment. This research has introduced innovative ways to model the corrosion growth for seabed sediment environment. Moreover, intensive statistical analysis has been utilised to determine the level of influence of sediment parameters towards corrosivity. The models enable the prediction of metal mass loss, thus assessing the corrosivity of seabed sediment condition for Malaysian tropical climate.

ABSTRAK

Kakisan luaran yang berlaku pada paip keluli di dalam sedimen air laut masih belum dapat diramalkan sepenuhnya. Ini disebabkan oleh banyak parameter yang menjejaskan paip pada kadar yang berbeza-beza. Sehubungan itu, model ramalan perkembangan kakisan berdasarkan kajian eksperimental jangka panjang sangat diperlukan untuk membantu dalam membuat keputusan menentukan integriti paip. Oleh itu, kajian ini bertujuan untuk mengkaji kehilangan berat dan mekanisme kakisan pada paip keluli di dalam persekitaran sedimen air laut. Seterusnya, penyelidikan ini telah menjurus kepada penghasilan model ramalan kakisan di bawah sedimen air laut dan mengenalpasti parameter-parameter yang wujud di dalam persekitaran tropika. Terdapat dua model ramalan kakisan yang telah dibangunkan berdasarkan persamaan hukum kuasa dengan penggunakan dua pendekatan yang berbeza iaitu tapak sebenar dan tapak simulasi. Kehilangan kakisan telah diramalkan dengan menggunakan model kakisan yang biasa digunakan iaitu model hukum kuasa ($P = kt^v$), di mana t ialah masa pendedahan, dan k dan n adalah pemalar regresi parameter-parameter sedimen. Kupon keluli karbon telah di tanam di dalam sedimen air laut selama dua tahun. Analisis juga telah dijalankan terhadap kandungan dan sifat-sifat sampel sedimen. Model diskriptif telah dibangunkan dengan bantuan perisian Statistica 6.0 terhadap data-data yang diperolehi melalui ujian makmal. Keputusan tersebut telah dianalisis dengan menggunakan kaedah statistik, analisis ujian korelasi (CTA), analisis komponen utama (PCA), regresi linear pelbagai (MLR) dan ANOVA dua-hala. Daripada analisis, ekstrak pembolehubah-pembolehubah berhubungkait dengan k dan n telah berjaya ditentukan. Bagi mendapatkan model ramalan terbaik, pembolehubah-pembolehubah yang diekstrak telah dimodelkan dengan menggunakan MLR dan diaplikasikan di dalam persamaan model hukum kuasa. Keputusan lengkung terbaik diperolehi di antara data eksperimen dan model yang dicadangkan. Dengan mengambilkira keboleharapan paip, ramalan kehilangan jisim akibat kakisan di dalam persekitaran sedimen air laut dengan menggunapakai model hukum kuasa adalah memberangsangkan dengan R^2 adalah 0.76. Model kakisan yang dihasilkan berdasarkan data dari makmal juga memaparkan ramalan kehilangan jisim yang memuaskan iaitu R^2 bersamaan 0.83. Ternyata, beberapa faktor sedimen memainkan peranana penting di dalam proses kakisan dan seterusnya menentukan kesan kakisan. Model ramalan kakisan telah dihasilkan dan dicadangkan untuk meramal perkembangan kakisan paip keluli di bawah sedimen air laut. Model ini juga mampu dalam meramal kehilangan jisim besi dan juga tahap kakisan tanah di rantau Malaysia. Penyelidikan ini juga telah memperkenalkan kaedah-kaedah inovatif dalam permodelan pertumbuhan kakisan di dalam persekitaran sedimen air laut. Tambahan pula, analisis statistik yang intensif telah digunapakai untuk menentukan kadar kesan parameter-parameter sedimen terhadap kakisan. Model ini juga mampu dalam meramal kehilangan jisim besi dan juga tahap kakisan persekitaran sedimen air laut bagi iklim tropika di Malaysia.

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LIST OF SYMBOLS AND ABBREVIATIONS

%	-	Percentage
°C	-	Degree Celsius
A	-	Area of sample in cm^2
Al	-	Aluminum
ANOVA	-	Analysis of variance
API X70	-	Grades of Steel Pipelines
ASTM	-	American Society of Testing of Materials
B_2	-	Boron
BL	-	Batu Layar
BS	-	British Standard
C	-	Carbon
Cl-	-	Content of chloride ion
Clay	-	Clay content
cm^2	-	Square centimeter
Co	-	Cobalt
C	-	Conductivity
CP	-	Cathodic Protection
CR	-	Corrosion Rate (mm /y)
Cr	-	Chromium
Cu	-	Copper
D	-	Metal density in g /cm^3
DB	-	Danga Bay
DoE	-	Design of experiment
Eh	-	Redox potential

ER	-	Electrical resistance
Es	-	Sulfur potential
FBE	-	Fusion bonded epoxy
Fe	-	Iron
g	-	Gram
g/cm^3	-	Gram per cubic centimeter
GDS	-	Glow Discharge Spectrometry
H_2O	-	Water
k	-	Constant regression parameters
kg	-	Kilogram
KK	-	Sungai Kim Kim
LL	-	Liquid limit
LPR	-	Linear polarization resistance
mg/kg	-	Milligram per kilogram
MIC	-	Microbiologically Influenced Corrosion
ML	-	Metal loss
mm/y	-	Millimeter per year
Mn	-	Manganese
Mo	-	Molybdenum
Nb	-	Niobium
Ni	-	Nickel
O_2	-	Oxygen
P	-	Dependence variable of metal loss
P	-	Phosphorus
Pb	-	Lead
PCA	-	Principle Component Analysis
pH	-	pH
PJ	-	Permas Jaya
PS	-	Particle size
RSM	-	Response surface methodology
S	-	Salinity
SBS	-	Seabed Sediment
SCC	-	Stress Corrosion Cracking

SEM	-	Scanning electron microscope
Si	-	Silicon
SO_3	-	Content of sulphide
SO_4^{2-}	-	Content of sulphate ion
SRB	-	Sulfate-reducing bacteria
t	-	Time
T	-	Temperature
Ti	-	Titanium
TR	-	Teluk Ramunia
V	-	Vanadium
v	-	Constant regression parameters
W	-	Weight loss in milligrams
X42	-	Grade of Steel Pipelines
X65	-	Grade of Steel Pipelines
X70	-	Grade of Steel Pipelines
μm	-	Micrometre

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Corrosion is defined as the destruction of a material due to its reaction with the environment. This form of degradation that occurs on metal elements causes plant shutdowns, waste of valuable resources, loss or contamination of products and reduction in efficiency. Moreover, the costly maintenance, expensive over design and increase in the risk of accident occurrences would result in failure of the structure from the effects of corrosion (Pierre, 2007). These serious damages due to corrosion occurrences have great impact on oil/gas industry. Generally, the oil/gas industry requires laying of long transmission pipelines across different environments. Soil and seawater environments or both together, as in seabed sediment, are the common exposure environments of pipelines. This study looks into occurrence of corrosion in bare pipes exposed to seabed sediment with consideration of coating breakdown. Seabed sediment is a special soil that is covered and saturated by water. Thus far, numerous studies (Batt and Robinson, 2002; Liu et al., 2009; Ricker, 2010; and Yahaya et al., 2011a) have been conducted on the corrosion of pipelines in seawater and on-shore soil. However, studies on corroded pipelines in seabed sediment (SBS), in terms of prediction of corrosion behaviour for better understanding of pipeline integrity, remains relatively silent.

The environment (e.g. soil, sea water or seabed sediment) has been determined as one of the key factors that cause corrosion. The definition and characteristics of this variable can be quite complex. Practically, it is important to realise that the environment is a variable that can change with time and conditions (Shreir et al., 1994, Brossia and Cragnolino 2000, Lo´pez et al., 2006). All types of structures including buildings, bridges, pipelines, railways and offshore structures are subjected to corrosion at any time depending on the corrosiveness of the environment. Basically, it is important to realise that all environments are actually aggressive to a certain extent. The investigation of environmental factors carried out in this study could be used to develop a reliable corrosion growth model that can predict the future of pipelines' integrity more accurately.

1.2 Background of the problem

In corrosion science, corrosion modelling has achieved significant development for structures in land soils and seawater. To illustrate, Alamilla *et al.* (2009) have developed a mathematical model to estimate the localized corrosion damage in buried structures for soil environment. Stress corrosion cracking behaviour of X70 pipeline steel in an acidic soil solution was investigated by Liu *et al*. (2009) proposing local additional potential model. By constructing a model, Jiang *et al.* (2009) investigated the influence of gas/liquid/solid three-phase boundary geometric parameters on the cathodic oxygen reduction process of soil corrosion. Saito and Kuniya (2001) proposed a predictive model for stress corrosion cracking growth in high temperature water of stainless steel. A study was conducted by Paik *et al.* (2004) to develop a model for low alloy carbon steel used as structures of seawater ballast tanks in ships. The study was believed to be useful for designing corrosion tolerant structures subjected to the seawater environment. In addition, mathematical models for the anaerobic phases of marine immersion corrosion for the diffusion of nutrients were proposed by Melchers and Wells (2006). In spite of all the advances achieved by previous studies on models of corrosion estimations, the modelling of the corrosion growth rate in seabed sediment is still lacking sufficient consideration.

Although there are models proposed for seabed sediment, the corrosion models for seabed sediment are scarcely available. Such that, King (1980) who regionally evaluated SBS corrosion data of the North Sea. The study used table of point factors to determine the probable corrosivity of seabed sediments by weighing some parameters. Duan *et al*. (2005) carried out Fuzzy clustering analysis in China to evaluate the corrosiveness of marine sediment. Recently, predictive models started to gain interest. The work had been carried out by Huang *et al.* (2012) reported results of predictive modelling of two seabed sediment parameters in Australia. The models were applied to create prediction maps, though the report did not relate the proposed model to corrosion behaviour.

Even if the available models were tailored for seabed sediment corrosivity, the models did not consider the variability of corrosion factors, hence limited corrosion parameters were incorporated in the model. Besides that, the existing models were not designed as a function of time, an important dimension in corrosion prediction. Instead the models are only able to calculate the metal loss volume in general without any prediction capability. The limited availability of corrosion data based on long term exposure to SBS makes it difficult to establish a reliable corrosion model especially for long term prediction. Indeed, detail investigation considering various environmental variables with long term exposure of samples to SBS is vitally required. This is to provide a clearer picture about the corrosivity level of the particular tricky region and to set up a corrosion predictive model. The purpose is to introduce an empirical formula predicting metal loss through intensive study focusing on environmental variables that play important role on deciding how serious the corrosion is.

Hou *et al*. (2001) used a simple oxidation-reduction degree (ROD) for evaluating the oxidation-reduction environment of the sediment. Few parameters were considered which are directly related to the oxidation-reduction potential *Eh*, potential of the membrane electrode *Es*, and the cube root of the *Fe3+/Fe2+* value, and is inversely related to the particle size. Based on ROD, the environment was divided into areas of reduction intensity. The study by Duan *et al*. (2005) measured environmental properties and determined carbon steel coupons weight losses for only one year. In the same study, although corrosion rates were calculated, Fuzzy Cluster Analysis (FCA) was the only form of statistics involved trying to predict the corrosiveness of marine sediment. Neither previous researchers nor King (1980) who predicted the corrosiveness of SBS have considered the real path where the pipeline is laid. These research efforts are novel by combining data from site investigation and laboratory experiment with various statistical approaches in developing a predictive empirical model for the SBS area. Unlike other investigations (e.g., King, 1980, Hou *et al*., 2001 and Duan *et al*., 2005) which analysed samples of sediment from sites in other parts of the world, this study focuses on tropical environment of Malaysia whereby the in situ experiment took place in the real site of pipeline installation. The main attention is towards the mathematical model incorporating power law equation with extra investigation by design of experimental procedure (DOE).

1.3 Problem statement

External corrosion due to seabed sediment has been a recognised problem in the oil and gas industry for many years. Although various research efforts have tried to analyse it, the underlying corrosion mechanisms are not fully understood. More importantly, the studies have not put forward an inclusive procedure in order to develop predictive corrosion models. As such, a corrosion growth model is required to reliably predict the life span of corroded pipelines buried under seabed sediments. Even though evaluation of SBS corrosion has achieved good development, available corrosion data of SBS is very limited, which makes the selection of predictive model difficult. There are many uncertainties which still require further research that would be beneficial to the pipeline operators. Therefore, a detailed investigation approach is needed to enrich the data base in the field and to build up appropriate and reliable models to predict the remaining life span of corroded pipelines.

There is another concern about corrosion factors in seabed sediment as external environmental factors influence the metal loss. The climate of high average annual temperature, humidity and rainfall would have detrimental effects on steel pipelines. In addition, there is variety of sediment conditions with different levels of corrosiveness faced by the buried pipelines, depending on combination of existing environmental parameters. These various surrounding conditions may contribute to failures in coating, inhibitors or cathodic protection. Therefore, environmental parameters are worthy of consideration to determine their level of influence towards corrosiveness of steel in seabed sediment. Concerns also rose regarding the limited number of corrosion parameters with no comprehensive statistics. Besides the limited statistics considered in the previous studies, the literature revealed short term experiments, thus providing insufficient data to generate a reliable corrosion predictive model.

There are many concerns regarding the external corrosion behaviour of oil/gas pipelines buried under seabed sediments. However, the amount of information on the behaviour of steel pipelines subjected to environmental conditions is still very limited. The outcomes of past research show inconsistencies in the results on the degradation effect of seabed sediment environment on steel structures (Hou, 1986; Hou, *et al.*, 2001; Duan, *et al.* 2005). Therefore, it is crucial to study the corrosion effect on pipelines buried under seabed sediment. This is especially true in a country which experiences incredible wet and dry cycles through rain, moisture and dry seasons. Nevertheless, this study takes into account the prior studies pay less attention to consider conducting the experiment on the same path where the pipelines are buried.

1.4 Aim and objectives of research

The aim of this work is to contribute to a better understanding of metal loss behaviour for pipeline steel buried under seabed sediments in order to reliably predict the growth of external corrosion on the pipelines' outer surface under the worst case scenario. Based on that, the main objectives of this research are to:

i. Examine and identify the metal loss for pipeline steel coupons buried under seabed sediments' environment.

ii. Investigate the relationship between seabed sediments environmental factors and metal loss of pipelines' steel.

iii. Develop external corrosion growth model for pipelines exposed to seabed sediment conditions.

1.5 Scope of research

This research is a continuation of limited studies on the corrosion of steel structures in seabed sediment environments. Therefore, the scope of this work is to investigate the external corrosion of bare steel pipelines only, regardless the effect of internal corrosion or its effect on the pipe. The investigation reflected the condition where bare pipelines are exposed to the real environment. Thus, the worst case scenario is expected due to coating breakdown. In this study, tropical seabed sediment is considered for conduction of an in-situ experimental long term study supported by a laboratory investigation. API X70 pipeline steel is used to investigate the corrosion under the effect of the seabed sediment environment, specifically near shore areas.

1.6 Significance of research

Findings from this research would provide significant information on seabed sediment and its corrosiveness highlighting the influential environment factors towards steel pipelines. Besides that, the study would show the metal loss behaviour of pipelines' steel when subjected to different types of seabed sediments. The study would also contribute towards the advancement of knowledge on the use of predictive models to assess corrosion growth in pipelines. In this study, experimental works have been conducted to provide sufficient data for building model predicts ed metal loss, and hence corrosion growth rate in reliable and accurate manner. This contribution is expected to have a positive impact on pipeline integrity management planning, highlighting the risk created by external corrosion of pipelines subjected to seabed sediments.

1.7 Thesis outline

Chapter One presented the introduction that gives an overall view of this research. It starts with the background of the problem followed by explanation on the research problem before moving further to the objectives and scope of this study. Then, the significance of the study is highlighted briefly before the thesis layout is presented at the end of the section.

Chapter Two of this thesis provides a review of selected major issues relating to the problem of steel pipeline corrosion under seabed sediment. It begins with an introduction to basic corrosion definitions and major issues in the pipelines' corrosion research. Emphasis is placed on the major factors in relation to the corrosion rate in seabed sediment. Highlighting is given for corrosion evaluation and prediction besides appropriate techniques for evaluating this rate. Finally, a discussion and conclusion section focuses on those issues to be further studied in this thesis.

In Chapter Three, the broad research plan and experimental methods utilised for this thesis are described. They have been developed on the basis of the conclusions from the literature review. The research plan includes four main parts. The main experiments were performed for long term use with steel coupons made of X70 pipe steel. The specimens were submerged in seabed sediment; this experiment, namely Component I, followed by simulation in the laboratory was named Component II. The influence of sediment parameters was studied in Component III using response surface methodology supported by electrochemical testing as a Component IV.

Chapter Four presents details of the experimental results of the pipeline steel specimens monitored over two years in seabed sediment. The influences of sediment environmental factors on metal loss are presented and evaluated. Statistical analysis of metal loss with seabed sediment parameters are conducted showing the developmental process of the corrosion predictive model. After that, the results of simulated work from Component II are presented. The experimental design and experimental results are presented with single response modelling. Using response surface methodology, an electrochemical corrosion study as Component IV is presented supporting Component III. This thesis develops a predictive formula to model the experimental metal loss behaviour of pipe steel under the influence of seabed sediment.

Chapter Five discusses the main results of the experiments, which involve the study and comparison of the corrosion rate of steel in different components. Evaluation of metal loss behaviour in seabed sediment is conducted followed by comparison between actual and simulated field works. Arguments were also carried out regarding the relationship of seabed sediments factors and metal loss. Finally, there is discussion on the statistical approach to corrosion of pipelines in seabed sediment, and the chapter ends with a summary.

Chapter Six summarises the major conclusions drawn from the investigations of this thesis and the recommendations which have also been outlined for future research. Overall, this thesis reports new experimental data in the study of the corrosion rate of pipeline steels submerged in seabed sediment and the influence of environment parameters. These experimental data have led to proposal of corrosion predictive model for steel in seabed sediment.

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