Parametric Study on the Factors of External Corrosion of Offshore Pipelines in Malaysia

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Abstract: - Offshore pipeline systems constitute a key element of the oil and gas industry. Hence, ensuring that each pipeline is designed, fabricated and operated in a safe, reliable and cost-effective manner is crucial, if not necessary. Corrosion is a significant issue in the operations of an oil facility, deteriorating the structural strength and integrity of a pipeline. Failure at any point along the pipeline could lead to oil leaks, with serious financial and environmental consequences. Although corrosion standards used locally are adapted from established codes, they could not able to fully represent local conditions. Thus, there is a need for a regional yardstick. As such, eleven pipelines of an operating field in the Malay Basin are selected to be analyzed for this study. The investigation aims mainly to analyze and interpret the parameters that affect external corrosion of pipelines and to develop a corrosion rate model for pipelines specific to the local region for more economical and reliable designs of pipelines. General linear method and correlation models are employed and further discussed in this paper.

Key-Words: - external corrosion; offshore pipelines; general linear method; parametric study.

1 Introduction

The development of offshore pipelines plays a vital role in the advancement of the oil and gas industry. Steel pipeline systems represent a key financial investment in the industry given their ability to withstand the high pressure and temperatures involved in transporting crude oil and natural gases [1]. However, as any engineering structure, steel pipelines do fail. Although pipeline failures rarely lead to public fatalities, they could be adversely costly affairs in terms of replacement, repair and remedial work [2][3].

A single pipeline failure can cost tens of millions of dollars if it occurs in an environmentally-sensitive area [3]. In 2006, BP Exploration Alaska, Inc. underwent an orderly and phased shutdown of the Prudhoe Bay oil field following the discovery of unexpectedly severe corrosion and a small spill from a Prudhoe Bay oil transit line. This incident reduced oil production of the United States by an estimated 400,000 barrels per day and in turn, hiked up world oil prices. At least 73 percent of the pipeline will need to be replaced because of the extensive corrosion, according to company officials [4][5].

One of the most common causes of damage and failures in offshore transmission pipelines is corrosion [6], due to aggressive environments [7] [8].

As corrosion could not be stopped, failure at any point along the length of a pipeline could lead to costly repairs or even oil leaks, with serious financial consequences. Assessment method is key in gauging the severity of such defects when they are detected in pipelines [6].

2 Fundamentals of Study

2.1 Problem Statement and Objectives

Pipeline codes and standards were developed as industrial guides to support the design, construction, and operations of pipelines. Generally, for operators with insufficient resources in developing their own codes, available codes and standards were adapted to suit local operating conditions [9].

The quandary of this practice is that these codes may never fully represent the adapted local conditions and environment [10]. Hence, the occurrences of the over-designed or under-designed pipelines [11]. This would also cost unnecessary maintenance and risk mitigation actions which increases operating costs.

As such, it is crucial in determined the 'localized' parameters that affects the corrosion of a pipeline. A sound asset maintenance plan will be able to improve the pipeline system, and at the same time avoiding unnecessary repairs.

The focus of this paper is to analyze and interpret pipeline data of an oil field off Peninsular Malaysia with regards to corrosion. Characteristics which contribute to corrosion of pipelines are then identified. Through parametric analysis, a parametric model is developed to predict corrosion rate for pipelines within the region.

The model would act as an extension to current arrays of corrosion analysis and assessment. With the inclusion of the most influencing corrosion parameters, this model will eventually lead to produce a more optimized and economical design and operations of pipelines, especially in Malaysian waters.

2.2 Scope of Study

This study covers eleven offshore pipelines of an unnamed oil field in the Malay basin was chosen to be studied. An inline inspection using Magnetic Flux Leakage (MFL) was carried out to determine the internal and external condition of the pipelines. The design and operational characteristic for eleven field pipelines used in this analysis were sorted accordingly. The properties of the pipelines are as the following.

Table 1: General properties of the studied pipelines

Material Type	Carbon steel
Material Grade	X42, X52, X60, X65
Predominant Pipe Type	Seamless
Water depth	~76.0 m

Table 1 shows the general properties of the pipelines in this study. Statistical analysis was done using PASW Statistics 18 in the development of a parametric corrosion model for local conditions.

3 Corrosion

3.1 Phenomenon of Corrosion

Corrosion causes gradual decay and deterioration of pipes, both internally and externally. It can reduce the life of a pipe by eating away at the wall thickness. Under certain conditions, the time for the decay to cause the pipe to fail is as short as five years [12]. Corrosion can also result in encrustation inside the pipe, reducing the carrying capacity of the pipe to a point that it has to be replaced to provide the flow needed.

Steel is essentially an unstable state of iron and corrosion is the process of iron returning to its natural state. The primary driving force of corrosion is due to natural electrochemical reaction with its environment. When metal is transformed from the atomic to ionic state, the process of deterioration and degradation occurs.

3.2 Parameters affecting pipeline corrosion rate

3.2.1 Pipeline Age

As a pipeline ages, it is affected by a range of corrosion mechanisms, which may lead to a reduction in its structural integrity and eventual failure. Due to exorbitant costs of a downtime, repairs, or replacement, pipelines are often kept in operation even though signs of corrosion are visible on their external surface. Most of these pipelines are allowed to operate after following the reevaluation of the maximum admissible internal pressure of the product being transported [13].

3.2.2 Temperature

At higher temperatures chemical reactions speed up. Generally, a 10°C rise in temperature doubles the rate of reactions in the corrosion cell. Even temperature variations within a single piece of metal can cause the warmer portions to become anodic, leading to severe metal loss. Therefore the potential for corrosion is greatest in heat exchangers where the temperatures are hottest [14].

3.2.3 Water Velocity

Water velocity is another factor affecting corrosion [15]. Particles in fast moving water are likely to wear away chemical coatings on the metal to protect it. Otherwise, solids in slow moving water are likely to settle on to metal surfaces, preventing chemical treatments from reaching the metal.

3.2.4 Galvanic Corrosion

Galvanic corrosion is caused when two different metals, joined together in construction of the cooling system, are exposed to the water [14]. In the galvanic series, which lists metals according to their tendency to corrode, the lower metals corrode first. Magnesium and galvanized iron is very active, gold and silver more stable. The further apart two metals are on the chart, the greater tendency for galvanic corrosion if they are joined.

4 Strategy and Tools

4.1 Parametric Analysis

Parametric and nonparametric are two broad classifications of statistical procedures. Parametric statistical procedures rely on assumptions about the shape of the distribution (i.e., a normal distribution) in a population and about the form or parameters (i.e., means and standard deviations) of the assumed distribution. While non-parametric procedures do not rely on such assumptions [15].

Nonparametric procedures generally have less power for the same sample size than the corresponding parametric procedure if the data truly are normal.

Given the nature of corrosion is random and the time series of most natural processes are normally distributed, a parametric corrosion model is recommended.

Parameters refer to quantities such as means, standard deviations and proportions. Common parametric procedures include Analysis of variance (ANOVA), Pearson coefficient of correlation, paired t-test and two-sample t-test.

4.2 General Linear Model

Field data is often accompanied by noise. A process of quantitatively estimating the trend of a pool of data, also known as regression, therefore becomes necessary. The modelled relationship between a scalar dependent variable (y) and one or more explanatory variables (x) is called linear regression.

In the presence of randomness, the relationship between a dependent variable and an independent variable will not be unique; given the value of one variable, there is a range of possible values of the other variable [16]. Regression analysis allows us to obtain a curve with minimal deviation from all data points by the method of least squares.

In this study, corrosion rate is termed the dependent variable 'y' and the other parameters as independent variables 'x'. The relationship between corrosion rate and other pipeline information is established through a multivariate general linear model. The general linear model is a parametric modeling technique and is an extension of linear multiple regression for a single dependent variable. Both techniques quantify the relationship between several independent or predictor variables and a dependent or criterion variable.

However, the general linear model allows for linear transformations or linear combinations of multiple dependent variables. This characteristic gives the general linear model important advantages over multiple regression models, which are fundamentally univariate (single dependent variable) methods.

$$Y = b_0 + b_1X_1 + b_2X_2 + \cdots + b_kX_k \tag{1}$$

Equation 1 illustrates a linear equation. k is the number of predictors. The regression coefficients ($b_1 \ldots b_k$) represent the independent contributions of each independent variable.

5 Results and Discussion

5.1 Parametric Analysis

Table 2: Mean, Standard Deviation and Number of Samples, N, of Design and Operational Information

Pipeline Information	**Mean**	**Std. Deviation**	**N**
Corrosion Rate	0.12127	0.092398	11
Age	19.18	2.523	11
Length	3.964	1.5788	11
Outer Diameter	251.491	75.0782	11
Nominal Wall Thickness	11.5545	1.76202	11
Material Type	1.00	0.000	11
Material Grade	2.73	0.786	11
Concrete Coating Thickness	25.309	0.2071	11
External Coating Type	2.18	0.603	11
Predominant Pipe Type	1.27	0.467	11
Design Temperature	58.600	14.4083	11
Operating Temperature	49.36	17.013	11
Design Pressure	140.091	11.5396	11
Operating Pressure	47.055	36.4506	11
Maximum Allowable Operational Pressure (MAOP)	116.073	49.0650	11
Test Pressure	188.627	32.1440	11
Product	2.09	1.044	11
Content Density	581.6764	467.40872	11

Design Life	20.00	0.000	11
Water Depth	77.891	1.8913	11

Table 2 illustrates the Mean, Std. Deviation and number of samples, N, of Design and Operational Parameters of the eleven pipelines.

$$\text{Range of Corrosion rate} = \text{Mean} \pm \text{Std. Deviation} \quad (2)$$

$$\text{Max} = 0.12127 + 0.0924 = 0.214 \text{ mm/year}$$
$$\text{Min} = 0.23237 - 0.0924 = 0.029 \text{mm/year}$$

Tabulations resulted in mean values of the corrosion rate to be 0.12127 mm/year and a standard deviation of 0.092398. From Equation 2, it concurs that the measured corrosion rates occur between 0.214 mm/year and 0.029 mm/year.

An evaluation of three pipeline design guidelines is done to gauge the extent of external marine atmospheric corrosion rate accepted by the industry globally.

Table 3: Comparison of Proposed External Marine Atmospheric Corrosion Rate for Offshore Pipelines

Design Guidelines	**Proposed External Marine Atmospheric Corrosion Rate**
ASM Metal Handbook Volume 13, Marine Corrosion, pg. 2406 [17]	0.025 mm/year - 0.79 mm/year
API 581 (2000), Appendix N-1 [18]	0.05 mm/year
NACE Papers & Experts point of view	0.1 mm/year - 0.2 mm/year

Table 3 demonstrates the variation in proposed corrosion rate accepted by the industry. The proposed range of corrosion rate is between 0.025 mm/year and 0.79 mm/ year. Mean rate is 0.4075 mm/year. This comparative exercise clearly attests the validity and severity of the measured mean corrosion rate. 0.1215 mm/year falls below the proposed 0.4075 mm/year. There is a possibility that the pipelines may be overdesigned.

5.2 General Linear Method

Pearson product-moment correlation coefficients were computed to estimate the degree of association between two quantitative variables. The outcome indicates that few of the observed relationships were positive and strong. The positive correlation means that as one variable increases in value, the second variable also increases in value

It is observed that the strongest correlation was between corrosion rate and operating temperature with correlation coefficient, r = 0.692, indicating that higher operating temperature contributes to a higher corrosion rate. There was a positive correlation between the two variables, r = 0.692, n = 11, p = 0.009.

In contrast, there are variables with negative correlations. These variables do not affect the corrosion rate.

The correlation matrix shows that the most significant factors affecting corrosion rate are as follows; operating temperature (r = 0.692), age (r = 0.692), external coating type (r = 0.530) and design temperature (r = 0.483).

Applying a one tailed test to all the correlations, it is observed that there is statistical significance between y and a few parameters, which are external coating type (p = 0.047), MAOP (p = 0.042), design pressure (p = 0.02) and age (p= 0.017).

The "Model Summary" box gives goodness of fit measures and measures of significance for the entire model.

Table 4: Model Summary

Model	**R**	**R Square**	**Change Statistics**				
			R Square Change	**F Change**	**df1**	**df2**	**Sig. F Change**
1	1.000[a]	1.000	1.000		10	0	

a. Predictors: (Constant), Water Depth, Content Density, Length, Ope. P, Ext. Coating Type, Conc. Coating Thck. , Age, Dsgn.T, Test. P, Mat. Grade
b. Dependent Variable: Corr. Rate

Table 4 above provides the R and R^2 value of the model. R is known as the correlation coefficient while R^2 is the coefficient of determination. This value determines how much of the variation in one variable is due to the other variable.

The R value of 1.0 is the multiple correlation coefficients between the predictor variables and the dependent variable. Similarly, R^2 is 1.000. Hence, it is established that all variations in the outcome is determined by the predictor variables.

Table 5: Coefficient Table

Coefficients						
Model		Unstandardized Coefficients		Standardized Coefficients	t	Significance
		B	Std. Error	Beta		
1	Constant	4.875	0		.	0
	Age	.018	0	.485	.	0
	Length	.023	0	.401	.	0
	Mat. Grade	-.108	0	-.920	.	0
	Conc. Coating Thck	-.129	0	-.288	.	0
	Ext. Coating Type	.162	0	1.056	.	0
	Dsgn.T	0.03	0	.452	.	0
	Ope.P	0	0	-.057	.	0
	Test. P	.001	0	.238	.	0
	Water Depth	-.030	0	-.615	.	0

Table 5 above gives information about the independent variables. The "B" column under "Unstandardized Coefficients" provides the regression coefficients of the model. Note that a few parameters have been omitted from the analysis due to collinearity issues.

Based on Equation 1, the empirical general linear model can be represented by Equation 3 below:

Corrosion rate = 4.875 + 0.018(Age) + 0.023(Length) – 0.108(Material Grade) – 0.129(Concrete Coating Thickness) + 0.162 (External Coating Type) + 0.003 (Design Temperature) + 0 (Operating Pressure)
+ 0.001(Test Pressure) – 0.03(Water Depth) (3)

Equation 3 estimates the predicted value of corrosion rate that will occur depending on the variables present. It is observed that for external coating type, concrete coating thickness and material grades are key external corrosion factors of the study area.

Table 6: Tested Corrosion Model

Model	**Unstandardized Coefficients**	**Mean Values**	**B* Mean Values**
	, B		
Constant	4.875		4.875
Age	.018	19.18	0.34524
Length	.023	3.964	0.091172
Mat. Grade	-.108	2.73	-0.29484
Conc. Coating Thck	-.129	25.309	-3.264861
Ext. Coating Type	.162	2.18	0.35316
Dsgn.T	0.03	58.6	1.758
Ope.P	0	47.055	0
Test. P	.001	188.627	0.188627
Water Depth	-.030	77.891	-2.33673
Corrosion Rate (mm/year)			0.132598
Corrosion Rate * 20 years (mm)			2.65196

Table 6 shows the computed corrosion rate, tested using mean values calculated in Table 2. From the corrosion model, the established baseline of overall corrosion is approximately 2.652 mm/lifespan for a 20-year design life.

Lastly, scatter plots are used to study the possible correlation between an input and an outcome. Even though a scatter plot depicts a relationship between variables, it does not indicate a cause and effect relationship.

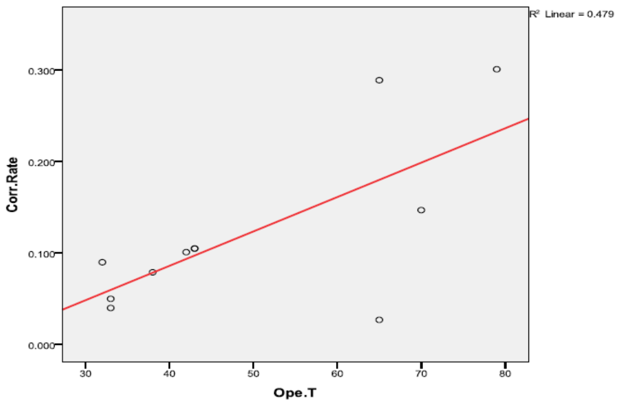

Fig. 1: Scatter plot of Operating Temperature vs. Corrosion Rate

Based on Figure 1, a positive relationship is observed between the two sets of data. An increase in operating temperature correlates with an increase in corrosion rate of pipeline. Operating temperature has the highest of regression value among other pipeline characteristics and environmental input (r = 0.692). This figure accounts for approximately 70% of all corrosion on pipelines within the study area. The remaining unaccounted for inputs may be affected by uncontrolled phenomena such as metocean criteria and salinity.

6 Conclusion

A site-specific general linear model can be formed to predict corrosion rates depending on the variables present. The model will be very beneficial for the rapid assessment of corrosion.

The corrosion model established the baseline of external corrosion to be 2.65 mm/ lifespan for a 20-year design life, which is similar to the recommended values of PETRONAS Technical Standard of 3 mm/lifespan [19]. Nevertheless, the discrepancies should be reconsidered as the difference of 0.35 mm could be significant in terms of economic and technical consequences.

The proposed corrosion model serves an effective initial measure to corrosion in local environments. Equation 3 can contribute as quick forecasting tool of future external corrosion rate in the design and maintenance of pipelines using PASW Statistics 18.

References:

[1] G. Barbey. (2006) What's in the Pipeline?: Pipelining & Refining, *O&G Next Generation*, Issue 1, E-Magazine.

[2] A, Patel. (2006, August 8). *Corroded Alaska Pipeline Untested for 14 Years* , August, 2006 [Online]. Available: http://abcnews.go.com/blogs/headlines/2006/08/bp_oil_field_sh/

[3] D.J. Hovey, E J Farmer. Liquid Pipeline Accident Statistics and Failure Rates, The Int. Pipeline Monitoring and Rehabilitation Seminar, Houston Texas, January 1994.

[4] W. Loy. *State and BP are still far from leak claim decision*. Petroleum News, July, 2012 [Online] Available: http://www.adn.com/2012/07/27/2559630/state-and-bp-are-still-far-from.html

[5] J. Roach. *Alaska Oil Spill Fuels Concerns Over Arctic Wildlife*, National Geographic News March, 2006 [Online], Available: http://news.nationalgeographic.com/news/2006/03/0320_060320_alaska_oil.html

[6] C. Andrew & P. Hopkins (2004). "The Assessment Pipeline Pigging and Integrity Management Conference" Amsterdam, The Netherlands, May 2005

[7] M. Ahammed. Probabilistic Estimation of Remaining Life of a Pipeline in The Presence of Active Corrosion Defects. *International Journal of Pressure Vessels and Piping* , 75, 321-329, 1998

[8] C. Andrew & R.A. Palmer. *Subsea Pipeline Engineering* (2nd Edition), PennWell Books, July 2008

[9] D. Alkazraji. *A Quick Guide to Pipeline Engineering*, Cambridge, Woodhead Publishing Limited, 2008

[10] Z. Mustaffa, System Reliability Assessment of Offshore Pipelines, Ph.D dissertation, Faculty of Civil Engineering and Geosciences, Delft Uni. of Technology, The Netherlands, 2011

[11] K. Lawson. Pipeline Corrosion Risk Analysis – An Assessment of Deterministic and Probabilistic Approaches, *Anti-Corrosion Methods and Materials*, Vol. 52, No. 1, pp. 3-10, 2005

[12] *Corrosion,* Minnesota Rural Water Association Corrosion [Online]. Available: http://www.mrwa.com/OP-Corrosion.pdf

[13] T.A. Netto. The effect of corrosion defects on the burst pressure of pipelines. *Journal of Construction Steel Research* , pp.1185-1204, 2005.

[14] *Beginners Guide to Corrosion*, National Physical Laboratory, 2003 [Online]. Available: http://www.npl.co.uk/upload/pdf/beginners_guide_to_corrosion.pdf

[15] J.E. Walsh, *Handbook of Nonparametric Statistic*, D. Van Nostrand, Princeton, N.J., 1962

[16] A.H.S. Ang, & W.H. Tang. *Probability Concepts in Engineering, Emphasis on Applications to Civil and Environmental Engineering* (2nd Edition), New York, John Wiley and Sons, Inc, 2007

[17] ASM Metal Handbook Volume 13, Marine Corrosion, pg. 2406

[18] American Petroleum Institute, Risk Based Inspection Base Resource Document, API Publication 581 (1st Edition), 2000

[19] PTS 20.214, Pipeline and Riser Engineering, 2008