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TOP-OF-LINE SPATIAL CORROSION PREDICTION IN GAS PIPELINES

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ABSTRACT
The top-of-line corrosion (TLC) is corrosion observed at the upper section of a pipeline, as measured from the circumference of the pipe. The magnitude of TLC is mostly determined using the mechanistic condensation models. The spatial prediction of TLC, however, has not been of the interest among researchers, so as to know at what o'clock orientations (with respect to pipeline cross section) corrosion may accumulate the most. TLC spatial prediction is directly related to the release of corrosion inhibitor (CI) in the pipeline. The probability of retaining CI at the upper part of the pipeline is always a challenge due to the inconsistency of the operational flow parameters coupled by acceleration due to gravity. Thus, there is the need to properly understand the development of TLC with regard to its space. This paper proposes the analysis on TLC spatial prediction to be carried out by means of statistical approaches called the Exploratory Data Analysis (EDA) due to the nature of corrosion that are random. EDA is a simple tool that is able to summarize the main characteristics of TLC data using visual methods. The TLC data was taken from a gas pipeline operating in Malaysian offshore region. A median polish model (of EDA) for the TLC was later generated. A prediction table was also developed to guide users on the estimate of TLC in gas pipelines with regards to the o'clock orientations of the pipe circumference.

1 INTRODUCTION
Corrosion is the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces deterioration of the material and its properties. In the oil and gas industry, corrosion weakens the durability of the pipes and in some cases leakage occurs resulting in serious environmental damage to the surroundings. Corrosion in a pipeline can be observed either at the internal or external side of the pipeline wall. Internal corrosion in a pipeline take place all around the pipe wall, and can be simply classified into two categories based on their location in the pipe, namely the top-of-line (TLC) and bottom-of-line (BLC).

This paper focuses mainly on the TLC corrosion in a pipeline. The TLC has higher concern than the BLC corrosion due to the complexity of corrosion process, the difficulty of analyzing them and there are various factors affecting the TLC corrosion. TLC has more attention in offshore industry due to the complexity of corrosion and the difficulty to maintain the

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defects. The difficulty lies on how to protect the top side of pipe where injection of inhibitor method is impossible because of low water existence.

This paper proposes a statistical model for the spatial prediction of TLC corrosion based on an approach called the Exploratory Data Analysis (EDA) technique. Most prediction models for corrosion in the pipeline are derived using the knowledge of traditional statistical methods such as the Analysis of Variance (ANOVA). The ANOVA approach relies on stringent assumptions such as normal distributed data etc. Unfortunately, the nature of corrosion data which are random may not always comply with the assumptions made in ANOVA. Outliers are also present in the corrosion data resulting in data that are more skewed and are not normally distributed. Due to the violation of these assumptions, the use of ANOVA method in the spatial corrosion prediction of TLC corrosion may not be appropriate. These assumptions do not hold and therefore there is a need to employ another alternative method known as EDA technique.

2 TOP-OF-LINE CORROSION (TLC)

Condensation is the accumulation of water on the pipe wall due to the differences of temperature between internal and external section of the pipe with the temperature of the gas flowing. Top-of-line corrosion (TLC) occurs when a wet gas transport throw the pipe internal wall allowing the wet gas to condense on the internal pipe wall by the force of heat exchange between the outside environment and inside environment temperatures (Fig. 1).

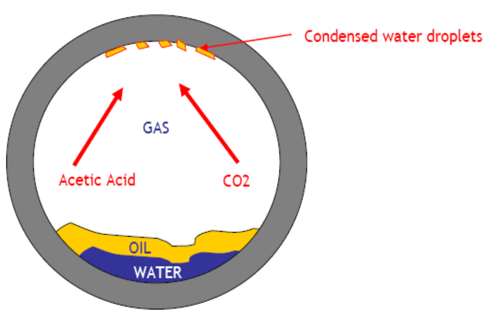


Figure 1. Water condensation inside a pipe wall

The TLC is primarily a concern in the first few kilometers of wet gas pipelines with relatively high inlet temperatures, as the water condensation rate is rapidly reduced when the temperature decreases. Bottom-of-line (BLC) corrosion occurs due to the gravity force where the water condensed at the top of line drives down through the internal wall to the BLC. The condensation rate does not influence the corrosion rate at the bottom of line, the reason being the significant amount of water presence on the bottom of line.

The condensing water is unbuffered with low pH, but can become rapidly saturated or supersaturated with corrosion products, giving rise to increased pH and possibility for iron carbonate film formation [1]. The TLC corrosion rate then becomes dependent on the water condensation rate and the amount of iron which can be dissolved in the condensing water [1].

3 TLC CORROSION MODEL

TLC corrosion studies are mainly concerned on the prediction of the magnitude of corrosion rather than its development in space. Because of this, more literature can be found on the model prediction itself, as described in Section 3.1 and 3.2. To the best knowledge of the authors, there is hardly any work on TLC spatial prediction, thus not much literature can be reported on this aspect.

3.1 de Waard, Lipucor and Hydrocor Models

One of the most widely used CO_2 corrosion model is a model developed by de Waard and coworkers in 1975. It was based on small scale experiments. The primary dependence factors were temperature and pCO_2. The Hydrocor model, which was developed by Shell to combine corrosion and fluid flow modeling, is Shell's preferred tool for CO_2 corrosion prediction in pipelines. The Lipucor corrosion prediction program is developed by Total and is based on both laboratory results and a large amount of field data.

The de Waard model includes a very simplified model for top-of-line corrosion, but little attention was paid to top-of-line corrosion until recently, when top-of-line corrosion has been included in the Lipucor and Hydrocor models [1].

3.2 Mechanistic Condensation Model

A mechanistic condensation model, which was previously developed by Srdjan Nešić and his research group, were established based on the corrosion growth rate [2]-[6]. The corrosion model is concerned about the most important parameters and its effect on TLC corrosion such as the gas temperature, CO_2 partial pressure, velocity of gas, condensation rate and acetic acid (HAc) concentration. These parameters are translated into mathematical equations in the model, which can eventually predict the effect of corrosion on pipeline with time.

The simulated mathematical model was later compared with experiments by [6], as shown in Fig. 2. Several arguments have been debated when comparing the normalized corrosion rates (CR) obtained from mathematical model and those from experiments, for which a summary on this is as given in Table 1.

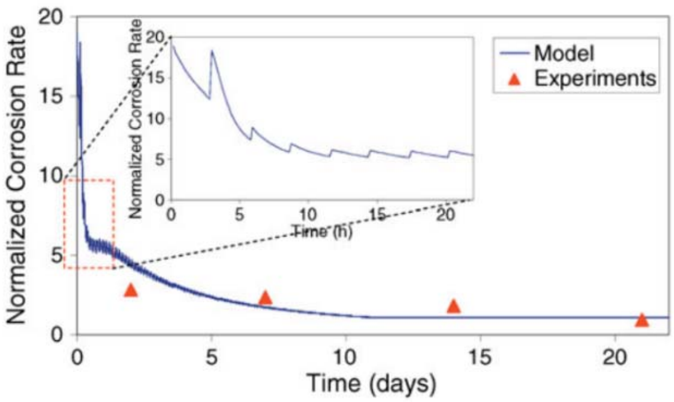


Figure 2. Comparison between the model and long term experiments (T=70°C, V= 5 m/s, P = 3 bar, PCO_2= 2 bar, condensation rate= 0.25 mL/m^2 /s) [6]

Table 1. Comparison between outcomes from the mathematical experimental models

Concerns	Remarks
Short term CR prediction *i.e.* 2 days	Mathematical model over predicted CR compared to the experiments.
Long term CR prediction *i.e.* 2 to 20 days	Good agreement between mathematical model and experiments.

The discrepancy observed in the short term CR prediction might be resulted from [6]:

- Approximation of a 2D problem in a 1D approach.
- Corrosion rate at the beginning is very high because of the initial condensed water which is very corrosive.
- Corrosion starts to reduce with time because of protective scales formation on metal surface. Over time, the scales becomes denser, thus the corrosion decrease dramatically and remains at very low state in long terms.
- Formation of scales retards the corrosion even at low temperature (e.g. 40°C).

4 CORROSION INSPECTION DATA

Pigging in the maintenance of pipelines refers to the practice of using pipeline inspection gauges or *pigs* to perform various operations without stopping the flow of the product in the pipeline. Pipeline pigs are inserted into and travel throughout the length of a pipeline driven by a product flow. They were originally developed to remove deposits which could obstruct or retard flow through a pipeline. Their occurrence usually does not interrupt production. The in line inspection (ILI) tool or *smart/intelligent pigs* (IP) are used to provide an overview (mapping) of the condition of a corroded pipe. The tool is extensively used to carry out inspection and maintenance works on corroded pipelines. The IP tools are not only able to provide information on the magnitude of corrosion, but also their location and orientation along the pipe.

The most common parameter used to describe corrosion is the depth, *d*. The amount of *d* is described by depth of penetration (mm) or amount of wall loss with respect to pipeline wall thickness (%) while the location can be described by two means, namely (i) distance as measured along the pipeline longitudinal view, and (ii) orientation as described by the o'clock position with respect to pipeline cross section view (Fig. 3).

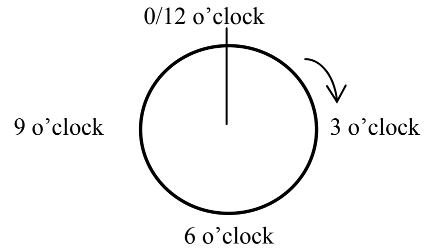


Figure 3. Cross section view of corrosion defect distributions as captured by an IP tool in a pipeline

5 PIPELINE DATA

The analysis in this paper utilized a 28" diameter steel offshore pipeline type API 5LX-65 containing internal corrosion [7]. The pipeline transports gas from shallow water of approximately less than 70 m to onshore. The site was at Kerteh, Terengganu, the east coast of Peninsular Malaysia, about 130 km in the South China Sea (5°50'30"N, 104°07'30"E). The pipeline was installed in 1999 and has been in operation for more than ten years. A total of 332 internal corrosion defects of various types were reported by the IP tool along the 128 km long pipe based on an inspection activity carried out in 2007 [7]. The minimum, average and maximum wall losses (corrosion depth, *d*) were 1, 7.6 and 29%, respectively, calculated with respect to the actual wall thickness.

Only one pipeline data was analyzed in this paper for the sake of illustration. When more data are available, it is hoped that the validation can be made further.

6 RESULTS AND DISCUSSION

6.1 Presentation of Corrosion Data

In order to simplify the data input into the analysis, the *o`clock orientation* of the pipe is divided into two halves, namely the TLC and BLC, as measured from the cross section of the pipe (Fig. 4).

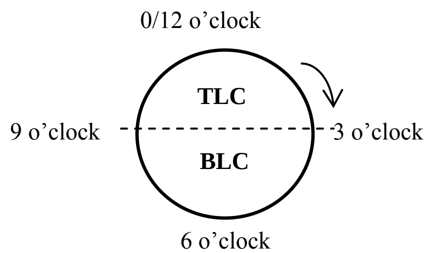


Figure 4. A pipeline divided into top and bottom halves section, resembling a TLC and BLC corrosions scenarios, respectively.

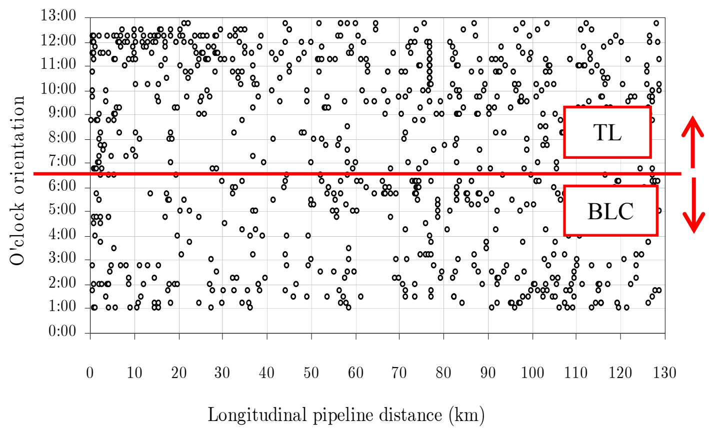


Figure 5. A representation of corrosion data (depth, *d*) as reported by an IP [7]

Fig. 5 describes internal corrosion reported at the pipe circumference, as measured along the length of the pipeline. Apparently, corrosions were observed at all o'clock orientations along the length of the pipeline. Some orientations experienced more corrosions than others. Nevertheless, no definite conclusions can be made about the amount of corrosion penetration at each point, thus the figure would not be able to provide sufficient information about corrosion condition in the pipeline.

For the sake of simplicity, the plot in Fig. 5 can be separated into two similar portions, namely the upper and lower halves with respect to the pipe circumference. Herein, the corrosions in the upper and lower portions of the pipe can be classified as the TLC and BLC corrosions, respectively.

6.2 Exploratory Data Analysis (EDA)

In this paper, corrosion data from the TLC section of the pipe would be used in the analysis using a statistical approach called the *Exploratory Data Analysis* (EDA) techniques. Note that EDA techniques are largely due to the work by [8]. The tools of EDA are applied to discover new knowledge and in this respect outliers would play a central role [9]. Note that the median is an important concept in the EDA. The tools of EDA techniques which are applied in this paper are Stem and Leaf Display, Letter Value Display, Box Plot, and Median Polish. Details on these can be found in [9] and [10].

6.2.1 Stem and Leaf Display

A *Stem and Leaf Display* is a representation of quantitative data in a graphical format which is similar to a histogram, to assist in visualizing the shape of a distribution. It displays whether the data is symmetrical, left skewed, bimodal or multimodal. It also reveals whether or not there are large gaps in the data set.

```
Stem-and-leaf of TLC
N = 332 defects
Leaf Unit = 1.0
 19   0  1111111111111111111
 58   0  2222222233333333333++++++++
124   0  444444444444444444555555555555555555555+
(74)  0  666666666666666666777777777777777777777+
134   0  888888888888888888999999999999999999999
 95   1  00000000000000000111111111111
 66   1  222222222222222223333333333333
 36   1  4444444444555555
 20   1  666667777
 11   1  8889
 7    2  01
```

Figure 6. Stem and Leaf Display of the TLC corrosion (depth, *d*) data

The stem and leaf contains more information in the sense that the actual data values are displayed. Fig. 6 presents the stem and leaf data for the TLC corrosion data. The figure shows a skewed data mostly to the right, hereby, the corrosion distribution is dominated in a limited area of the pipe. The median positioned within the result forth row (leaf), which indicates in parenthesis (). The figure reveals that corrosions data are more concentrated to the left portion of the median.

6.2.2 Letter Value Display

Another approach of understanding the data is through the *Letter Value Display* (Fig. 7). The figure gives a quick summary of the data set as well. The figure illustrates that the corrosion data is skewed to the right as the mid values are increasing. Mid values indicates that the data is approximately symmetrical.

```
Depth  Lower    Upper      Mid  Spread
     N=     332
     M    166.5  7.000    7.000    7.000
     H     83.5  5.000   10.000    7.500    5.000
     E     42.0  3.000   13.000    8.000   10.000
     D     21.5  2.000   15.000    8.500   13.000
     C     11.0  1.000   18.000    9.500   17.000
     B      6.0  1.000   21.000   11.000   20.000
     A      3.5  1.000   25.500   13.250   24.500
     Z      2.0  1.000   27.000   14.000   26.000
     1    1.000  29.000   15.000   28.000
```

Figure 7. Letter Value Display of the TLC corrosion (depth, *d*) data

From the display below, the median impact factor was 7.00. The minimum impact factor was 1.00 while the maximum was 29.00 and the range was 28.00. The letter (H) represents the word *hinge*. The lower hinge spread is an important parameter to be used in the *Median Polish* modeling later on.

6.2.3 Box Plot

From this point onwards, the corrosion data was analyzed based on the *box plot* technique of EDA. A box plot reveals the range of the data, whether or not the batch is symmetrical and also draws attention to the presence of extreme values [8]. The type of box plot described herein is the *skeletal box plot* (Fig. 8).

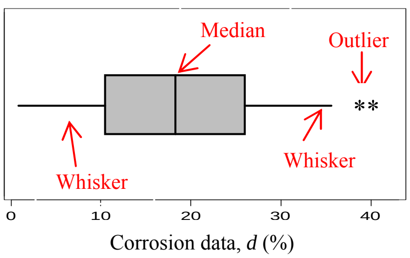


Figure 8 Presentation of a box plot

The information required to construct the box plot are the median, lower-H, upper-H, minimum and maximum values. The plot consists of a box with the edges being the lower-H and upper-H. The *median* divides the box. From the edges of the box, the *whiskers* stretch to the minimum and maximum values. *Outliers* in the data can be denoted by the * symbol. The outliers are sometimes described as the extreme values of the data. Details on these can be found in [8] and [9].

The box plot prepared for the TLC and BLC data is as shown in Fig. 9. [Herein the magnitude of corrosion is given by the amount of wall loss with respect to pipeline wall thickness, given in %.] From the figure, the medians for the TLC and BLC are addressed as 7 and 6%, respectively, which are considered to be almost the same. The two whiskers stretch lines seemed to take longer stretch on the maximum side. This implicitly means that more corrosion has the magnitude larger than the median. The size of the box, however, reveals that larger corrosion range is captured by the BLC, but more threats are given by the TLC because of the presence of the outliers. Thus this conforms well to the theory of TLC in a gas pipeline because of the high possibility to experience more condensation in the pipe.

For the sake of understanding corrosion distribution at each o'clock orientation, another box plot was prepared as shown in Fig. 10. On examining the data, it can be clearly seen that the corrosion (depth, *d*) distributions occupied all o'clock orientations (*i.e. y*-axis). This means that corrosions were developed everywhere at the circumference of the pipe, without leaving any empty space among it.

From the figure, it can also be seen that all medians (of the box plots) fall in the range of less than 10%. Longer whisker lines are found at the maximum side of the boxes. The 10, 11 and 12 o'clock orientations (represent TLC) for instance, experienced higher corrosion values (>20%). Extreme corrosion values were observed from the outliers at 11 and 12 o'clock orientations. These findings support the fact that TLC provides more threats to the pipeline as compared to the BLC.

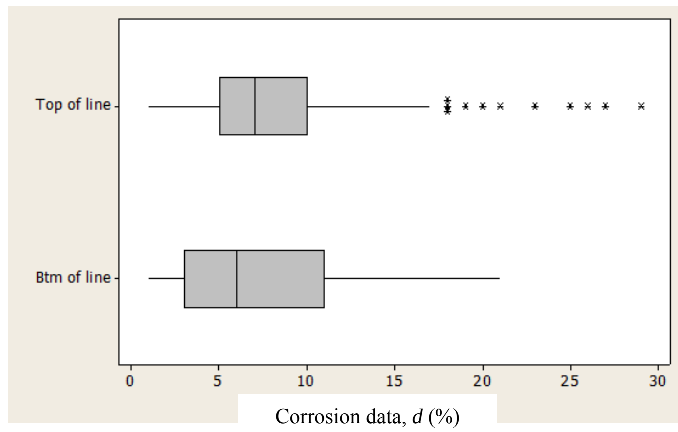


Figure 9 Box plot of the TLC and BLC corrosion (depth, *d*) data

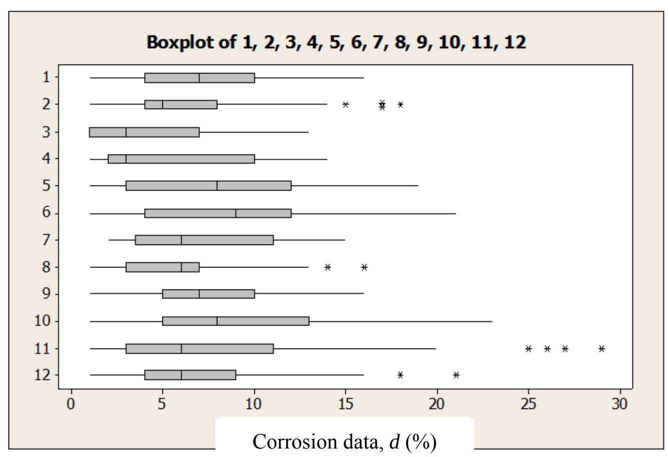


Figure 10 Box plot of the TLC and BLC corrosion (depth, *d*) data at each o'clock orientation

6.2.4 Median Polish

A *Median Polish* model resembles a regression line of an ANOVA method. However, the presence of outliers in the corrosion data resulted the data to be more skewed (as in Figs. 6, 9 and 10) and are not normally distributed. There are unequal variances for different o'clock orientations. Due to the violation of these assumptions, the traditional ANOVA method is not meaningful. Therefore, the median polish technique was used in order to fit a model. It is a more suitable technique used to develop a relationship (model) which is able to estimate TLC corrosion development with respect to its o'clock orientation in the pipeline, as given by,

$$d_{ij} = \mu + \tau_j + e_{ij} \tag{1}$$

with, $i = 1, 2, \ldots\ldots, n_j$
$j = 1, 2, \ldots\ldots, 12$ o'clock orientations

where, d_{ij} is the external corrosion depth (unit %), μ is the *overall effect*, τ_j is the *orientation effect*, e_{ij} is the *residuals*, and n_j is the sample size of the *j*th orientation. The fitting of the model as in Eq. (1) was done by using the *Minitab Statistical package Released 16*. The fitted model is given by,

$$d_{ij} = 7.6 + \tau_j + e_{ij} \tag{2}$$

where,

τ_1 (9 o'clock) = 1.5
τ_2 (10 o'clock) = 9.0
τ_3 (11 o'clock) = 10.0
τ_4 (12 o'clock) = 5.5
τ_5 (1 o'clock) = 0.5
τ_6 (2 o'clock) = 1.0

The e_{ij} term can be addressed using the *H-spread* value (*H-spr*) of the residuals, which is determined as 5% in this analysis. It is computed as ± (*H-spr*) of the predicted value, *i.e.* $(\mu + \tau_j) \pm$ (*H-spr*). Thus the final predicted value for external corrosion depth (unit %) is given by,

$$d_{ij} = 7.6 + \tau_j + \pm (1.5 \times 5) \tag{3}$$

For instance,
For 9 o'clock orientation,
Corrosion, $d = 7.6 + 1.5 \pm (1.5 \times 5) = 9.1 \pm 4.5 = (1.6\ \%, 16.6\ \%)$, which implies that the 9 o'clock orientation is likely to have corrosion depths in the range of 1.6 and 16.6% of the pipe wall thickness. Based on this model, the following Prediction Table as given in Table 2.

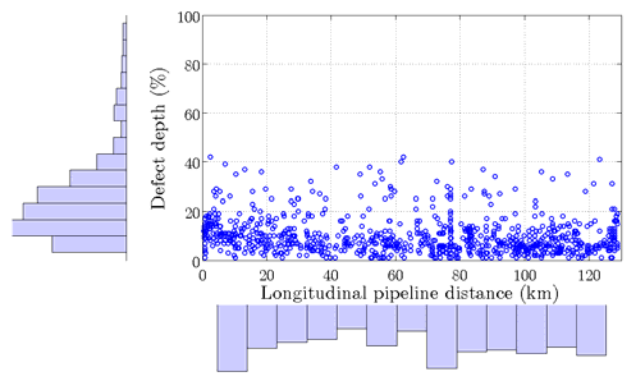
Table 2 Prediction Table for TLC corrosions (*d*, unit %) in gas pipeline at different o'clock orientations

Orientation	Predicted value	Prediction interval
9 o'clock	9.1 %	1.6 – 16.6 %
10 o'clock	16.6 %	9.1 – 24.1 %
11 o'clock	17.6 %	10.1 – 25.1 %
12 o'clock	13.1 %	5.6 –20.6 %
1 o'clock	8.1%	0.6 – 15.6 %
2 o'clock	8.6 %	1.1 – 16.1 %

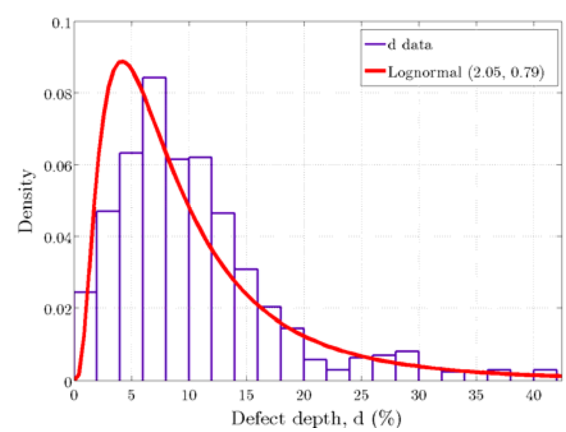
The table provides some overviews on the estimate of TLC corrosions, *d* (unit %) in gas pipelines at different o'clock orientations. From the model, it was noticed clearly that the 10, 11 and 12 o'clock orientations experienced higher values as compared to the other orientations. This exhibits strong orientation effect at those respective points for which the characteristics of corrosions might have primarily been influenced by the condensation rate of the TLC. Pipeline operators would then expect a pipeline to be heavily corroded at these points and special precaution should be given to these o'clock orientations.

6.3 Appropriateness of EDA for Corrosion Data

There has been considerable debate in the choice of applying EDA techniques to pipeline corrosion data. The significance of EDA is always undermined by the assumption of it being too simple to be applied to a complex engineering problem. Quite often the strength of EDA is neglected when compared to other complex mathematical methods.



(a) Scatter plot of corrosion data with its corresponding histograms



(b) Histogram of corrosion data fitted with a density function

Figure 11 Illustration of skewness and heavy-tailed distribution in corrosion data

Note that the strength of EDA is its ability to summarize the main characteristics of data sets using visual methods. Primarily EDA is for seeing what the data can tell us beyond the formal modeling or hypothesis testing task [8].

Corrosion data in offshore pipelines exhibit skewed or heavy-tailed distributions distributed due to the presence of outliers (extreme values), sample as shown in Fig. 11. The figure is an example through which corrosion data are analyzed based on mean and standard deviation approaches. Consequently, such data do not comply with the assumptions made in ANOVA, thus the traditional ANOVA method cannot be applied.

The quartiles and median of EDA are more robust to skewed or heavy-tailed distributions than other traditional summaries which use the mean and standard deviation. The two parameters being functions of the empirical distribution are defined for all distributions, unlike the mean and standard deviation [8]. Fig. 11 supported the fact that other statistical properties of corrosion data cannot be simply translated from it, whereas EDA is able to provide such illustration better (refer to Fig. 9 and 10, for instance).

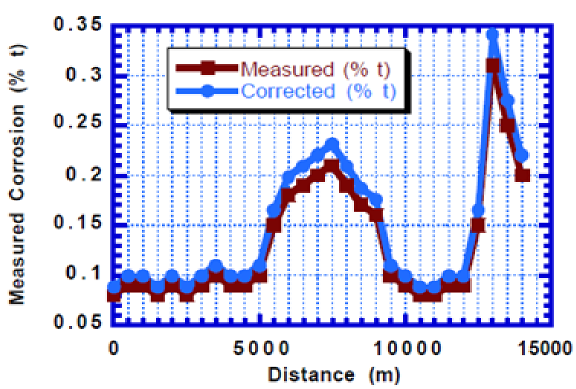


Figure 12 Systematic error observed in pipeline IP tool [12]

The intelligent pig (IP) tool is considered as a trusted primary source in providing information about corrosions in a pipeline. The accuracy of the tool (refer Fig. 12), however, remains as an issue among pipeline operators. The figure describes comparison between the measured and corrected corrosion value taken from an IP tool. One of the factors that undermine the advantages of using the IP is its measurement tolerances. A particular IP tool provider measures the corrosion defect size at certain given tolerances. Such tolerance may be assumed to contribute to the incomplete description of the data, an example of 'missing' data. In such case, EDA will handle the missing values better, narrowly checking assumptions required for model fitting and hypothesis testing, and handling missing values and making transformations of variables as needed [8].

CONCLUSIONS

Results presented in this paper are meant at illustrating an approach that can be considered in the spatial prediction of a TLC using EDA. The approach is proven to be able to summarize the main characteristics of the corrosion data using simple visual methods. This enables one to extract valuable information from it before pursuing to the next stage of reliability assessment.

A linear model was proposed using the median polish approach and a prediction table was prepared. The table provides an overview on the influence of corrosion magnitude at different o'clock orientations. The usefulness of this model is that it is simple and is not based on stringent assumptions which are rarely fulfilled in real world situations.

Results from this study will become useful outcomes for future research involving the effectiveness of corrosion inhibitors (CI) in managing TLC.

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