A Discussion of Deterministic vs. Probabilistic Method in Assessing Marine Pipeline Corrosions

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ABSTRACT
This paper provides comparisons between the deterministic and probabilistic methods through results obtained from a recent reported work. The study focuses on corrosions, a mechanism that leads to reduction in pipeline structural integrity. It has been shown in this paper that certain limitations in the deterministic method, through the failure pressure models, have been counter parted by results obtained from the probabilistic method. In addition to that, the paper summarizes some insights on the significance of fluid-structure interaction between the external flow and pipeline itself, in which this new discovery is very much relevant to be carried out in a probabilistic manner as well.

KEY WORDS: pipeline; corrosions; fluid structure interactions

INTRODUCTION
Marine pipelines, a complex system comprises a total length of thousands of kilometers, have been the most practical and low price means of transporting hydrocarbon (oil, gas, condensate, and their mixtures) in the offshore oil and gas industry. These pipelines are among one of the main factors contributing to marine environmental risks, exposing damages from material defects and pipe corrosion to ground erosion, tectonic movements on the bottom, and encountering ship anchors and bottom trawls. Depending on the cause and nature of the damage (cracks, ruptures, and others), a pipeline can become either a source of small and long-term leakage or an abrupt (even explosive) blowout of hydrocarbons near the bottom. Recent statistics data by the Offshore Environment shows that the average probability of accidents occurring on the underwater main pipelines of North America and Western Europe are $9.3 \times 10^4$ and $6.4 \times 10^5$, respectively. Corrosions in pipelines for instance, was the major cause of reportable incidents in North America and pipeline failures in the Gulf of Mexico. The corrosion-related cost to the transmission pipeline industry is approximately $5.4$ to $8.6$ billion annually.

The structural integrity of aging pipelines to withstand various operational, environmental and accidental loads has been a major concern to many parties. Therefore, the reliability of marine pipelines under various service conditions should be warily evaluated in order to protect the public, financial investment and environment from such failures.

Apart from the existing deterministic method used in structural design, there is a trend in the development of safety concepts as well as in economical approaches by implying more probabilistic concepts. This paper is aiming at providing comparisons between the deterministic and probabilistic methods when assessing risk in aging marine pipelines. An overview of deterministic method is presented at the beginning of the paper followed by a brief introduction to the probabilistic method. The application of the latter is shown through corrosion defects in a marine pipeline. A new insight on fluid-structure interactions is summarized at the end of the paper, in which the significance of uncertainties in pipeline hydrodynamics may be used to support the application of probabilistic method into the existing pipeline designs.

DETERMINISTIC METHOD
In structural design, the level of safety in each design component may be evaluated in several ways, as given in Table 1.

Level I method have been used as the common practice when designing a structure. It offers values of partial safety factors for the most common strength and load parameters, as shown in Figure 1(a). Some of the disadvantages of deterministic method as reported by Vrijling (2006) are (i) unknown how safe the structure is, (ii) no insight in contribution of different individual failure mechanisms, (iii) no insight in importance of different input parameters, (iv) uncertainties in variables cannot be taken into account and (v) uncertainties in the physical models cannot be taken into account.

Level II and III on the other hand, are formed by knowledge of probability and reliability theory concepts.
The random variables are characterized under the load ($L$) and strength ($S$), in which they are normally presented in the form of probability density function as shown in Figure 1(b). This is in contradictory to a single value chosen for $L$ and $S$ as illustrated in Figure 1(a). This paper does not attempt to explain in details the probabilistic method, however, interested readers are recommended to refer to Vrijling (2006), Mohitpour et. al. (2000) and Thoft-Christensen and Murotsu (1986), Madsen et.al. (1986), Ditlevsen and Madsen (1996) and Melchers (1999) for detail descriptions on structural systems reliability theory.

**ILLUSTRATIVE EXAMPLE**

This section presents comparisons between deterministic and probabilistic models. An example of risk assessment of an aging marine pipeline system is presented. Nevertheless, only failure due to corrosion defect is discussed here. For this purpose, this paper adapts results obtained from study by Caleyo et al. (2002).

**Failure Pressure Models**

The current practice among engineers to assess defects caused by corrosion involves computation of failure pressure ($PF$) with respect to internal pressure exerted to the marine pipelines. Table 2 shows deterministic equations describing $PF$ for several established existing design codes with Figures 2 and 3 visually describe the parameters involved. These codes are used to evaluate the remaining strength of corroded pipelines and are mostly developed from extensive series of full-scale tests on corroded sections. Each model is governed by input parameters of pipe outer diameter ($D$), wall thickness ($t$), minimum yield strength ($\sigma_{\min}$) or ultimate tensile strength ($\sigma_{uts}$), longitudinal extend of corrosion ($L_c$), and corrosion defect depth ($d$). Detailed discussions in each code may be obtained elsewhere, namely Caleyo et al. (2002), Lee et. al. (2006), Pluvinage (2007) and Cosham (2007).

**PROBABILISTIC METHOD**

The use of reliability analysis for the purpose of improving designs has the advantage that it provides a complete framework for the safety analysis, in which the actual probability of failure, and not some empirical safety rule is used as a measure of the performance of a design (Plate, 1993). According to Yen and Tung (1993), reliability analysis involves two major steps: (1) to identify and analyze the uncertainties of each of the contributing parameters, and (2) to combine the uncertainties of the random variables to determine the overall reliability of the structure. Step (2) may be further carried out in two ways; (i) directly combining the uncertainties of all the parameters, and, (ii) separately combining the uncertainties of the parameters belonging to different disciplines or subsystems to evaluate first the respective reliability and then combining the component reliabilities of the different disciplines or subsystems to yield the overall reliability of the structure. The former way applies to very simple structures whereas the second way is more suitable for complicated system with the aid of an Event Tree or Fault Tree. The random variables are characterized under the load ($L$) and strength ($S$), in which they are normally presented in the form of probability density function as shown in Figure 1(b). This is in contradictory to a single value chosen for $L$ and $S$ as illustrated in Figure 1(a). This paper does not attempt to explain in details the probabilistic method, however, interested readers are recommended to refer to Vrijling (2006), Mohitpour et. al. (2000) and Thoft-Christensen and Murotsu (1986), Madsen et.al. (1986), Ditlevsen and Madsen (1996) and Melchers (1999) for detail descriptions on structural systems reliability theory.

**Table 1. Safety levels applied in structural design**

<table>
<thead>
<tr>
<th>Safety level</th>
<th>Description</th>
</tr>
</thead>
</table>
| Level 0      | Deterministic method  
|              | Should not be applied |
| Level I      | Semi-probabilistic approach  
|              | Also known as load resistance factored design |
|              | Standard design procedures (codes and guidelines)  
|              | Utilizes a single partial coefficient (safety factor)  
|              | to represent an uncertainty variable  
|              | Design strength < design load x safety factor |
| Level II     | Approximations of the full probabilistic approach  
|              | Each variable (strength and load) is approximated by a standard normal distribution |
|              | Probability of failure computation is simplified by idealizing (linearising) a failure surface |
| Level III    | Full probabilistic approach (more advanced)  
|              | Each variable (strength and load) is defined by its own probability density functions  
|              | All variables are treated based on the knowledge of (joint) distribution  
|              | Utilizes the exact failure surface which requires numerical integration or simulation  
|              | Information needed for this method is not always available and even if they were, the calculations would be overwhelming |

**Fig. 1 Comparison in load and strength definitions for two methods**

**Fig. 2 Corrosion defect in a pipeline wall**

**Fig. 3 Assumptions made on corrosion defect shapes**

**Deterministic vs. Probabilistic Method**

One can easily compute the failure pressure of a marine pipeline using any of the expressions in Table 2. However, $PF$ obtain from each code will result in significant variations. Most researchers have also agreed that these models are somewhat over conservative.
Table 2. Failure pressure models used to compute remaining strength of pipeline subjected to corrosions

<table>
<thead>
<tr>
<th>Failure pressure models</th>
<th>Failure pressure expression, ( PF )</th>
<th>Bulging factor, ( M )</th>
<th>Corrosion defect shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASME B31G</td>
<td>[ PF = 1.11 \frac{2 \sigma_{uts}}{D} \left[ \frac{1}{1 - \frac{(d/t)}{M}} \right] ]</td>
<td>[ M = \sqrt{\frac{1 + 0.893 \left( \frac{L}{D} \right)^2 \left( \frac{D}{T} \right)}{4}} ]</td>
<td>Parabola</td>
</tr>
<tr>
<td></td>
<td>for [ \sqrt{0.5 \left( \frac{L}{D} \right)^2 \left( \frac{D}{T} \right)} ] &gt; 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified ASME B31G</td>
<td>[ PF = 1.11 \frac{2 \sigma_{uts}}{D} \left[ \frac{1}{1 - \frac{(d/t)}{M}} \right] ]</td>
<td>[ M = \sqrt{\frac{1 + 0.63 \left( \frac{L}{D} \right)^2 \left( \frac{D}{T} \right)}{4}} ]</td>
<td>Arbitrary</td>
</tr>
<tr>
<td></td>
<td>for [ \sqrt{0.5 \left( \frac{L}{D} \right)^2 \left( \frac{D}{T} \right)} ] &gt; 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ M = 3.3 \left( \frac{L}{D} \right)^2 \left( \frac{D}{T} \right) ]</td>
<td>Rectangular and river bottom profile</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[ M = 0.0034 \left( \frac{L}{D} \right)^2 \left( \frac{D}{T} \right) ]</td>
<td>Rectangular</td>
<td></td>
</tr>
<tr>
<td>DNV RP F101</td>
<td>[ PF = \frac{2 \sigma_{uts}}{D} \left[ \frac{1}{1 - \frac{(d/t)}{M}} \right] ]</td>
<td>[ M = \sqrt{\frac{1 + 0.31 \left( \frac{L}{D} \right)^2 \left( \frac{D}{T} \right)}{4}} ]</td>
<td>Rectangular</td>
</tr>
<tr>
<td>SHELL-92</td>
<td>[ PF = \frac{1.8 \sigma_{uts}}{D} \left[ \frac{1}{1 - \frac{(d/t)}{M}} \right] ]</td>
<td>[ M = \sqrt{\frac{1 + 0.805 \left( \frac{L}{D} \right)^2 \left( \frac{D}{T} \right)}{4}} ]</td>
<td>Rectangular</td>
</tr>
<tr>
<td>RSTRENG</td>
<td>[ PF = \frac{2 \sigma_{uts}}{D} \left[ \frac{1}{1 - \frac{(d/t)}{M}} \right] ]</td>
<td>[ M = \sqrt{\frac{1 + 0.63 \left( \frac{L}{D} \right)^2 \left( \frac{D}{T} \right)}{4}} ]</td>
<td>River bottom profile</td>
</tr>
<tr>
<td>PCORRC/ Batelle</td>
<td>[ PF = \frac{2 \sigma_{uts}}{D} \left[ \frac{1}{1 - \frac{(d/t)}{M}} \right] ]</td>
<td>[ M = 1 \exp \left( 0.157 \frac{L}{\sqrt{D(t/d)}} \right) ]</td>
<td>Rectangular</td>
</tr>
</tbody>
</table>

This is due to the fact that safety factors applied in each expression were resulted from some limitations occurred during their development. Also, since corrosion occurrence is random in nature, the assumption of corrosion defect shapes (Figure 3) as well as the measurement of the defect length and depth (Figure 2) for each model is something to be deliberated about. The models mostly assume rectangular defect cross-section (Figure 3b) whereas, the actual defect is more like a saucer. This makes the use of models even more conservative. Other uncertainties that may significantly affect the evaluation are pipe manufacturing data (pipe diameter, wall thickness and yield strength) and pipeline operating conditions (operating pressure and human errors). Therefore, it may not be wise to conclude which design code suits certain corrosion scenario the most. The attempt of applying probabilistic approach may be appropriate instead.

The discussion on this section onwards adapts partly results obtained from a study by Caley et. al (2002) on the risk assessment of marine pipelines subjected to corrosion defects. The authors have applied \( PF \) models in Table 2 to be used in a probabilistic framework. It is important to highlight here that in principle, any theoretical equations represented by safety factors should not be analysed in a probabilistic manner, as what have been reported. However, for discussion purpose, their results are simply presented in this paper as an aid to show the difference between the deterministic and probabilistic methods.

In their work, a pipeline containing 50 defects was analyzed, with diameter of 914.4 mm, wall thickness of 20.6 mm, material type of API-5L-X52, material yield stress of 358 MPa, material ultimate tensile strength of 455 MPa and operating fluid pressure 7.8 MPa. The corrosion defect depth was taken as 50% of the wall thickness while the defect length was in the range of 50–200 mm. The pipeline elapsed life was 15 years.

The corrosion model was formulated using a linear growth approximation as given below, which enable one to compute the changes of corrosion defects with respect to time.

\[
d(T) = d_o + V_o (T - T_o) \tag{1}
\]

\[
L(T) = L_o + V_r (T - T_o) \tag{2}
\]

with \( d \) represents the defect depth, \( L \) the axial length of the defect, \( T \) the elapsed time and \( T_o \) the time of last inspection. \( d_o \) is a percentage of defect occurrence with respect to the pipeline thickness with \( L_o \) governs its corresponding length. The axial and radial corrosion rates were assumed to be constant. The axial \( (V_o) \) and radial \( (V_r) \) corrosions rates were computed with defect depth and length, respectively, acting as the numerators, with the elapsed time as the denominator.
Each parameter presented in Table 2 was treated as random variable, but only normal distribution was utilized for this purpose. The corresponding data and statistical parameters associated to the study can be found in their full paper. Two interesting plots from the study are presented here, as shown in Figure 4. This paper is not aiming to critically compare and contrast results obtained from each design code in both figures, but to provide an overview of the limitation in the deterministic method, which may not be feasible enough to best describe the performance of an aging pipeline. This brings the probabilistic method into picture, in which the corresponding results of Figure 4(a) were then presented in the form of Figure 4(b).

![Failure pressure vs Normalized defect length](image)

**a. Deterministic method**

The first discussion is about the results presented in Figure 4(a). This plot was simply based on calculation of PF in Table 2. Failure pressures for each model were plotted against the normalized defect length. One would be in preference of a higher PF that a pipeline could withstand before failure takes place. The higher the value of PF, the greater the capability for the pipeline to resist load exerted to it. However, the plot was general in nature without being able to describe the stage of failure, except for the defect shape. An engineer would appreciate the results better if the values were referred to a certain meaningful control value. For instance, the graph reveals that the pipeline could withstand higher pressures as long as the corrosion defect size was small. The trend somehow decreased and finally became constant when the defect became larger in size. This is true because the pipeline is now incapable to accept more loads. But how would we know the final optimum point (from this constant pattern) before the pipeline starts to fail? Implicitly we only know that as long as the PF is higher than the operating pressure, the pipeline is considered to be safe. The small change in the constant line would never be able to guide us to the failure point of the pipeline and this is one of the limitations of the graph.

Now, if we were to treat the PF in Table 2 in a probabilistic manner, we would be able to compare them with respect to the operating pressure ($P_{op}$) in the pipeline itself, in which this information could be incorporated into a limit state function given by,

$$Z = PF - P_{op}$$  \hspace{1cm} (3)

The probability of failure, $P_f$ at which $P(Z < 0)$ in Eq. 4 was computed numerically using the First Order Second Moment (FOSM) reliability method which finally brought us to the results in Figure 4(b). This figure presents the $P_f$ in the pipeline with respect to the elapsed time since last inspection. This time period is normally known as the service time for a particular pipeline. The x-axis, however, may be represented by other parameters if needed. It is important to readdress that the $P_f$ computed here was a measure of the pipeline capability (strength) to resist the incoming operating pressure (load). It can be seen from the figure that the probability of the pipeline to fail at the beginning of its lifetime was low, and the trend (line) became significant as it approached its mid life time. This is due to the fact that damages caused by corrosion have reduced the initial pipeline wall thickness, making it incapable to withstand normal operating loads. Finally, as the pipeline was approaching its final design life, it was prone to fail with $P_f$ closer to 1.0. Herein, one could directly understand the current performance of this pipeline for the service time it has been operating. This plot ensures better explanation of the reliability of an aging structure without having to refer to other results or plots for further justification.

In one way or another, this probabilistic approach has taken into account all the uncertainties in the random variables (parameters) governing the strength and load equations. The presented results are capable to provide us with a direct explanation on the reliability of the aging pipeline of interests with respect to its remaining service time.

**b. Probabilistic method**

The second discussion is about the results presented in Figure 4(b). This approach was incorporated into a limit state function given by,

$$Z = PF - P_{op}$$  \hspace{1cm} (3)

This plot ensures better explanation of the reliability of an aging structure without having to refer to other results or plots for further justification.

In one way or another, this probabilistic approach has taken into account all the uncertainties in the random variables (parameters) governing the strength and load equations. The presented results are capable to provide us with a direct explanation on the reliability of the aging pipeline of interests with respect to its remaining service time.

**Fluid-Structure Interactions**

This section discusses another mechanism that governs the development of corrosions in a pipeline. External flows exert pressure and forces that contribute to external corrosions on a particular pipeline. Some new insights on fluid-structure interaction with regard to external flows approaching the unburied pipelines are presented. Description on this matter supports the application of probabilistic method in evaluating the reliability of aging marine pipelines. The discussions, however, are qualitative and are subjected to further quantitative work.

When the pipeline is near the seabed, the presence of the seabed changes the symmetric flow. The flow of wave and/or current around a pipeline can result in the generation of sheet vortices, as shown in Figure 5. These vortices are shed alternately from top to bottom of the pipeline. Due to vortex shedding, fluids may generate vibrations of the pipeline system, which are to be suppressed if significant. During this stage, there is a pressure difference between the top and bottom of the pipeline, in which top (Point A) has lower pressure than bottom (Point B). Following the Bernoulli Equation, velocities on top of the pipeline will be higher whereas the bottom part is nearly stagnant.
A negative lift force is produced, as shown in Figure 6. This force has a significant influence on the behavior of the pipeline which may lead to its deformation. The attracting force of the seabed tends to pull a pipeline down to the seabed, exerting high bending stresses in the pipeline (Lam et al., 2002). Under normal operational environments, the pipeline may experience instability failure or strength failure. Despite the complexity of the theory of vortex shedding surrounding a pipeline placed close to the seabed, Ming et al. (2005) has proven the concept numerically. Their numerical work conformed well to an experimental work by Jarno-Druaux et al. (1995), as shown in Figure 7. Interested readers are advised to refer to the actual papers for further description of these works.

The above information has supported the significance of fluid-structure interaction between the pipeline close to the seabed and the approaching flow. But how far these new insights have been updated into the pipeline designs is still uncertain. A brief summary is provided in the next paragraphs to support this argument.

In the traditional pipeline designs, the pressures and forces exerted onto a pipeline were incorporated into the section of (i) wall thickness determination and (ii) stability analysis. We will now briefly compare and contrast these two sections separately.

When determining the wall thickness of the pipeline, the hydrostatic pressure is part of the important parameter governing the equations, as shown in Table 3. For design purpose, codes and standards have selected safety factors of 1.0 and 1.5 to represent the hydrostatic pressure term. How can one tell whether these values are sufficient enough to cater the behavior of fluid-structure deliberated earlier?

Eq. (4) is a common equation used to assess the pipeline hydrodynamic stability, with $\mu$ as the soil friction factor, $W_s$ as the pipeline submerged weight, $\delta$ as the slope of the seabed, $F_L$ as the lift force, and $F_D$ as the drag force.

$$\mu (W_s \cos \delta - F_L) \geq [(F_D + F_D)_{max} + W_s \sin \delta]$$

Looking at the variations and uncertainties found in the external pressure exerted to the pipeline, these new insights may be wise to be carried out in a probabilistic manner rather than the deterministic method. There are many ways to go about solving this problem and one of the most recommended methods is by applying the finite element method. This is due to the fact that the problem may not be easily represented by simple limit state functions. This paper does not attempt to discuss further on results pertaining to this section as they will be presented in different papers and publications.

CONCLUSIONS

This paper is aiming at comparing the probabilistic and deterministic methods, in which awareness from this is beneficial in assessing risks of any civil engineering structures. Risk assessment in an aging marine pipeline was taken as an example to differentiate the two approaches with focus particularly given to corrosion defect type of failure. It has proven that certain limitations in the deterministic method have been counter parted by the probabilistic method in one way or another. New insights on fluid-structure interaction also support the application of probabilistic method. Consequently, the probabilistic approach may be able to provide better insights in the design, construction, maintenance and inspection of certain failure, and thus allowing for better prevention measures to be implemented before the problems take hold.
Table 3. Equations for pipeline wall thickness determination

<table>
<thead>
<tr>
<th>Type of pressures</th>
<th>Governing equations</th>
<th>Remarks on external pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal pressure design</td>
<td>( t_{\text{internal}} = \frac{P_D}{2E_a} + t_a )</td>
<td></td>
</tr>
<tr>
<td>External pressure design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buckle initiation</td>
<td>( t_{\text{buckle initiation}} = D\left( \frac{P_a}{0.02E} \right)^{\frac{1}{214}} )</td>
<td>( P_a = P_{\text{to}} = P_e ) with ( P_e = 1.5 \cdot gh )</td>
</tr>
<tr>
<td>Buckle propagation</td>
<td>( t_{\text{buckle propagation}} = D\left( \frac{P_{\text{bu}}}{24} \right)^{\frac{1}{214}} )</td>
<td>( t_{\text{buckle propagation}} ) is the pure elastic collapse pressure.</td>
</tr>
<tr>
<td>Hydrostatic collapse</td>
<td>* ( P_e = \frac{g(r_d)P_D P_e}{\sqrt{P_{\text{ub}}^2 + P_e^2}} )</td>
<td>(</td>
</tr>
</tbody>
</table>

Note that \( t \) refers to the pipeline wall thickness, \( P_e \) is the design internal pressure defined as the difference between the internal pressure (\( P_i \)) and external pressure (\( P_e \)). \( D \) is the nominal outside diameter, \( t_a \) is the thickness allowance for corrosion, \( E_a \) is the weld efficiency, \( r \) is the specified minimum yield strength, \( E \) is the Young’s Modulus, \( w \) is the weld efficiency, \( \rho \) is the density of sea water, \( g \) is acceleration due to gravity and \( h \) is the height of water. \( P_i \) is the collapse pressure, \( P_e \) is the pure plastic collapse pressure, \( P_{\text{bu}} \) is the pure elastic collapse pressure.

\* Note that the parameter \( t \) is defined under the \( P_{\text{th}} \), \( P_e \) and \( g(r_d)P_D P_e \) terms and requires comprehensive mathematics solver for its computation. Interested readers are advised to refer to standards and codes for the full expansion of the equation.

REFERENCES


