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Reliability assessment of free spanning subsea pipeline

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ABSTRACT

Reliability of free spanning subsea pipeline has been estimated using theory of Probability of Failure (POF) and has been analyzed in accordance with a target safety level. The POF has been calculated using First-Order Reliability Method (FORM) and Monte-Carlo Sampling (MCS). The changes in POF with regard to six different ratios of span length to pipeline diameter and six clay types and also three sand classes are calculated. Finally, sensitivity analysis is carried out to determine the contribution of each parameter on POF. It is concluded that FORM analysis can be applied for large ratios of span length to pipeline diameter.

1. Introduction

Subsea pipelines are used for a number of purposes in development of subsea hydrocarbon resources. Generally, subsea pipelines carry oil and gas products from wellhead to the riser base. The design of pipelines is usually performed in three stages; conceptual design engineering, Front End Engineering Design (FEED) engineering and detail design engineering [1].

The main objectives of FEED are; verifying the size of pipeline, determining Pipeline Wall Thickness (PWT) with its relevant grade, and validating pipeline in accordance to design and codes requirements for installation and operation stages [1,2].

Subsea pipelines are subjected to various types of phenomena, like fatigue, corrosion, etc. which cause pipeline failure and should be monitored to guarantee safety of pipeline [3]. According to DNV-Os-F101, fatigue assessment of pipeline must be performed at any stages (i.e. installation and operation) [4]. The free spanning as one of the important causes of fatigue occurs due to seabed unevenness, changes in seabed topology, artificial supports, and scours [1,5].

If the vortex shedding frequency which is caused by a normal flow reaches to the natural frequency of pipeline, pipeline starts to vibrate and Vortex Induced Vibration(VIV) occurs which may eventually causes pipeline fatigue damage [5]. Based on the interaction of adjacent spans, free span analysis is performed in two ways; static analysis (for isolated span i.e. single span) and dynamic analysis (for interacted spans i.e. multi-span) [6].

In this paper, first deterministic-based VIV fatigue assessment is carried out to determine fatigue life capacity of a pipeline located in Iranian South Pars Gas Field. Then, considering the uncertainties in both pipeline specifications and soil stiffness, POF is estimated using FORM and MCS for various clay types. Finally, sensitivity analysis considering nine soil classes and six span length to pipeline diameter is carried out to determine effect of each parameter on POF.

2. VIV fatigue assessment

2.1. Methodology

For determining fatigue life capacity of a pipeline, the following procedure should be done (see Fig. 1).

In Fig. 1, L is the span length, D is the pipeline outside diameter (considering coating layer), U_c is the current velocity amplitude, and U_w is the significant wave-induced velocity amplitude.

DNV divided the free spanning pipeline behavior into three categories based on the ratio of span length to pipeline diameter; beam dominant behavior (for $30 < L/D < 100$), combined beam and cable behavior (for $100 < L/D < 200$) and cable dominant behavior (for $L/D > 200$) [6]. In the first category, pipeline response can be estimated by deterministic theories, i.e. Bernoulli's beam theory. However, in the second and third classes, the beam theory is not applicable and the dynamic response must be predicted by solving differential equation i.e. equation of motion (for more information see reference [8]).

2.2. Fatigue criterion

There are three approaches for fatigue assessment as shown in Fig. 2 [9].

The traditional stress-based approach was developed in 1955 which

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Nomenclature

A	Maximum Stress Amplitude
C_L	dynamic stiffness factors in horizontal direction
C_v	dynamic stiffness factors in vertical direction
CSF	concrete stiffness enhancement factor
D	Pipeline outer diameter
D_s	steel diameter
D_{fat}^{cum}	Cumulative Palmgren-Miner fatigue damage
E	Young's modulus
$g(x)$	LSF in real space
G	Cumulative form of LSF in standard normalized space
K_L	Horizontal soil stiffness
K_V	Vertical soil stiffness
L_{eff}	effective span length
m	the negative inverse slope of S-N curve
N_i	number of cycles to failure for stress block i
n_i	number of stress cycles for stress block i
R_i	Reliability value of ith block
s	Standard deviation
T_{fat}	Fatigue life capacity
U_c	the significant current-induced velocity amplitude
U_w	the significant wave-induced velocity amplitude
α_i	Important measurement for ith parameter
β	RI
$\Delta\sigma$	Stress range
ν	Poisson's ratio
ρ	water density
ρ_s	soil density
C.O.V	Coefficient of Variation
FORM	First-Order Reliability Method
LSF	Limit State Function
MCS	Monte-Carlo Sampling
POF	Probability Of Failure
PWT	Pipeline Wall Thickness
RI	Reliability Index
SMYS	Significant Mean Yield Stress
SMTS	Significant Mean Tensile Stress
VIV	Vortex Induced Vibration

is based on the nominal (average) stresses. The nominal stress that can be resisted under cyclic loading is determined by considering mean stress [9]. DNV recommends using stress-based approach for pipeline fatigue assessment [4,7]. The main method for determination of fatigue damage in stress-based approach due to cyclic loads is S-N curve which can be plotted using test data (see Fig. 3) [11].

According to DNV-RP-C203, the basic design S-N curve is given as [1,10]:

$$\log N = \log \bar{a} - m \log \Delta\sigma \tag{1}$$

Where N is the predicted number of cycles to failure, $\Delta\sigma$ is the stress range, m is the negative inverse slope of S-N curve, $\log \bar{a}$ is the intercept of log N-axis by S-N curve. $\log \bar{a}$ is given by the following equation:

$$\log \bar{a} = \log a - 2s \tag{2}$$

Where a is a constant relating to mean S-N curve and s is the standard deviation of $\log N$. The strain-based approach involves more detailed analysis of the localized yielding that may occur at stress raisers during cyclic loading. Finally, fracture mechanics approach specifically treats growing cracks by the methods of fracture mechanics (for more information see reference [12]).

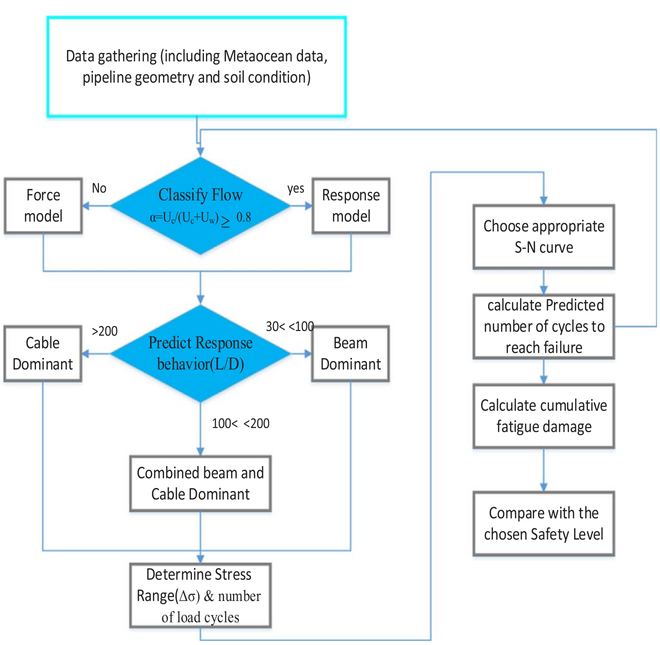

Fig. 1. VIV fatigue assessment procedure [1,4,5].

2.3. Pipe-soil interaction

DNV classifies seabed soil into two classes; clay and sand. DNV classifications with their subsets are presented in Fig. 4.

The soil stiffness in both horizontal and vertical directions affects the maximum amplitude response of oscillation. In the absence of sufficient detailed information about soil specification, soil stiffness can be calculated through the following equations [6]:

$$K_V = \frac{C_v}{1-\nu}\left(\frac{2}{3}\frac{\rho_s}{\rho} + \frac{1}{3}\right)\sqrt{D} \tag{3}$$

$$K_L = C_L(1+\nu)\left(\frac{2}{3}\frac{\rho_s}{\rho} + \frac{1}{3}\right)\sqrt{D} \tag{4}$$

where K_V and K_L are vertical and horizontal stiffness, respectively. C_v and C_L are dynamic stiffness factors in vertical and horizontal directions, ν is the Poisson's ratio, ρ_s is the soil density and ρ is the water density. The value of the above parameters can be determined from Table 1. Because of neglecting the effect of soil interaction for single span, DNV recommended equations for determining soil stiffness (Eqs. (3) and (4)) lead to conservative results [13].

In order to determine the *Maximum Stress Amplitude*(MSA) (A) due to VIV, DNV recommended the following equation (valid for $L/D_s < 140$) [6]:

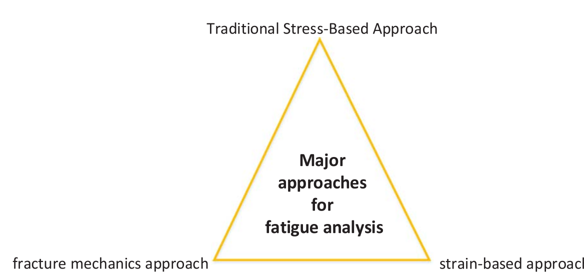

Fig. 2. Major approaches for analyzing and designing fatigue [9].