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Quantitative risk assessment of submarine pipeline instability

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A B S T R A C T

Ensuring the on-bottom stability of the submarine pipeline is very important for safety concern during the operational stage of submarine pipeline. Due to the action of the external factors, e.g. strong current, wave and soil liquefaction, the submarine pipeline may have lateral displacement, vertical floatation or sinking. Although the submerged weight of submarine pipeline is designed to meet the requirement of on-bottom stability, the loss risk of pipeline on-bottom stability still exists due to the change of ocean environment or seabed. This paper presents a reliability-based assessment methodology for submarine pipeline instability. Firstly, a mechanical model of pipeline on-bottom state is built considering the hydrodynamic loads and pipe-soil interaction, which is the static forces equilibrium equations essentially, and a detailed analysis of loading condition of pipeline on seabed is also conducted. Then, based on the reliability theory, the limit state equations of pipeline instability are developed through converting the forces equilibrium equations. Because the parameters in limit state functions possess random uncertainty, such as wave and current loads, etc., the specific probability distributions are employed to present the random uncertainty of the parameters in limit state functions. The Monte Carlo method is then employed to solve the limit state equations for assessing the pipeline instability probability. The risk level of pipeline instability is judged using the risk ranking in DNV-RP-F107. The case study indicates that the proposed risk assessment methodology for pipeline instability possesses a good application performance. In essence, the assessment results could provide a powerful support for risk management or decision-making of submarine pipeline instability.

1. Introduction

Although the on-bottom stability problem has been considered in the design stage of submarine pipeline, the engineering practice indicates that the phenomenon of lateral displacement or vertical sinking and floatation of submarine pipeline still exists. The excessive lateral or vertical displacement may cause excessive stress level of pipeline, and if the pipeline stress exceeds the allowable value, the structure failure of pipeline will occur (Zhou et al., 2014; Youssef et al., 2013). The possible collision with the near pipeline may be caused by lateral displacement, and the free span that could induce fatigue failure of pipeline may be caused by integrated effect of pipeline floatation and wave-current scouring (Zhu and Chen, 2009). Moreover, some special pipeline structures such as joint of connection with vertical pipeline, submarine valve and expansion elbow etc., are usually not allowed to move. Therefore, it is necessary to conduct a risk assessment for submarine pipeline instability, which is useful for risk management or decision-making of submarine pipeline instability.

At present, a lot of efforts are made for the study of on-bottom stability of submarine pipeline, which includes experiments, numerical simulation and mathematical model etc. (Gao et al., 2006; Tang et al., 2016; Bai et al., 2015). But these studies mainly focused on the on-bottom stability design, and the recommended practice in standard file or finite element method are usually employed to analyze the pipeline stability. The authoritative design recommended practice DNV-RP-E305 released by Det Norske Veritas in 1988, and new vision DNV-RP-F109 updated in 2010 recommends three methods for pipeline on-bottom stability design, i.e. dynamic, generalized and absolute static methods, respectively. The above three methods are the basic approaches for the study of pipeline on-bottom stability. Recently, the finite element method is also an available approach for pipeline on-bottom stability design. The dynamic response of pipeline on seabed after suffering the lateral displacement is investigated using the finite element software

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ABAQUS (Bai and Yu, 2011). Tian et al. (2011) conducted a series of works and developed an integrated fluid-structure-soil interaction program for analysis of unburied pipeline stability. In addition, a new dynamic lateral stability analysis package is also developed by Tian et al, 2015 in order to conduct a systematic study of on-bottom stability analysis. The above studies about on-bottom stability are only available in pipeline design stage for determining and optimizing the required submerged weight from structural strength perspective.

In practical operational condition, various factors, e.g. fall of weight coat or seabed change etc., are able to cause the pipeline on-bottom stability loss which could cause serious structure failure of submarine pipeline. However, studies for on-bottom stability in operational stage of pipeline from risk perspective can only be found sporadically in literature. The instability could be regarded as a kind of failure type of submarine pipeline, which might lead to serious consequence. Thus, it is necessary to conduct a study to address the pipeline instability risk assessment in operational stage for the actual engineering requirement.

In essence, the pipeline on-bottom state is a problem of mechanical balance, including stability and instability, which could be described using limit state function. Moreover, pipe-soil interaction and environmental loads possess the random uncertainty, and the change of them usually tends to follow a certain probability distribution which is suitable for using Monte Carlo method. In practice, the limit state function and Monte Carlo method are usually regarded as a whole, and have been widely applied in quantitative risk assessment of oil and gas pipeline (Hasan et al., 2012; Leira et al., 2016; Gomes et al., 2013; Carr, 2014). In the previous studies, remaining life prediction and corrosion failure probability assessment of corroded pipeline were investigated using the limit state function and Monte Carlo method (Luo et al., 2000; Aljaroudi et al., 2015; Zhang and Peng, 2016). In addition, reliability analysis of corroded submarine pipeline was also conducted using the above methods (Han and Zhou, 2015). These studies indicate that limit state function and Monte Carlo method possess the good application performance in the field of quantitative risk assessment of oil and gas pipeline. Therefore, the limit state function and Monte Carlo method are employed to investigate the instability probability of pipeline in the present study.

The objective of this paper is to build a risk-based model for submarine pipeline instability, which could be used to assess the instability risk of pipeline in operational stage. The instability is regarded as a kind of failure type of pipeline, and the instability probability of pipeline is assessed using the developed model. Essentially, the study not only could provide a powerful support for risk management or decision-making of pipeline instability, but also give a reference for design and construction of new pipeline. It is worth noting that present study mainly focuses on the submarine pipeline which located close to a platform or subsea template within 500 m. In operational stage, the allowable maximum lateral displacement of submarine pipeline mentioned above is 0 m (DNV-RP-E305, 1988). Therefore, it could be considered to be instability once the pipeline moves.

The rest of paper is organized as follows: Section 2 builds the mechanical model of pipeline on-bottom state; Section 3 proposes the methodology to assess the risk of pipeline on-bottom instability; Section 4 presents a case application; Section 5 gives the conclusion of this paper.

2. Mechanical model of pipeline on-bottom state

The objective of pipeline on-bottom stability analysis is to validate whether the submerged weight of pipeline meets the stability criterion or not (DNV-RP-E305, 1988). The pipeline on seabed is mainly subjected to three kinds of loads, i.e. self-weight, pipe-soil interaction and hydrodynamic loads such as wave and current. The key influence factors of pipeline on-bottom stability are pipe-soil interaction and hydrodynamic loads, which determine the value of submerged weight of pipeline directly. In the present study, the mechanical model of pipeline on-bottom state is built considering the hydrodynamic loads and pipe-soil interaction.

2.1. Hydrodynamic loads

The submarine pipeline is subjected to wave and current loading. In shallow water, the wave load on pipeline is more significant than current. While in deep water, the current load on pipeline is more significant than wave. In the engineering practice, the submarine pipeline is always subjected to the coupled effect of current and wave. At present, the classical and common calculation method of hydrodynamic loads is Morison equation, which divides the hydrodynamic loads into drag force, inertial force and lifting force, etc. (Bai and Bai, 2005). According to Morison equation, the hydrodynamic loads acting on unit length of submarine pipeline can be calculated using following equations (DNV-RP-E305, 1988):

$$F_L = \frac{1}{2}\rho_W D C_L (v_S \cos\theta + v_C)^2 \tag{1}$$

$$F_D = \frac{1}{2}\rho_W D C_D |(v_S \cos\theta + v_C)|(v_S \cos\theta + v_C) \tag{2}$$

$$F_I = \frac{\pi D^2}{4}\rho_W C_M A_S \sin\theta \tag{3}$$

Where F_L, F_D and F_I are the lift force, drag force and inertial force of unit length of submarine pipeline, respectively, N/m; D is the total outside diameter of pipeline, m; C_L, C_D and C_M are the coefficient of lift force, drag force and inertial force, respectively; ρ_W is the seawater density, kg/m^3; v_s is the significant near-bottom velocity amplitude perpendicular to pipeline, m/s. v_C is the current velocity perpendicular to pipeline, m/s. A_S is the significant acceleration perpendicular to pipeline, m/s^2; θ is the phase angle of the hydrodynamic force in the wave cycle.

2.2. Pipe-soil interaction

There is an interaction between submarine pipeline and seabed, which can be divided into coulomb friction and passive resistance of soil. The coulomb friction is estimated using classical coulomb friction model as showed in Eq. (4), which represents that the coulomb friction is proportional to contact pressure between pipeline and soil. The ratio between the friction force and contact pressure is the friction coefficient which is related to soil type and pipeline settlement in soil.

$$F_f = \mu F_C \tag{4}$$

Where F_f is the coulomb friction force, N/m; F_C is the vertical contact force between pipeline and soil which is the submerged weight minus lift force, i.e. $F_C = w_s - F_L$, N/m; μ is the friction coefficient, and the friction coefficient of pipeline on sand can be taken as 0.6.

The practical measured value of lateral resistance of soil is far greater than the value obtained from coulomb friction model. Therefore, in addition to coulomb friction force, the passive resistance of soil due to initial settlement caused by self-weight of pipeline and additional settlement caused by lateral movement of pipeline also should be considered in the pipe-soil interaction. According to DNV-RP-F109 (2010), the passive resistance of