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Submarine pipeline lateral instability on a sloping sandy seabed

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ABSTRACT

Ocean-current induced pipeline on-bottom stability on a sloping sandy seabed involves a complex interaction between the hydrodynamic loading, the untrenched pipeline and the neighboring soil. In this study, a newly-designed pipe–soil interaction facility and a flow–structure–soil interaction flume have been utilized for full-scale physical modeling of the pipeline instability on a sloping sand-bed, including the downslope instability and the upslope instability. Unlike the pipeline lateral stability on the horizontal seabed, an initial lateral-soil-resistance is developed and the static-instability might be triggered for the sloping seabed. According to dimensionless analyses, an ultimate lateral-soil-resistance coefficient is proposed to describe the interaction of the pipe with the sloping sand-bed. Experimental results indicate that sand-bed slope angle, pipe submerged weight and end-constraints have much influence on pipe on-bottom stability. No matter for the upslope instability or the downslope instability, the corresponding lateral-soil-resistance coefficient for a sloping sand-bed is larger than that for a horizontal sand-bed.

1. Introduction

The theme for submarine pipeline on-bottom stability design is the instability criteria under various environmental conditions. To avoid the occurrence of pipeline on-bottom instability, i.e., the pipe breakouts from its as-laid original site, the seabed must provide enough soil resistance to balance the hydrodynamic loads upon the untrenched pipeline. The on-bottom stability of a submarine pipeline involves complex interactions between the wave/current, the untrenched pipeline and the neighboring soil. In the recent decades, numerous experimental studies on the pipeline on-bottom stability have been carried out with 1*g* mechanical-actuator simulation (e.g., Lyons, 1973; Brennodden et al., 1989; Wagner et al., 1989), with N*g* centrifuge tests for calcareous sand–pipe interaction (e.g., Zhang et al., 2002), and the oscillatory-flow tunnel or wave flume modeling (e.g., Gao et al., 2003, 2007; Teh et al., 2003).

1.1. Literature review on physical modeling of pipeline on-bottom stability

1.1.1. Pipe–soil interaction mechanism

Before 1970, Coulomb friction theory was employed to estimate the pipe–soil friction force under the action of ocean waves in shallow waters. However, the pipe–soil interaction experiments by Lyons (1973) showed that, wave-induced pipe–soil interaction is too complex to describe with Coulomb friction theory. That is, the pipeline on-bottom stability involves a complex pipe–soil interaction process.

Since the 1980s, base on the results of a series of large scale pipe–soil interaction tests, several pipe–soil interaction models were proposed to predict the ultimate soil resistance to the pipeline in waves. The ultimate soil resistance is defined as the maximum soil resistance to the untrenched pipe against on-bottom instability under the action of environmental loadings including waves, currents, etc. In the pipe–soil interaction model proposed by Wagner et al. (1989), the ultimate soil lateral resistance (F_{Ru}) was assumed as the sum of the two components, i.e., the sliding resistance component and the passive soil resistance component:

$$F_{Ru} = \mu(W_s - F_L) + \beta\gamma' A \tag{1}$$

where the passive soil force (the second component) modeling the resistance offered by the sand in front of the slightly embedded pipeline is expressed as the effective (buoyant) unit weight of sand (γ') multiplied by a characteristic area (A) and an empirically determined coefficient (β). The empirical coefficient (β) is a function of the pipe displacement and the lateral loading history (see Wagner et al., 1989). In the energy-based pipe–soil interaction model proposed by Brennodden et al. (1989), the aforementioned soil passive resistance component is, however, relative to the work done by pipe during its movement. In the above two

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Nomenclature

C_D	drag force coefficient;
C_L	lift force coefficient;
C_u	coefficient of uniformity of sand grains ($C_u=d_{60}/d_{10}$);
d_{10}	effective size of sand grains;
d_{50}	mean size of sand grains;
d_s	sand grain diameter;
D	outer diameter of pipeline;
D_r	relative density of sand;
e	settlement of pipe while losing stability;
e_0	initial settlement of the pipe;
e_s	void ratio of sands;
F_{Cu}	pipe–soil contact force while pipe instability occurs;
F_D	drag force on the pipe;
F_{Du}	ultimate drag force on the pipe;
F_L	lift force on the pipe;
F_R	lateral soil resistance to the pipe (parallel to seabed surface);
F_{R0}	initial lateral soil resistance to the pipe on a sloping seabed;
F_{Ru}	ultimate lateral soil resistance for pipe instability;
g	gravitational acceleration;
G	non-dimensional submerged weight of the pipe;
s	lateral displacement of the moving pipe;
U	flow velocity of the current;
U_{cr}	critical flow velocity for the pipe instability;
W_S	submerged weight of the pipe per meter;
α	slope angle of the seabed surface;
ϕ	internal friction angle of soil;
γ'	buoyant unit weight of soil $(=\gamma'\rho_{sat}g-\rho_w g)$;
λ	pipe end constraint conditions;
μ	coefficient of sliding friction;
θ	inclination angle of the mechanical loading ($\theta=\arctan(F_L/F_D)$);
ρ_{sat}	mass density of saturated sand;
ρ_w	mass density of water;
η_α	coefficient of ultimate lateral-soil-resistance for pipe instability on a sloping seabed;
β	empirical coefficient in the pipe–soil interaction model by Wagner et al. (1989);
A	one half the area of a vertical cross section of the soil displaced by the pipe during the penetration and oscillations (see, Wagner et al. (1989));

pipe–soil interaction models, a few empirical coefficients without implicit physical meanings are difficult to be determined. The underlying physical mechanism for pipe–soil interaction has not yet been well understood, as stated by Hale et al. (1991).

To investigate the interaction of a shallowly-embedded pipeline with the calcareous sand, Zhang et al. (2002) conducted a series of centrifugal tests. A non-associated bounding surface model was then constructed on the basis of test data and the theory of plasticity was used to simulate the response of a pipeline embedded in sandy soil under combined vertical and horizontal monotonic loading.

Foray et al. (2006) studied the pipe–soil interaction with special emphasis on the conditions leading to liquefaction around a pipe. By employing a large-scale experimental setup with an electro-mechanic actuator to simulate the hydrodynamic loadings, White and Cheuk (2008) investigated the soil resistance on the pipeline during large cycles of lateral movement. To reveal the pipe–soil interaction mechanism for steady-flow induced pipeline on-bottom stability, Gao et al. (2011) conducted a series of tests with an updated pipe–soil interaction facility including a load–displacement synchronous measurement system. It was indicated that, for the equivalent level of dimensionless submerged weight, the value of the critical Froude number for the directly-laid pipe instability in currents is higher than that in waves. Note that the aforementioned studies focused mainly on the pipe–soil interaction modeling with mechanical-actuators for hydrodynamic loading simulations.

1.1.2. *Flow-pipe–soil interaction mechanism*

As aforementioned, the ocean wave/current induced on-bottom stability of a submarine pipeline involves complex flow-pipe–soil interaction, i.e., the interaction between the hydrodynamic loading, the untrenched pipeline and the neighboring soil. Recently, a series of water flume tests have been made to reveal the flow-pipe–soil coupling effects on the wave-induced pipe lateral instability (e.g., Gao et al., 2002, 2003, 2007; Teh et al., 2003).

For simulating the oscillation of water particles near the seabed, a U-shaped oscillatory flow water tunnel was employed to investigate the wave-induced pipeline instability (Gao et al., 2002, 2003). Three characteristic times in the process of pipeline losing lateral stability in waves, i.e., (i) onset of sand scour, (ii) pipe rocking, (iii) pipe breakout, were identified from the pipe displacements records and experimental observations. This process of pipeline instability was also verified with the wave-flume experimental observations by Teh et al. (2003). Based on experimental results, the criteria for the pipeline on-bottom stability on sand-bed for two kinds of constraints, i.e., Case I: the pipe is free at its ends and Case II: the pipe is constrained against rolling, have been established as the following form, respectively (Gao et al., 2003):

$$\frac{U_{cr}}{\sqrt{gD}}=a+b\frac{W_s}{\gamma' D^2} \tag{2}$$

An improved analysis method was further proposed by Gao et al. (2006) for the on-bottom stability of a submarine pipeline, taking into account the coupling effects between wave, pipeline, and sandy seabed. The proposed improved method comparable with the DNV recommended Practice provides a helpful tool for the engineering practice of pipeline on-bottom stability design.

Local scour at submarine pipelines under the action of currents or waves also drew much attention among numerous researchers, e.g., Sumer et al. (1988), Chiew (1990), Pu et al. (2001), Liang et al. (2005). In those studies, the pipelines were fixed or spring-supported above the soil surface, i.e., the pipeline on-bottom instability was not directly involved. Sand scour, as an indicator of the wave-pipe–soil coupling, was observed usually accompanying in the process of the pipeline losing on-bottom stability (see, Gao et al., 2002). The onset of tunnel scour underneath the shallowly-embedded pipeline (see, Sumer et al., 2001; Zang et al., 2009; Gao & Luo, 2010) may further induce the occurrence of pipeline spanning.

1.2. *The significant of the pipeline stability on a sloping seabed*

As more and more oil and gas reservoirs having been found at the continental slopes, e.g., in the Western and Northern Gulf of Mexico, the South China Sea etc, the stability of deepwater pipelines on a sloping seabed attracts much attention of engineering designers and researchers. The continental slope is the area between the offshore shallows and where the continental shelf dips steeply to the sea floor. One of most interests to the offshore petroleum industry in Gulf of Mexico is the Louisiana-Texas slope, which occupies 120,000 square km and in which