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Steady flow-induced instability of a partially embedded pipeline: Pipe–soil interaction mechanism ☆

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ABSTRACT

The steady flow-induced instability of a partially embedded pipeline involves a complex process of pipe–soil interaction. In accordance with the hydrodynamic loading and the dimensionless analyses, a series of pipe–soil interaction tests have been conducted with an updated pipe–soil interaction facility including a load–displacement synchronous measurement system, to reveal the underlying pipe–soil interaction mechanism. The effects of pipe surface roughness, end-constraint and initial embedment are investigated, respectively. The values of lateral-soil-resistance coefficient for the rough pipes are bigger than those for the smooth pipes. For a fixed value of non-dimensional submerged weight, the values of lateral-soil-resistance coefficient for the anti-rolling pipes are much larger than those for the freely laid pipes. The effects of initial embedment on the ultimate soil resistance get less with the decrease of the submerged weight of the pipe. A comparison is made between the results of the present mechanical-actuator tests and those of the previous water-flume tests, indicating that those results are quite comparable. For the equivalent level of dimensionless submerged weight, the directly laid pipe in currents has higher lateral stability than in waves.

1. Introduction

The submarine pipeline on-bottom stability in the severe ocean environments involves a complex pipe–soil interaction process. To avoid the occurrence of pipeline on-bottom instability, i.e. the breakout of the pipe from its original site, the seabed must provide enough soil resistance to balance the hydrodynamic loads upon the untrenched pipeline. When a pipeline is laid on the seabed, e.g. during installation as well as in the operational phase, its on-bottom stability is largely related to the interaction between the pipeline and the neighboring soil. For pipeline geotechnical engineers, one of the main concerns for pipeline on-bottom stability design is to properly determine the ultimate soil resistance in severe ocean environments (Det Norske Veritas, 2007).

In the past few decades, the pipe–soil interactions have attracted much interest from pipeline researchers and designers. Before 1970s, Coulomb friction theory was employed to estimate the friction force between pipeline and soil under the action of ocean waves. Actually, Coulomb friction theory is far from the realistic pipe–soil interaction. Lyons (1973) experimentally explored the wave-induced stability of the untrenched pipeline, and concluded that the Coulomb friction theory was not suitable to describe the wave-induced interaction between pipeline and soil. In the 1980s, a few large projects had focused particularly on solving wave-induced pipe–soil interaction problems, such as the PIPESTAB project (Wagner et al., 1989), the AGA project (Brennodden et al., 1989) and a project at DHI (Palmer et al., 1988). Numerous experimental studies on the lateral stability of untrenched pipelines have been previously carried out with a mechanical-actuator simulation method. Among these, Wagner et al. (1989) improved the Coulomb friction theory into an empirical pipe–soil interaction model, in which the total lateral resistance was assumed to be the sum of the Coulomb friction component and the soil passive resistance component. Brennoden et al. (1989) further proposed an energy-based pipe–soil interaction model, in which the soil passive resistance component is related to the work done by the pipe during its movement. Using the PIPESTAB, AGA and DHI experimental data, Verley and Sotberg (1992) and Verley and Lund (1995) developed pipe–soil interaction models on sandy and clay soils, respectively, taking into account of the penetration effects of the pipe subjected to oscillatory forces in waves. Zhang et al. (2002) conducted a series of centrifugal tests to investigate the pipe–soil interaction for a shallowly embedded pipeline in calcareous sand. Foray et al. (2006) studied the pipe–soil interaction with special emphasis on

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the conditions leading to liquefaction around a pipe. White and Cheuk (2008) investigated the soil resistance on seabed pipelines during large cycles of lateral movement. The aforementioned studies focused mainly on the wave-induced pipeline on-bottom stability, in which some kinds of cyclic mechanical-actuators were employed for the simulation of wave loads on the pipe. Recently, a series of water flume tests were made to further reveal the flow-pipe-soil coupling effects on the wave-induced pipe lateral instability (e.g., Gao et al., 2003; Teh et al., 2003).

With the oil and gas exploitation moving into deeper waters, ocean current becomes the prevailing hydrodynamic load for on-bottom stability of submarine pipelines (Jones, 1985). Although the pipe on-bottom stability in currents seems less complex than in waves, till now, the underlying physical mechanism has not been well revealed (Jones, 1978; Gao et al., 2007). The ocean current-induced pipeline instability has been investigated by Gao et al. (2007) with small-scale water flume tests. Recently, numerical method was also adopted by a few researchers to investigate the pipe–soil interaction mechanisms for the on-bottom stability of partially embedded pipes for various loading conditions, e.g., the wave loading (Takatani, 2005) and the ocean-current loading (Gao et al., in press).

This paper aims to explore the physical mechanism of pipeline on-bottom stability in ocean currents. The ultimate lateral soil resistances to the partially embedded pipes with two kinds of constraint conditions, i.e. freely laid pipes and anti-rolling pipes, are studied experimentally. Furthermore, a comparison is made between the results of the mechanical actuator experiments and those of the previous water-flume tests.

2. Dimensional analyses for current-induced pipeline instability

The ocean current induced pipeline on-bottom stability on a sandy seabed is an interaction between the flow, pipe and soil. The ultimate lateral soil resistance (F_u) is mainly related to the following characteristic parameters of the pipe, the soil and the hydrodynamic load

$$F_u = f(W_S, D, k, \rho_{sat}, \rho_w, d_s, D_r, \phi, g, \tan\theta, e_0, \lambda, \ldots) \tag{1}$$

where W_S is the submerged weight of the pipeline per meter; D the outer diameter of pipeline; k the roughness of the pipe surface; ρ_{sat} the mass density of saturated sand; ρ_w the mass density of fluid; ds the diameter of sand particles; D_r the relative density of sand; ϕ the internal frictional angle of sand; g the gravitational acceleration; tan θ the ratio of the lift (vertical) and the drag (horizontal) force on the pipe (see Fig. 1); e_0 the initial settlement of the pipe, which is a deduced (not independent) variable if the pipe settles into the soil under its submerged weight; and λ represents the end constraint conditions of the pipe. In this study, two kinds of end constraints are taken into account, i.e. freely laid pipes and anti-rolling pipes.

Based on the Buckingham Pi-Theorem in the dimensional analysis theory, the dimensionless variables can be obtained from Eq. (1) as follows:

$$\eta = f'(G, k/D, \rho_{sat}/\rho_w, D/d_s, D_r, \phi, \tan\theta, e_0/D, \lambda, \ldots) \tag{2}$$

where the lateral-soil-resistance coefficient (η) is defined as

$$\eta = \frac{F_u}{W_S - F_u \tan\theta} \tag{3}$$

whose physical meaning is the ratio of the ultimate lateral soil resistance (F_u) to the vertical pipe-soil contact force ($W_S - F_u \tan\theta$); G is the non-dimensional submerged weight of

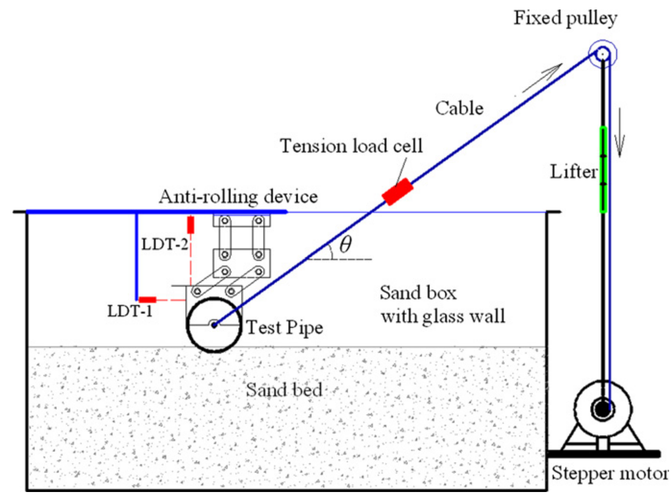

Fig. 1. Schematic diagram of the displacement-controlled experimental setup for pipe–soil interaction.

the pipe

$$G = \frac{W_S}{\gamma' D^2} \tag{4}$$

where $\gamma' = (\rho_{sat} - \rho_w)g$ is the buoyant unit weight of the saturated sand; k/D the relative roughness of the pipe surface; ρ_{sat}/ρ_w the specific gravity of the saturated sand, i.e. the ratio of the density of the saturated sand to that of the pore water; D/d_s the ratio of pipe diameter to sand diameter; and e_0/D the dimensionless initial settlement.

In this study, a kind of saturated sand-bed was adopted, whose index properties are given in Section 3.3, thus the values of the dimensionless parameters ρ_{sat}/ρ_w, D_r, ϕ (see Eq.(2)) keep constant. Three values of the pipe diameter were chosen (D=0.10, 0.15 and 0.20 m), so D/d_s is approximately in the range from 250 to 500, indicating the characteristic size of the pipes is prevailingly larger than that of the sand particles. The inclination angle (θ) of the exerted loads is approximately between 53° and 57° in the tests, thus values of the ratio of the lift and the horizontal drag force on the pipe (i.e. tan θ) is about 1.4 ± 0.1. In Section 4, the effects of the relative roughness of the pipe surface (k/D), the end constraint conditions of the pipe (represented as λ) and the dimensionless initial settlement (e_0/D) on the pipe lateral stability will be discussed, respectively.

3. Mechanical-actuator simulation of pipe–soil interaction

3.1. Hydrodynamic loads on submarine pipeline in currents

To efficiently simulate the ocean currents induced hydrodynamic loads upon a submarine pipeline is crucial for evaluating pipeline lateral on-bottom stability. According to Morison's equation, the horizontal and lift (vertical) components of the steady flow-induced hydrodynamic forces can be written as follows (Morison et al., 1950):

$$F_D = 0.5 C_D \rho_w D U^2 \tag{5}$$

$$F_L = 0.5 C_L \rho_w D U^2 \tag{6}$$

where F_D is the horizontal drag force, F_L the vertical lift force, C_D the drag coefficient, C_L the lift coefficient and U the effective water particle velocity. Variations of the drag and lift coefficients, C_D and C_L, with the Reynolds number (Re) for various values of pipe surface roughness have been obtained by Jones (1978). As shown