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The effect of a berm on the lateral resistance of a shallow pipeline buried in sand

Le Wang, Run Liu *

State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China

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ABSTRACT

As the development of offshore oil and gas exploration moves into deeper waters, pipelines experience lateral buckling due to high temperatures and high pressures in submarine. The pipe–soil interaction plays a critical role in the thermal buckling characteristics of pipeline. Large-amplitude lateral movements of pipelines tend to cause soil accumulation in front of pipelines. The accumulated soil in front of pipelines is generally called as "berm". The berm is an important factor in forecasting the changes in the lateral buckling characteristics of pipelines. In this study, a pipe segment with 16-cm outer diameter is considered as the object. Pipe–soil interaction model tests of lateral movement under different initial embedments and different pipe segment weights of 0.05, 0.1 and 0.15 kN/m are performed in sand. The large deformation behaviour of seabed and the changing process of berms are investigated; a formula to calculate the berm resistance is also proposed. Compared with the existing calculation methods, the lateral residual resistance including the influence of berms is more significant in this study if the weight of the pipe segment equals or exceeds 0.1 kN/m. However, the existing calculation methods tend to exaggerate the lateral residual resistance when the pipe segment weight is less than 0.05 kN/m.

1. Introduction

Lateral buckling is an important issue in subsea pipelines. Long subsea pipelines are typically operated at high temperatures, which results in significant axial stresses in the pipeline. The foundation soil restrains the free deformation of the pipelines; thus, the axial stress in the pipelines tends to accumulate continually and eventually causes lateral buckling to occur.

A typical design for lateral buckling involves controlling lateral pipe movements to within 5–20 diameters and up to 1000 thermal cycles throughout the life of the pipeline. During lateral buckling, the trajectories of the pipelines are influenced by the resistance of the subsoil. The soil in front of the pipe tends to be gradually uplifted with an increase of the lateral pipe movement, generating berms in front of the pipelines. The berm then increases the soil resistance and restrains additional lateral pipe movements. The influence of berms on the soil resistance is not considered in the existing pipeline design process, which causes the underestimation of the resistance of subsoil and leads to the problems in the current design for lateral buckling. Thus, this study of the resistance of a berm is important to this field of research.

Our understanding of berms is relatively deficient; the methods frequently used to analyse berms include physical model tests, theoretical analyses and numerical analyses. In physical model tests, a centrifuge is typically used. Bruton et al. (2006a) analysed the SAFEBUCK JIP pipe–soil interaction test in a mini-drum centrifuge and found two characteristic types of large-amplitude lateral responses after breakout; the "heavy pipes" and "light pipes" were presented to distinguish two different types of large-amplitude lateral responses and to demonstrate that the berms in front of the pipes played a critical role after breakout. Bruton et al. (2006a) considered four stages of pipe–soil interaction: pipe embedment during installation, breakout during buckling based on different levels of initial pipe embedment, large-amplitude lateral displacement as buckling began and cyclic lateral displacement influenced by the building of soil berms. Based on the results of the pipe–soil interaction centrifuge test, the soil berms were shown to play a critical role in the lateral resistance in the fourth stage. Bruton et al. (2006b) analysed the SAFEBUCK JIP pipe–soil interaction test in clay and identified the factors that affected the resistance of a dormant berm. Jayson et al. (2008) analysed the pipe–soil interaction cyclic test of BP's Greater Plutonio in clay; these tests were conducted in NGI, and the "heavy pipes" and "light pipes" cases in these tests were found to be similar to the results found by David As Bruton et al. (2006c). Dingle et al. (2008) performed centrifuge tests and analysed the movement process of the pipes and the changes in the lateral resistance in clay. In this test, they found that the gradually growing berms experienced shear

* Corresponding author.
E-mail address: liurun@tju.edu.cn (R. Liu).

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along the bottom of the pipes, and the soil, which was near the bottom of the pipes, was pushed into the berms, which caused the berms to grow.

Cheuk and Bolton (Cheuk et al., 2006) analysed the typical pattern of the soil resistance on a short section of pipe that was subjected to lateral cycles of movement on a soft clay seabed. The short section of pipe was swept back and forth across a subsoil model of kaolin clay under a constant vertical load, while the horizontal resistance was measured. White and Dingle (2011) simulated the processes of large-amplitude lateral pipe movements using different weights and different initial embedments; they limited the rotation of the pipelines and found that the lateral responses were governed predominantly by the passive resistance due to the growing berms during the testing.

Using the available theoretical analyses, White and Cheuk (2007) found that the lateral resistance generated by berms was proportional to the berm volume and thus proposed a formula to calculate the lateral resistance; however, the ploughing depth was assumed to be a constant that is unaffected by the berm size. This assumption may be overly simplistic because the pipe may rise relative to the original seabed level as the berm grows. With the development of the large-deformation finite element method, a finite element analysis of the pipe–soil interaction has developed in recent years. Wang Dong et al. (2010) used the RITSS method in ABAQUS to simulate the pipe–soil interaction in clay while considering the berm ahead of the pipe and found excellent agreement with the result of the centrifuge test in terms of both the instantaneous soil flow mechanisms and the lateral resistance reported by Dingle et al. (2008). Deepak V. Datye (2010) and Tho et al. (2010) used the Coupled Eulerian–Lagrangian method to simulate the pipe–soil interaction in clay: Deepak V. Datye (2010) researched the process of the lateral pipe movements and described the influence of the berm on the lateral resistance with different initial pipe embedments; Tho et al. (2010) simulated the cyclic lateral motion of pipelines in clay and found that a dormant berm would enlarge due to the accumulation of new berms after each cyclic movement.

In conclusion, the resistance caused by a berm is an important part of soil resistance during the process of lateral motion of shallowly buried submarine pipelines. Many researchers have conducted extensive studies of the berm during lateral buckling in clay and have revealed the laws of berm production and discovered formulas with which to calculate berm resistance. However, the study of this phenomenon in sand is currently not complete. The testing of the pipe–soil interaction model with lateral motion in sand was thus performed in this study. During testing, the influence of the pipe section mass and the initial pipe embedment on the formation of the berm was analysed, and the lateral resistance caused by the berm was described in detail. Based on the experimental results in this study, a formula to calculate the lateral resistance of a berm was proposed.

2. Model tests

2.1. Testing apparatus

To investigate the changes in the soil resistance and ensure that the pipe segment is not restrained in the vertical direction, a continuous lateral force was applied to the pipe segment using the device shown in Fig. 1.

Figs. 1 and 2 show the testing apparatus, which consisted of a test tank, a power transmission system, a data collection system and an image acquisition system. The test tank was a steel tank with a length, width and height of 3 m, 1.1 m and 1 m, respectively; tempered glass was installed around the test tank to allow the observation of the test phenomenon. The power transmission system consisted of a speed control box, a reducer, a servo motor, a coupling, a guide screw and a guide rail. The data collection system consisted of pull and pressure sensors, a dial indicator, a depth transducer, an elevator, a DH-3817F dynamic and static strain data acquisition device and a computer. The servo motor transmits power to delivery plate through guide screw and controls the rotational speed of guide screw. The delivery plate transmits power to pipe segment through knockout plate. During the power transmission process, the horizontal travelling speed of pipe segment can be controlled by servo motor. At the same time, the pipe segment is not confined in vertical direction.

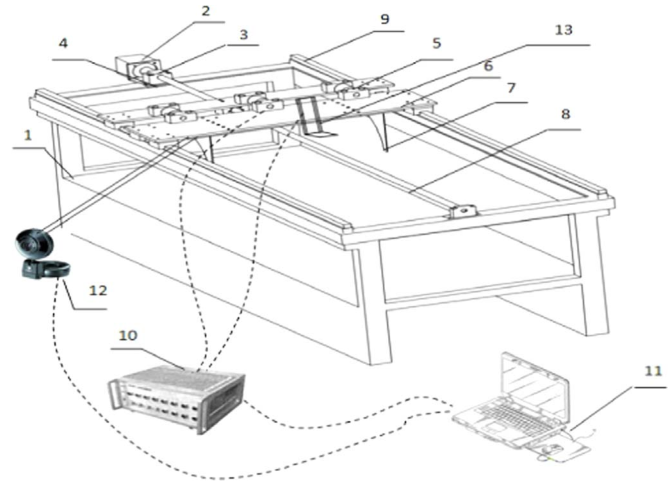

Fig. 1. Schematic of testing apparatus: 1. test tank; 2. servo motor; 3. coupling; 4. support of guide screw; 5. pull and pressure sensors; 6. delivery plate; 7. knockout plate; 8. guide screw; 9. guide rail; 10. DH-3817F dynamic and static strain data acquisition device; 11. computer; 12. camera; and 13. elevator.

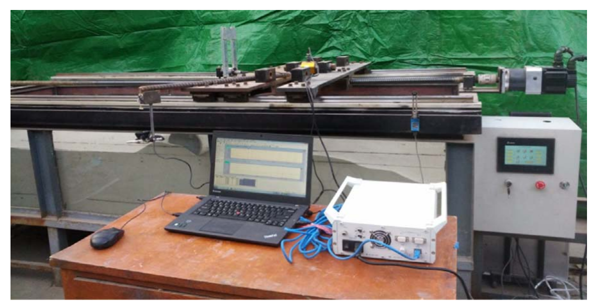

Fig. 2. Photograph of the testing apparatus.

2.2. Testing programme and its results

The sand used in the tests was a fine sand with a uniform gradation; its maximum dry density ($\rho_{d\ max}$), minimum dry density ($\rho_{d\ min}$), natural dry density (ρ_d) and internal friction angle (φ) were 1673 kg/m^3, 1414 kg/m^3, 1455 kg/m^3 and 30°, respectively. The density of sand which is used in the direct shear box tests is equal to the density of the topsoil in the test tank which was obtained by cutting ring. The curve describing the soil grain size and the mechanical parameters of the sand are shown in Fig. 3.

To describe the influence of the weight and the initial embedment depth of the pipe segment on the soil resistance, the pipe segment weight (W) was set to 0.05 kN/m, 0.1 kN/m, and 0.15 kN/m, and the initial embedment depth of the pipe segment (Z_0) was set to 1/8D, 1/4D, and 3/8D. The length (L) and the outer diameter (D) of the hermetic PVC pipe segment were 1 m and 0.16 m, respectively.