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Interaction between catenary riser and soft seabed: Large-scale indoor tests

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ABSTRACT

Nowadays, steel catenary riser (SCR) has become the most favorable method for oil and gas transportation in deep water. Accurate analysis of riser fatigue is heavily dependent on the interaction between riser and the seabed soil, which is a research focus in recent years. This paper aims to simulate the 3D interaction between SCR and typical clay seabed through large-scale indoor tests in 1g condition. The dynamic pipe–soil interaction is modeled through applying cyclic motion at one end of the pipe. The trench formation, pipeline behavior and the excess pore water pressure beneath the pipe invert are all analyzed in detail.

The apparently dynamic embedding process and the ladled shape trench at touchdown zone (TDZ) were observed, which can be attributed to soil softening. The suction at the pipe/soil interface was captured and the accumulation of excess pore pressure was visualized. The results based on this study indicate that: the excess pore water pressures at different positions along the pipe axis vary with different trends, which may be attributed to their corresponding pipe trajectories. Therefore the accurate loading history simulation is very important for conventional 2D plane strain tests. It is found that, after 200 cycles, the maximum dynamic embedment factor f_{dyn} along the axis of the model riser was up to 1.6, the pipe embedment depth increased by up to 60% and the average bending moment increased by up to 31.0%.

1. Introduction

With the depletion of relatively shallow water fossil fuel reserves, more and more oil and gas reserves in ever deeper water have been exploited significantly in recent years, where the floating production vessels or platforms such as semi-submersible or SPAR production platforms, floating production storage and offloading vessels (FPSO) are often utilized instead of fixed production structures. In addition, a floating production system (FPS) usually consists of a mooring system and risers, which transport the hydrocarbon production or export the processed fluid between the subsea wells and the floating platforms. The introduction of these compliant floating systems for offshore hydrocarbon production has led to the development of new designs for the risers.

Steel catenary risers (SCRs), which are steel pipes with typical diameter of 150–600 mm slung from the floating structure to the seabed in a catenary (Fig. 1), can be a more cost effective option than traditional vertical or flexible risers in deep water, therefore are often employed nowadays. As the mooring system is flexible, the floating platforms will move back and forth under wave motion, causing the dynamic motion of the touchdown point (TDP), where the riser first touches the soil surface. So the zone, denoted as the touchdown zone (TDZ) as shown in Fig. 1, often proves to be a fatigue hotspot due to its largest variation range of bending stress [1,2]. At TDZ, the accurate assessment for fatigue damage due to repetitive loading throughout the lifetime of the SCR depends significantly on the assumed pipe/soil interaction model in the vertical direction. Consequently, the vertical response of seabed to SCR has been a research focus in the last decade due to its complexity.

A typical but simple approach is to conduct 2D experiments on a short, rigid section of pipe, to explore the elemental behavior of the riser/soil interaction under a range of different amplitudes and frequencies as well as different load conditions (force or displacement control). Various researchers such as Fontaine et al. [3], Orozco et al. [4], Aubeny et al. [5], Clukey et al. [6], Langford and Aubeny [7], Hodder et al. [8], Hodder et al. [9] and Hu et al. [10] have performed monotonic or cyclic pipe tests under plane strain condition.

3D interaction between riser and the seabed was first investigated by Wills et al. [11], Bridge et al. [1], Bridge et al. [2] and Bridge [12], which served as part of the STRIDE JIP – Steel Risers in Deepwater Environments Joint Industry Project. The test program was conducted at Watchet harbor in Somerset, UK, where the soft clay was found to have properties similar to a typical deepwater GOM seabed. To simulate the area around TDP of a deepwater SCR at cut-down scale, a 110 m long, 168 mm diameter and 6.9 mm wall thickness welded steel 'riser' was suspended in a catenary from an actuator on the harbor wall, and ran out across the natural seabed to anchors located at the other end of the model riser. The designed actuator can impose different displacement paths in vertical or horizontal direction,

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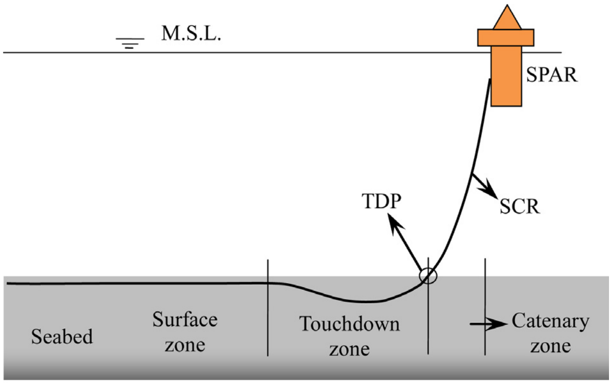

Fig. 1. Schematic of typical SCR configuration.

which resulted from the second order slow drift vessel motions and wave loading (day-to-day or extreme storm loading). To monitor the test process in real-time, instrumentation mounted on the cut-down riser consisted of full bridge bending moment strain gauges, triaxial accelerometers and load cells. In addition, natural trenches, artificial trenches, back-filled trenches and rigid seabed cases were all tested for comparisons. The soil suction beneath the pipe was apparently visualized because the bending moments recorded throughout the lift-up/lay-down cycle differed significantly when it rested on the natural trenches, but were similar when testing on the wooden planks which simulated an rigid seabed. Over the six week testing period, the trench was observed to deepen and widen around the TDP from 0.5*D* to 1.2*D* and 1*D* to 2.5*D* respectively, which was thought to be produced by the dynamic motions of the riser combined with the scouring and sediment transportation effects of the seabed currents. While the harbor test provided invaluable information about pipe/soil interaction, there were still some shortcomings. For example, there was no direct measurement of suction at the pipe invert and trench formation at different riser positions.

To characterize the behavior of the pipe/soil interaction in more detail, Hodder and Byrne [13] conducted three-dimensional model studies in laboratory-controlled conditions to investigate SCR responses at touchdown zone on sand. The model riser pipe was 7.65 m in length, 110 mm in diameter and 5.3 mm in wall thickness, which was made from PVC (polyvinyl chloride). A computer-controlled actuation system located at one end of a 8 m long flume can apply both monotonic and cyclic motions vertically. Instrumentation such as draw wire displacement sensors, bending moment strain gauges, pore water pressure transducers as well as a load cell were used to monitor the response of model pipe and seabed in real-time. Trench formation was observed due to hydrodynamic 'jetting' effects as the pipe moved in and out of the trench, which can be attributed to the low critical velocity for scouring for the fine sand used in the experiments. Additionally, soil suction with minimal value beneath the cut-down riser pipe was seen evidently upon lifting of the pipe.

However, soft clay soils with low strength and high plasticity are typically encountered in deepwater environment where SCRs are usually used [14]. Moreover, the response between riser and clay seabed is more complicated than that of sand seafloor because suction at pipe/soil interface can strongly influence the riser fatigue life as well as trench depth.

This paper put insight into the mechanism of vertical pipe/soil interaction, which was inspired from the work of Hodder and Byrne [13]. A series of large scale model tests within laboratory-controlled condition were conducted in the present study to investigate the interaction between SCR and the soft clay seabed, with particular attention on the development of soil suction as well as trench formation. The detailed test results are presented in this paper.

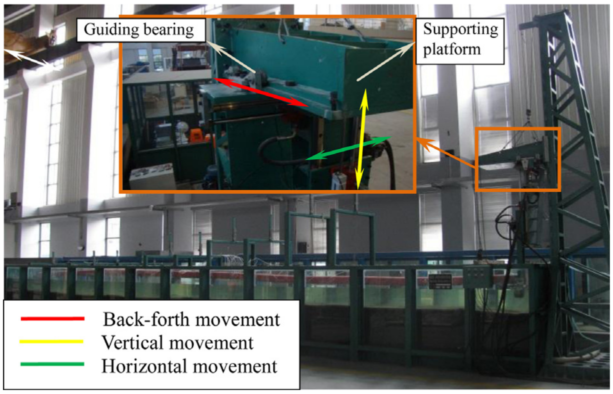

Fig. 2. Overall view of the large scale 3D soil/structure interaction test system.

Table 1
The actuator parameters.

Parameter	Vertical	Lateral
Displacement range (mm)	±240	±160
Maximum velocity (m/s)	0.3	0.2
Maximum acceleration (m^2/s)	0.4	0.25
Maximum load (kN)	5	1
Maximum loading frequency (Hz)	0.2	0.2

2. Experimental set-up

2.1. Experimental equipment

The experiments described in this paper were conducted using the large scale 3D soil/structure interaction test system at Zhejiang University, shown in Fig. 2, it consists of two main parts: a long flume with soil and water in it, a bidirectional loading actuation system located at one end of the flume. The inner dimensions of the tank are 15 m in length, 1.2 m in width and 1.5 m in depth.

The actuation system can apply specified displacement paths (i.e. displacement controlled form) in two directions separately or simultaneously. The actuator is controlled by a computer and it is possible to move at either constant velocity or cyclically in the form of a sine wave at a range of amplitudes and frequencies. More complex motions can be applied but require specific control programs to be developed. The key parameters of the actuator are summarized in Table 1. In this work, we aim to illustrate the pipe-soil interaction when the actuator moves in the vertical direction only.

The actuation system has two guiding bearings on either side of a supporting platform (Fig. 2) to allow free motion along the longitudinal axis of the model pipe, but the guiding bearings can be fixed if necessary. The supporting platform can be adjusted in the vertical direction to simulate different neutral positions. The instrumentation was powered and amplified by signal conditioning equipment. The data were logged on a computer using a LABVIEW program via a 16-bit data acquisition card. The maximum logging frequency could be up to 10 Hz. The data logging program was also responsible for the control of the actuation system.

2.2. Model pipe

The details about the model pipe are given in Table 2. PE (polyethylene) was chosen for its low material stiffness, which ensured the portion of pipe furthest from the actuator would remain stationary