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Riser-seabed interaction in the touchdown zone using fibre optic sensing in a geotechnical centrifuge

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ABSTRACT: Fatigue damage of Steel Catenary Risers (SCRs) is typically greatest within the touchdown zone (TDZ), where cyclic interaction of the riser with the seabed results in complex changes of soil properties and potential changes in riser curvature, especially if a trench forms. This complex phenomenon has prompted researchers to pursue improved understanding of SCR behaviour in the TDZ, to enhance design life assessment and overall design. Past studies have shown that modelling a section of the riser around the TDZ can satisfactorily capture touchdown behaviour. However, the use of conventional strain gauges may result in unwanted stiffening of the model, while also limiting the number of data points at which strain is measured. This paper presents centrifuge tests performed using a SCR model instrumented with a novel fibre optic sensing system. The system comprises three Fibre Braggs Grating fibre strands along the SCR model, separated circumferentially by 120º in cross section, with each strand measuring over 350 points of strain. Realistic sea states were scaled and translated to the cut-off point on the riser above an elastic (dummy) seabed, with surge, heave and sway motions simultaneously applied using three degrees of actuation. The riser-seabed interaction along the TDZ was successfully captured, with experimental results validated against finite element analyses. Following the success of this campaign, the model is now being used to explore response on clay seabed samples, which will further advance understanding of SCR behaviour at the TDZ.

Keywords: steel catenary riser, fibre optics, centrifuge modelling, elastic seabed.

1 INTRODUCTION

Steel catenary risers (SCRs) are used to transport hydrocarbons up through the water column and comprise long unsupported pipe spans that form a catenary between the hang-off end (at the floating facility) and the seabed (Fig. 1).

The fatigue life of SCRs is governed by wave and current induced displacement of the floating facility, vortex induced vibration of the SCR, and interaction with the seabed in the Touchdown Zone (TDZ). The latter is often considered the most critical component of fatigue damage (Aubeny and Biscontin, 2009), as stresses concentrate along a span of riser cyclically interacting and 'abrading' the seabed. Over time, this can form a trench around the SCR, changing the curvature of the riser. In addition, the soil will experience several cycles of softening (through damage) and hardening (through consolidation), thereby changing its properties over time. The overall process is complex and affected by a range of factors including SCR motion amplitude and velocity, soil response and soil-fluid interaction (Bridge and Willis, 2002) – prompting many recent studies to pursue better understanding of SCR behaviour in the TDZ.

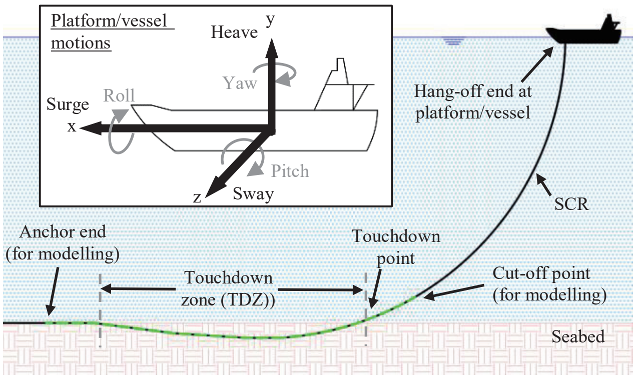

Fig. 1. Steel catenary riser and vessel motions.

Finite element studies show that motion observed at the hang-off end can be scaled and translated to a 'cut-off' point near the seabed to satisfactorily capture TDZ behaviour (e.g. Bhattacharyya et al. 2011). This is especially beneficial for physical modelling – warranting only a 'sectional' SCR model to be used, typically starting just above the touchdown point and extending through the TDZ as highlighted in green on Fig.1. Various studies have capitalised on this, notably centrifuge tests described by Elliot et al. (2013 & 2014).

However, the typical approach for measuring response has been to instrument the SCR with strain gauges. This can impact minimum model sizes in the centrifuge, as well as result in local stiffening (da Silva et al. 2016).

This paper presents centrifuge modelling with a sectional SCR of outer diameter 8 mm, and instrumented with a fibre optic sensing system providing a total of more than 1000 individual points of strain measurement. It describes the complex apparatus – which enables for five degrees of freedom at the cut-off end – and presents validation of the model on a 'dummy' elastic seabed against finite element analyses.

2 MODEL AND SETUP

Testing was at the National Geotechnical Centrifuge Facility at the University of Western Australia, in a 3.6 m diameter beam centrifuge (Randolph et al. 1991) at an enhanced acceleration of 100 times Earth's gravity (g). While this paper only discusses tests on a 'dummy' seabed – to assess model functionality and structural integrity – it is part of a broader research campaign on clay seabeds to be reported in due course.

2.1 Testing arrangement

The general test arrangement is shown on Fig. 2 and Fig. 3. A model SCR was located within a 1.3 m long sample box and three actuators were used (simultaneously) to translate specified motions to the SCR in-flight.

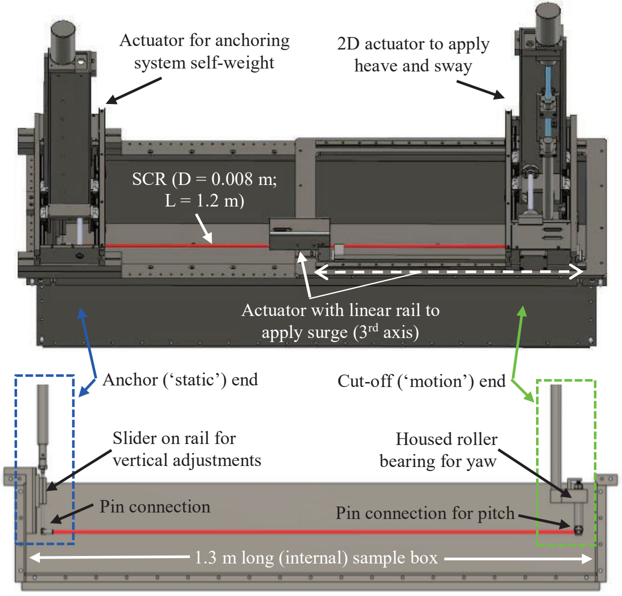

Fig. 2. Centrifuge testing layout.

At the cut-off (or 'motion') end, heave and sway motion was applied with the vertical and horizontal axes of a 2D actuator. This actuator was mounted onto a '3rd axis' rail fitted atop the sample box to apply (simultaneous) surge motion. The yaw and pitch rotation were free to occur by means of a tapered roller bearing (housed within an aluminium block) and a pin-connection (Fig. 2).

At the anchor (or 'static') end, an actuator controlled the SCR position in the vertical plane, with a slider block to allow for self-weight induced 'settlement'.

2.2 General instrumentation

Yaw and pitch were measured with a high-resolution magnetic angular position sensor (or 'Hall sensor') capable of resolving small rotation with high accuracy.

At the anchor end, the SCR was fitted (via pin connection) to an instrumented titanium rod (Fig. 3). The rod featured top and bottom (full-bridge) bending strain gauges, which translate the force at this location and are needed to understand the influence of the section of SCR (beyond the anchor) that is not included. The free length of rod (to the pin) can be adjusted, allowing modelling of different axial stiffnesses at this location.

Although not included in the original configuration, an additional load cell is to be incorporated at the cut-off end to enable better control of SCR tension.

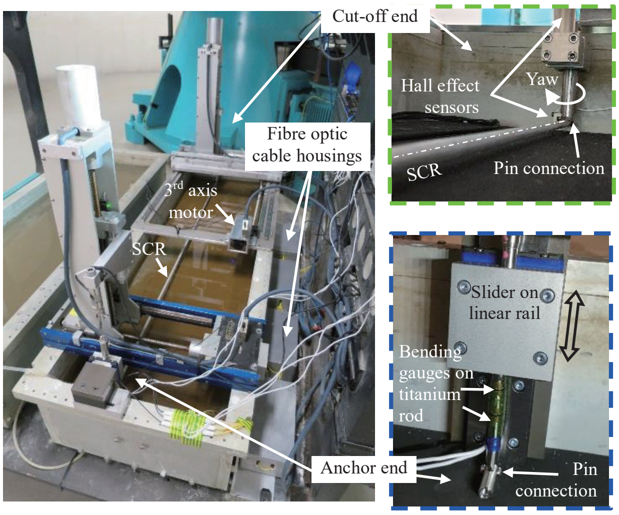

Fig. 3. Apparatus and instrumentation overview.

2.3 Instrumented SCR

The model SCR was fabricated from solid aluminium, with an outer diameter of 8 mm and a total length (pin-to-pin) of 1.2 m. Its outer surface was fitted with three optical fibre strands bonded along its full length and separated by 120º in cross section (Fig. 4). Each strand is imprinted with Fibre Braggs Grating (FBG) sensors, which reflect light at specific wavelengths (Beemer et al. 2018). FBGs are extremely sensitive to nonuniform strain distribution, allowing deformation to be detected with a sensitivity of only 1 microstrain. Each strand has a spatial resolution of 3.17 mm, measuring over 350 points of strain along the length of the model SCR. The fibre arrangement makes it possible to evaluate stress at any location around the SCR and determine its three-dimensional shape.

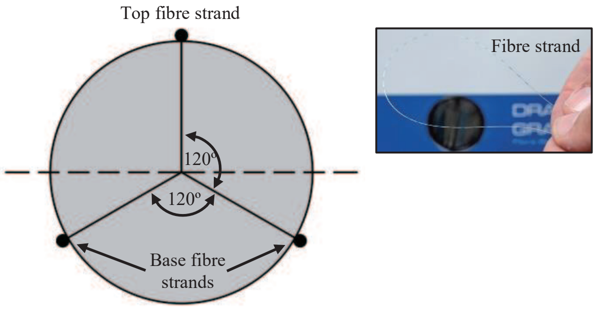

Fig. 4. Instrumented SCR cross section.

3 TESTING PROCEDURES

Calibration and mapping of the FBGs, using physical reference points along the model SCR, was first undertaken on the laboratory floor. Here, the SCR was positioned horizontally and simply supported at each end, with known masses then added at its midpoint. Microstrain output by the fibre sensing system (at 16 Hz) was analysed against theoretical bending strain, and a correction factor calculated (and then optimized using a root mean square error approach) which could be applied to the FBG data in subsequent centrifuge tests.

A typical centrifuge test on a 'dummy' (neoprene) seabed involved the following steps: (1) while at 1g, elevate the cut-off end to 6 mm above the seabed, (2) ramp up to an acceleration of 100g and activate a load control at the anchor end to offset any (added) system self-weight, such as from the slider block and titanium rod, (3) adjust the the 3rd axis (surge) to achieve a target tension in the SCR, (4) incrementally raise the cut-off end to a pre-determined height above the 'seabed', all the while adjusting surge to maintain the tension, (5) while at the desired neutral cut-off position, initiate a cyclic sequence (waveform) input of combined heave, sway and surge at the cut-off.

4 SELECT DATA AND DISCUSSION

4.1 Actuation capability

Along with assessing the structural integrity of the model and reliability of the FBG sensing system, a key objective was confirming the ability of the actuation system to model irregular motions. Real sea states recorded aboard an offshore platform (at the hang-off) in the Gulf of Mexico were provided by an industry partner. These motions were scaled and translated to the cut-off and applied in centrifuge tests lasting up to 20 hrs.

Samples of input (demand) against output (actual) model scale data are shown on Fig. 5 for each of the three planes of motion. The data are limited to only 200 s but are typical of motions applied during long tests in the centrifuge. The actuation system is capable of speeds greater than 3 mm/s in each of the heave/sway/surge axes and was shown to track motion demand with no apparent discrepancies. This was also confirmed with independent laser displacement sensors.

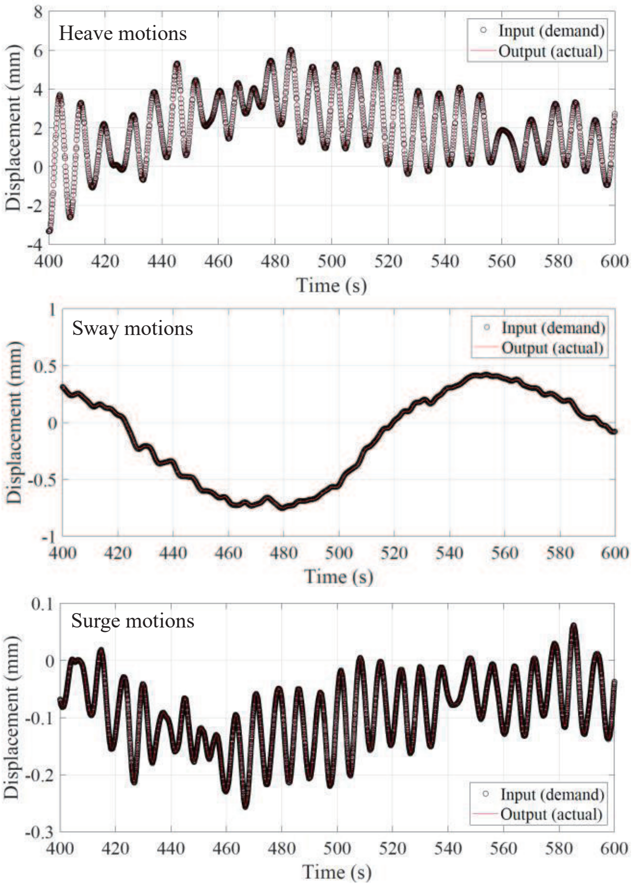

Fig. 5. Waveform of heave/sway/surge with resulting tension.

4.2 FBG data validated against FEA

To assess the performance of the FBG sensor system, the Von Mises stress (σ_{VM}) measured along the SCR was compared to results from finite element (FE) simulations. The FE simulations were performed using the software package Flexcom, with the SCR-soil interaction incorporated via Winkler elastic 'soil' springs. For this, the vertical stiffness was derived from in-flight model T-bar (8 mm diameter × 40 mm long) penetrometer tests, indicating a neoprene stiffness of approximately 150 kPa.

Fig. 6 compares the σ_{VM} measured in the centrifuge test with that obtained from FE simulations. At each measuring point, σ_{VM} was calculated by multiplying the measured strain by the SCR Young's modulus, and the results clearly demonstrate the ability of the FBG sensor system to capture near continuous σ_{VM} along the SCR. Relative to conventional strain gauges, where important changes in stress profiles may be missed due to discrete measuring limitations (Ni et al. 2018), the near continuous profile improves the accuracy of deriving other important parameters, such as soil resistance, SCR deflection and associated body forces.

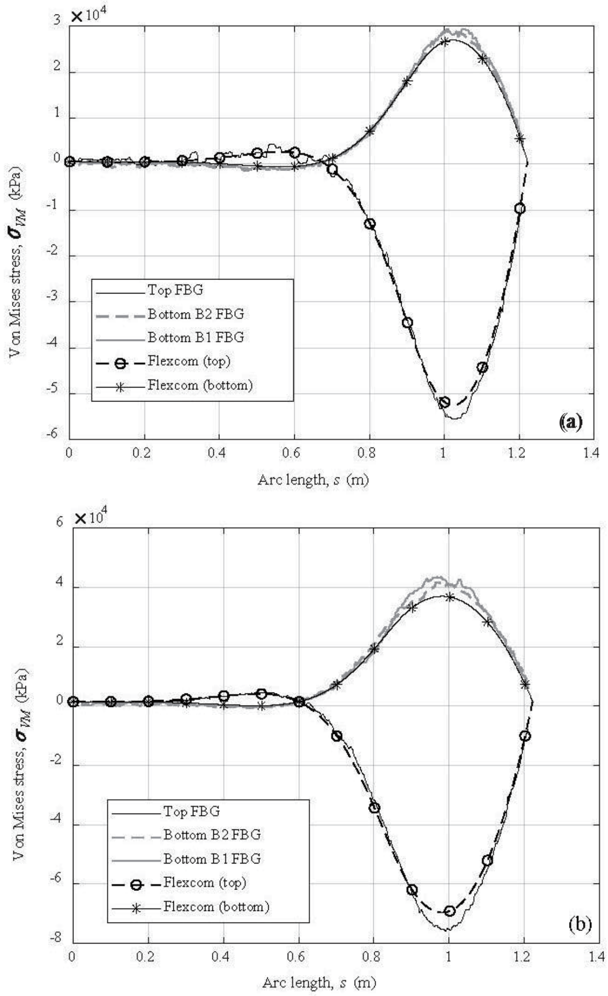

Fig. 6. Von Mises stress along SCR: (a) cut-off located 10 mm above seabed; (b) cut-off located 20 mm above seabed.

5 CONCLUSIONS AND ONGOING WORK

This paper has outlined a new experimental model for capturing SCR motions at the touchdown zone through centrifuge testing. Of particular novelty has been the ability to instrument a small diameter model SCR with optical fibre strands which tracked strains continuously at over 1000 locations. The relatively insignificant diameter and rigidity of the cables does not affect the SCR stiffness as strain gauges would.

Motions were simultaneously applied in three planes at the cut-off to successfully simulate real sea-states.(b) All the while, resulting yaw and pitch rotations were uninhibited and measured to high accuracy. Experimental Von Mises stresses (σ_{VM}) compared well with FE simulations, demonstrating the ability of the FBG sensing system to capture near continuous σ_{VM} along the SCR. The centrifuge apparatus is now being used on clay seabed samples to assess the influence of trench formation and to ultimately gain greater insight on fatigue stresses in the TDZ – the results of which will be fully reported in due course.

ACKNOWLEDGEMENTS

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