

Fourth Year Project
Model Testing of Riser-Seaflor Interaction
(D-GB479-3)
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Technical Abstract

Brief

Floating oil rig platforms are being increasingly used in deep and ultra-deep waters. These rigs consist of a floating platform with steel catenary riser (SCR) systems used to transport oil from the well head on the seafloor to the offshore floating structure. Fatigue stresses associated with extreme storms, vessel movements, and vortex-induced vibrations are critical to riser performance. The critical location with respect to fatigue often occurs in the zone where the riser touches down at the seafloor, an area in which cyclic bending moments are significantly influenced by seabed stiffness. Current practice typically models seabed stiffness in terms of equivalent non-linear springs supporting a riser pipe. The goal of this project is to carry out small centrifuge tests to assess the response of a model riser subjected to cyclic loading similar to that experienced by SCRs in the field.

Project Definition

In this project a correctly scaled physical model of a steel catenary riser will be built and tested in the mini drum centrifuge of the Schofield Centre, Cambridge at conditions equivalent to those found in situ. PIV will be used to photograph the model in the centrifuge and observe the deflected shape of the riser pipe which rests on the clay bed. Dressmakers pins were inserted into the pipe vertically (see Figure) so that the heads of the pins would provide a clear point to map using PIV.

The aim of the project was to assess the riser response to cyclic loading applied by an actuator and generate parameters which could be inputted to a MATLAB model of the SCR response to the same loading.

Approach

Over-consolidated kaolin clay was used for the soil.

Tests

Conclusions

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1 Introduction

1.1 Motivation for Research

The increasing global demand for oil and gas is driving the development of oil rigs suitable for deep and ultra-deep waters. At these depths gravity structures are unsuitable and floating platforms are the preferred method of oil production. These platforms are connected to the seabed by steel catenary risers (SCRs); steel pipes with a typical diameter of between 150mm and 600mm which are suspended from a single point (the oil rig) and form a catenary profile before touching the seabed at the touchdown point (TDP). The floating oil rig moves vertically by some displacement due to the motion of the waves on which it rests which has the effect of causing the fixed end of the SCR to oscillate up and down. This, in turn, causes the suspended length of pipe to move in the vertical direction and so affects the tension in the riser and consequently the amount of the pipe which is suspended and the location of the touchdown point. The area in which the TDP occurs over the cyclic loading path is referred to the touchdown zone (TDZ) and it is this area which is of particular interest to engineers researching riser-seafloor interaction as the mechanisms of soil erosion at this point are unknown and the bending moments in the riser are highest.

The variation in curvature of the riser during the cyclic loading described above and subsequent changes in bending moment in the touchdown zone leads to high induced stresses in the pipe and causes the length of riser within the TDZ to be susceptible to fatigue failure. This failure is not at all well understood and is often regarded as the critical element in riser design so drives the factors of safety used in the system. It is generally agreed that SCR systems are more economical to install and operate than traditional vertical riser systems, however there are concerns that designs are over conservative and contain safety margins that are too high due to the lack of understanding of the failure mechanisms of the pipe in the TDZ and the riser-seafloor interaction, so research is needed in these areas to promote the development of more efficient (and thus economical) designs.

As well as riser stresses being unknown, there is a lot of discussion into how to model the seafloor within the TDZ as the riser movement causes trenching to occur and the riser shape to change, although it is unknown how this trenching occurs and what the effect of it on the riser stresses is. It is common to model the seafloor within the TDZ as a series of non-linear springs, however the degree of non-linearity is also currently being debated along with how to input this into computer FEM or MATLAB models.

If the deformed shape of the riser in the TDZ is known then this will enable engineers to understand the curvatures and thus induced stresses and failure life of the pipe.

1.2 Problem Statement

This project will produce quantitative data for the deformed shape of a riser pipe under cyclic loading. To do this, centrifuge testing of a correctly scaled model will be undertaken with dressmakers pins inserted into the pipe so that the heads of the pins can be mapped using PIV.

Preliminary 1g testing will be undertaken before the Christmas vacation to investigate the feasibility of the project. This will be followed by further 1g testing of the exact

experimental set up which will be put into the centrifuge and finally 100g testing to gain the data for PIV analysis. This analysis will then be done in the final stages of the project to gain quantitative values for pipe deflection.

The aim of the project will be to assess the riser response to cyclic loading applied by an actuator and generate parameters which could be inputted to a MATLAB model of the SCR response to the same loading.

1.3 Literature Review and Previous Work

A literature review was undertaken for this project to establish the extent of existing research. It was discovered that, broadly speaking, research into SCR behaviour could be divided into three categories: computational modelling, full-scale testing and small-scale centrifuge testing.

1.3.1 Computational Modelling

There have been many attempts to generate computer models for riser-seafloor interaction. C.P. Aubeny and G. Biscontin presented a seafloor-riser interaction model which simulated the seabed as a series of non-linear springs where the stiffness of the springs was described by complicated load-deflection relationships[6]. The benefits of this approach was that the authors were able to model the uplift, reload cycles and detachment of the pipe and develop a load-displacement loop to fit the data. The model has not yet been validated by experimental data which is another motivation for undertaking the research contained in this project. A common challenge for computational modelling of riser-seafloor interaction is that the soil softens as the cycles are repeated and so hysteresis loops are formed. This problem caused Shiri to develop an advanced hysteretic non-linear riser-seabed interaction model to predict fatigue performance[16]. This article concluded that the movement of a riser did affect the fatigue life of the pipe but the author did not manage to quantify the magnitude of the affect, indicating instead the need for more accurate models.

A slightly different approach to computational modelling was that of C.P. Aubeny, H. Shi and J.D. Murff. In their 2005 paper the authors investigated the sediment resisting force and consequent embedment depth of a horizontal cylinder within a vertical trench[5]. This 2D experiment on a short length of pipe explored the elemental behaviour of the riser assuming plane strain conditions. FEM was used to develop simplified equations to relate these two parameters, considering linearly varying strength profiles of purely cohesive soil. Lower and upper bound solutions were successfully presented along with simplified curve fits, however the authors raised the issue that the parameter of initial open trench depth is unknown[5]. This project seeks to investigate this issue.

1.3.2 Full-Scale Testing

A small amount of full-scale or large-scale model testing of SCR systems has been undertaken, most famously the full-scale SCR model testing by Bridge et al in Watchet Harbour[4] where a 110m long pipe was attached to an actuator on the harbour wall for three months and the 3D effects examined. More recently, M.S. Hodder and B.W. Byrne conducted tests on a large-scale model SCR in an 8m flume at Oxford University[14] with

a uniform silica sand soil and Wang et al conducted a cut-down riser system at Zhejiang University in a tank 15m by 1.2m with a depth of 1.5m[11].

These tests were useful in discovering bending moment profiles, cumulative displacements and water pressure measurements along the pipe[14] and also confirmed that a trench formation would occur and develop due to the plastic deformation of the clay[4][11]. Wang et al also discovered that the length of time required to accumulate the excess pore pressures varied along the pipe[11] which was an interesting conclusion.

Another discovery that was made in the Watchet Harbour tests by Bridge et al was their measurement of the shape and dimensions of the trench which formed and their ability to prove the presence of suction under the pipe when cyclic loading was applied to the riser[4]. They were not able to measure the magnitude of this suction accurately, however, due to limitations in the instrumentation of the experiment. They were also unable to control the soil conditions on the site as it was a natural setting and so, although the soil was described as 'soft [naturally consolidated] clay with an undrained shear strength of 3 to 5 kPa'[4] it would have had a varied soil profile which may have affected the results, something which was improved upon in the laboratory tests by Hodder et al. In the harbour tests, the trench was observed to be tear-drop shaped, up to 2.5 pipe diameters wide and as much as 1.2 diameters deep[4], the exact mechanism by which this trench formed, however, is unknown. Wang et al investigated this phenomenon and concluded that the embedment of the pipe is mainly due to the softening and remoulding of the clay on which it rests[11] but there is still considerable scope for improving the understanding of the mechanisms of trench formation.

Although the tests of Hodder et al[14] are useful for quantifying trench formation and pore pressure along the pipe, care must be taken when applying the results to the research covered in this project report as the authors used sand soil conditions whereas this report concerns kaolin clay conditions where suction and clay deformation effects will be significant.

1.3.3 Small-Scale Centrifuge Testing

An alternative to the full-scale testing described in the previous section is the use of a centrifuge where the scaling laws explained in Section 2.3 are used to model SCRs on a smaller scale. Some research has been done into centrifuge testing of entire SCRs such as that of Elliott et al[2, 3] however some researchers such as Hodder, Cassidy and White[15] and Hu et al[9] have focussed solely on short sections of pipe which are moved vertically to model a small section of the riser. This effectively can be simplified into a T-bar test, so literature on this subject by White et al[7] was also read .

The short section test by Hu et al[9] established that the normalised load-displacement curves of the pipe do not vary when the diameter of the pipe is changed. This study also confirmed the presence of a trench in the clay under the pipe which formed after the first penetration cycle which reduced the penetration resistance of further cycles. The suction beneath the pipe was also investigated in this report and was found to be first overcome at the base of the pipe before moving to the centre of the elevation of the pipe as it rises. A limitation of the study, however, was the fact that it did not consider the whole SCR and that the pore pressure migration was not quantified. This could be done by installing pore pressure transducers on top of the pipe but is beyond the scope of this

project. The study also proved that pipe displacement rate does not correlate with soil strength degradation.

Hodder et al[15] also tested a short section of pipe in a centrifuge to investigate riser-seafloor interaction. They concluded that conventional bearing capacity equations could be used to predict the initial penetration resistance and that heave present around the pipe would cause a modification of Archimedes' buoyancy equation. Another conclusion was that the component of resistance due to soil strength reduces by a factor of 7.5 which can be attributed to the entrainment of water. They also found that a steady cyclic loading pattern was reached within 5-10 cycles which is useful for the development of this project.

Elliott et al produced two papers on their experiments modeling whole SCR at touchdown zone in a centrifuge. The first paper dealt with the development of the experimental set-up[2] and the second contained analysis of the collected data[3]. The outcome of the first paper was a successful method of modeling a SCR within the touchdown zone which was useful in the development of the experimental set-up for this project covered later in this report. The report also confirmed that centrifuge scaling laws could be applied to this problem. The second report concluded that the experimental set-up had performed 'very satisfactorily' which was encouraging as the experiment performed in this project drew on the work of Elliott et al. This research mainly highlighted the presence of issues such as trench formation and its influence on fatigue life, the interaction mechanism between the fluid, the soil and the riser and the profile of the pore pressure around the riser. The set-up did not, however, manage to fully model the water velocity field on the riser-seafloor interaction, but this is beyond the scope of this project. The loading motions used in the research were around four times slower than those encountered outside of the lab. This will be rectified if possible in this project. Erosion scaling was also not included in the modeling, and will be also be neglected in this project.

A very interesting conclusion from the whole SCR centrifuge modeling by Elliott et al[2, 3] was the observation that the fatigue life seemed to increase with a deeper trench. This was contrary to research on pipe sections carried out by Giertsen et al[3, 8] and Liera et al[3, 1].

1.3.4 Other Relevant Literature

It was planned that another fourth year project would design and build an epoxy ball penetrometer to measure the soil strength gradient of the kaolin clay used in this experiment. This project will be largely based on the work of Kuen, Cassidy and Randolph[10] and will be referenced often within this report.

1.3.5 Conclusions From Literature Review

The literature review undertaken as part of this project and summarised above indicated that there is a definite gap in current research for whole SCR centrifuge testing, especially with loading motions equivalent to those found in situ. The review also highlighted the contrast in experimental predictions as to whether trench deepening increases or decreases fatigue life of pipe, something that this project will explore.

It was also found that the most common material to use for experiments into riser-seafloor interaction was kaolin clay. It was decided, therefore, to use kaolin in these experiments. This is discussed further in Section 3.6. It was also decided, in light of research into common practice that T-bar or ball penetrometer testing would be done in flight at a location within the clay but away from the centre line of the pipe to establish the soil strength gradient of the clay.

2 Theory and Planning of Experiments

2.1 Seafloor-Riser Interaction

2.2 Centrifuge Testing

Centrifuge testing is useful to model situations where the geometry is too large to practically model at 1:1 scale. Situations can be scaled down to more manageable geometry as long as the acceleration is adjusted accordingly by following the scaling laws summarised in Section 2.3. Centrifuge modeling has been validated as a reliable method of simulating geotechnical phenomena that occur in nature. It is particularly useful in the analysis of complex problems where the mechanisms by which failure occurs are unknown. Riser-seafloor interaction in the TDZ is one example of such a problem and so centrifuge modelling is employed in this project to research the pipe deformations. The tests undertaken as part of this project will be clearly detailed so as to be repeatable by third parties to improve the reliability of any results produced.

REF TEACHING CENTRIFUGE STUFF

Talk about complementary nature of centrifuge testing and numerical modelling.

2.3 Scaling Laws

Centrifuge models can be related to the real-world scenarios they represent by the use of centrifuge scaling laws. If these laws are correctly applied then the observed behaviours during a test should be a direct representation of the true case, provided all of the relevant elements of the prototype are incorporated within the model. All the length dimensions of a prototype are scaled down by a factor of N when the acceleration of the centrifuge is increased by the same factor N , meaning that area is scaled by N^2 and volume by N^3 . This rule can also be applied to observed phenomena within the experiment such as settlement which will also scale with N as it is a measurement of length.

An interesting application of these laws is that the stresses and strains in the model will be identical to those found in the field. This is because the reduction in area over which the stress is experienced is directly cancelled out by the increase in acceleration. In his 2014 book[12], Gopal Madabhushi uses the example of a cuboid of dimensions $L \times B \times H$ and mass M to explain why the stresses remain constant in the case of the model and the prototype. He shows that the vertical stress experienced by soil on which this block is seated is calculated by: $\sigma_v = \frac{Mg}{L \times B}$. If all the dimensions of the block are scaled down by a factor of N then it follows that the mass of the block will become M/N^3 . If this block is

	Parameter	Scaling Factor
1	Length	$\frac{1}{N}$
2	Area	$\frac{1}{N^2}$
3	Volume	$\frac{1}{N^3}$
4	Stress	1
5	Strain	1
6	Force	$\frac{1}{N^2}$
7	Time	$\frac{1}{N}$
8	Frequency	N
9	Velocity	1
10	Acceleration	N
11	Strain Rate	N

Where N is the amplification factor at which the sample in the centrifuge experiences gravity relative to the normal gravitational field on earth (1g).

Table 1: Dynamic Centrifuge Test Scaling Laws[13]

placed in a gravity field of Ng then the vertical stress becomes $\sigma_v = \frac{\frac{M}{N^3} \times Ng}{\frac{L}{N} \times \frac{B}{N}} = \frac{Mg}{L \times B}$. Thus the vertical stresses below the blocks in both cases are identical. Strains will also follow the same rule as $\varepsilon = \frac{\delta\alpha}{N} / \frac{\alpha}{N} = \frac{\delta\alpha}{\alpha}$

This is summarised in Table 1.

The flexural stiffness (EI) of the model must also match that of the riser in situ.

2.3.1 Properties of Model

The following properties were scaled between the riser and the model. In the case of the mass, the pipe was filled with silicon to gain the correct mass without compromising the stiffness. In the following calculations N was taken to be 100g.

2.4 Speed of Centrifuge

Due to length scaling $N=100g$, and using the equation $Ng = r \frac{d\theta}{dt}$ we can calculate the speed of rotation of the centrifuge. It is known that the radius of the minidrum centrifuge is 370mm so the speed must be 2650 rad/s or 25300 RPM.

3 Experimental Set Up and Apparatus

3.1 Preliminary Feasibility Test

Preliminary testing was undertaken in a 1g environment. In this test two cameras were set up in two directions to record the movement of the pins in a pipe when one end was raised cyclicly. The videos produced were analysed using PIV. The test set up can be seen in Figure 1 and the images produced by each camera in Figure 2.

Parameter	Riser Value	Calculated Model Value	Actual Model Value
Diameter[14]	L	L/N	
	200mm-600mm	2mm-6mm	6mm
Length	L	L/N	
	20m	200mm	200mm
Displacement[4, 14]	L	L/N	
	$\pm 1m$	$\pm 10mm$	to be measured
Depth[4]	L	L/N	
	10m	100mm	100mm
Clay Strength	1	1	
	3-5kPa, 39% PI	3-5kPa, 39% PI	Kaolin, 3-5kPa
Stiffness (EI)	1	$1/N^3$	
	178×10^{61}	$1.78Nm^2$	$0.184Nm^2$
Mass	M	M/N^3	
	7265kg	7.27g	$7.35g^2$

Table 2: Properties of Model

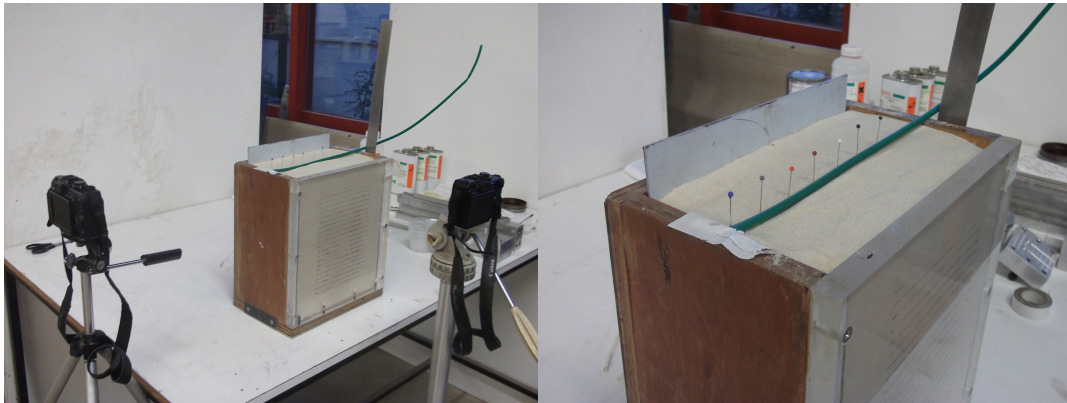


Figure 1: Preliminary Test Set Up



Figure 2: Preliminary Test Results

In this experiment the location of TDZ was established meaning that in future experiments the pins can be placed closer together in within this zone. It was also found that the pins do not move when viewed end on meaning that PIV analysis on them can be ignored. It was also concluded that the second camera should be positioned above the experiment rather than at the end looking on as then the vectors from the camera to the pin heads will not be different for each pin. Overall it was found that the experiment is feasible provided a suitable actuator and experiment box can be found.

3.2 Secondary Tests

3.2.1 Summary of Experimental Procedure

3.2.2 Instrumentation

Actuators

3.3 Calibration

3.4 Mini-Drum Centrifuge

Geometry

Use

H&S

3.5 PIV

3.6 Soil

Wang et al state that the usual condition of soil in deep-water environments is a clay of low strength and high plasticity[11] so normally consolidated kaolin clay will be used as this is readily available in the lab and will not take a long time to prepare.

3.7 Pipe

Hodder et al used PVC pipe in their large-scale tests due to its low stiffness so that the end of the pipe furthest from the actuator would remain stationary during the experiment[14]. Wang et al used PE (polyethylene) for the same reason[11].

3.8 Ball Penetrometer

A ball penetrometer (fabricated as another fourth year project) will be used in this experiment to measure the strength of the kaolin clay.

4 Experimental Procedures

5 Results and Discussion

6 Application of Results

7 Conclusions

7.1 Conclusions

7.2 Further Work

Acknowledgements

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