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Interaction between Deepwater Catenary Risers and a Soft Seabed: Large Scale Sea Trials

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Abstract

The paper describes experiments completed in June 2000 as part of the STRIDE JIP – Steel Risers in Deepwater Environments[1,2].

The tests investigated the interaction between a soft clay seabed, typical of deepwater developments, and a steel catenary riser (SCR). ROV surveys of deepwater SCR's attached to floating production vessels have shown that they can cut deep trenches into the seabed. The following objectives were set:

(1) To assess the effect of seabed to SCR interface forces on local riser stresses for wave and slow drift vessel motions
(2) To assess the effect of different riser trenches on local riser stresses for wave and slow drift vessel motions
(3) To identify the key trenching mechanisms and rates.
(4) To use the test program findings to benchmark riser FEA tools, and to adjust modelling parameters to better simulate the real case as necessary.

To achieve this, the seabed end of a deepwater SCR was simulated using a 360-ft long 6-inch diameter steel pipe, hung as a catenary across the soft seabed of a tidal harbour. A particular harbour location was found that had seabed properties similar to those of a deepwater Gulf of Mexico seabed. The top end of the pipe string was then actuated with carefully controlled wave and vessel drift motions to simulate a spar platform in 3,300-ft water depth.

Introduction

Deepwater (>1500-ft) oil and gas fields usually have seabeds of soft, sticky clay. A popular strategy for developing deepwater hydrocarbon reserves is the use of steel catenary risers to a floating production vessel, both for well production and processed fluid export purposes (Figure 1). This technology is still relatively young, and whilst there are a number of SCR's now installed most are just starting a field life of 25 years or more.

ROV surveys of installed catenary risers, steel and flexible, have shown deep trenches cut into the seabed beyond the touchdown point (TDP). Even after just a few months, trenches have been seen that are four to five pipe diameters deep and three to four pipe diameters wide, and with an amount of soil backfill in the trench.

Current practise for catenary riser design takes little account of such circumstances, with FEA programs typically assuming a flat, rigid, "non-interacting" seabed. The dynamic nature of deepwater SCR's connected to floating platforms suggests that such an approach may be un-conservative. Storm and current action on a deepwater production vessel can pull the riser upwards from its trench, or laterally against the trench wall. The suction effect of the soft seabed on the riser, coupled with trench wall interaction, could increase the local riser stresses by causing tighter riser curvatures or higher tensions than are predicted by conventional FEA.

As part of the STRIDE III JIP, 2H Offshore Engineering conducted a test programme to investigate the effects of a deepwater seabed on catenary riser response and wall stresses. The objective was to assess the importance of such seabed/riser interaction, and to produce FEA techniques to match the real response as necessary.

Pre-Analysis

Full scale configuration: FEA analysis was performed using MCS Flexcom 3D[3] to predict the motions of a 6-inch diameter SCR attached to a spar platform in 3,300-ft water depth in the Gulf of Mexico – Figure 1. A variety of day-to-day and extreme environmental load-sets were applied, including wave and drift effects both in and out of the riser plane (in-plane and transverse). The riser motions near the seabed were recorded as output from these analyses, and in particular the local velocity of the riser as it peels away from the seabed.

Cut-down configuration: A second FEA model was then used to simulate the planned test set-up, comprising a welded steel pipe that represented the bottom 300-ft of the full scale riser. The model simulated a linear actuator at the top end, and the actuation cycles were varied within the FEA model until similar SCR motions were obtained for the reduced size model as for the full depth case. These actuator motions were then used in the design of the actuator rig for the intended tests, allowing a deepwater riser to be simulated at cut-down scale.

Test Location

After evaluating a number of candidate test sites, the test programme was conducted at a harbour location in Somerset, UK. The harbour seabed was found to have properties similar to a deepwater Gulf of Mexico seabed - soft clay, typically 3 to 5 kPa undrained shear strength, with a naturally consolidated shear strength gradient below the mudline. Extensive geotechnical testing confirmed this and established the site as suitable for the proposed test programme. Water depth varied from 5m at high tide to exposed seabed at low tide. The sea current velocity in the test area as the harbour filled or emptied was almost negligible, and any trenches formed by the testing remained unchanged over numerous tide cycles. It was established that the mudline had no discernible “crusting” that could have been caused by surface drying at low tide, and that might have effected the tests. It was also established that there was a flat and undisturbed area of the harbour seabed that would suit the intended tests.

Small Scale Tests

In order to make an assessment of the expected suction forces that would be experienced at the test site, a small-scale test jig was initially set-up (Figure 2). This comprised a frame and pulley that allowed a 3-ft section of 6-inch diameter pipe to be pushed into the soil at known load, and then pulled out at constant rate whilst recording the pull-out load. This rig was used at the test site at low tide, and a tank of the seabed clay was excavated for further tests in laboratory conditions. These tests looked at the effect of consolidation load and time, and also the effect of actuation velocity – Figure 3. The tests could only simulate a flat lift, and not the peel-away that would be the case for the true catenary, and the short section meant that end effects could contaminate the results. Nevertheless, the tests provided a good appreciation of the suction forces to be expected, and allowed prediction of design loads and instrumentation requirements for the large-scale test set-up.

Harbour Test Set-up

The intention at the harbour location was to simulate the TDP area of a deepwater SCR. To do this, a 300ft long x 6in diameter welded steel ‘riser’ was suspended from an actuator on the harbour wall, and run out across the seabed to a set of mud anchors (Figures 4 and 5). The seabed over this area was flat and undisturbed, and careful probe tests were done to check that there were no hidden obstacles below the mudline.

A tight catenary shape was needed to simulate the full-scale riser, calling for the pipe to depart the actuator at an angle of 70 degrees from the vertical. This tight catenary meant that the configuration was sensitive to the actual pipe length, including all stack-up tolerances – a 1-inch change in “riser” length would change the nominal TDP position by 1-ft. For this reason the pipe length could be tuned using a heavy-duty turnbuckle in the rigging to achieve the correct starting position in accordance with the pre-analysis models.

The test set-up allowed the use of a number of virgin test corridors at the flattest part of the harbour seabed. It was important that these corridors were undisturbed before the testing. To ensure this, the riser was floated to the various positions using temporary buoyancy, then the outgoing tide allowed it to settle onto the seabed.

Personnel access to all parts of the catenary was provided by an interlocking steel plank walkway laid across the soft mud, but avoiding the test corridors. As testing in a test corridor was completed, the pipe was refloated to the next.

Actuator

The riser was fixed at its top end to an actuator unit. This comprised a heavy-duty truss frame with a 10-ft linear ball screw driven from one end by a PLC controller (Figure 6). The riser was attached to the ball screw nut. The linear screw could be swivelled to operate in vertical or horizontal directions to provide the prescribed motions accurately to the top end of the cut-down riser, and produce the vertical and lateral pipe motions being sought at the seabed. This meant linear ramps, simulating vessel drift, and sinusoidal motions of different amplitudes and frequencies, simulating wave loading.

In addition the whole actuator frame was designed to move on a set of 10 m long rails, simulating a large transverse excursion of the vessel and pulling the riser laterally from its trench while pipe stresses were monitored. The actuator design and mountings had to support up to 15 tonnes top tension in the test pipe.

The various offshore motions simulated and the actuator parameters are given in Table 1.

Offshore equivalent	Travel at Actuator
Heaving storm wave about nominal vessel position	Vertical sine wave, 0m datum, +/- 0.4m, 25 second period
Heaving storm wave about 0.5% WD near vessel offset	Vertical sine wave, -0.4m datum, ,+/- 0.4m, 25 second period
Heaving storm wave about 1.1% WD far vessel offset	Vertical sine wave, +1.0m datum, +/- 0.4m, 25 second period
Surging or swaying storm wave about nominal	Horizontal sine wave, 0m datum, +/- 0.4m, 18 second period
Spar failed mooring drift speed, near 0.8% to far 1.5% WD	-0.8m to +1.4m @ 0.1m/s
Spar failed mooring drift speed, far 1.5% to near 0.8% WD	+1.4m to –0.8m @ 0.1m/s
Spar second order slow drift, near 0.8% to far 1.5% WD	-0.8m to +1.4m @ 0.01m/s
Spar second order slow drift, far 1.5% to near 0.8% WD	+1.4m to –0.8m @ 0.01m/s

Table 1 – Actuation Parameters

Geotechnical Testing

Extensive soil testing was performed to fully document the soil properties along the test corridors. This involved multiple core samples taken for full laboratory analysis, and the use of in-situ field torvane equipment to monitor the shear strength of soil at predefined points during the test programme. Shear strength values and gradient below the mudline were compared with data supplied by Fugro UK for deepwater seabeds in the Gulf of Mexico – Figure 7 – and the harbour seabed was confirmed to be in good agreement. In addition particle density, bulk density, and the high moisture content were all consistent with a soft, deepwater seabed sediment, as was the plasticity index, typically 46 to 52%.

Instrumentation

Full bridge strain gauge sets were welded at 13 axial positions along the riser, spanning the dynamic TDP area. Each position provided vertical and horizontal bending strain on the pipe. In addition, a triaxial accelerometer unit was mounted just above the nominal TDP, there were tension load cells top and bottom of the pipe string, and shear force measurement at the connection between pipe and actuator. All instrumentation was hardwired to a multi-channel logging station able to monitor in real-time at 40 Hz.

The first attempt at strain gauging did not achieve adequate waterproofing, and the entire set had to be removed and replaced with a better system. Even then, as the testing progressed, some of the gauges failed, but fortunately there was still a good spread along the dynamic TDP.

Test Programme

The test programme allowed investigation into a number of possible soil interaction phenomena, whilst making best use of the available test corridors and time available.

Accommodating and working with the natural tide cycle presented particular complications, but also allowed tests to be conducted under low and high tide conditions, enabling different effects to be isolated and investigated. The tidal water gave zero visibility, but low tide allowed full access to test personnel.

The pipe could be filled with water or air to vary the seabed interaction force. Tests were performed at different stages of trench development, and as well as these ‘natural’ trenches, artificial trenches were dug to expose stiffer soil material. Back-filled trench cases were also tested.

By placing steel sheeting under the riser, ‘rigid’ seabed tests could be performed for comparison with the soft clay, and also to allow benchmarking of analysis programmes that are limited to rigid seabed cases. These tests were performed at the end of the test programme since there were concerns that the rigid surface could damage the strain gauges. Tests were also conducted looking at the trenching effect of higher frequency vibration from vortex-induced vibration or process flow.

Results

Full results from the test programme are restricted to STRIDE ticket holders, though some have been approved for inclusion within this paper.

In-plane vessel drift: It had initially been intended to compare the strain gauge response along the pipe for the real seabed compared with an artificial seabed comprising perforated steel sheets laid under the pipe. In practice it proved to be difficult to compare the responses directly since the pipe would quickly trench into the soft soil and then presented a different starting point from the rigid seabed simulation, and made it difficult to compare strain gauge response between the two cases.

Instead an effective technique was used that relied on comparing a riser lift (representing vessel drift near to far) with a lay down (far to near). The lift would see the soil suction, the laydown would not.

Figure 8 gives an example of this. For this test the pipe was in a backfilled trench and had been allowed to consolidate the soil overnight. The test then simulated movement of the production vessel from near to far, which means a linear upward ramp at the actuator. For such a test, a series of bending moment plots was recorded for each of the axial positions at which the strain gauges were placed. From these a “suction peak” could be discerned travelling along the pipe TDP towards the anchor during the actuation cycle. It could also be seen that the peak would grow and then shrink during its journey. The strain gauge position with the highest suction peak would be given closer attention, and an example is given in Figure 8. The curve labelled “lift” shows a sharp peak in the bending moment as the peel-off point traverses the strain gauge position. After the upward actuation, the pipe is laid down again at the same actuation rate, simulating a far to near vessel drift. The curve produced is also shown in Figure 8 - “Laydown”. By comparing the bending moment plot for the upward lift to the laydown, the local stress delta due to the soil suction effect can be visualised.

Tests such as these were conducted using a variety of starting positions and with varying parameters:

High tide and low tide
Water-filled and air-filled pipe
Different duration’s of soil consolidation time
Different trench depths, exposing soil layers off varying stiffness
Different actuation rates

Approximately 80 tests were performed looking at these in-plane vessel drift effects.

Tests were also conducted on the simulated rigid seabed, and these did not show the suction peak identified in Figure 8. Figure 9 shows bending moment traces from strain-gauges at different riser positions along the test pipe. It can be seen that the lift and lay-down strain gauge curves are almost identical. This was as expected and indicated that the suction peaks were due to soil suction, and not a result of the actuation system or the elastic hysteresis of the system.

The linear actuation tests described above simulated vessel drift, or second order motions, which has implications for riser extreme design loads. Fatigue effects were examined by looking at wave actuation.

Wave effects: The actuator was proven to provide accurate sinusoidal wave motions according to the period and amplitude parameters input by the operator. Day-to-day and extreme storm wave cycles were applied in the vertical and horizontal planes. Once again, by comparing upward and downward parts of the wave cycle, an assessment could be made of any local wall stress increase due to soil interaction effects, which could then have a direct impact on riser fatigue damage.

Trench rates and mechanisms: The depth and width of trenches formed by "riser" motions were limited by the 6 week duration of the test programme, and because a number of different test corridors were used for the different tests. Trenches up to 6" deep and 18" wide were produced and trenching rates and mechanisms identified. The rates recorded were more than enough to produce the trenches seen on offshore ROV footage of installed SCR's.

Transverse drift: A transverse vessel drift could be simulated by using the actuator drive in the horizontal position and further by moving the entire rig on its rails. It was found that with trenches up to 12" deep, the pipe rode up the side of the trench to exit and there was little evidence of the pipe pushing through the wall of the trench. It was found that the trench could force a hinge effect at the exit point. Peak stresses seen here were time-transient, even after the end of the actuation cycle, as the soil deformed further and the pipe shape relaxed.

Vortex Induced Vibration (VIV) simulation: An eccentrically loaded motor was strapped to the test pipe in the free hanging catenary. The position and rotary speed could be tuned to cause the pipe to vibrate in different natural Eigen modes at typically 2 to 5 Hz. It was intended to simulate SCR vibration attributable to VIV or to process flow. The trenching effects of the vibrating pipe were assessed. In addition a comparison was made between the pipe on the seabed with the pipe on the rigid surface, to assess the damping effect the seabed could have on VIV. Vibration monitoring was done by using accelerometer units along the pipe, including the TDP, and recording the local vibration amplitude.

Back-analysis

Back-analyses of the test programme results have been performed using the FEA programs Flexcom3-D[3], ABAQUS[4] and ANSYS[5]. The pre-analysis model was updated to model the actual bathymetry of the test corridors that was obtained from site survey. In addition, the test-pipe was subject to ongoing trenching effects that required additional adjustments to the analysis models.

Specific contact elements were developed that simulated the soil interaction effects, in particular the non-linear and hysteretic force/distance curves that are associated with the interaction between a solid member and a clay soil ("backbone curves"). These curves were originally developed using data from the small scale 2D experiments based on a flat lift (Figure 2), but in effect the analysis achieved good matching with the empirical data for the 3D case with the pipe peeling from the seabed.

Conclusions

It is apparent that deepwater seabeds typical of areas such as the Gulf of Mexico can cause stress delta effects on dynamic catenary risers. Such effects are not normally modelled within FEA design analysis, which usually assume a rigid, non-interacting seabed. The significance of these effects within the overall design of SCR's has yet to be established.

Important parameters to the soil interaction effects are soil shear strength; the velocity of pipe motion; the loading history of the soil; the sensitivity of the soil, i.e. how much its strength is lost due to remoulding or soil disturbance.

Seabed trenching was found to occur quite rapidly due to riser motion, and the dominant mechanisms were identified. 3D interaction between the riser and the trench wall for lateral "vessel" motions was demonstrated and shown to have an effect on local riser wall stress.

Future Work

The significance of the soil interaction effects within the global design of a catenary riser system has yet to be established, and is the subject of further work as part of STRIDE Phase IV[6], running within 2001. The workscope includes the following:

FEA: The data collected from the harbour tests relates to a specific riser configuration, and work is ongoing to establish the trends and to extend the results to cover other configurations, e.g. larger riser diameters, different soil shear strengths, rate effects. This has meant developing a set of soil interaction elements within an FEA package that can match the response of the test riser.

Riser Case Studies: A number of typical riser case studies will be run looking at fatigue and extreme load design aspects, in order to establish whether the soil interaction effects are true design drivers.

Offshore Trenches: The ongoing development of offshore SCR trenches is also of interest, since SCR technology is still young and few risers have been installed for more than a year or two. STRIDE instrumented the Allegheny gas export SCR in 1000m in the Gulf of Mexico, primarily for VIV monitoring. However, the opportunity was taken during visits 7 months and 14 months after installation to perform ROV survey of the trenches being formed by the export and production SCR's. It is apparent that trench development is ongoing.

Real Riser Motions: Accelerometer loggers were also positioned near the TDP of the Allegheny SCR, and data is now available covering two 6-month periods that will provide the local riser velocities due to vessel and riser motions, including any VIV due to loop currents or vessel motions. The motions of the riser are important to the level of stress delta caused by the soil interaction effects, and these can be compared with prediction and with the TDP velocities used within the harbour tests.

CARISIMA JIP: STRIDE has agreed to data exchange and collaboration with the CARISIMA JIP (CAtenary RIser Soil Interaction Model for global riser Analysis [7]). This project has been run by Marintek/Statoil 1999/2001 and has performed a number of laboratory experiments looking at the interaction of small-scale pipe sections with clay in carefully prepared soil bins. Tests have simulated in-plane (vertical) and transverse (horizontal) motions with a view to developing soil reaction models suitable for implementation in FEM based computer codes. By combining the results from the carefully controlled but small scale experiments with the larger scale STRIDE field experiments, it is intended to increase the understanding and value of each data-set, and to further the development of design tools for deepwater SCR deployment.

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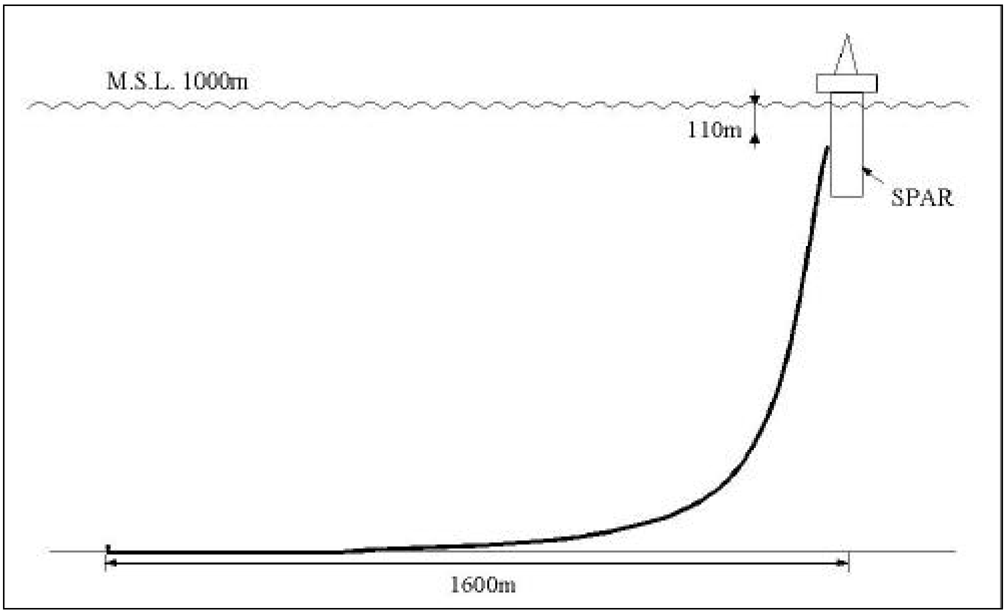


Fig. 1 – Full Scale Riser Configuration

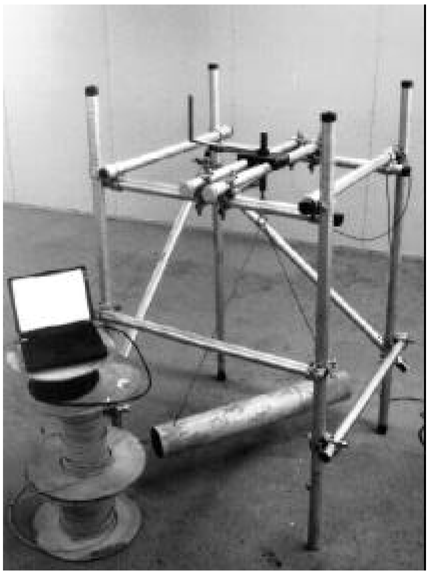


Fig. 2 – Small Scale (2D) Rig

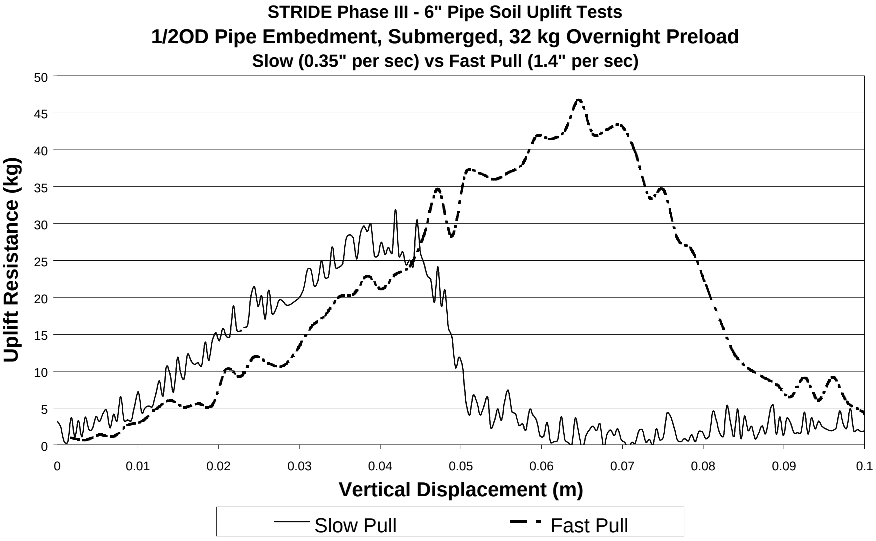


Fig. 3 - 2D Rig - Effect of Actuation Velocity

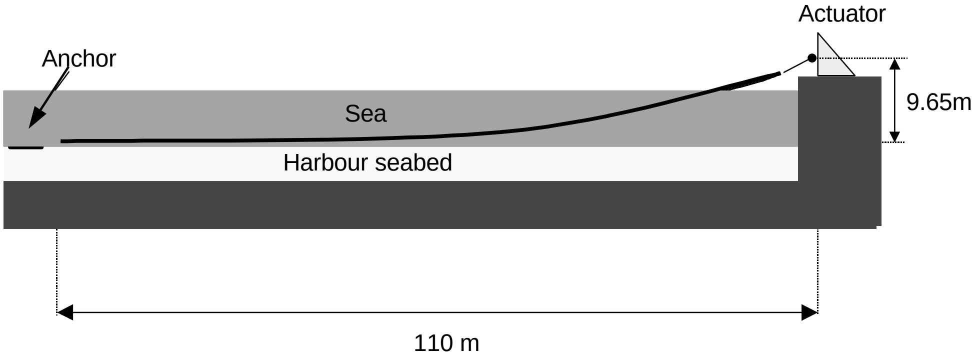


Fig. 4 – Harbour Test Set-up Schematic

Fig. 5 – Harbour Test Site at Low Tide

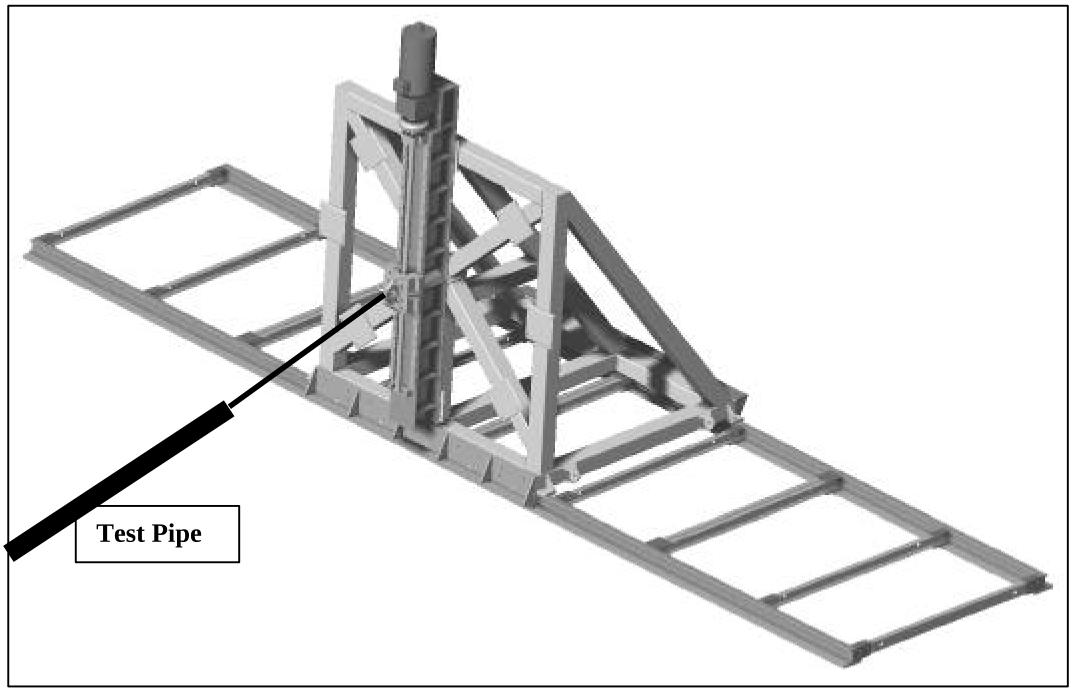


Fig. 6 – Actuator

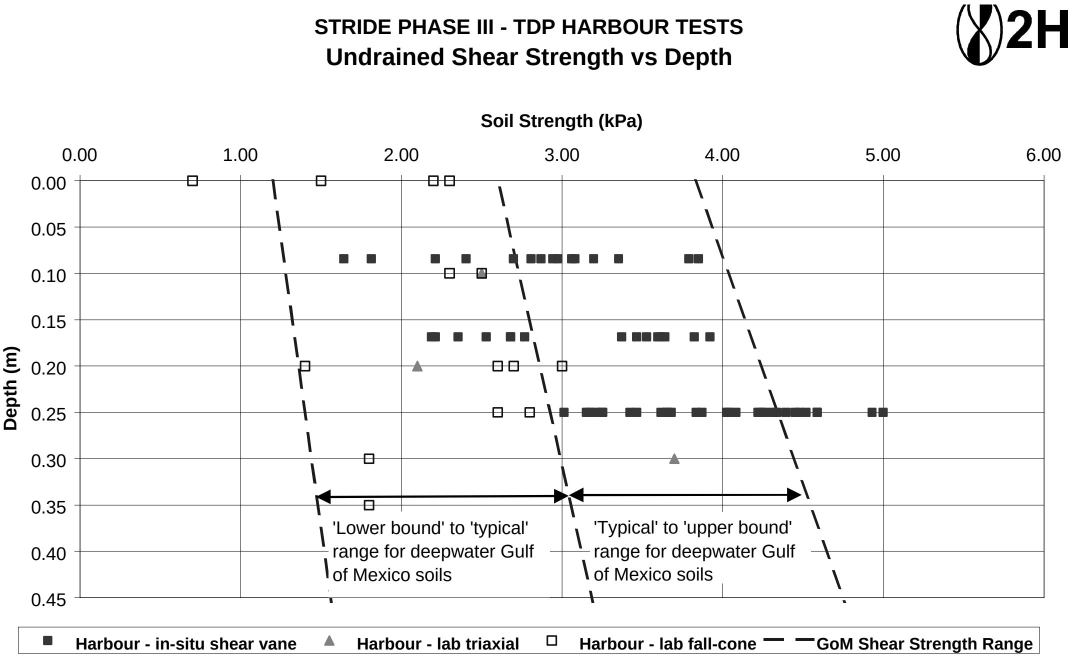


Fig. 7 – Seabed Shear Strength

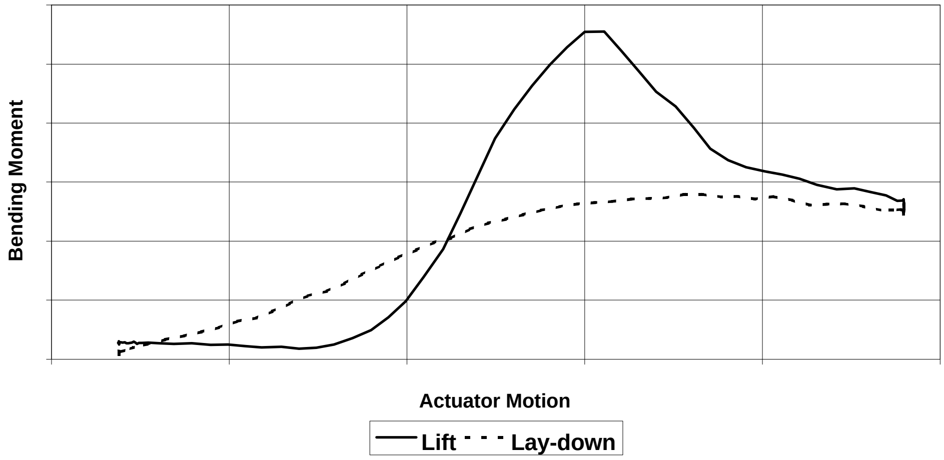
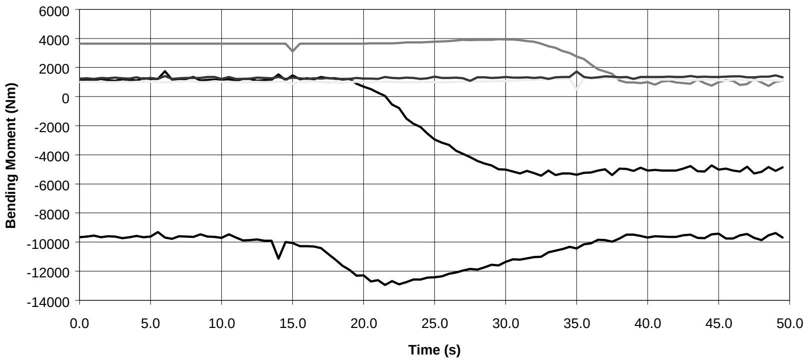
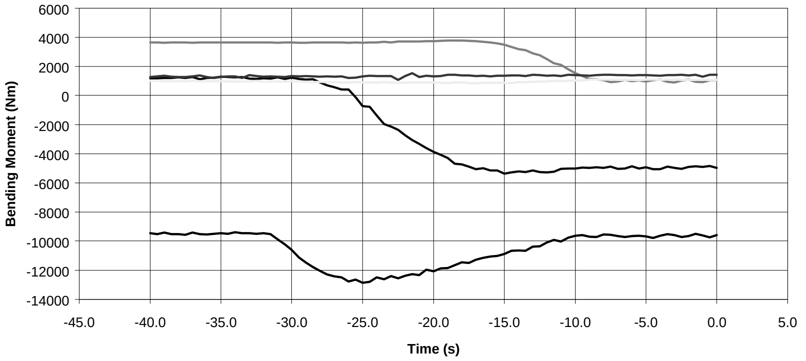


Fig. 8 – Soil Suction Peak for Vessel Drift Simulation



(a) Lift (Near to Far)



(b) Lay-down (Far to Near)

Fig. 9 – Strain Gauge Data from Rigid Surface Tests