STRIDE JIP - Steel Catenary Risers in Deepwater Environments - Progress Summary

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Abstract
The STRIDE JIP has performed test initiatives into several areas considered to be crucial to the design of steel catenary risers for harsh, deepwater environments. The following investigations are described:

- Water-tank testing of a ¼" diameter x 100ft long catenary riser model, looking at response to production vessel motions, in particular the response in the touch-down region for rigid and elastic seabed simulations.

- Vortex induced vibration tests on riser models 20ft long, 6" in diameter, in simulated currents up to 16.5 ft/s (5 m/s - Reynolds 6.7x10^5). Helical straked and bare pipe models were towed at angles of up to 45° to the flow, simulating current flow over non-vertical riser sections of simple catenary and buoyant wave risers. The requirement and effectiveness of strakes on inclined sections was investigated.

- Vortex induced vibration tests on riser strings 650ft long, 10.75" diameter in simulated currents up to 5.8 knots (3 m/s - Reynolds 6x10^5). Helical straked and bare pipe models were towed at angles of up to 75° to the vertical in a Norwegian Fjord between two tugs, continuing the investigation into non-vertical riser response to high currents.

Introduction
Phase II of the STRIDE JIP was initiated by 2H Offshore in March 1998, and is sponsored by 15 operators and 5 engineering contractors. During Phase I of the project, 2 areas were identified as being of prime importance to the design of deepwater steel catenary risers: the touch down point (TDP) and vortex induced vibration (VIV).

TDP - A deepwater catenary riser TDP can actually involve a wide region of possible contact between different parts of the riser and different areas of the seabed, as dictated by the environmental loading on the floating production vessel and riser system. STRIDE Phase I identified this area of a catenary riser as critical with regards to the strength and fatigue life of the whole system. Confidence in analysis techniques was considered to be of paramount importance to such developments, and this lead to the proposed test program.

VIV - Lack of empirical data on VIV of inclined and curved structures required a conservative design approach in STRIDE Phase I. In particular, it had to be assumed that VIV suppression strakes would be required over most of the riser length. The increase in riser drag due to such heavy straking produces a succession of technical and commercial knock-on effects. A high drag catenary riser needs extra ballast in the vertical section to accommodate the current loading, otherwise the riser can be pushed into shapes that overstress the TDP – Figure 1. Within the analysis, ballast was assumed to be most effectively applied as increased riser pipe wall thickness, and resulted in an increase of +40% on that required for pressure considerations alone. Increased wall thickness was shown to have a major impact on installation costs, particularly the amount of temporary buoyancy required for what was found to be the leading installation method at the time, controlled depth tow out.

At the kick-off meeting for STRIDE Phase II, it was agreed by all participants that VIV and TDP be top of the list for further investigations.

TDP Testing Program
The main objective of these tests was to benchmark the ability of industry software to predict the response of a riser pipe catenary at its TDP, particularly as it is put into compressive loading or buckling as a result of extreme motions at the top end, for instance due to extreme storm motions on the floating production vessel.

TDP Test Set-up
A 100 ft long catenary riser model was constructed from high grade ¼" diameter stainless steel tubing. This was suspended in a catenary shape in a water tank 17ft deep, with its
top end being actuated above the water line by a lever arm attached to a motor – Figures 2 and 3.

The top end of the model could be rotated at amplitudes up to 31° at 8 rpm, both in the plane of the catenary and normal to the plane. The connection between pipe and actuator arm was configured as a ball joint preventing any moment transmission at this point.

Along the bottom of the tank a number of trays were constructed containing 2” thick mats of spun polyester fiber matting, which simulated an elastic seabed condition, for which the spring stiffness was established empirically. The trays had sheet metal lids, such that the test configuration could quickly change between rigid and elastic seabed simulation.

The pipe was fully instrumented to give real-time in-plane and out-of-plane bending histories, along with tension loads at the top and the bottom of the pipe model. TDP motion was monitored using underwater video from 2 directions.

TDP Test Results and Conclusions
(Certain results and conclusions do not have JIP agreement for release at this time)

The tests simulated a variety of riser motions, including lateral and in-plane buckling, whipping and “skipping rope” motions. Analysis by FEA packages FLEXCOM\(^2\) and RIFLEX\(^5\) correlated well with experimental results in predicting motion, tension and bending response for the rigid and elastic seabed simulations, though it was found to be critical that the analytical models be set up correctly.

VIV Tank Testing
A test program was initiated to look at the VIV response of cylinders at different angles to incident water flow, and the success of vibration suppression devices at the different angles. The first investigation was done in a laboratory test tank.

VIV Tank Testing – Background Theory
Flow past a bluff body can shed alternating vortices that put an oscillating force on the body. If the shedding frequency is similar to a natural vibration frequency of the body, the body may resonate, which can lead to high fatigue damage. This is true of marine risers in ocean currents, and catenary risers have the added complication that they present a variety of angles to incident current, and can resonate at a large number of closely spaced current speeds.

For a circular cylinder, the vortices are shed periodically at a frequency given by:

$$f_s = S_{at} \frac{V}{D}$$

where:

- \(S_{at}\) : Strouhal number,
- \(V\) : flow velocity,
- \(D\) : cylinder diameter.

The Strouhal number of a stationary circular cylinder is a function of Reynolds number and, to a lesser extent, of surface roughness and free stream turbulence. The alternate shedding of vortices generates an oscillating load transversally to the flow direction, with a frequency equal to the vortex shedding frequency. Resonance between the natural frequency of the cylinder and the vortex shedding induced loads will occur when the two frequencies approach each other.

The parameter commonly adopted to describe the vortex induced vibration phenomenon is the reduced velocity, defined as:

$$V_{r,n} = \frac{V}{f_n D}$$

where \(f_n\) is the cylinder \(n\)th natural frequency, and \(V\) is the velocity normal to the cylinder.

Resonance in the cross-flow direction can thus be expected when….

$$\frac{f_s}{f_n} = V \cdot S_t$$

…equals \(1\), i.e., for sub-critical regimes \((St=0.20)\), when the reduced velocity is approximately 5. As the shedding mechanism locks onto the natural frequency of the cylinder, resonance occurs over a broad range of reduced velocities, typically from ~4 to ~9. Experiments have shown that within the resonance region the phenomenon is self-limited with typical response amplitudes up to ~1.5 diameters.

To prevent VIV lock on, it could be suggested to change the natural frequencies of the riser by structural modification, though this is largely impractical. Instead, it is better to inhibit the formation of vortices or disrupt their structured formation, through the application of suppression devices.

The different types of suppression devices are commonly grouped into four categories, namely surface protrusions, shrouds, near wake stabilisers and streamlined fairings, though it is common to merge the last two categories into a more general category called fairings. Shrouds provide a slotted second surface to the pipe, but are difficult to engineer for SCR’s, and restrict riser inspection activities. Fairings must involve moving parts to enable them to rotate to suit the prevailing current direction, and are considered impractical for a typical 25 year subsea life requirement.

The most widely used technique to reduce VIV on cylindrical structures is the application of a surface protrusion type device, and in particular a helical strake system. This has been used widely on chimneys, process towers, and vertical marine risers, but never on the inclined sections of SCR’s.

Helical strake systems are defined by the height, the number of starts of the helix and the pitch of each helix. Previous work on vertical structures has indicated that the height of the strakes should be between 0.1 and 0.15 times the pipe diameter. This provides suppression without high drag penalties. A 3-start helix with a pitch of five diameters has been shown to

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be successful at low vibration mode numbers, but recent tests have shown that a pitch of 15 diameters is effective for higher modes.

**VIV Tank Tests - Test Set-up**

The tests were carried out in the towing tank facilities of the BMT/DERA Hydrodynamic Test Centre, at Gosport, Hampshire, UK. The tow tank was 885 ft long, 39 ft wide and 17 ft deep. A yoke structure was designed and built to provide a stiff and robust mounting for the test pipe, to be horizontally towed at 3 ft below water level (Figures 4 and 5). The yoke structure was attached to the towing carriage, and could be rotated to provide different angles of inclination between the tow pipe and the towing direction, in order to establish the desired current angles relative to the cylinder axis. The model cylinder was towed at different constant speeds to establish the variation in reduced velocity.

Each model “riser” was made of glass-reinforced plastic (GRP), 6” diameter, 20 ft long. The pipe was almost neutrally buoyant.

The pipe was attached to the rig via universal ball joints at either end. Fairings on the vertical struts of the yoke structure could be rotated before each test to always face into the flow direction, regardless of the angle of the main structure. In a similar way, a pair of vertical fences could also be rotated to face into the flow. These were included to help separate the turbulent flow around the end fittings from the main pipe span.

A hydraulic cylinder was attached to one end to provide an axial tension of 1 ton on the pipe, and this was monitored and recorded by a pressure transducer near the cylinder. The hydraulic system included a nitrogen accumulator to maintain a reasonably constant mean tension on the pipe regardless of hydraulic system variations.

The above data was intended to allow the following:

- The pipe was excited in first and second modes at frequencies corresponding with analytical prediction
- Results indicated that the tests spanned the critical Reynolds region, where the boundary layer and wake are changing from laminar to turbulent flow.
- The strake configuration used was effective at suppressing mode 1 VIV, even at the higher inclination angles.
- Single hand rotation helical strakes can provide a significant torque as riser angle increases. This was shown to produce a displacing force on the curved test pipes, either arching them upwards or downwards, depending on the hand of the helix.

**Open Water Test Program**

The objectives set for this test program were as follows:

- Evaluate the VIV response of a long pipe string (650 ft) at high Reynolds numbers (to 5x10^7) at different angles of inclination to the current
- Investigate response at high angles of incidence up to 75 degrees (to vertical)
- Determine response of curved risers e.g. catenary shapes
- Determine effect of tension variation due to first order vessel motion

The above data was intended to allow the following:

- Provide data to benchmark and recommend improvements for SHEAR7® (and other packages)
- Better understanding of strake design and coverage requirements
- Development of VIV design guidance
- Optimisation of STRIDE Phase I riser configurations
Once again the current over a moored catenary riser was simulated by towing the riser in still water. To obtain sufficient water depth without significant ambient currents, the testing was performed in Boknafjorden in Norway.

Open Water Tests – Pre-analysis

MCS FEA computer program FLEXCOM3D² was used to predict riser configurations and loads, looking at different tow velocities for different angles and drag coefficients. Sea-state analysis was used to obtain an acceptable configuration for the exposed water transit tow, and to establish the weather window limitations, based on available fatigue life. Examples of predicted riser shapes are given in Figure 10. The catenary shape produced by the pipe drag meant that the velocity profile normal to the pipe was sheared (non-uniform) as illustrated in Figure 11.

MIT program SHEAR7 version 2.0³ was used to predict VIV modes, amplitudes and frequencies for the various test configurations, and based on the riser shapes predicted by FLEXCOM. SHEAR7 has been developed primarily for application to vertical top-tensioned risers. The program can be applied to steel catenary risers (SCR’s), but even though version 2.0 includes some new features to assist in this, it is still necessary to introduce some modelling simplifications:

- The riser is assumed to be straight and variation of tension along the riser length is input from FLEXCOM3D using an external data file.
- The riser length is taken as the length of the riser suspended between the touchdown point (TDP) and vessel.
- The current velocity component normal to the riser must be calculated which is dependent on the angle variation along the riser and the incident angle of the current.

Tables 2 and 3 indicate the vibrational response of the riser as predicted by the pre-analysis for the 4.7 knot (2.4m/s) tow speed, and estimates of fatigue life under these conditions.

Open Water Tests - Test Pipes

The test arrangement is illustrated in Figures 9 and 15, with a 650 ft (200m) riser towed between 2 tugs and rigged to allow a variety of angles and catenary shapes to be configured. 2 Pipe strings were tested, each welded from 10.75” OD, 3/8” wall steel pipe. Pre-analysis predicted high levels of fatigue damage due to VIV, and pipe girth welding was very carefully controlled, with 100% inspection using magnetic particle, ultrasonic test and X-ray, and a full hydro-pressure test to 80% of pipe wall yield. The pipes were tow-tested air filled, which reduced handling loads in water (approximately 3 tonnes per string) and which also increased the fatigue life according to the pre-analysis.

Details of the pipe properties are given in Table 1.

Open Water Tests - VIV Suppression

One of the pipes was fitted with VIV suppression strakes, the other left bare. The strake profile was scaled on the successful profile used for the 6” tank tests at Haslar, but configured to provide a 3-start helix with 15D pitch, which has previously been shown to be effective for multi-mode VIV suppression on non-inclined structures⁴.

The hand of the strake helix was reversed 8 times along the pipe (Figures 12 and 14). This was done to balance the hydrodynamic torque created as the inclined pipe was towed through the water. This helped reduce the likelihood of the pipe spinning within its rigging, and also helped balance the deflection force that would be felt by a curved pipe undergoing such torque, which had been clearly seen on the reduced scale tests at Haslar.

Open Water Tests - Instrumentation

In order to monitor loads and vibration on test, each pipe was fitted with the following instrumentation:

- 2H data-logger units were fixed at 40 locations along each pipe, positioned on the lee side from the incident flow (Figure 13). These are stand-alone devices and log time, temperature, and tri-axial acceleration at 10Hz. Two of these loggers were also hard-wired back to the rear tug to be monitored on line. Stand-alone loggers were required because of the amount of data to be simultaneously recorded, and the impracticality of logging this at the station on the tug. They also minimised the hard-wiring and umbilical requirements, and increased the level of redundancy within the instrumentation system.
- A pressure sensor at the bottom of the pipe gave the water depth at this point, hard-wired back to the rear tug. This gave confidence that the pipe was in the correct tow configuration, and recorded data from this would also help indicate the catenary curvature as the pipe was brought to speed.
- A 2H rotation logger recorded tri-axial rotation at the centre of the pipe string to indicate any spinning or “fish-tailing” of the pipe during the tow.
- Load shackles at the tow wire connections at the top and bottom of the pipe were hard-wired back to the rear tug, and indicated drag levels, and thereby could also indicate the level of VIV.

It was important to take measures to synchronise the instrumentation, because most of the data would be collected within the loggers, each of which was in isolation from the others. This was necessary because vibrational response has many transient features, resonance can lock-on and off, and standing mode waves may not be truly stationary, but can travel along the pipe. To this end, several measures were taken:

- All loggers were initialised before deployment with
the same master computer. In addition, the clock for this computer was controlled by a radio signal atomic clock, and the same computer was used to log the hard-wired instruments.

- The clocks on the loggers are subject to a small drift due to temperature effects. By logging temperature at each logger, compensation could be made.
- Before each set of tests, the tow wire to the top of the pipe string was paid in and out with abrupt stops. This provided a clear signature on the axial accelerometer readings on each logger.

All hard-wiring was fixed as a “ribbon” to the lee side of the pipes, and was routed via an umbilical to the control station on the rear tug. This comprised power and signal conditioning units, UPS, and full data record and processing facilities. Online data processing included ‘Fast Fourier Transform’ for frequency isolation, and fatigue damage estimations to establish fatigue life as the tests progressed. This processed data was used to modify test durations as required, and keep within damage allowable.

Open Water Tests - Clump Weight
A 15 tonne clump weight applied a nodal constraint at the bottom of the pipe, made up from 12” link anchor chain. To reduce internal friction and vibrational damping within the clump weight, it was banded to form a more solid mass.

Open Water Tests – Rigging
The tow wire and clump weight attachments to the pipes were via pad-eyes welded to the pipe end flanges. These were positioned slightly off the axis of the pipe to help maintain a stable pipe configuration on test, i.e. to stop the pipes spinning, and keep the externally mounted instrumentation on the lee side of the pipe.

Because of the high level of fatigue damage expected, and the possibility the pipe might break on test, a safety wire was included within each pipe string and fixed to each end flange. This was a 40mm steel wire, sized to catch the pipe if it broke and flooded with water. In order to constrain the wire from vibrating within the pipes, which may have influenced the system vibration response, lightweight footballs were pushed into the pipes to fill the radial gap between wire and pipe wall.

Open Water Tests – Pipe Deployment
Brown and Root/Rockwater were responsible for rigging, pipe deployment and marine operations. Each pipe was lifted into the water using 5 cranes, requiring a maximum difference of 1m between relative hook elevations for adjacent cranes, in order to prevent pipe plastic strain (Figure 14).

Once in the water, rigging had to be connected to each tug, which then applied the required minimum 10 tonne pull. Only then could the crane slings be removed from the submerged pipe.

Open Water Tests - Transit tow
Throughout the 12 hour tow from the launch quay to the sheltered test area, the tugs maintained 20 tonnes tension to the pipe. Several different tow configurations were required to negotiate shallow water areas, and areas exposed to open sea conditions, all the time aiming to minimise the loss of precious fatigue life before the spread could get to the test location. The pipe data-loggers were operative throughout this period, and one was secured at the wire overboard position on the trailing tug. The transit tow itself will therefore produce useful data on riser response to different top-end motions, since at times significant wave height reached 2m.

Open Water Tests – Testing
All base scope tests were achieved, apart from the near vertical case which was prevented when the pipe was in danger of clashing with the bow of the trailing tug as it was deflected by the water flow.

Tests were therefore conducted for the bare and straked pipes at 5 speed increments typically between 1 and 5 knots (0.5 and 2.5m/s) for each of 4 catenary configurations. The catenary configurations were identified by the angle of the pipe to the vertical before the tow test commenced, and were 75°, 60°, 45° and 30°. Test durations were adjusted, depending on the predicted and observed fatigue severity of the individual test, typically between 3 and 5 minutes.

A number of additional tests had been proposed as options to the base scope, in particular to tow at faster speeds over longer durations. In the event, these were not conducted, due to the following factors:

- The base scope data was still filed onboard the submerged loggers, and there was a danger of losing this data if the pipe failed during additional tests
- The remaining fatigue life of the pipe had been estimated from the hardwired loggers, but this was obviously subject to number of factors of uncertainty, e.g. was the weld quality as good as we assumed? Was the vibration at the hard-wired loggers less than at other parts of the pipe?
- Confidence in the weather window for the transit tow back to base, through the open sea areas

It was therefore decided to return to base to “bank” the data already obtained, and to demobilise the test program.

Open Water Tests – Results and Conclusions
Testing concluded in late December 1998, and data from the tests was not available at the time of submission of this paper. In addition, formal approval will be required from the JIP Steering Group before any distribution of results beyond the JIP participants.

It can be reported that all loggers performed to order, and the raw data totaled over 4 Gigabytes. All strakes stayed fully secured during the tests, and had a significant effect on the level of vibration.

It is fully expected that the results will provide a better understanding of riser VIV response and allow validation of VIV...
prediction software. The work will allow a higher level of design confidence, meaning less conservative, lower cost risers can be proposed, which can be fundamental to the technical and economic viability of deepwater developments.

Acknowledgement
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STRIDE Phase II Lead Engineering Contractor:
2H Offshore Engineering

Oil company participants in STRIDE Phase II:
ARCO
BHP Petroleum
BP Amoco
Chevron
Conoco
Elf
Enterprise Oil
Exxon Production Research
Mobil North Sea
Norsk Hydro
Saga Petroleum
Shell UK Exploration & Production
Statoil
Total Oil Marine

Engineering Contractor participants in STRIDE Phase II:
Brown & Root Energy Services
ETPM
Single Buoy Moorings
Sofec
Stolt Comex Seaway

Program manager STRIDE Phase II:
Offshore Technology Management

References and Bibliography

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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Riser model length</td>
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</tr>
<tr>
<td>Pipe OD</td>
<td>10.75&quot; (273.1mm)</td>
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<tr>
<td>Pipe wall</td>
<td>0.365&quot; (9.271mm)</td>
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<td>Pipe weight in air, air filled, straked</td>
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<td>Pipe weight in water, air filled, straked</td>
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<td>Pipe grade</td>
<td>API5B seam welded</td>
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<td>Pipe yield strength (min from certs)</td>
<td>48 ksi</td>
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<td>Distance between tow vessels</td>
<td>984 ft (300m)</td>
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<tr>
<td>Lower clump weight</td>
<td>15 tonne</td>
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<tr>
<td>Lower clump weight material</td>
<td>Steel chain, 20m lengths, stropped to form a clump</td>
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<tr>
<td>Diameter of tow wires</td>
<td>2&quot; (50 mm)</td>
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<tr>
<td>Pipe internal fluid (design)</td>
<td>Air</td>
</tr>
<tr>
<td>Pipe internal fluid (failed)</td>
<td>Sea water</td>
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<tr>
<td>Test angles (to vertical)</td>
<td>30, 45, 60, 75 degrees</td>
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**Table 1 – Open Water Test Parameters**

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<thead>
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<th>Inclination [deg]</th>
<th>Cₜ = 0.7</th>
<th>Cₜ = 1.4</th>
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<td>Damage Rate [1/hours]</td>
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<td>45</td>
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<td>9,8 .511E-1</td>
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<tr>
<td>75</td>
<td>5,4 .150E-2</td>
<td>5 .140E-2</td>
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**Table 2 – Predicted VIV Modes and Damage Rates at 4.7 knots (2.4m/s) Tow Speed**

<table>
<thead>
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<th>Inclination [deg]</th>
<th>Cₜ = 0.7</th>
<th>Cₜ = 1.4</th>
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<td>45</td>
<td>10 1.473 0.55 0.50</td>
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<td>60</td>
<td>8 1.002 0.61</td>
<td>9 1.229 0.41</td>
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<tr>
<td>75</td>
<td>5 0.528 0.62 0.56</td>
<td>5 0.528 0.62</td>
</tr>
</tbody>
</table>

**Table 3 – Predicted Modes, Frequencies and Amplitudes at 4.7 knots (2.4m/s) Tow Speed**

Learn more at www.2hoffshore.com
Figure 1 – Deflection of a High Drag, Low Weight Catenary Riser

Stainless steel pipe:
- 1/4 inch OD
- 105ft length
- 0.035” wall thickness
- 95ksi yield strength

TDP range of 36ft

Clump weight
and load cell

Cantilever load cell

Video camera

Test Pipe

TDP range of 36ft

17ft

Clump weight
and load cell

Rotary arm

Figure 2 – Touch Down Point Test Schematic

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Figure 3 – TDP Test Set-Up
Figure 4 – Tank Test Tow Rig at 0° and 45° Inclination (CAD Drawings)
Figure 5 – Tank Test Tow Rig

Figure 6 – Tank Tests - Straked Pipe

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Figure 7 – Tow Rig From Below

Figure 8 – “Classical” VIV Response Curve

Learn more at www.2hoffshore.com
MAXIMUM DEPTH (STATIC)  168M
TOW SPEED               2M/S
STRAKED PIPE            Cd=1.4

Figure 9 – Open Water Test - Tow Configuration Schematic

Figure 10 – Predicted Pipe Shapes (Flexcom3D)
Figure 11 – Variation in Normal Velocity to the Riser Due to Catenary Shape

Figure 12 – Strakes and Loggers (CAD drawing)
Figure 13 – Vibration loggers

Figure 14 – Pipe Load-Out
Figure 15 – Tow Testing Schematic