

**OMAE2007-29344**

## **DEEPWATER SPAR STEEL CATENARY RISER MONITORING STRATEGY**

**Shreenaath Natarajan**  
Senior Engineer, 2H Offshore Inc

**Mateusz Podskarbi,**  
Manager – Integrity Monitoring, 2H Offshore Inc

**Metin Karayaka, Ph.D.**  
Chevron, ETC

**Hugh Howells, Ph.D.**  
Director, 2H Offshore Ltd

### **ABSTRACT**

Steel catenary risers (SCRs) in deepwater environment exhibit complex dynamic response governed by various factors such as environmental conditions, vessel motions, soil-structure interaction and material degradation. Uncertainties in the SCR design exist in the design data, analysis methodologies, fabrication, and hence a conservative approach has been adopted to overcome these shortfalls.

Recent advances in monitoring systems installed on SCRs provide operator the assurance of the integrity of the SCRs in service, verify the SCR design, and enhance basic understanding of the SCR response.

This paper outlines a strategy for monitoring the SCRs to characterize the response due to vessel motions, vortex induced vibrations (VIV), and soil-structure interaction.

A detailed example of real-time SCR monitoring system with optimized array of motion and strain measurements is presented. The methodology for sensor selection and optimization is based on linear regression analysis. The measured data processing methods include shape matching the response amplitudes with correlating response frequencies. The principles and methods of measured data interpretation to capture global response shape due to wave and vessel motions induced and VIV are presented.

The pipe-soil interaction such as soil stiffness, suction, softening and trenching effects characterized using the strain measurements in the touch down zone are presented. In addition, the methods to calibrate the individual vertical, lateral and axial models for pipe-soil interaction are presented.

### **INTRODUCTION**

The uncertainties in the deepwater environment and the shortfalls in the riser design methodologies pose a significant challenge to the performance of installed riser systems. Monitoring installed riser systems in deepwater is becoming more popular to confirm the integrity of the riser, assist in operational decisions, optimize inspection, maintenance and repair (IMR) schedules and calibrate the existing design tools to improve future riser design.

Typical SCR loading components such as floater motions, and underwater currents determine the strength and the fatigue response of the structure. Studies carried out in the STRIDE and CARISIMA JIPs have shown that riser strength and fatigue response are also influenced by the seabed soil and the touch down region geometry.

Henceforth, the primary objective of an SCR monitoring program is to capture the following:

1. Fatigue loading due to vortex induced vibrations (VIV), wave loading, first and second order floater motions;
2. Extreme loads and stresses along the critical locations such as hang-off and touch down region.
3. Characterize the riser/soil interaction.

The SCR monitoring objectives can be accomplished by installing multiple monitoring devices, a combination of strain and motion sensors, along the entire length. From technical standpoint it is desired to place as many monitoring station as possible, but an optimal configuration is determined by many competing factors such as cost, sensor installation pre- or post-installation of the risers, sensor sensitivity, sensor types (accelerometer or strain based devices), data communication methods to topside facilities (online or remote access), integration of the monitoring system with the project teams.

The riser system performance characterization drives for larger number of sensors, whereas rest of the factors drives for a lower number of sensor stations. Hence the monitoring system design requires methods to characterize the riser response with minimal number of sensors critically placed along the riser. The following sections discuss the methods and strategies for SCR monitoring data interpretation.

**NOMENCLATURE**

- $m$  = Number of modes considered for the assessment
- $n$  = Number of sensors used
- $A_{i,j}$  = Mode shape of  $j^{th}$  mode at  $i^{th}$  sensor location
- $\kappa_{i,j}$  = Mode curvature of  $j^{th}$  mode at  $i^{th}$  sensor location
- $W_m$  = Peak amplitude of mode  $m$
- $\hat{W}_m$  = Peak amplitude of mode  $m$  in Fourier space
- $\hat{D}$  = Array of measured amplitudes from all the sensors for any peak response frequency in Fourier space

**SENSOR PLACEMENT STRATEGY**

All monitoring systems will be based on measuring riser response (strain or accelerations) of discrete points along the riser. Interpretation of dynamic response of the entire riser from discrete data points is complex and requires careful consideration in the instrumentation design process.

In order to characterize global riser response it requires sufficient number of instruments along the riser with appropriate spacing to capture the entire range of response expected. The data obtained at discrete locations need to be extrapolated along the whole riser which requires time domain or frequency domain data processing techniques as discussed in [1], [2] and [3]. The instrumentation can be distributed along the whole riser or clustered in groups near the critical regions.

The numbers of measurement locations required depends upon the range of modes expected to be excited, level of accuracy required, and in general will be dictated by costs. In principle to capture the VIV response, the spatial extent of the instrumentation should enable to capture at least a quarter wave length of the shape of lowest mode number expected. To capture the shape of the highest mode expected, there should be at least two instruments available to capture the quarter wave length. A technique to obtain an optimum instrumentation locations and the number required is discussed in [4].

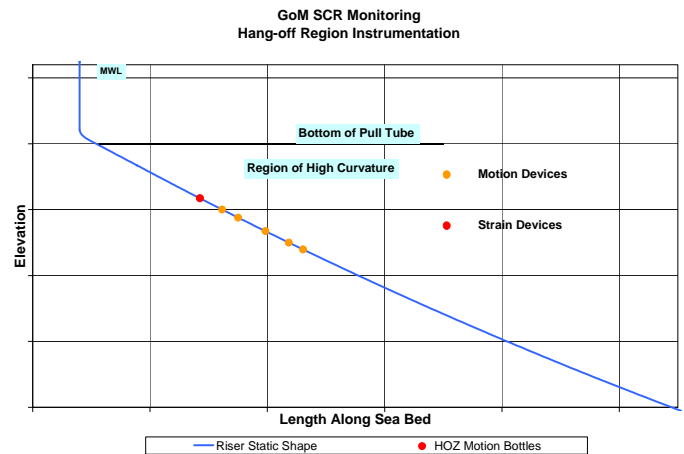
In order to verify the processed results from a set of instrument, an additional independent set of instrument(s) should be considered.

Redundancy should be built in the system to account for any sensor failure and increase the reliability of the monitoring system in the critical areas. Redundancy can be introduced by considering the following:

1. Additional sensors;
2. Sensor communication and power cables divided in to groups;
3. Employ field proven instruments;
4. Provide capability for periodical inspection and replacement.

The details of improving system reliability and installation considerations are discussed in [7].

Typical optimized sensor arrangement proposed for a GoM SCR is shown in Figure 1 and Figure 2. The example configuration has sensor arrangement near the hang-off and the touch down region with an optimized combination of strain and motion sensors. This arrangement is proposed to capture the VIV, wave or floater motion response, and soil-structure interaction. The methodology to interpret the riser response is discussed in the following sections.



**Figure 1 – Optimized Sensor Arrangement in the Hang-off Region Considered for a Typical GoM SCR**

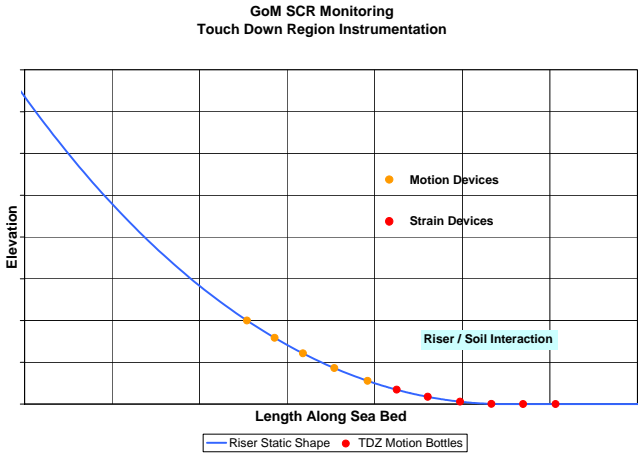


Figure 2 – Optimized Sensor Arrangement in the Touch Down Region Considered for a Typical GoM SCR

**SENSOR PLACEMENT STRATEGY TO CHARACTERIZE WAVE AND FLOATER MOTION INDUCED RESPONSE**

Riser accelerations along the length from various design fatigue seastate bins are shown in correlation with the measurement locations in Figure 3. Threshold motion level above which the riser fatigue damage is considerable can be determined based on the design fatigue seastate bins. Multiple threshold motion levels may be required to characterize the response at the hang-off and touch down region which can be used to set alarm to indicate the fatigue damage rates in case of real time processing.

Figure 4 and Figure 5 show that the strain stations are optimally located to capture the riser stresses in the touch down region during extreme storms and offset conditions. The dynamic strains are high near the TDP, however, it is difficult to monitor the peak TDP stresses due to varying TDP location during the storms. Therefore, extensive instrumentation near the TDP may still not be adequate to capture the peak stresses. Hence, the number and location of touch down region instrumentation is decided based on the expected TDP excursion during the normal and extreme seastates.

**WAVE AND FLOATER MOTION INDUCED RESPONSE CHARACTERIZATION METHODOLOGY**

Based on the riser motion response, the wave and floater motion induced response is characterized in two levels:

1. Preliminary evaluation of measured data in terms of standard deviations of motions and strains;
2. Processed data estimating the riser loads and stresses;

An approach similar to the motion response screening discussed above can be adopted to the strain measurements in the fatigue critical areas near the hang-off and the touch down region.

Dynamic strain measurements during the extreme seastates can be used to compute the stresses and bending moments at the measurement location. The stresses computed can also be used to calculate fatigue damage rate in real time using Rainflow cycle counting method, [8].

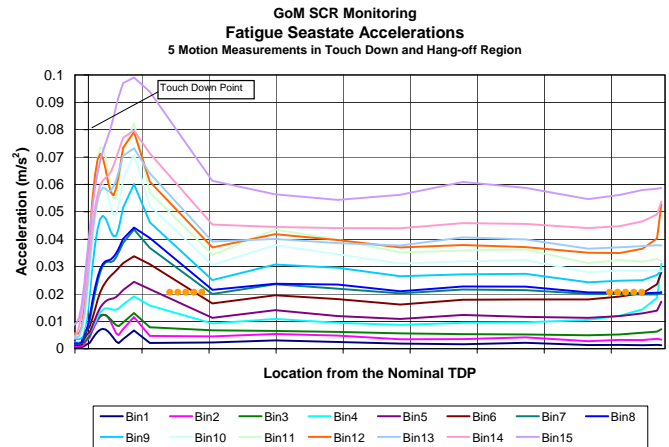


Figure 3 – Riser Accelerations for a Typical GoM SCR

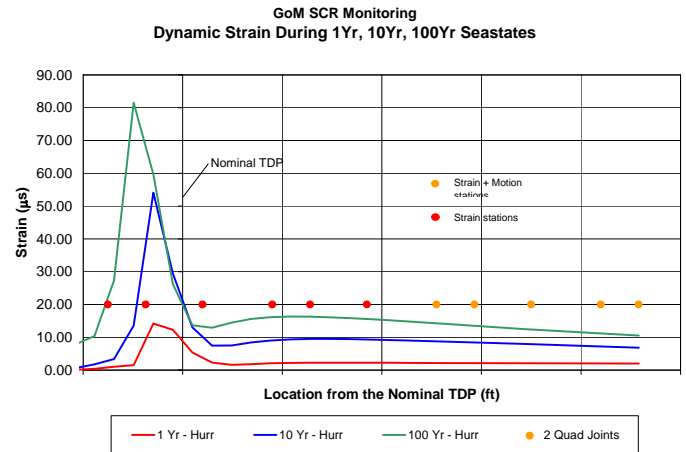
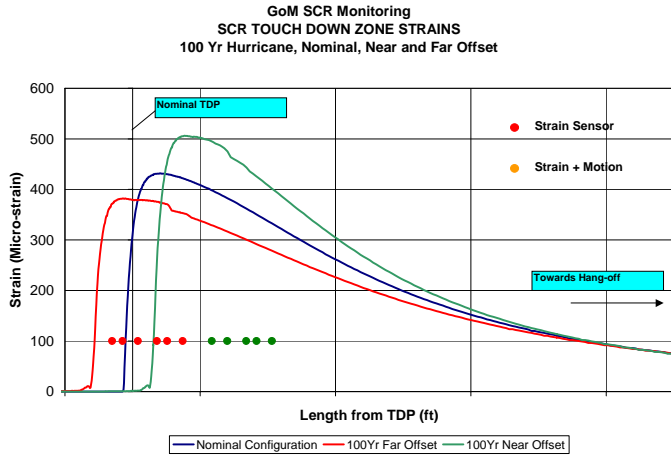


Figure 4 – Extreme Storm Riser Strains for a Typical GoM SCR



**Figure 5 – Extreme Storm Riser Strains for a Typical GoM SCR**

#### VIV RESPONSE CHARACTERIZATION METHODOLOGY

A popular and a commonly used method to characterize SCR VIV response is the principle of modal decomposition. The motion measurements obtained in the form of accelerations and/or angular velocities at selected location are extrapolated along the remainder of the riser using either time domain or frequency domain methods.

Frequency domain analysis can be applied to both synchronized real time measurements and un-synchronized stand-alone measurements, [1], [2] and [3]. The approach includes the following main steps:

1. Conduct spectral analysis at each motion sensor location;
2. Identify the peak response frequencies above a threshold measurement level determined based on VIV design;
3. Correlate the response from all the motion sensors along the riser length at each peak response frequency;
4. Assume normalized theoretical mode shapes predicted by FEA for the as-installed riser configuration;
5. Using linear regression analysis identify the shape and amplitude that provides the best-fit shape through the measured response peaks along the riser, [4];
6. Re-construct the riser shape based on the mode shape and amplitude determined from shape matching;
7. Compute stresses along the riser from the re-constructed mode shape.

The frequency domain approach involves the assumption that response is stationary. In order to capture the transient nature of the response a time domain approach or a pseudo-frequency domain approach with appropriate response duration is preferred.

Time domain modal response data interpretation requires synchronized measurements. The measurements at each time instant are expressed as a sum of modal response components, as given in the equation below,

$$x_i(t) = \sum_{m=1}^{m_2} W_m(t).A_{i,m}; \quad i = 1, N \quad (1)$$

Applying the above mentioned modal decomposition principle, the measured motions can be formulated in Fourier space, as given below,

$$-\omega^2[A]\{\hat{W}\} = \{\hat{D}\} \quad (2)$$

The peak response modes and the corresponding amplitudes can be determined using the regression analysis of the system of equations given in Equation 2. Global riser response can be constructed at each instant using all the participating mode shapes along with the associated amplitudes.

Both time and frequency domain approaches may be limited by assumptions made in calculation of mode shapes. Tension, contained fluid weight and added mass may vary from the values assumed. Such variations could change the modal frequencies and mode shape of the riser and therefore the riser response could be misinterpreted. Modal decomposition method is adopted for short durations to account for the transient nature of VIV response.

#### RISER – SOIL INTERACTION METHODOLOGY

Riser touch down point is critical to the design of the SCR where the largest bending loads occur. Also, TDP is not a single point on the riser and will move constantly with the floater motions, hence the riser-soil interaction significantly impacts the riser response near the touch down region.

Current riser design methods for seabed stiffness modeling involve rigid or linear elastic seabed with axial and lateral friction coefficients. The seabed stiffness used affects the fatigue damage near the TDP, [9]. Extreme storm stresses are not sensitive to the seabed stiffness, however, they are affected by seabed friction coefficients, [10]. Riser curvature is the highest near the TDP, hence the maximum VIV fatigue damage occurs at the TDP. The seabed stiffness assumption can also impact the VIV fatigue life near TDP. ROV surveys of the installed riser systems shown evidences of deep and wide

trenches near the touch down region, which could significantly change the maximum curvature and also induce lateral riser loads.

Touch down region monitoring using strain measurements can determine the following:

1. Trace the peak stress near the TDP as the riser moves dynamically;
2. Compute the riser lateral loads;
3. Calibrate pipe/soil interaction models to dynamic strains under known current/wave loading.
4. Appropriate values for pipe/soil stiffness
5. The degradation factor to apply to soil stiffness due to soil softening effects from continues riser cycling.
6. The influence of pipe/soil suction on a field riser by comparing the difference in strain cycles from upward motions to downward motion

### SOIL STIFFNESS CALIBRATION

Full scale touch down region measurements can be used to calibrate the existing soil stiffness and soil suction effects. Strain monitoring is proposed over a sufficient length of the touch down region to capture the TDP excursion during extreme vessel offsets in a fashion similar to the harbour test conducted during STRIDE JIP, as shown in Figure 6.

STRIDE JIP pull up and lay-down tests of the test riser provided an estimate of seabed soil stiffness based on bending moment range captured by the touch down zone strain measurements. During the pull up test of the test riser, the touch down zone out-of-plane bending moments remain constant, as shown in Figure 7, while the in-plane bending moments drop to a minimum value and increase back to a steady state bending moment value. The bending moment variation for a strain station during the TDP migration is shown in Figure 7. The pull up scenario presents the effect of pipe/soil suction on the riser. The lay down test is considered to represent the no pipe/soil suction on the riser. The lower bending moment range on the same strain station during the TDP migration indicates that the pipe/soil suction force is holding the riser in place.

The strain stations will be located near the touch down zone with sufficient coverage to capture the extreme vessel offsets during storms. Subsequently, the peak in the bending moment response will be captured by the touch down region strain sensors.

The motion sensors located along the riser provide the angles and hence the riser configuration and the touch down point can be predicted. The bending moment envelope from the TDZ measurements can be obtained during the storm events along with associated vessel offsets.

The bending moment envelope predicted from analytical model of the SCR with the seabed soil stiffness modelled can be compared against the measured bending moment envelopes. A similar comparison between analytical predictions and measurements for the STRIDE JIP results are shown in Figure 8. The bending moment ranges for tests 2 to 11 are shown for the pulling up and laying down of the test riser on the seabed. The pull-up tests reflect the soil suction effects on the riser bending moment range. The analytical response without the soil suction effect show the bending moment range compares well for the lay down tests, however the increased bending moment ranges during the pull-up tests are matched using a suction model. Based on this comparison, the seabed soil stiffness value can be calibrated.

Similar soil stiffness calibration can be conducted for various environmental events to study the behavior of soil softening effects.

Calibrated analytical modeling of the SCR can provide an accurate estimate of fatigue damage consumed in the riser.

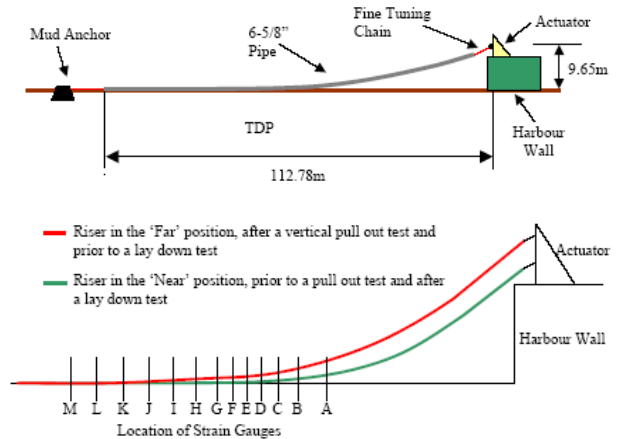
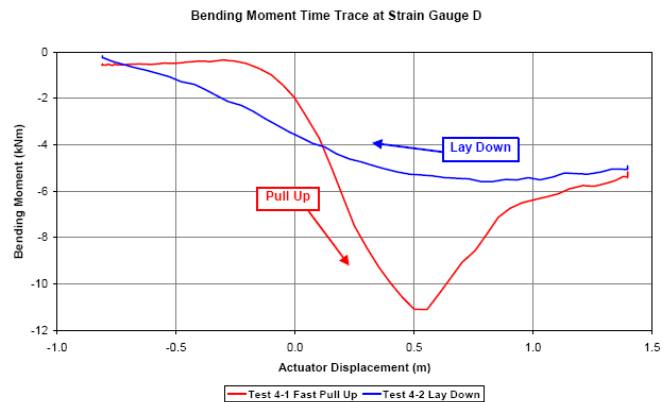
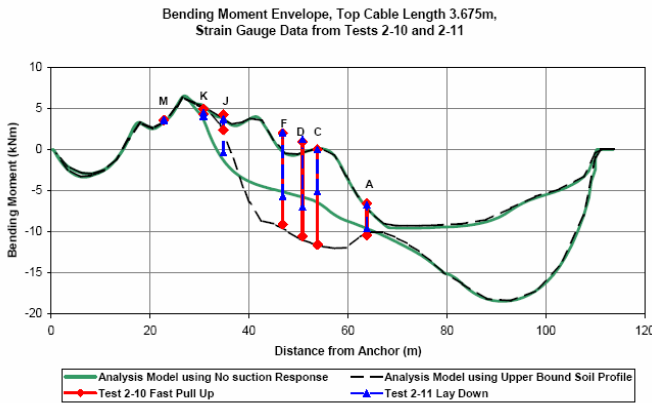


Figure 6 – STRIDE JIP Harbor Test Setup



**Figure 7 – Touch Down Bending Moment Comparison During Riser Pull-up and Lay Down Test**



**Figure 8 – Seabed Soil Stiffness Model Calibration Based on Harbor Test Results**

**TRENCHING LOAD ESTIMATION**

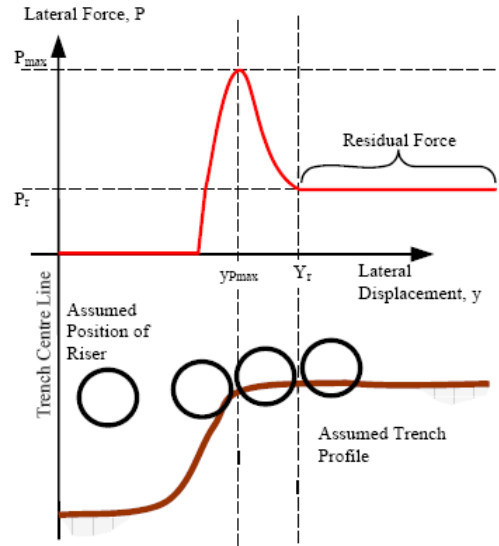
Effects of trench wall loads during extreme storm events can impact the strength response of the SCR. Transverse floater offsets are translated into vertical lift off and lateral movements at the TDP. Typically, the effect of trench wall resistance can be modeled using spring elements in the lateral plane.

The effect of pull-out resistance on a pipe in a clay soil was studied as part of CARISIMA JIP, [10], [11]. An example of the soil resistance effect on the riser pipe lateral force during a lateral pull-out is shown in Figure 9 and Figure 10. The soil resistance increases as the riser pipe is pulled out of the trench to the peak lateral force and drops down to a constant residual friction force. Figure 9 shows the riser moving laterally in a trench when the riser is suspended. The pipe moves with no resistance until it comes into contact with the trench wall and then the restraining force increases until the peak lateral force is reached. Figure 10 shows the riser pipe climbing out from the bottom of the trench.

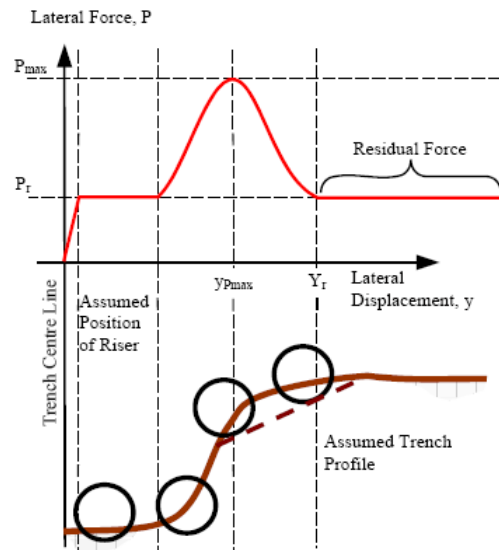
The lateral pipe/soil interaction effects are obtained by comparing the normalized pipe/soil interaction curves, as shown in Figure 11.

The touch down region strain measurements can be used to obtain the pipe lateral forces. The peak lateral force can be used in correlation with an ROV survey of the trench to identify the trench width, which can be used as a displacement at the peak lateral force. Based on the curves, the lateral pipe/soil interaction model can be developed and calibrated. This requires identification of a seastate condition at which large

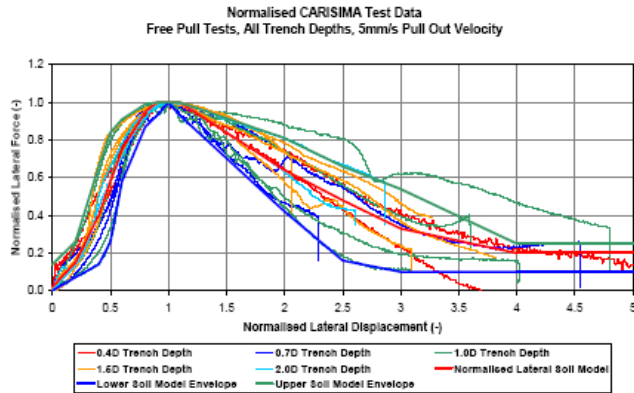
vessel offsets are observed with relatively small dynamic touch down region motions.



**Figure 9 – CARISIMA JIP Lateral Trench Pull Out Forces**



**Figure 10 – CARISIMA JIP Deep Trench Lateral Pull Out Forces**



**Figure 11 – Calibrated Trench Lateral Force Model, CARISIMA JIP**

## CONCLUSIONS

A suitable steel catenary riser monitoring strategy that can confirm the integrity of the risers is obtained through a combination of an optimized monitoring system and the state-of-the-art data processing methods are presented.

The monitoring system is capable of capture all the fatigue components of an SCR due to wave, VIV, and floater motions. The combination of the motion and the strain sensors placed along the critical locations of the riser with sufficient coverage provides the ability to track the extreme loads on the SCR to confirm the integrity and also provides the response along the un-monitored locations along the riser.

In addition, the monitoring system can provide in-valuable information for understanding the complex dynamic response of the SCR, and enable calibrate the pipe/soil interaction. This will provide a good basis for the future SCR design.

## REFERENCES

- [1]. Campbell, M., Shilling, R., Howells, H. – “Drilling Riser VIV Analysis Calibration Using Full Scale Field Data”, Deepwater Offshore Technology, Victoria, Brazil, 8-10<sup>th</sup> Nov 2005.
- [2]. Thethi, R., Howells, H., Natarajan, S., Bridge, C., – “A Fatigue Monitoring Strategy & Implementation on a Deepwater Top Tensioned Riser”, OTC, Houston, TX, USA, 2-5<sup>th</sup> May 2005.
- [3]. Kaasen, K., Lie, H., Solaas, F., Vandiver, K., – “NDP: Analysis of VIV of Marine Risers Based on Full-Scale Measurements”, OTC, Houston, TX, USA, 2-5<sup>th</sup> May 2005.
- [4]. Natarajan, S., Howells, H., Deka, D., Walters, D., – “Optimization of Sensor Placement to Capture Riser VIV Response”, OMAE, Hamburg, Germany, 4-9<sup>th</sup> June 2006.

- [5]. Pei An, Neil Willis & Steve Hatton – “Standalone Subsea Data Monitoring System”, 6<sup>th</sup> Underwater Science Symposium, Aberdeen University, Scotland, UK, 3-6<sup>th</sup> April 2003.
- [6]. Podskarbi M., Thethi, R., & Howells, H., – “Fatigue Monitoring of Deepwater Drilling Risers”, Subsea Rio, Rio de Janeiro, Brazil, 8-10<sup>th</sup> June 2005.
- [7]. Karayaka, M., Podskarbi, M., Walters, D., & Hatton, S., – “Design Consideration of Monitoring Systems for Deepwater Catenary Risers”, ISOPE, Lisbon, Portugal, 1-5<sup>th</sup> July 2007. (*To be published*)
- [8]. ASTM standards – “Metals Test Methods and Analytical Procedures”, Vol. 03.01, Section 3, pp. E1049.
- [9]. “STRIDE JIP – Detailed Fatigue Analysis Report” - 1094-RPT-015, October 1997, 2H Offshore Engineering, Woking, UK.
- [10]. “STRIDE JIP – Detailed Fatigue Analysis Report” 1094-RPT- 023, November 1997, 2H Offshore Engineering, Woking, UK.
- [11]. “CARISIMA JIP – Interpretation of Suction Test Results”, Report No. 700039.00.03, Trondheim, Norway.
- [12]. “PhD Thesis – Effect of Seabed Interaction on SCR”, Chris, D. Bridge, 2005, University of Surrey, UK.