SOIL INTERACTION EFFECTS ON SIMPLE CATENARY RISER RESPONSE

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Abstract

The paper discusses the effects of riser-seabed soil interaction relating to the design of steel simple catenary risers (SCR) for deepwater developments.

Current riser-soil modeling practices are simplistic compared with testing and field observations, which reveal the potential riser stress raising mechanisms of soil suction and trench wall resistance. Improved riser-soil interaction models are given and their effects on SCR response is shown from parametric analysis conducted in the STRIDE (STeel Risers In Deepwater Environments) Joint Industry Program. The effect of seabed stiffness and soil damping on riser fatigue life is also discussed.

An account is given of the STRIDE Phase III large scale testing initiative to better understand riser-seabed soil interaction and validate riser-soil models.
Introduction

The use of steel simple catenary risers in deepwater developments is becoming more popular with a number of SCR’s already installed offshore Brazil and in the Gulf of Mexico. Upcoming deepwater field developments in the Gulf of Mexico, Brazil and West Africa have planned SCR configurations for large diameter export and subsea tie back production lines. A typical SCR configuration is shown in Figure 1.

The concept of the steel catenary is inherently simple and is often thought of as an extension of the flow line or pipeline. However, the dynamic movements experienced by the SCR from vessel motions and hydrodynamic loading result in a more complex behavior of the structure compared with flow lines and pipelines. This results in a requirement for sophisticated numerical tools to assist in the design process, in particular for the prediction of extreme storm stresses and long-term fatigue life due to vessel motions and vortex induced vibrations (VIV).

Current developments of steel catenary technology have focused on better understanding of these issues, one of which is the SCR touch down region and its interaction with the seabed. Studies carried out in the STRIDE JIP have shown that riser strength and fatigue response are influenced by the seabed soil and its local geometry in the touch down region. Their potential implications on SCR design have led the industry to investigate this area further. Recent initiatives include large and small scale testing programs carried out in the STRIDE JIP and CARISMA JIP [1] respectively.

This paper defines the mechanisms and uncertainties surrounding riser-seabed soil interaction, describes improved riser-soil interaction models and their effects on SCR response, and outlines the STRIDE Phase III large scale testing initiative to better understand and model riser-soil interaction.

The Importance of Riser-Seabed Interaction on SCR Design

The design of a SCR is an iterative process that is typically conducted as follows:

- Wall thickness sizing
- Storm analysis
- Fatigue analysis

Preliminary wall thickness sizing should be carried out using a design code that covers burst, collapse and buckling criteria. Preliminary global analysis is then conducted using a finite element program to account for the SCR’s complex non-linear behavior. A load case matrix considering combinations of current, waves, vessel motions, vessel offsets, riser contents, and operating pressures, ensures that for all load cases, riser response is within code limits. It is normal that following preliminary analysis, optimization of the initial configuration is required. Changing the wall thickness, top angle, and material grade may be considered.

Following storm analysis, a detailed fatigue assessment should be conducted. The analysis is best conducted in the time domain to account for non-linear effects and must take into account issues such as seabed interaction and the directionality of the environmental loading. In addition
to the first order fatigue, damage due to second order vessel motions and VIV must be established.

Areas of particular interest are the touch down point (TDP) and the connection to the vessel. These are the fatigue hot spots where the largest bending and tension loads occur respectively. The TDP is defined as the point where the riser touches down onto the seabed. The TDP is illustrated in Figure 1.

Having established that the TDP is critical to the design of the SCR, it should be noted that the TDP is not a single point on the riser. The TDP will move constantly with time reflecting movements of the vessel and riser. Hence, the term touch down zone (TDZ) may be more applicable.

Current riser analysis methods for modeling the seabed typically involve the use of a rigid or linear elastic seabed with friction coefficients assigned in the axial and lateral directions relative to the longitudinal axis of the riser.

Fatigue damage is affected by the seabed stiffness assigned in the analysis. The use of a rigid seabed gives higher maximum fatigue damage in the critical TDZ compared with an elastic seabed [2]. Extreme storm stresses are not particularly sensitive to seabed stiffness [3] but are more influenced by lateral friction coefficients when current and wave loading are in the direction transverse to the riser longitudinal axis.

In order to obtain estimates of long term VIV fatigue damage, analysis must be conducted with a computer program such as SHEAR7 [4], developed at MIT under a JIP. The program can account for variation in current speed through the water depth and enables prediction of multi-mode VIV response of a uniform riser in sheared or uniform current and has been extensively validated using model tests. While SHEAR7 was developed for analysis of nominally straight, top-tensioned risers, such as drilling risers and TLP production risers, it can be used to predict VIV response of a steel SCR.

Unlike most riser FE analysis packages, SHEAR 7 is unable to model a change in riser incidence angle along the length of the riser. Instead the SCR configuration has to be simplified to a uniform vertical riser and a length corresponding to the catenary length between the vessel and TDP. Fixed, pinned or rotational springs may be considered for the TDP boundary condition. To improve prediction of VIV fatigue damage, the natural frequencies, modal curvatures and mode shapes of the SCR can be calculated in a separate FE analysis program and input into SHEAR 7 [5].

Typically, maximum VIV fatigue damage occurs at the TDP where the tension is lowest. Using a fixed boundary condition at the TDP gives higher fatigue damage than using a pinned condition due to the higher local curvatures resulting from a fixed support.

Many uncertainties surround riser-seabed soil interaction as field observations have shown deep steep sided trenches developed in the TDZ of the SCR in the Gulf of Mexico. Also, potential riser stress raising mechanisms such as soil suction and trench wall resistance are not currently accounted for in SCR design. The industry has attempted to deal with these issues through a number of forums. The STRIDE JIP has achieved this by developing improved modeling techniques that have been validated against large scale testing.

The following sections discuss and develop these issues.
Field Observations

ROV surveys of installed steel and flexible catenaries have shown deep trenches cut into the seabed beyond the touchdown point (TDP). Even after just a few months following installation, 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. Such trenches have been observed in the Auger and Allegheny Gulf of Mexico field developments.

The trenches are profiled over the length of the TDZ in both depth and width. Video evidence suggests that the deepest and widest part of the trench tends to be at the nominal vessel offset TDP position, where the most frequent riser motions occur. Either side of the nominal TDP, the trench profile becomes shallower and narrower.

It is difficult to predict the trench profile and the rate at which it develops as both depend on the degree and frequency of riser movements at the TDP, which in turn depend on the environmental loading and vessel motions. However, the TDZ can be mapped using riser analysis to reflect the occurrence of TDP movements within the TDZ and define its limits. Such a plot is shown in Figure 2 for a 14” deepwater Gulf of Mexico SCR connected to a Spar. The plot shows that over the service life of the riser, 97% of the riser movement occurs in a +/-17m (+/- 56ft) long narrow strip centered about the nominal TDP and in the direction of the riser longitudinal axis [6]. TDP mapping is useful in defining the TDZ limits and identifying sections of the riser in the TDZ that move very frequently such that the soil within this region is always in a remoulded condition. To develop such a plot requires sufficient first and second order vessel motion data covering day-to-day to extreme sea states along with associated mean vessel offset and sea state exceedence probability data.

Riser-Seabed Soil Interaction Mechanisms

Riser-seabed soil interaction mechanisms may be subdivided into three categories:

- The effect of riser movements on the seabed

  The result of this mechanism is degradation of the soil through plastic deformation and riser self-burying. This may be through predominantly vertical movements of the riser, some of which may be coupled with lateral motions.

- The effect of water on the seabed

  Riser movements into and out of a depression in the seabed produces a mechanism termed “pumping”, whereby water accelerates out of a depression as the riser lays down, and accelerates back in as the riser lifts up. The water flow velocities resulting from this “pumping” action helps to dislodge already degraded soil from riser impact and provides effective sediment transport out of the seabed depression. Thus the initial depression evolves into a trench.

- The effect of the seabed on the riser
The seabed soil exerts a complex resistance to riser movement in the vertical, lateral and axial directions relative to the riser longitudinal axis.

Vertical soil resistance can be further subdivided into downward penetration resistance and upward resistance. On the downward cycle, the soil exhibits some degree of elasticity at small initial penetration strains, which is beneficial to riser fatigue life in the TDZ. On the upward cycle, the riser may experience suction forces from soils such as soft clays adhering to the pipe. The suction phenomenon is analogous with someone standing for a period of time in a “sticky” clay mud, where a considerable vertical pull force is required to break away from the suction developed between the boot and the mud. Additionally, the weight of any backfill will provide further resistance to riser upward movement.

Lateral resistance consists of friction between the riser and seabed, and the passive resistance of the soil as the riser moves sideways out of a depression or into a trench wall. Consider a case of the riser TDP embedded half a diameter at the bottom of a very soft clay trench with dimensions five diameters deep and three diameters wide. Should a large lateral vessel excursion take place, the TDP will be moved sideways, initially mobilizing the friction resistance of the soil combined with passive resistance of the soil its embedded in. As it shears out of the depression, the riser experiences only frictional resistance of the trench bed until it impacts the side of the trench. Break out of the trench is dependant on the load imparted by the riser and passive shear resistance of the trench wall.

Axial resistance is only frictional and can be accounted for in current riser analysis tools through the assignment of a friction coefficient.

Finally, the TDP is also the point of maximum fatigue damage along the catenary length for VIV motions in plane with the riser longitudinal axis. As an elastic seabed stiffness is beneficial for critical TDP fatigue life resulting from vessel first order motions, it can be postulated that seabed stiffness will have the same effect on VIV fatigue damage at the TDP.

Another property of the soil that could be beneficial to riser fatigue is the additional damping on SCR vibrations resulting from vortex shedding.

**Improved Analysis Modeling of Riser-Seabed Soil Interaction**

An assessment must be made on which of the mechanisms described above are important to SCR design. Video evidence indicates trench formation in soft clays is inevitable for SCR-floating vessel configurations. Mechanisms involved in trench formation are a combination of soil plastic deformation and the pumping action of water around the riser. The interaction between these mechanisms and the random nature of riser movements along the TDZ complicates the prediction of a trench profile. As a result, trench depth and width profiles along the length of the TDZ should be selected in the riser analysis based on the deepest trenches observed in ROV surveys of existing developments and conservative soil strength assumptions.

Improvements in modeling soil resistance in the vertical and lateral directions are possible by using load-deflection spring elements in a riser FE program. Sufficient data for pipe penetration into the soil, based on bearing capacity theory and pipeline-soil interaction studies,
enables improved modeling of seabed stiffness and lateral soil resistance of a riser embedded or trenched into the seabed. The largest uncertainty is in the suction response, however, various small scale testing has been carried out prior to the recent CARISMA JIP initiative. This enabled preliminary soil suction curves to be developed for a parametric analysis study carried out in late 1999 as part of STRIDE Phase II program [7].

The use of existing analysis tools with improved riser-soil interaction modeling techniques has been used in STRIDE Phase II to investigate the potential effect on SCR design. By selecting upper and lower bound soil parameters, investigation through preliminary analysis achieved the following:

- Determination of the significance of riser-soil interaction mechanisms for a SCR/vessel configuration case study
- Critical soil parameters identified
- Critical riser load cases identified
- A focused development plan for small and large scale testing

A typical deepwater Gulf of Mexico soil was selected as a good case study to show the effects of soil resistance on SCR response. Deepwater Gulf of Mexico soils are typically soft clays with typical mud line strengths of 2.6 kPa (54 psf), linearly increasing with depth by 1.25 kPa/m (8 psf/ft) [7].

Improved riser-seabed modeling is described in the following sections, and example analysis load cases are given for typical deepwater Gulf of Mexico steel SCR configurations.

**Soil Response Curves**

Riser/soil response curves may be modeled as structural or ‘soil support’ spring in a structural analysis model. However, owing to time varying behavioral phenomenon associated with the repeated loading and gross plastic deformation of soils, it is not possible to represent the soil response at a riser element by a single soil support spring, which is applicable throughout the riser’s modeled life. Instead, the shape of the spring may change radically with time, evolving from a virgin soil response curve to a degraded response. Furthermore, a riser element may have zero contact over a large displacement range, until the displacement becomes greater than previously experienced, whereupon the element may suddenly resume contact with the virgin resistance curve.

The virgin response curve can be considered as a ‘backbone curve’, which serves as a building block and bounding surface for subsequent riser/soil response curves. Conversely, the riser/soil response curve can be considered as a load path bounded by the backbone curve. The concept is illustrated in Figure 3 schematically, presenting penetration and suction backbone curves, and examples load-displacement paths of subsequent and successive load reversals.

Aside from the dependence on soil properties and riser diameter, the riser/seabed load-deflection characteristics are also dependent upon the burial depth, which vary over sections of the riser in the TDZ over the service life. Hence, for the soil type/embedment scenarios involving buried sections of riser, it is necessary to provide response characteristics for different burial depths. Incorporation of the depth dependence can be done in one of two ways:
1. The load components of the response characteristics can be expressed as functions of depth;
2. Different sets of response characteristics can be provided, each set approximately appropriate for a given depth range.

Approach (2) is vastly simpler than approach (1), both in terms of formulating the response characteristics, and in terms of inputting into a FE analysis package. This approach has therefore been used in STRIDE and implemented through the introduction of depth ‘zones’, where each depth zone applies over a different range of riser burial depth.

**Seabed Soil Stiffness**

The selection of a linear elastic stiffness for riser first and second order fatigue analysis is dependent on the type of seabed soil and the mean vertical riser movements expected in the TDZ for a particular sea-state and loading direction. Due to the many combinations of load cases, first pass fatigue analysis should be conducted with a rigid bed or upper bound stiffness on an elastic bed.

Should the factored minimum fatigue life of the SCR be unacceptable on the first pass analysis, iteration on the fatigue analysis using a more rigorous approach of selecting an elastic stiffness from a non-linear pipe-soil interaction model can be used to improve the result. A pipe penetration model is shown in Figure 4 with a load deflection relationship relating to the pipe embedding into the soil half a diameter [8].

This variation of first order fatigue damage with seabed stiffness is shown in Figure 5, which shows the fatigue damage of a 28” and 12” SCR as a percentage of rigid bed damage for increasing seabed stiffness. The sea state and loading direction defined in Figure 5 has typically a high contribution to long-term fatigue damage in the Gulf of Mexico. The relationship between stiffness and damage is logarithmic with damage initially increasing sharply but only gradually increasing as the soil becomes stiffer.

Accounting for seabed stiffness in a SCR VIV analysis can also improve fatigue life at the critical TDP region. Current practice involves modeling the SCR between the vessel and TDP. The difference between fatigue damage predicted using a fixed and pinned boundary condition at the TDP can be considerable and in either case the effect of the riser length on the seabed is not captured. One method of accounting for seabed stiffness is to conduct modal analysis using a FE analysis package with a length of riser on the seabed. This data is input into a VIV analysis package such as SHEAR 7, with the equivalent vertical riser model extending from the vessel to the end of the riser lying on the seabed. The section of riser lying on the seabed is assumed to be in water and has no current loading.

Figure 6 shows fatigue life at the critical TDP location increasing with seabed stiffness for a 28” riser under long-term loop current loading out of plane with the static SCR curvature. As with first order fatigue, the fatigue life improves with a softer seabed.

**Soil Suction**

The effect of soil suction forces on SCR response can be modeled using non-linear plastic spring elements in a riser FE analysis package. The suction scenario is applicable where in-plane riser movements occur, resulting in riser lift off forces in the TDZ. Figure 7 shows the model set up for a SCR configuration with soil suction spring elements added to determine the effect of
suction resistance on the local riser bending moments in the TDZ as the vessel moves from its current position to an offset that increases the vertical top angle of the SCR. Such a movement of the vessel can occur during a failed mooring event, planned offset to a drilling location, or slow drift offset.

The load-deflection relationship defining the suction response, developed by Fugro for the STRIDE Phase II program [7], is shown in Figure 8 and represents an upper bound response of a riser in a deep narrow back-filled trench. The loading curve is highly non-linear exhibiting an initial mobilization distance to full suction load followed by a plateau terminating in a sharp drop to zero load. The plateau region represents the plastic straining of the soil as the riser starts to move upwards out of the trench, and the sharp drop is the break away of the riser from the soil. It should be noted the suction curve shown is specific to pipe diameter and soil shear strength, and only applicable for riser movements occurring after the riser has been in contact with the soil for a long period of time.

The increase in peak bending moment in the TDZ due to the suction force is shown in Figure 9. A significant increase in bending moment is observed at the TDP as the vessel offsets and suction forces resist the riser in the TDZ lifting off the seabed. Equivalent stresses with the internal fluid operating pressure should be determined for such a scenario to check that suction forces do not increase stresses at the TDP above the maximum allowable.

The suction curve used for vessel quasi-static offsets is not appropriate for a fatigue analysis due to the cyclic nature of TDZ riser motions. Instead a suction curve is developed for a remolded soil condition. Although the curve exhibits the same non-linearity as the quasi-static response, the peak suction forces are reduced due to the soil softening from repeated loading. A suction curve for a remoulded soil conditions is shown in Figure 8. In addition, the load cycle is non-linear plastic whereby after break out, the riser does not see any soil resistance on its downward motion cycle until it has reached the base of the trench. Existing commercial riser analysis packages are unable to account for this plastic behavior, so a full scale SCR-soil model was developed in ABAQUS [9] during STRIDE Phase II with a user subroutine to define the cyclic soil suction loading curve.

The effect of suction on Spar/SCR fatigue damage for different significant wave heights (Hs) is shown in Figure 10. The % increase in damage increases with Hs ranging from 5% in the small sea states to 25% in the largest sea state.

The suction curves developed for the above case studies are predominantly dependent on soil shear strength for a given riser diameter. Small 2D testing carried out in STRIDE Phase II showed the suction response to also be dependent on the following:

- Rate of lift off – peak suction force and plateau distance increasing with speed of lift off
- Number of lift off cycles – rapid suction forces degradation after a few cycles of break out
- Resting period between lift offs – suction forces regained after a period of rest allowing the soil under the pipe to re-consolidate

**Trench Wall Lateral Resistance**

The application of spring elements can be used to assess the effect of trench wall resistance during large vessel transverse offsets such as in a failed mooring scenario or planned movement to a drilling location. The lateral soil loading curves are de-coupled from the vertical riser
movement and are analogous with lateral pipeline movements [10]. These curves are relevant to sections of the trenched riser, which do not lift out of the trench during the course of the vessel transverse offset. Transverse vessel movements translate into vertical lift off and lateral movements at the TDP. The section of riser subject to trench wall resistance at the mouth of the trench changes as the vessel offset progresses. Different load deflection curves can be applied over the TDZ to reflect varying trench depth and width dimensions.

Figure 11 shows the increase in resultant bending moment of a 14” SCR in a water depth of 1200m (4000ft) and at 5% transverse vessel offset for varying trench widths in a deep trench. A significant increase in bending moment is observed at the TDP. Equivalent stresses with the internal fluid operating pressure should be determined for such a scenario to check that trench wall resistance does not increase riser stresses at the TDP above the maximum allowable.

Due to the complexity in predicting long-term trench profiles, analysis must be conducted using a deep narrow trench along the entire length of the TDZ. Video evidence suggests that this may be conservative and sensitivity analysis using wider trench dimensions in the nominal TDP region is recommended.

Uncertainties surround how the riser moves inside the trench during a transverse vessel offset. As the vessel offsets, the riser may ride up and out at the trench mouth due to its 3-D geometry, thus relieving the high stress concentration on the riser at this location in the trench. In addition, during vessel slow drift, the low frequency lateral loading on the trench wall will degrade the soil strength and inevitably widen the trench mouth during the course of the offset.

Areas Of Investigation – STRIDE III Large Scale Testing

As part of STRIDE Phase III, 2H Offshore Engineering carried out a large-scale test program to investigate the effects of seabed soil interaction with the touch down region of a deepwater SCR. The objectives of the test were to assess the following:

- Effect of soil suction forces on riser stresses for wave and slow drift motions
- Effect of different trenches on riser stresses for wave and slow drift motions
- Investigate trenching mechanisms and formation rates
- Identify key soil modeling parameters
- Benchmark analysis tools

The test setup modeled the TDZ of a 6-inch SCR. A harbor in SW England was found that had soil properties surprisingly similar to those of a deepwater Gulf of Mexico seabed, in particular undrained shear strength and plasticity index. Water depth varied from 15ft at high tide to an exposed bed at low tide, revealing undisturbed and relatively flat “seabed” corridors to test upon. The riser consisted of a 360-ft long 6-inch diameter steel pipe, hung in a catenary across the soft clay bed of a harbor as shown in Figure 12.

The top end of the riser was actuated with carefully controlled wave and vessel drift motions to simulate motions at the TDP from a spar platform in 3,300-ft water depth. In-plane vertical and out of plane horizontal actuation was provided by a 10ft linear ball screw that was driven from one end by a PLC controller mounted on a heavy truss frame. The actuator could simulate linear ramped motions of vessel slow drift, and sinusoidal motions of wave loading with different
amplitudes and frequencies that covered both typical day-to-day movements and extreme storms. The actuator frame could also be moved along on a set of 30ft rails to simulate a large vessel transverse excursion that would generate riser lateral motions in the trench.

The riser was instrumented in the TDZ at 13 positions providing vertical and horizontal bending strain measurement. Additional instrumentation included a triaxial accelerometer positioned just above the nominal TDP and tension load cells at the ends of the pipe.

Conducting tests at high and low tide respectively allowed effects due to water to be isolated and investigated. Tests were performed both ‘wet’ and ‘dry’ in different trench depths either in trenches developed as a result of riser TDP motions or in artificially deepened trenches. In addition, tests were carried out on rigid steel planking placed on the harbor bed under the riser to isolate soil effects on riser bending response and to provide controlled data from which comparisons could be drawn.

Finally, TDP vibration testing work was carried out for BP using the STRIDE harbor TDP test rig. The test program was designed with the following objectives:

- To understand the correct boundary condition to be applied to FE models at the TDP point when conducting riser analysis.
- To understand the level of damping of vibration caused by the soil.

The vibration test program used an out of balance motor to vibrate the pipe. Accelerometers were used to measure the levels of vibration along the pipe. Testing was conducted on both the harbor soil and on steel planking.

The results from the STRIDE test program and vibration tests are restricted to the participants. However, the large-scale tests showed the following:

- Stress raising effects of soil suction and trench wall resistance on a 3D steel catenary as indicated by STRIDE II analysis results using soil suction and lateral resistance models developed from 2D tests.
- Higher levels of damping of pipe vibrations in trenched soil conditions compared with a more rigid steel planked bed.
Conclusions

It is evident that current modeling of the seabed for SCR design using a flat rigid or elastic seabed is simplistic compared with the deep profiled trenches observed at the touch down zone of existing SCR’s in the Gulf of Mexico. Current modeling techniques do not account for the potential stress raising effects of soil suction and the passive soil resistance of the trench wall.

More rigorous modeling techniques using pipe-soil models to better account for seabed stiffness, soil suction and trench wall resistance can be used to improve prediction of riser fatigue life and strength, and also assess the significance of these mechanisms on overall SCR design. Critical load cases are found from parametric analyses, which show that seabed stiffness and soil suction can affect riser fatigue damage, and trench wall resistance and soil suction can cause a local increase in riser stress during a large vessel offset.

Uncertainties surrounding the mechanisms of riser-seabed interaction and validation of the riser-soil models developed have been addressed in large scale testing within the STRIDE JIP Phase III program. Further investigation is required on the damping of vortex induced vibrations when the riser is trenched riser into the seabed.

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STRIDE Phase III Lead Engineering Contractor: 2H Offshore Engineering

Oil company participants in STRIDE Phase III:
BP
Chevron
Conoco
Norsk Hydro
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Texaco
TotalFinaElf
Vastar

Engineering Contractor participants in STRIDE Phase III:
Aker
Brown & Root
Stolt Offshore
Single Buoy Moorings
Sofec

Programme manager STRIDE Phase III:
Offshore Technology Management
References

9. ABAQUS General Purpose FEA Program, Hibbit, Karlsson & Sorensen, Inc., Pawtucket, USA
Figure 1 – Simple Catenary Riser

Plan Length 0.75-1.5 Depth

Mean Top Angle 10-25 degrees

Simple Catenary

TDP Touch Down Point
1300m SCR GoM, TDP Location Probabilities, Plan

Probability Occurrence (%) [Approx Return Period]

- Blue: 0.004 [100 Yr Event]
- Purple: 0.01 [50 Yr Event]
- Green: 0.2 [1 Yr Event]
- Orange: 3 [1% Exceedance]
- Dark Purple: 21 [3% Exceedance]
- Red: 76 [24% Exceedance]

Vessel Anchor

Near - Far Axis (m)

Transverse Axis (m)

Figure 2 – SCR/Spar TDP Global Dynamic Movements
Figure 3 – Concept Of Backbone & Load-Deflection Curves
Figure 4 - 28" OD Pipe/Soil Penetration Model
Figure 5 - Variation of First Order Fatigue Damage with Elastic Seabed Stiffness
Figure 6 - Variation of VIV Fatigue Damage with Elastic Seabed Stiffness
Figure 7 - Modeling Of Suction and Backfill Resistance for Quasi-Static Vessel Offset
SOIL SUCTION LOADING RESPONSE FOR 14" SCR
Typical Gulf Of Mexico Soil Profile, 5D Trench Depth

Figure 8 - Suction Loading Curves
Figure 9 - Effect of Suction on TDZ Bending Moment
Figure 10 - Effect of Suction on TDP First Order Fatigue Damage
**14" SCR LATERAL RESISTANCE RESULTANT BENDING MOMENTS**

GoM Typical Soil Profile, 1 & 5 Dia. Trench Widths, 5 Dia. Trench Depth

Extreme Transverse Vessel Offset = 65.0m

**Figure 11 - Effect of Lateral Resistance on TDP Bending Moment**
Figure 12 – STRIDE Phase III Large Scale Test Set Up