

# Advances in Deepwater Top Tensioned Riser Design Consideration

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## ABSTRACT

A high proportion of cost in any deepwater field development comes from drilling, completion and workover activities, due to increased day rates and limited rig availability. Dry tree floating production facilities such as spars or TLP's provide a direct well access below the platform, and eliminates the need to mobilize specialist vessels for drilling and completion activities.

This paper presents the key design challenges involved with the top tensioned riser (TTR) systems. The TTR's have numerous specialist components and interfaces which require accurate modeling and analysis techniques. Typically, riser tension is provided by means of aircans or hydro-pneumatic tensioners. The aircans are guided within the hull at multiple locations along the riser, resulting in complex interactions between them. In addition, these guide surfaces are sometimes pre-loaded and result in a stick-slip effect that further complicates the design. At the seabed, the riser pipe-soil interaction and the fatigue critical conductor casing connector beneath the mudline has a significant effect on the taper stress joint design.

This paper describes the advances in TTR design understanding and the methods to accurately predict the strength and fatigue response of the riser to ensure fitness of purpose through life.

## INTRODUCTION AND BACKGROUND

Commercial development of deepwater oil and gas fields face a significant challenge due to increased day rates and reduced availability of deepwater drilling vessels that can be used for drilling, completion and work-over activities. The requirement to reduce the cost of these activities has increased the attraction towards dry tree production systems such as spars, TLPs, and possibly deep draft semi-submersibles, Figure 1 – 3, which are continually being evaluated, selected and installed for deepwater developments worldwide.

Top tensioned risers for dry tree facilities can be either single or dual casing riser systems depending upon the work-over requirements. Top tensioned risers provide direct well access for drilling and completion operations and potential cost savings by eliminating the need to mobilize deepwater drilling rigs for subsea well development drilling and future workover.

Trends show that dual casing risers are typically preferred by operators since they provide the capability for improved thermal performance

during production mode, and a way of reducing risk during work-over mode. The production fluids are carried through the internal production tubing during the production mode. In case of critical work-over operations the internal production tubing is removed and the completion fluids are contained within the inner casing. In case of inner riser leak, the outer riser provides a pressure barrier and also helps detect the leak by the pressure build up in the outer annulus.

Typically, dry tree riser systems are supported using buoyancy cans, Figure 4, or using hydro-pneumatic style tensioners, Figure 5. The outer casing for both dual and single casing riser systems consists of standard riser joints within the hull which are connected to a dual tapered keel joint keel ball arrangement, Figure 6, to react the drag loads on to the keel of the dry tree FPU. Standard riser joints are run through the water column below the keel joint to the lower taper joint that connects to the subsea wellhead via a tieback connector. The taper joint either has a crossover joint above or connects directly to standard risers joints, depending on the structural performance at the base of the riser. The keel joint near the vessel keel and the tapered joint above the wellhead are used to alleviate the stresses in the high bending areas. The standard riser joints are centralized at a few locations along the hull to relieve local bending stresses, particularly near the top of the riser.

The buoyancy can supported systems consists of a stem pipe that runs through the hull. The buoyancy can and the stem pipe are centralized at multiple locations along the hull which provides reaction points between the riser and the hull. The riser pipe runs inside the stem pipe and guided through a series of centralizers inside the stem pipe.

The standard riser joints are connected using either 'weld-on' threaded connections or threaded and coupled (T&C) connections. The inner riser pipe for dual casing riser system consists of standard riser joints between subsea tieback connector and surface wellhead.

The top tensioned riser interfaces with the subsea conductor casing system at the subsea wellhead. The subsea wellheads are usually connected to either 38-inch or 36-inch conductor pipe which are the primary load carrying members of the conductor casing system. The mudline casing strings use quick mate-able casing connectors and exhibit poor fatigue performance.

The top tensioned riser system incurs significant fatigue loading at the critical locations near the vessel interface, the subsea wellhead and at the conductor connector beneath the mudline.

This paper highlights the advances in modeling the above mentioned design complexities and their benefits towards achieving an optimum top tensioned riser design.

## KEY DESIGN CHALLENGES

Key aspects of the top-tensioned riser design are the feasibility of the riser system and the influence it has on the vessel interfaces. The water depth, reservoir pressure and the pipe material grade has a significant effect on the riser weight. Typically the riser is supported with a top tension higher than the overall submerged riser weight, in order to prevent the riser from compressive buckling near the wellhead. Increased riser tension requirements implies increased buoyancy can lengths or large capacity hydro-pneumatic tensioner cylinders. Thus the riser tensioning capacity has a direct effect on the increased vessel payload and the hull dimensions.

For the hydro-pneumatic tensioned riser systems, the tensioner characteristic is non-linear in nature, Figure 9. Tensioner rods stroke in/out due to vessel offsets causing the riser to stroke relative to the vessel and a result the riser up-thrust applied changes. The rate change of the applied up-thrust depends on the accumulator volume used. The non-linear tensioner force-displacement characteristic adds to the modeling complexity of these top tensioned riser systems. The non-linear tensioner response characteristic defines the riser stroke extremities. The riser design should consider adequate reaction points with the hull to minimize any reaction loads at the tensioner attachment elevation. These reaction points with the hull introduces the friction on the riser system and if not considered correctly may pose a strength and fatigue risk to the riser system.

For the buoyancy can riser systems, the air cans and stem pipe are usually guided through the hull by a series of guides at multiple locations, as shown in Figure 7. The frictional interfaces at multiple locations along the air can and stem are complex to model in order to correctly capture the vessel reaction loads transferred to the riser pipe. Usually, the guides are pre-tensioned to provide additional lateral constraint and results in an increased frictional loading on the riser pipe. Additional complexity arises from the guide wear surfaces causing the riser to stick/slip due to vessel motions.

Despite the spar hard tank shielding the riser from the majority of wave and current loading near the surface, the spar wave and slow drift motions introduces local moonpool hydrodynamics inside the spar hard tank. Considering the large air can diameters in the region of 12-14ft, with typical air can length exceeding 200ft inside a spar hard tank, the hydrodynamic drag forces cannot be neglected in considering the impact loading on the air can and stem pipe.

The riser keel joint is a dual tapered section with a keel ball in the middle connecting the upper and lower tapered sections, as shown in Figure 8. The keel ball in the center reacts the lateral loads on the hull and is the location of largest bending moment along the riser. The keel ball consists of steel contact surfaces, which adds an additional complexity of friction between moving steel surfaces. The high friction coefficient between steel surfaces introduces tension cycles in the riser system. The reaction loads at the keel ball location is high for deepwater top tensioned risers and the friction effects introduces additional stress utilization at the keel joint.

The effect of soil-structure interaction cannot be neglected. Assuming the stiff soil reaction on the conductor system beneath the mudline can

provide conservative design of the tapered stress joint. Typically, the soil provides high resistance for initial displacement of the conductor pipe and reduced resistance upon initial displacement which could result from mean vessel offsets due to extreme environmental conditions. The increased compliance in the soil added with the vessel motions during normal design fatigue seastates increases the conductor pipe dynamic response and thus the fatigue loading on the critical mudline conductor connector.

This paper addresses the following modeling advances:

- Hydro-pneumatic tensioning system model;
- Moonpool hydrodynamics model for buoyancy can systems;
- Friction modeling at the riser-hull interfaces;
- Soil-structure interaction.

## ADVANCED TTR MODELING METHODS

### Hydro-pneumatic Tensioning System Modeling

Hydro-pneumatic tensioner systems use hydraulic pressure to stroke multiple compensation cylinders as the vessel moves up and down. The hydraulic pressure is powered by pressurized gas stored in accumulator bottles. The gas expands or contracts inside the tensioner cylinders and the pressure applied on to the piston rods are transferred to the riser as top tension.

Due to the tensioner piston rods stroking in/out of the cylinder the gas inside the cylinder follows the ideal gas expansion law. The riser tension can be calculated through the gas law:

$$T = T_o \left( 1 - \frac{z}{z_o} \right)^{-m} \quad (1)$$

where,

- $T_o$  is the nominal tension;
- $z_o$  is the corresponding initial tensioner accumulator length;
- $z$  is the tensioner stroke;
- $m$  is the ideal gas constant.

The first derivative of the tension and stroke relationship provides the tensioner stiffness. The initial accumulator lengths,  $z_o$ , determines the tensioner stiffness characteristics. Small initial accumulator lengths provide high tensioner stiffness. Increasing the tensioner accumulator volume reduces the tensioner stiffness.

The riser axial stiffness,  $K_{riser}$ , along with tensioner stiffness,  $K_{tensioner}$ , modifies the overall stiffness of the riser system as follows,

$$\frac{K_{riser} K_{tensioner}}{K_{riser} + K_{tensioner}} \quad (2)$$

The total stiffness is close to the tensioner stiffness when the tensioner stiffness is low. As the tensioner stiffness increases with downstroke, riser stiffness dominates.

In order to illustrate the effect of the combined riser system stiffness a typical top tensioned riser for a 1500m water depth and a tension factor of 1.6 is considered. Tension factor is the term used to define the factor by which the riser top tension applied is higher than the riser wet weight. The non-linear tension determined based on different accumulator initial lengths are shown in Figure 9.

The effects of non-linear tension modeling versus constant tension

application are studied using the following parameters:

- Riser stroke;
- Top tension factor.

The stroke limits are defined by extreme mean vessel offsets and dynamic vessel motions. The effect of tension modeling on riser stroke during an extreme 100yr environmental condition is shown in Figure 10. The increased tensioner stiffness reduces both riser up-stroke and down-stroke and thus restricting the overall stroke range. The trade-off on restricting the tensioner stroke range is shown in the increased riser tension factor, as illustrated in Figure 11. The nominal tension factor applied is 1.6. The riser up-stroke reduces the riser tension factor and vice versa. The tension factor increases by as much as 2.3 during riser down-stroke. As a result the overall stress utilization on the riser pipe increases. The increased riser tension will induce a large bending moment at the keel, thus requiring an increased length and/or diameter of the keel joint.

This illustrates the importance of non-linear tensioner stiffness modeling during design to capture the riser stresses accurately and ensuring the riser stroke extremities are within limits.

### Moonpool Modeling for Buoyancy Can Systems

The hydrodynamics of buoyancy cans inside the spar moonpool affect both the response of the riser and the loads on the buoyancy can guides. Inside the moonpool, the enclosed water moves with the spar. Beneath the moonpool, the velocity of the water is that of the ambient wave field and current. Between the two regions, the velocity of the fluid transitions from that of the enclosed spar moonpool to the open water. Therefore, the sections of the riser contained within the spar moonpool should consider the hydrodynamic effects of the entrained water moving along with the hull.

Considering the large diameters of the buoyancy cans supporting the risers, the Froude-Krylov forces cannot be neglected. The moonpool effects should consider the water particle velocities and accelerations within the moonpool, which are the same as vessel motion velocities and accelerations, rather than the ambient wave field. The upper aircan guide reaction forces will be dominated by Froude-Krylov forces, whereas the lower aircan guides located near the transition region is affected by a combination of Froude-Krylov and inertial forces.

In order to avoid a discontinuity the water particle velocities and accelerations are interpolated linearly from those in the moonpool and those in the ambient wave field at the bottom of the spar hard tank.

The moonpool hydrodynamics effect on the aircan guide loads are shown in Figure 12. Without the moonpool effect, the entire drag load due to the vessel motions are reacted on the aircan guides thus resulting in guide loads that are more than 100% higher.

### Friction Modeling

Top tensioned risers have a number of reaction points along the hull that introduce friction forces in to the riser system. Considering the complexity involved in correctly modeling the interaction, the friction effects are often neglected during design. The aircan and stem guides are usually made of polymeric material which upon contact with steel surfaces introduces friction forces. The tapered keel joint which consists of flange connection between the dual tapered sections is centralized inside the vessel keel through a ball joint that wraps around the flanges. The ball joint serves as the load transfer interface with high friction coefficients due to the steel contact surfaces.

In order to illustrate the effect of friction on the riser response a detailed finite element analysis is conducted using ANSYS, Ref 2, Figure 13. A basic Coulomb friction model is used between the contact surfaces. The friction model containing two contact surfaces can carry shear stresses up to a certain magnitude across their interface before they start sliding relative to each other. This friction model can also simulate stick-slip effects. Typical static friction coefficients for steel contact surfaces are assumed to be between 0.1 and 0.3 in the finite element analysis conducted.

The friction forces imparted on the riser also depends on the normal reaction force:

$$F_{fr} = \mu N \quad (3)$$

where,

$F_{fr}$  is the friction force;

$\mu$  is the friction coefficient;

$N$  is the normal reaction force.

The contact elements enforce sticking condition until,

$$F_{fr} > \mu K_N \quad (4)$$

The amount of penetration between contact and target surfaces depends on the normal contact stiffness  $K_N$ . Higher stiffness values decrease the amount of penetration, but can lead to convergence difficulties. Lower stiffness values can lead to a certain amount of penetration and produce an inaccurate solution. Ideally, you want a high enough contact stiffness that the solution is well-behaved in terms of convergence. If the preload on the contact surface is known, such as for an aircan guide, then the load can be used to define the normal contact stiffness.

The effect of keel ball friction modeling on the riser tension variations is shown in Figure 14. The tension cycles are observed at the wave periods along with a large variation in tension due to stick-slip effect. For a typical deepwater top tensioned riser, the tension variation is approximately 1 to 3% of the overall riser top tension. The tension variations results in axial stress fluctuations which introduces additional fatigue loading on the riser pipe as shown in Figure 15.

The keel ball friction has a pronounced effect on the bending response along the keel joint as shown in Figure 16. The center of the keel joint being the main hull reaction point, as the riser enters the hull, experiences a large bending moment. The component of the tension variation due to friction increases the bending moment by as much as 10% at the keel center. This will result in higher stress utilization at the keel joint middle. Similar effects can also be observed at the base of the lower stress joint. However, the effect of friction on the bending response is minimal along the along the riser and thinner sections of the tapered joints. This illustrates the significance of friction modeling in the design of tapered stress joints.

### Soil Modeling

The soil-structure interaction should be considered for the structures running through and below the mudline. The soil-structure interaction is modeled using load vs. deflection curves which define the soil resistance to lateral motion. In order to illustrate the effect of soil stiffness model on the conductor pipe and riser response a detailed finite element model of a top tensioned riser with casing strings below the mudline has been developed. The casing strings below the mudline

are modeled using beam elements and are supported using linear stiffness springs to represent lateral soil resistance.

Typical un-drained shear strength values are used to calculate the soil stiffness. During extreme vessel offset conditions the conductor pipe displacement is large and may result in lower soil resistance until the soil around the conductor pipe settles down. To capture this effect a lower bound stiffness value is considered. In addition to the typical soil stiffness values a stiff and a loose soil model is also considered, as shown in Figure 17, to illustrate the effect on conductor and riser response.

The soil modeling has a pronounced effect on the conductor pipe response, as shown in Figure 18. The maximum stress along the conductor pipe can be as high as 30% of the yield strength for a loose soil model. The stress utilization may not pose any strength concerns. However, the conductor casing string beneath the mudline utilize fatigue critical connectors with high stress amplification factors, and will incur severe fatigue loading on the conductor pipe. Therefore, ignoring the soil-structure interaction may pose a serious risk to the integrity of the conductor pipe system.

The tapered stress joint response above the wellhead is also affected by the soil modeling. The stiff soil model amplifies the stresses at the base of the lower stress joint, thus resulting in a conservative design. This may prove to be over-conservatism for ultra deepwater top tensioned riser design and proper soil modeling will provide optimum design for tapered stress joints.

## CONCLUSIONS

This paper highlights several modeling advances for an optimum design of the top tensioned riser system. Accurate finite element modeling of the riser system including the tensioner effects, moonpool hydrodynamics, friction surfaces at the keel and aircan, soil-structure interaction are required to adequately design the top tensioned risers.

The key features to consider in the top tensioned riser design are discussed in this paper, and are as follows

- Hydro-pneumatic tensioning system model;
- Moonpool hydrodynamics model for buoyancy can systems;
- Friction modeling at the riser-hull interfaces;
- Soil-structure interaction.

The non-linear tensioner stiffness characteristics of hydro-pneumatic tensioners have significant effect in determining the riser stresses accurately and ensuring the riser stroke extremities are within limits. For buoyancy can supported risers the moonpool hydrodynamics should be considered to accurately predict the drag loads on the risers and the resulting guide loads.

Similarly, the importance of friction modeling has been established.

Friction along the riser system has a significant effect on the stress utilization along key riser components such as the keel joint and tapered stress joint. Overall stress utilization at the thicker sections of the keel joint and the tapered stress joint can be at least 10% higher due to friction. However, the effect of friction on the bending response is minimal along the along the riser and along the thinner sections of the tapered joints.

Soil-structure interaction affects the conductor pipe below mudline and tapered stress joint response above the wellhead. The stiff soil model amplifies the stresses at the base of the lower stress joint, thus resulting in a conservative tapered stress joint design.

Dry tree riser systems may be continually considered for future ultra deepwater field developments considering a significant cost and schedule benefits that it provides the operators. If the ultra deepwater dry tree systems are to maintain design integrity throughout the life of the field, a more comprehensive design approach is required. Ignoring or simplifying the design complexities may prove detrimental to the overall system performance.

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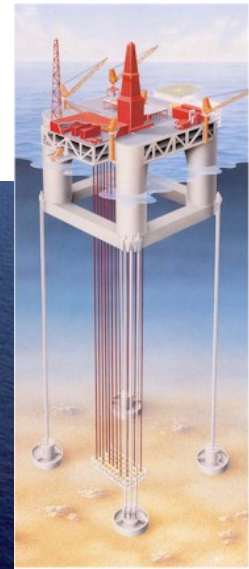
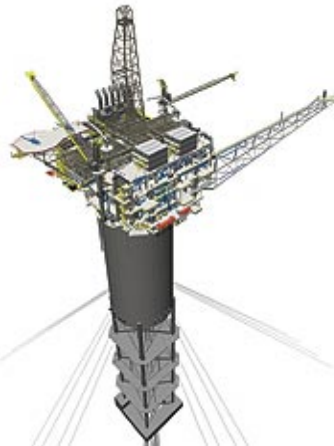


Figure 1 – Spar Dry Tree Production Facility, Reference 3

Figure 2 – TLP Dry Tree Production Facility, Reference 6

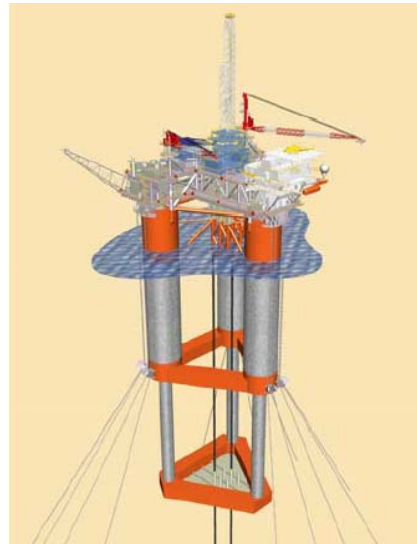


Figure 3 – Deep Draft Semi-submersible Dry Tree Facility, Reference 7



Figure 4 – Buoyancy Can Riser Tensioner System

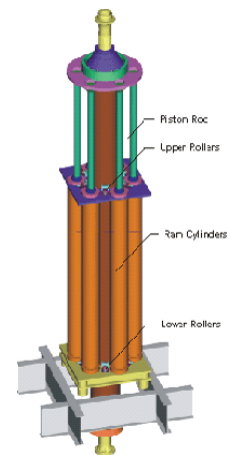


Figure 5 – Hydro-pneumatic RAM Style Riser Tensioner System, Reference 8

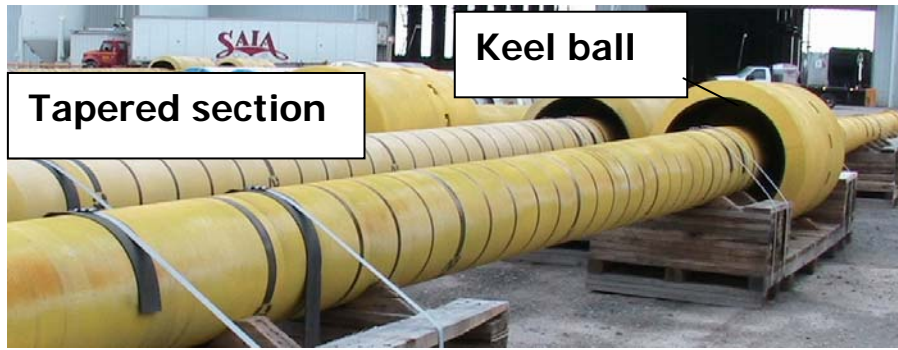


Figure 6 – Top Tensioned Riser Keel Joint with Keel Ball in the Middle

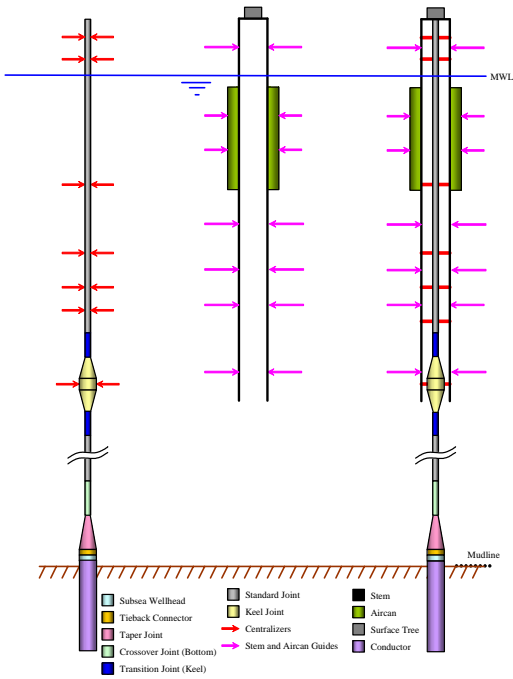
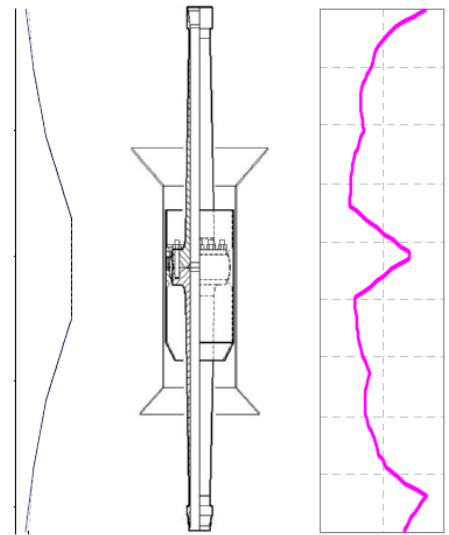


Figure 7 – Buoyancy Can Top Tensioned Riser



Thickness Profile

Keel Joint Assembly

Stress Utilization

Figure 8 – Top Tensioned Riser Keel Joint Profile, Reference 4

NON-LINEAR TENSIONER LOAD CHARACTERISTICS

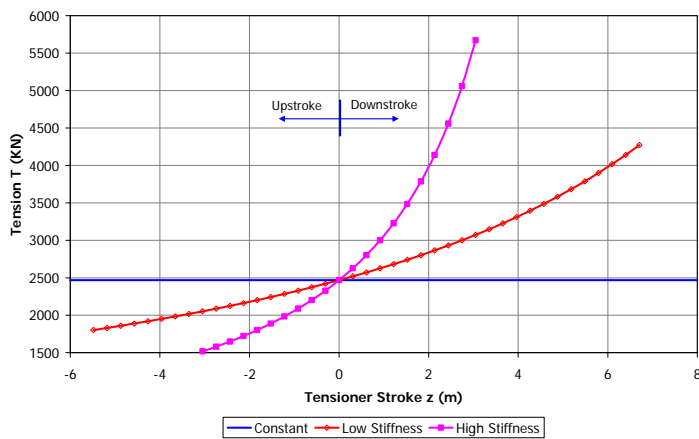


Figure 9 – Hydro-pneumatic Tensioner Non-linear Stiffness Curve

TTR STROKE VARIATION DUE TO TENSIONER MODELING  
Extreme 100yr Environment Event

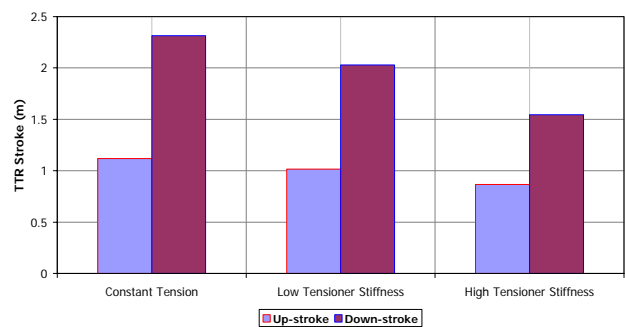
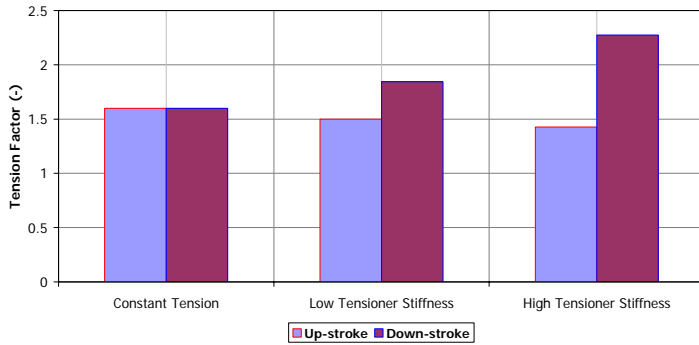


Figure 10 – Non-linear Stiffness Modeling Effect on TTR Stroke

**TTR TENSION FACTOR VARIATION DUE TO TENSIONER MODELING**  
**Extreme 100yr Environment Event**



**MOONPOOL HYDRODYNAMICS EFFECT COMPARISON**

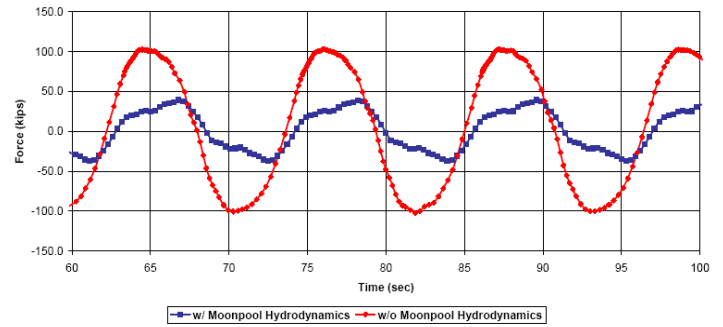


Figure 11 – Non-linear Stiffness Effect on TTR Tension Factor

Figure 12 – Effect of Froude-Krylov Forces on the Buoyancy Can Guides

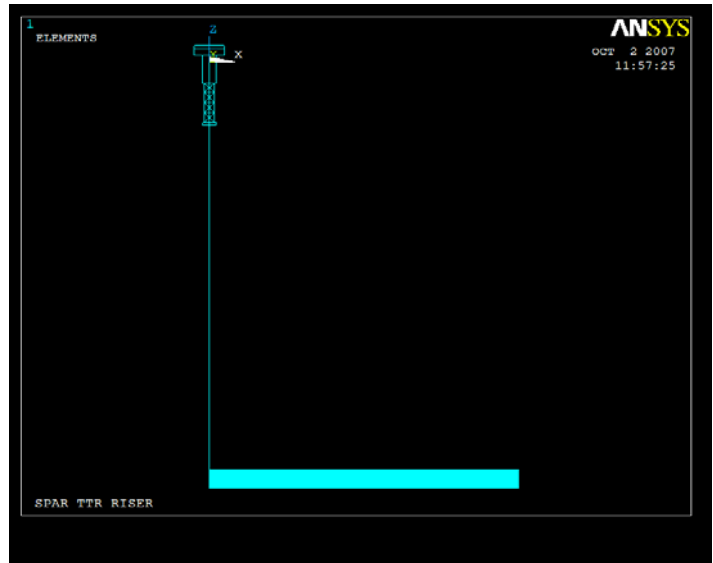
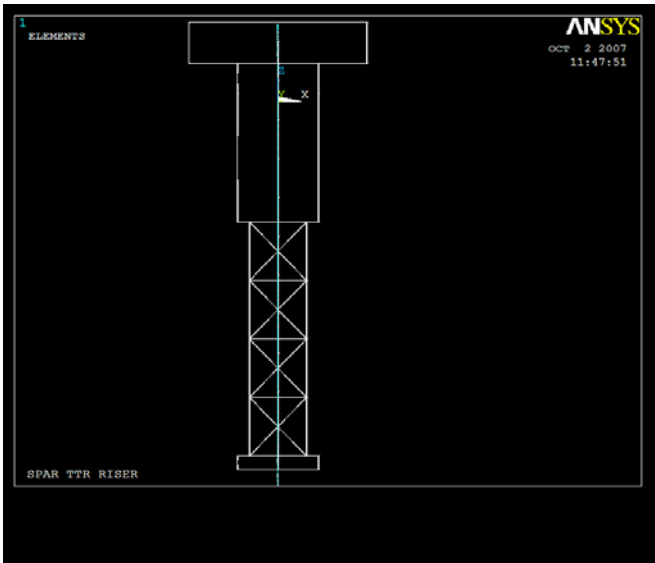


Figure 13 – Spar Top Tensioned Riser Model

**KEEL JOINT BOTTOM TENSION COMPARISON,**  
**Extreme 100yr Environment,**  
**ANSYS Coulomb Friction Element Model For Keel Ball Friction**

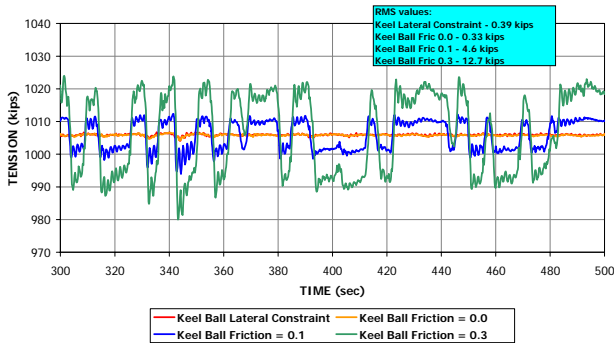


Figure 14 – Spar Top Tensioned Riser Tension Variations Due to Coulomb Friction Model

**OUTER RISER DAMAGE HISTOGRAM COMPARISON**  
**Extreme 100yr Environment, Tension Fluctuations Only**  
**ANSYS Coulomb Friction Element Model for Keel Ball Friction**

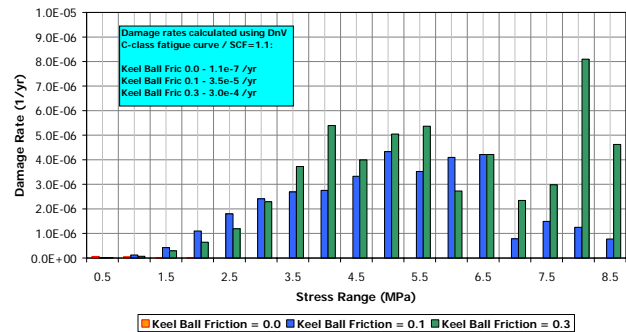


Figure 15 – Outer Riser Pipe Damage Rate Due to Tension Variations

**KEEL JOINT MAX BENDING MOMENT COMPARISON ALONG RISER,  
Extreme 100yr Environment,  
ANSYS Coulomb Friction Element Model for Keel Ball Friction**

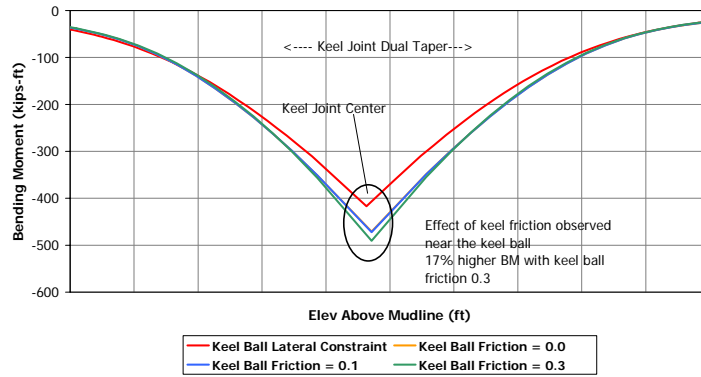


Figure 16 – Outer Riser Keel Joint Bending Response Due to Coulomb Friction Model

**LATERAL SOIL STIFFNESS 2FT BELOW MUDLINE**

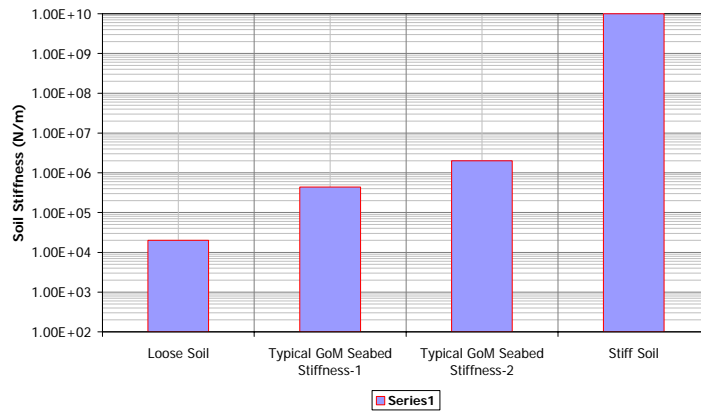


Figure 17 – Typical Soil Stiffness Model

**EFFECT OF SOIL STIFFNESS ON PIPE STRESS UTILIZATION  
Conductor Pipe and Tapered Joint Stress**

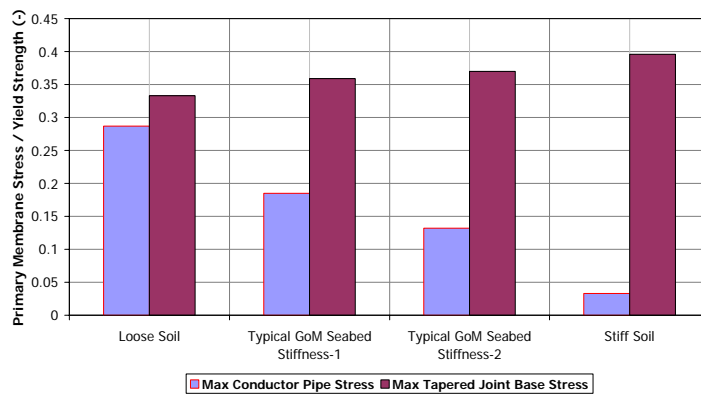


Figure 18 – Effect of Soil Modeling on Pipe Stresses