OTC 16720

Global Analysis of Shallow Water FPSOs

Arun S. Duggal, Y. H. Liu (Allen), and Caspar N. Heyl, FMC SOFEC Floating Systems, Inc.

This paper was prepared for presentation at the Offshore Technology Conference held in Houston, Texas, U.S.A., 3–6 May 2004.

Abstract

The paper focuses on the global analysis of FPSOs in shallow water, with an emphasis on vessel motions and offsets, mooring and riser design. The paper emphasizes the complex hydrodynamic interaction between the vessel and the environment, and the prediction of the vessel responses unique to shallow water. This done by using two examples of FPSOs moored in shallow water using an external turret mooring system and a tower yoke mooring system. Results are presented that illustrate the unique nature of both mooring systems and their sensitivity to variation in the environment and system damping. The design of compatible riser systems for both mooring systems is also presented and discussed.

Introduction

The Floating Production, Storage and Offloading (FPSO) system is the most mature of all floating production systems with over 100 installed and operating worldwide. It is also one of the most versatile floating production systems being installed in water depths from 20 meters to over 1800 meters, for a wide range of environmental conditions and can be easily extended to water depths even greater than 3000 meters. The majority of the FPSOs have been installed in water depths less than 200 meters of water. This is in contrast with other floating production systems that are focused on deepwater (greater than 500 meters). The market for shallow water FPSOs or Floating Storage and Offloading Systems (FSOs) is still very strong with a large number of facilities being designed and planned for water depths of 100 meters or less.

From a global analysis perspective, shallow water FPSO/FSO systems can be much more challenging to analyze and design than ultra-deepwater systems. This is due to the:

- Environmental loading on the system in shallow water,
- "Hardening" nonlinear stiffness of the mooring system that at extreme offsets can result in large variability in loads,
- Low level of associated damping in the system, and
- Design of an appropriate riser system for fluid transfer.

The first objective of this paper is to provide the reader with the basic information to understand the analysis and design methodologies for a shallow water FPSO system focusing on the four items discussed above. Due to the focus on ultra-deepwater systems, the complexity and challenges of shallow water hydrodynamic design are not always well understood, and software tools and global analysis methodologies are being developed for these ultra-deepwater systems without much verification or application to shallow water systems.

The second objective of the paper is to review two typical shallow water FPSO systems and the associated riser systems and relate their response to the discussion above. The examples are based on actual mooring system designs and help illustrate the challenges and solutions available for mooring FPSOs in shallow water. These examples are also important as they apply to future shallow water concepts, e.g. LNG offloading terminals.

Typical Shallow Water FPSO Mooring Systems

Shallow water FPSO systems have been developed using a number of vessel-mooring configurations depending on site specific and project requirements. Typical configurations include mooring to a CALM buoy using hawsers or hard yokes, spread-moored, internal or external turret catenary mooring systems, or mechanical mooring systems like tower yoke moorings. In addition a few other catenary or mechanical mooring systems have been developed for specific applications. Reference [1] provides a good database of the various systems in use worldwide. A key component of the FPSO system is the riser system that must be considered along with the selection of the mooring system to ensure compatibility.

In reviewing the various mooring systems currently in use in shallow water it is clear that they can be represented by two type of mooring systems (a) soft yoke mooring to fixed tower, and (b) single point mooring with catenary anchor legs. For the purpose of this paper the catenary anchor leg SPM discussed will be the external turret system.

Tower Yoke Mooring System: The tower yoke mooring system is a commonly used mechanically coupled system in shallow water depths from approximately 20 meters to 50 meters [2]. The mooring system has been used with both converted and newbuild FPSOs/FSOs in many locations worldwide.

The tower-yoke mooring system consists of a tower fixed at the seabed and a mooring yoke assembly connecting a vessel with the tower. The mooring yoke assembly attaches the FPSO vessel to the turntable on the tower and allows the yoke and vessel to weathervane around the tower while allowing transfer of products to the FPSO and electric power to the tower. The yoke contains a yoke head with a two-axis joint that allows the vessel to roll and pitch relative to the tower and heavy liquid ballast to provide restoring forces to moor the vessel. The vessel is attached to the yoke with two pendant linkages, which have one double-axis joint on upper end (upper U-joint) and one triple-axis joint on lower end (lower U-Joint). The pendants hang over the vessel bow (or stern) and are attached to the vessel mooring support structure. Typically, the heavy ballast tank hangs above the water in a location that minimizes green water loading and prevents contact with the vessel.

Figure 1: Tower Yoke Mooring System

The principle of the tower-yoke mooring system is that with the excursions of the vessel, the heavy weight is lifted up and thus potential energy is available to restore the vessel to its original position. The tower-yoke mooring system requires a minimum modification to the bow/stern of the vessel.

The biggest advantage of the tower-yoke mooring system is that riser design is dramatically simplified and jumper hoses and umbilicals in a simple free-hanging catenary configuration in air can be utilized to transfer products between the vessel and the tower. This eliminates the challenge in designing flexible riser systems for shallow water and thus increases the window for FPSO system feasibility in shallow water.

External Turret Mooring System. External turret mooring systems have evolved from mooring to CALM buoys with a hawser or hard yoke, to an FPSO concept with a chain table and fluid swivel being directly connected to the vessel hull. This mooring system has now evolved to one that can support a large number of risers (greater than 20) and the associated equipment for an FPSO. This is currently one of the more popular turret mooring systems with a wide range of applicability from shallow water (~30 meters) to deep water (2000+ meters).

The external turret mooring system can be used with either converted or new build vessels and has an advantage that fabrication and integration of FPSO and turret is fairly simple and schedule friendly compared to an internal turret system. Typically the turret is located on a turret support structure cantilevered from the bow of the vessel in a location that minimizes green water loading of the turret, and contact of the anchor legs with the vessel. To help optimize the motions at the turret, the FPSO vessel hull is usually modified to have a bow shape that has the same profile as the anchor leg, allowing the turret to be located as close as possible to the hull. The mooring system typically consists of all chain or chain and wire catenary anchor legs. Typically the mooring arrangement has 6 to 9 anchor legs.

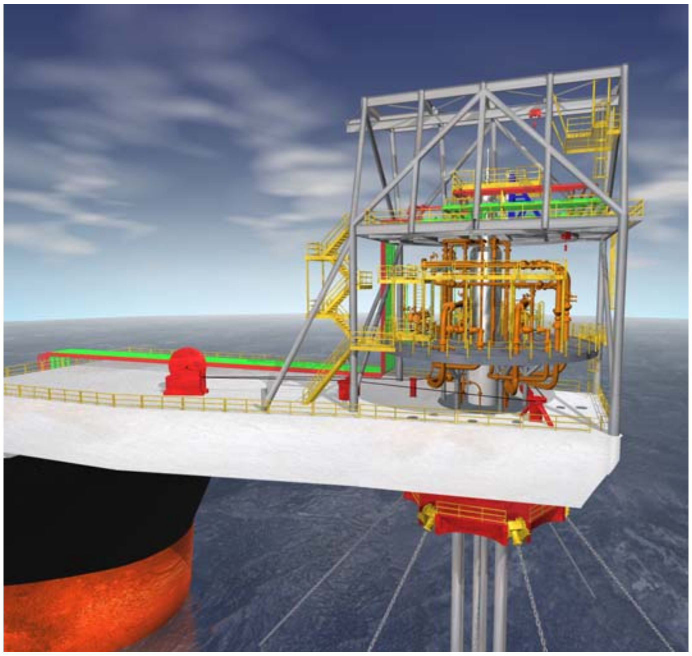

Figure 2: External Turret Mooring System

Flexible risers are used to interface flowlines on the seabed to the FPSO. These flexible risers can be of unbonded steel pipe or bonded rubber hose (commonly used for CALM buoys). Several riser configurations can be used with a common element that the configuration be very flexible and allows for a wide range of vessel offsets and turret motions compared to the water depth. A key component of the global analysis of an FPSO with an external turret system is the compatibility of the turret mooring with the riser design and the various interfaces between the vessel, mooring, risers, seafloor, etc. This design process will be detailed in Example 1.

Riser Systems for Shallow Water. As mentioned earlier, the compatibility of the turret mooring system with the riser system is important since in shallow water the selection of the mooring system has a significant effect on the design of the riser system.

In shallow water (less than 100 meters) two types of risers are available. First there is the unbonded steel flexible pipe, consisting of steel layers wound around an inner carcass, covered with a plastic sheathing. Currently unbonded steel flexible pipe designs are available for diameters ranging from 1” to 20” with design pressures up to 15,000 psi. Second, there is the bonded rubber hose, also known as a “marine hose”. Marine hoses are available in diameters from 2” to 24” for working pressures up to 300 psi. Marine hoses offer an alternative to flexible pipe when design pressures are low and there are no stringent pigging requirements.

One of the main characteristics of riser systems in shallow water is the large degree of compliancy required to accommodate the relatively (as a percentage of the vertical end point separation) large turret offsets. The maximum damaged offset of a shallow water mooring system can easily be in the order of 40% of the vertical end point separation. Over the years a large variety of riser configurations have been developed that offer a large degree of compliancy each with their own particular characteristics.

Compliancy is typically achieved by creating alternating sections of free hanging catenary and inverted catenary shape. The inverted catenary shape can achieved by buoyancy applied on the riser, either in discrete modules or integrated in the riser, or by buoyancy applied trough an external buoyancy tank, which can be either tethered to the seafloor or free to move with the riser(s).

It is the high level of compliancy, required to accommodate the large vessel offsets, that also creates design challenges in shallow water. A riser system that is very compliant to accommodate large vessel offsets will also be sensitive to hydrodynamic loading from waves and current.

There are several factors unique to shallow water that create challenges to the riser design:

- Wave kinematics from large design storms affect riser from turret to PLEM
- Marine growth over the complete depth
- Close proximity between risers, moorings and tethers
- Potential for riser contact with seafloor and vessel keel

In shallow water the wave kinematics will be felt over the whole length of the riser. This in contrast with deep water, where only the top part of the riser is exposed to the large wave kinematics and where the compliant section of the riser can be located close to the seafloor where the wave kinematics are negligible. In addition, risers attached to an external turret will go through the splash zone where wave kinematics in the wave crest can impart large loads on the risers. This added to the fact that the relatively short length of the riser results in lower effective tension in the riser can lead to large curvatures in the riser section just below the turret close to the water surface. A possible solution to this problem is to place ballast modules on the riser so as to increase the effective tension in the riser and to reduce the resulting curvature. Another solution is to add steel wires to the pipe that results in a larger mass and in turn a larger effective tension.

Marine growth can be another issue when dealing with riser design in shallow water. Because of the shallow water any marine growth that is present will likely extend over the entire water column. The marine growth leads to an increase in hydrodynamic loads on the riser from the increased mass and drag area as well as from a change in drag and inertia coefficients.

The problem arises when adjacent risers have different diameters. Even though the risers have the same configuration and may respond in a similar way to excitations at the top (vessel motions), the response of the risers in shallow water can be very different due to the different hydrodynamic loads that result from the difference in diameter.

A parameter often used in riser design is the ratio between the riser diameter and the weight in water. This parameter is a measure of the sensitivity of the riser to drag loading. When adjacent risers have a similar diameter to wet weight ratio, they will behave more in phase and the likelihood of riser clashing is reduced. It is possible to design riser structures such that adjacent risers, even if they have different diameters have a similar diameter to wet weight ratio.

When both risers are modeled with marine growth of the same thickness (as is typically done) both risers will be affected by the marine growth differently. The riser with the smaller diameter will see the largest increase in hydrodynamic loads relative to the situation without marine growth. This is because the smaller riser will see a larger relative increase in diameter, so its behavior will be affected more by the marine growth than the behavior of the riser with the larger diameter.

For shallow water riser systems there is a risk of seabed touch down of the free hanging catenary on the one side and the risk of hull contact of the inverted catenary section on the other. Though occasional contact is allowed, the design process seeks to avoid such contact if possible. A simple but effective way of achieving clearance at all times from the vessel hull is achieved with the use of a buoyancy tank to provide the inverted catenary. In case of a wave configuration, it is likely that the tank will have to be tethered to the seabed, but in a steep configuration the tank can be un tethered and free to move with the riser(s).

Environmental Loads on Shallow Water FPSO Systems

FPSOs have been designed and installed in shallow waters for the past 20 to 30 years, and currently about 50 % of FPSOs are in 100 meters of waterdepth or less. The challenges associated with shallow water hydrodynamics are well known and have been studied for many years [3, 4, 5].

Wave and current interaction with large floating structures in shallow water varies greatly as a function of water depth with a decrease in water depth typically resulting in an increase in loading. The seafloor topography and proximity to the coast also has a large impact on wave and current directionality, water level variations due to tides and storm surge, etc. These site specific conditions are very important and must be addressed in metocean design criteria developed for the site/system to ensure accurate loading and a thus a robust design are developed.

For very shallow water installations (say in 20 meters of water depth) care must also be taken to ensure the installation location has fully accounted for all aspects of the offloading operation from vessel size, approach and maneuvering, and parcel size. Many times the installation location will need to be changed to accommodate the requirements of offloading (usually a seabed clearance issue that can be further complicated by the wave and current loading on the offloading tanker and its response).

Seafloor topography plays a major role in determining the joint distribution of wave and current intensity and directionality that is very important in estimating the response of the single point mooring in shallow water. Most large hindcast studies use a coarse grid that can provide estimates of intensity and direction in deep water but may not have the resolution to provide the desired accuracy in shallow water. It is important to ensure that hindcast study results are transformed to be applicable in shallow water region of choice. This can have a large impact on FPSO system feasibility, response, and operability.

Tides in shallow water can have large amplitudes depending on location. The large tidal elevation changes result in large tidal velocities that contribute to the current environment for the design of the system. The estimation of the tides is accurate in both location and time and tide tables are available for most coastal regions in the world. From a global analysis perspective this is important as changes in mean water level can have a large impact on the mooring system stiffness, and thus the response of the system. It is quite common for the metocean specialist/analyst to combine the effect of the tidal current with the extreme environmental conditions and develop a set of current criteria for design. However, peak currents due to tides are of short duration, and occur at clearly defined periods, and may not occur during the season of the most extreme storm conditions. Note that typically peak wind driven currents also lag peak wind and wave conditions. Thus from an analysis perspective there is value to keeping the various components separate and combining them as necessary.

Current Loads. Current loading on ships in shallow water has been studied extensively over the years due to its impact on vessels navigating in shallow water. A key reference for current loads on VLCC hulls is Reference [6] that provides coefficients that have been derived from towing tests on a VLCC and presented in a non-dimensional form as a function of water depth to draft ratio. Tests in a wind tunnel (for deep water) or towing tests are commonly used to extract coefficients for these vessels; in addition numerical methods like Computational Fluid Dynamics (CFD) can be used fairly efficiently to obtain similar results [7]. One advantage with CFD is that various hull forms can be studied, as the OCIMF coefficients may be more applicable to VLCCs rather than for example, newbuild barge hulls.

Figures 3 and 4 present current coefficients (surge and sway) derived from the OCIMF coefficients for a 140,000 DWT FPSO at full draft in water depths of 25, 50, 100 and 500 meters. It is observed that the current loads increase with a decrease in water depth for the shallow water depths and that there is very little difference between the 100m and 500m water depths. The large change in current loads in shallow water can have a large effect on the relative vessel heading to the waves (when the waves are at an angle to the current) and thus the system damping, response and motions.

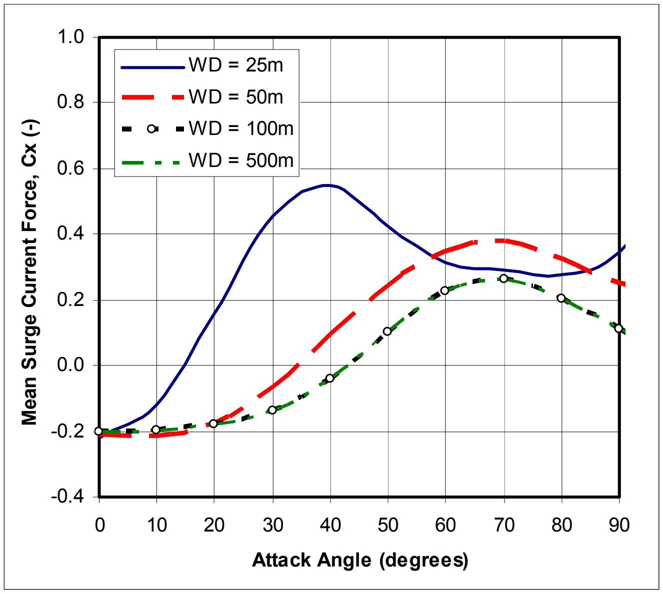

Figure 3: Current Surge Force Coefficients

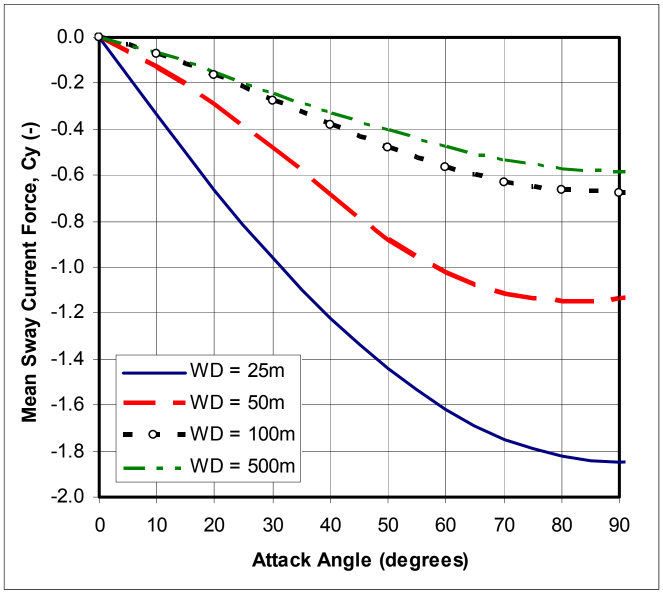

Figure 4: Current Sway Force Coefficients

Wave Loads. The seafloor topography and the shallow water depth have a pronounced effect on the wave propagation and the characteristics of the waves. The seafloor topography and coastline also affect the wave direction, refracting the waves so that they arrive almost perpendicular to the coast. The wave kinematics are modified as the waves transition to shallow water with wave characteristics like length, crest height, and slope also being affected. Reference [8] provides information regarding the propagation of waves in shallow water and the interaction with the coastline. The enhanced crests in shallow water also require close attention for FPSO systems as they can result in slamming loads on the hull and turret, and green water over the vessel deck.

The wave structure interaction problem in shallow water is also very sensitive to the water depth in terms of both wave frequency loading (motions) and loading due to non-linear wave effects (mean and variable drift forces). These effects can be studied using diffraction models of the vessel in the appropriate water depth.

Figure 5 presents an estimate of the drift force coefficients for a 140,000 DWT fully loaded tanker in water depths from 25m to 500m. Similar to the current loading the mean drift force increases with a decrease in water depth. Figure 6 presents a comparison of the mean drift force and the variable drift force density for the same vessel and water depths considered earlier and subjected to waves with Hs=5m and Tp=12 seconds. The data is presented as a percentage of the value at 500 meters of water depth (deep water). From the figure it is seen that at 25 meters water depth the mean drift force is almost 50% greater than the force at 500 meters, and the variable drift force density is greater than 150% than the reference value. The estimation of these forces is extremely important for shallow water FPSO systems as the damping in the system is very low and coupled with the non-linear mooring stiffness small variations in loading or damping can result in large variations in component loads. For a weathervaning FPSO the accurate estimation of the mean wave (and current) forces accounting for the interaction between vessel, seafloor and environment is even more important as it can influence the heading of the vessel with respect to the environment and thus the system performance and operability. Note that the interaction of current and waves, though not discussed in this paper, is extremely important and can also have a large influence on the forcing on the vessel.

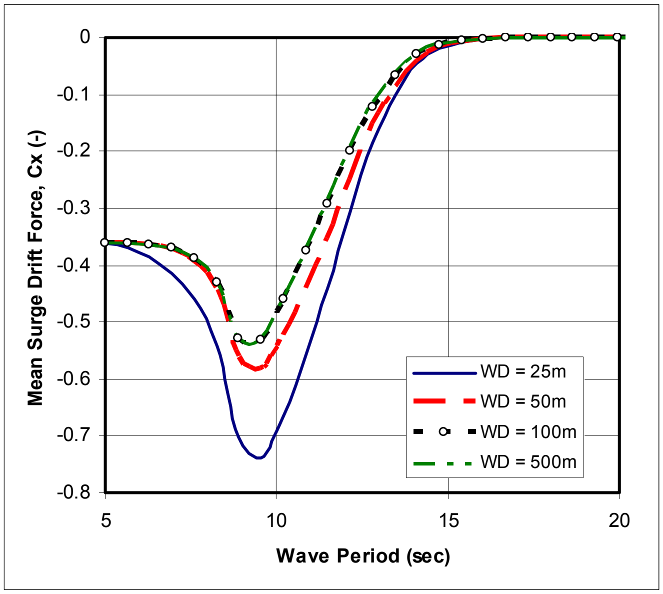

Figure 5: Wave Drift Force Coefficients

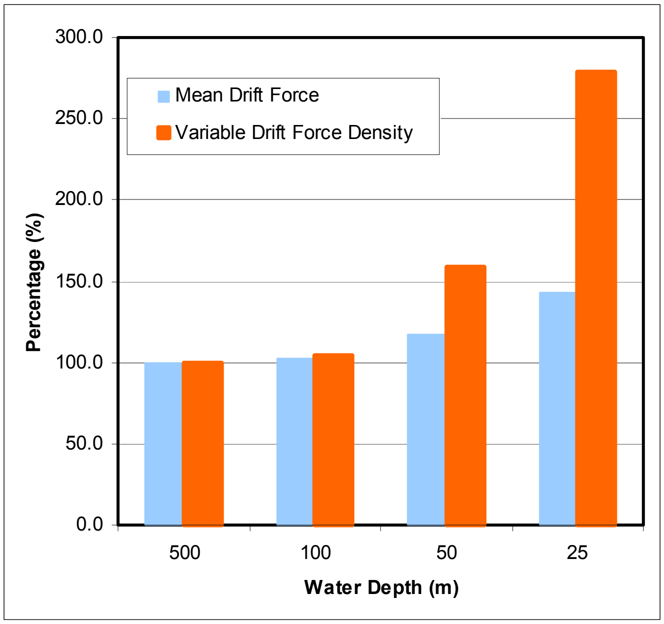

Figure 6: Wave drift forces as a function of water depth

Example 1 External Turret Mooring

The example selected is based in 50 meters of water in South East Asia. The region is subject to typhoons and the monsoon. The tidal elevation and storm surge results in a variation of water depth of approximately +/- 3 meters. The FPSO hull is a 140,000 DWT converted tanker. The FPSO is moored with an external cantilevered turret and the mooring system has anchor legs (all chain) in a 3X3 arrangement. The extreme storm conditions (100-year typhoon) are summarized below:

- Waves: Hs = 8.2 m, Tp = 14.0 sec.
- Current: 1.5 m/sec.
- Wind: 30 m/sec. (1-hour mean at 10 meters).
- Current can occur up to 45 degrees to the waves and wind can occur up to 30 degrees to the waves.

The design environmental conditions are quite severe for this water depth and the design of the mooring system and riser systems is quite challenging. The first step in the design of such a system is the optimum location of the turret. This requires a detailed motion analysis of the vessel that also includes a study of relative wave elevation at the possible turret locations to determine the elevation of the turret above the keel to minimize green water loading. In addition the turret has to be located forward of the forward perpendicular (FP) to minimize or eliminate anchor leg contact with the vessel bow. The mooring system has to be stiff enough to provide reasonable offsets for riser design, and at the same time maintain a catenary profile that minimizes interference with the bow of the vessel. This design process requires a few iterations of modifying the vessel bow to provide clearance, raising the turret to prevent green water, and moving the turret forward of the FP to prevent chain contact. The pitch motions of the vessel require raising the turret as the centerline is moved further away, thus increasing the size of the turret support structure and the vertical motions of the riser attachment point! This also requires input from the riser designer to ensure compatibility with the mooring. This interface is an important component of the global analysis to ensure appropriate vessel boundary conditions for design environments are used for the riser analysis.

As discussed earlier catenary mooring systems in shallow water are non-linear and at extreme bounds of their performance envelope small changes in offset can result in large tensions in the anchor leg. The change in anchor leg tension and the restoring force to the vessel is a function of the geometric stiffness of the anchor leg (from its weight and the catenary profile) and the axial stiffness of the mooring components. Thus knowing the dynamics of the vessel and the anchor leg system the anchor leg can be designed with a concentration of weight at the touchdown point that allows the anchor leg to provide geometric stiffness even at large offsets. If this section of weighted anchor leg is properly designed it can result a less non-linear mooring system with reductions in vessel offsets and anchor leg tensions.

For this example the mooring system was designed with a heavy section of chain at the touchdown point with a weight of approximately 1 MT/m. The restoring force characteristics of this mooring system are presented in Figure 7.

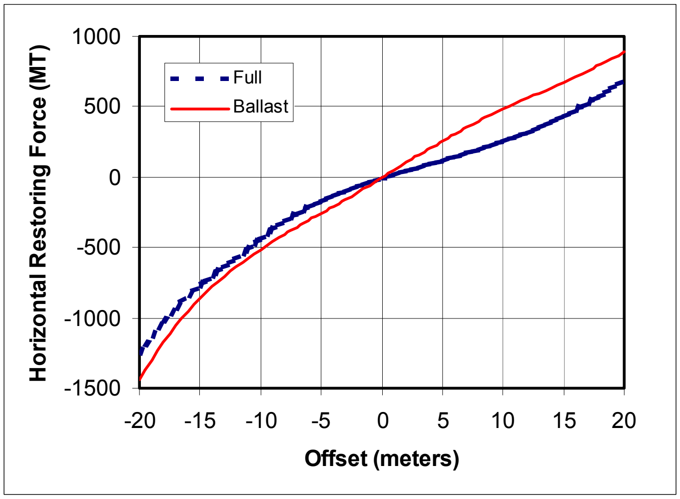

Figure 7: Force-Deflection Curve for Catenary Mooring System

The figure presents the horizontal restoring force of the mooring system with offsets both inline (0 to –20 meters) and in-between (0 to 20 meters) the anchor leg groups. It is seen that the mooring system is fairly linear when pulling against two mooring groups (0 to 20 meters) and more non-linear when pulling against one group (0 to –20 meters). The restoring force characteristics are very similar for the vessel at full and ballast load conditions and the full range of water depth variations.

One issue that was discussed in the previous section is the importance of defining the joint distribution of wind, wave and current intensity and direction for weathervaning systems. Crossed conditions typically tend to govern the design of the shallow water systems but very often insufficient data is provided to actually determine realistic conditions and thus the analyst has to resort to using "experience" or design recipes from mooring design guidelines or classification society codes and standards.

Figure 8 presents a study performed with the example FPSO system where the current is rotated 90 degrees (no change in intensity) from the wave direction for one particular design load case. The tension, turret loads, and vessel offset is seen to increase as the current is rotated to about 45 degrees and then decreases slightly as the angle increases to 90 degrees. In reviewing the loads and offsets it is seen that the magnitude increases quite dramatically from 0 to 45 degrees (about 25%). A conservative estimate would be to use 45 degrees for this example (as suggested by ABS) but this could result in large load increases and offsets that may impact the feasibility of both the mooring and riser systems (both technically and commercially). Also keep in mind that as the current is rotated the relative wave-vessel heading increases and can result in large wave frequency motions that can affect riser and topsides design.

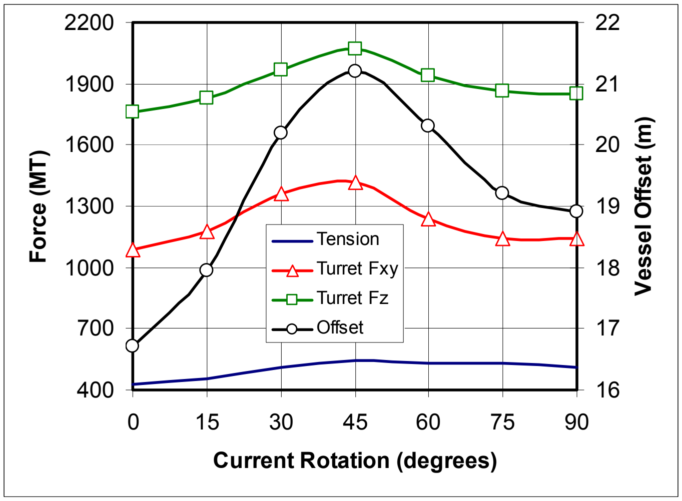

Figure 8: Effect of Current Rotation on Mooring System Performance

As discussed earlier shallow water systems are lightly damped and estimation of system damping (especially in surge) can be very important in obtaining accurate estimates of the FPSO response. The surge damping for one extreme load cases was estimated to be 8.8% of critical with approximately 5% from the FPSO vessel interaction with the environment and the remainder from the mooring and riser systems. This damping was varied +/- 3% of critical for the same load case and the results presented in Figure 9. For the entire range of damping varied +/- 3% the response varied from –10% to + 25% as shown in the figure.

Another important issue in studying FPSO response in shallow water is the sensitivity of the system to variations in significant wave height and peak period. Traditional metocean reports either provide a unique Hs-Tp pair for each return interval or prescribe one significant wave height and a range of peak periods. As demonstrated by [9] a 100-year contour line of significant wave height and period can be derived from the joint probability distribution of significant wave height and period at the site. This contour line can be used to develop a set of Hs-Tp pairs with the required return period over a wide range of peak periods [4]. The application of this method ensures that a wide range of peak periods with the associated significant wave height is used to analyze the system. Figure 10 illustrates the response of this example using (a) a fixed significant wave height and varying the peak period (+/-1.5 seconds) versus (b) using the 100-year Hs-Tp contour line to study the response for the same range of peak periods. In this particular example the peak 100-year contour results in a reduced response compared to the traditional method as the significant wave height of 8.2 meters is at the peak of the contour line. This illustrates the design optimization that can be made if such data is made available as part of the design basis.

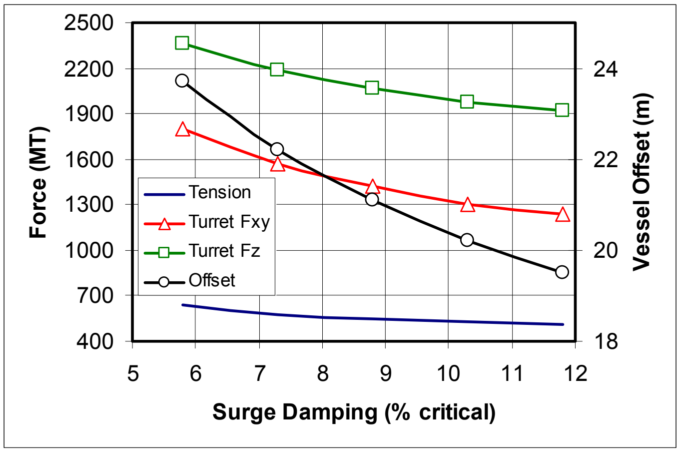

Figure 9: Influence of Surge Damping on FPSO Response

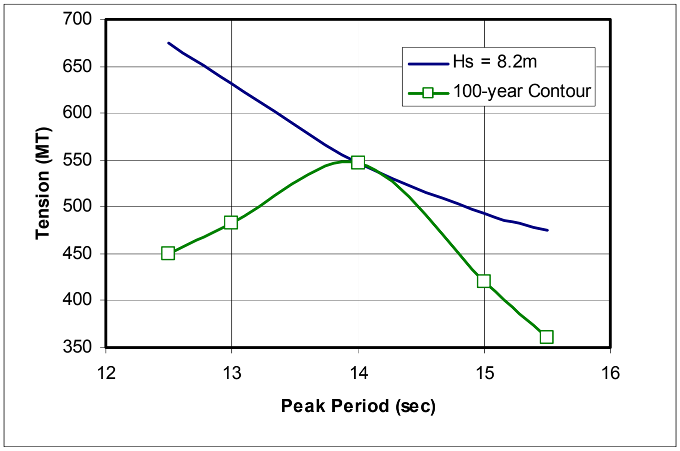

Figure 10: Influence of Peak Period variation on FPSO Response

As one last illustration of the complexity of the dynamics of a shallow water system the analysis was repeated with a time domain model of the system. Nine 3-hour realizations of the environment were run for the same load case (only random seeds were modified) and the results for maximum tension and offset are presented in Table 1. The table indicates a wide variation in the extreme value of both tension and offset that is to be expected because of the random nature of the excitation and the distribution of the extreme value. This is an important demonstration of the variability of response as many model test programs and analysis efforts use just one 3-hour realization for each load case, and thus the maximum value estimated has a large variation associated with it that is not always considered. This underscores the importance of running multiple realizations when using time domain analysis (or model tests) to predict the most probable extreme values of the response.

Table 1: Extreme Response estimates from Time Domain Analysis

Simulation	**Maximum Tension** (MT)	**Maximum Offset** (m)
1	560	19.5
2	450	17.2
3	434	18.1
4	576	18.6
5	512	17.4
6	506	17.1
7	580	18.1
8	490	17.0
9	579	20.8
Mean	**521**	**18.2**
Std. Dev.	**56**	**1.3**

Riser System Design. In an earlier section of this paper, it was demonstrated how shallow water can pose unique challenges to the design of the riser system of an FPSO. In this section two riser systems will be discussed to illustrate possible solutions to those challenges. Both riser systems were designed for an external turret mooring system in approximately 50 meters of water.

The first riser system consists of two, 8-inch marine hoses in a Steep-S configuration. An elevation view of the system is shown in Figures 11 and a plan view is shown in Figure 12. The use of an un-tethered buoyancy tank gives the system a little bit more compliance compared to a tethered buoyancy tank. In this specific case the buoyancy tank was very effective in preventing contact between the risers and the vessel keel and the seafloor. Due to a fairly large current, it was necessary to connect two tethers to the sag bend of the catenary. The tethers consisted of a catenary section of chain that prevents excursions of the sag bend towards the PLEM in the near case (Figure 13), but allows excursions of the sag bend away from the PLEM in the far offset cases (Figure 14). In all, the risers are interconnected in three places to prevent clashing.

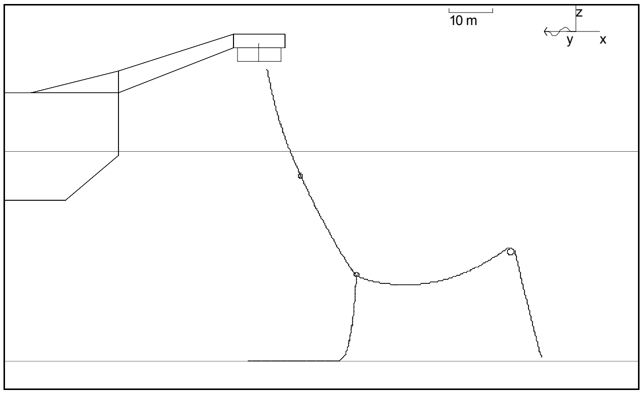

Figure 11: Flexible Riser Configuration 1 (elevation)

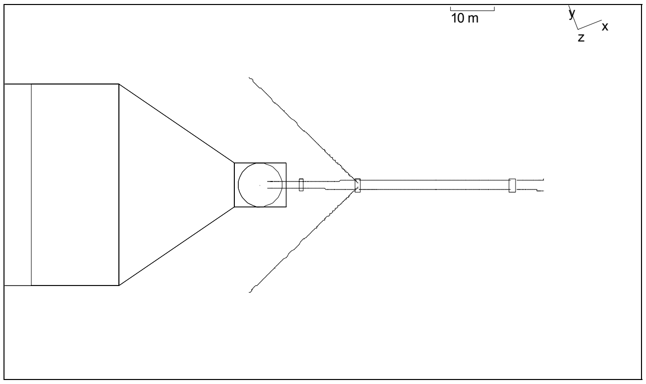

Figure 12: Flexible Riser Configuration 1 (plan)

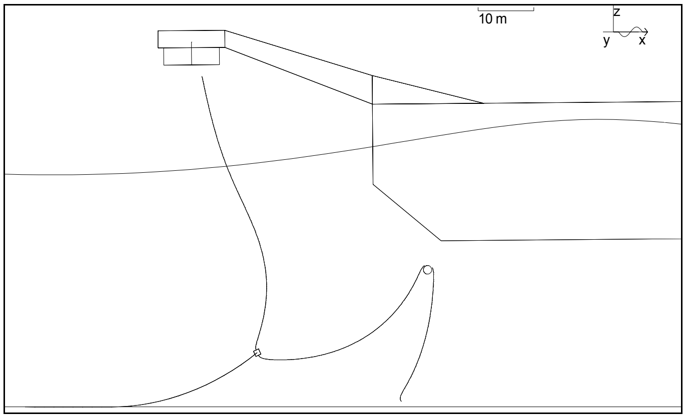

Figure 13: Response of Riser Configuration 1 for Near Offset

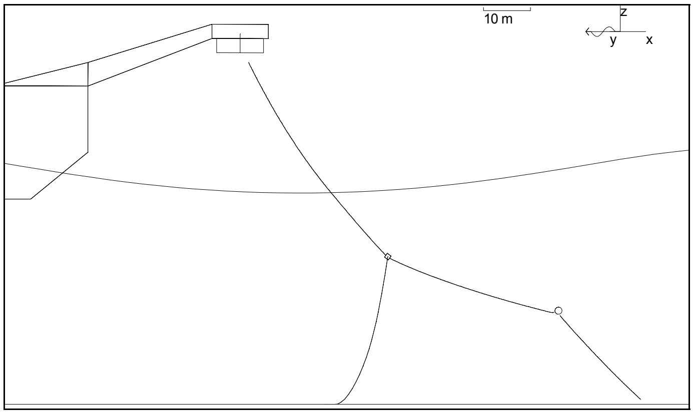

Figure 14: Response of Riser Configuration 1 for Far Offset

The second riser system consists of 6 risers, all unbonded steel pipe. Because of the field layout, all six risers departed the FPSO in the same general direction that led to small clearances between individual risers. As the offsets of the FPSO were very large (approximately 40% of water depth), a Steep Wave configuration was chosen. In order to prevent interference with the vessel hull, the distributed buoyancy on the risers was chosen such that the resulting buoyancy arch was long and shallow. The configuration is illustrated in Figure 15. A drawback of this approach is that the sensitivity of the riser configuration to changes in fluid density is even more pronounced. The risers were also fitted with ballast modules located in the catenary section not far below the turret to prevent over bending of the risers in the splash zone. Figure 16 illustrates the behavior of one of the risers before the addition of the ballast modules.

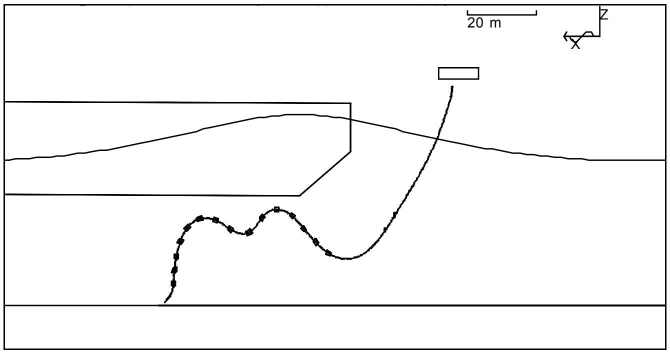

Figure 15: Response of Riser Configuration 2 (with ballast)

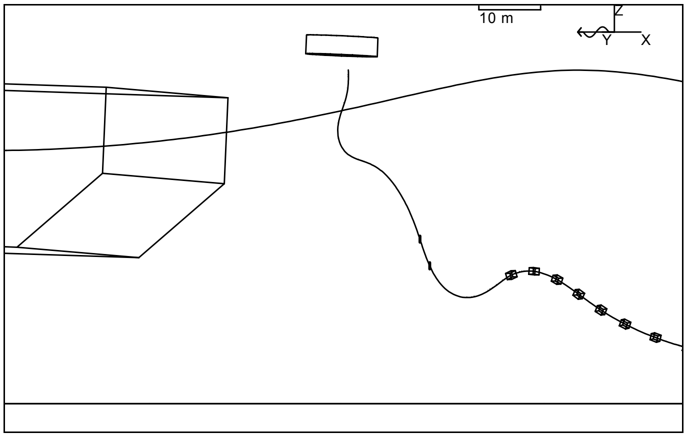

Figure 16: Response of Riser Configuration 2 (without ballast)

Example 2: Tower Yoke Mooring System

The example selected is for an FPSO located in East Asia, in an average water depth of 25 meters. The vessel to be moored is a converted 160,000 DWT vessel with the tower yoke connected to the bow. The weight of the ballast tank is approximately 1,000 MT. The tidal variation and storm surge in this area is approximately 4.5 meters, and the maximum storm conditions are summarized below:

- Waves: Hs = 5m, Tp = 10.1 sec.
- Current: 1.4 m/sec.
- Wind: 24.3 m/sec. (1-hour mean at 10 meters)
- Current can occur up to 45 degrees to the waves.

From Figures 2 and 17 it can be observed that the vessel is moored by the weighted yoke suspended between the mooring support structure on the vessel and the top of the tower. Thus the yoke mooring system performance is affected by the relative change in elevation between the two connection points on the vessel and the tower and not the water depth. This relative elevation change is the result of the combination of the tidal elevation, storm surge in extreme conditions, and draft and trim variation of the vessel as a function of loading.

As the relative height increases the yoke mooring system becomes stiffer and more non-linear, with larger loads developing in the components. As the relative elevation is driven by the elevation change at the yoke attachment point on the vessel it can be optimized by developing a loading plan that maintains this elevation change at a minimum as a function of product stored.

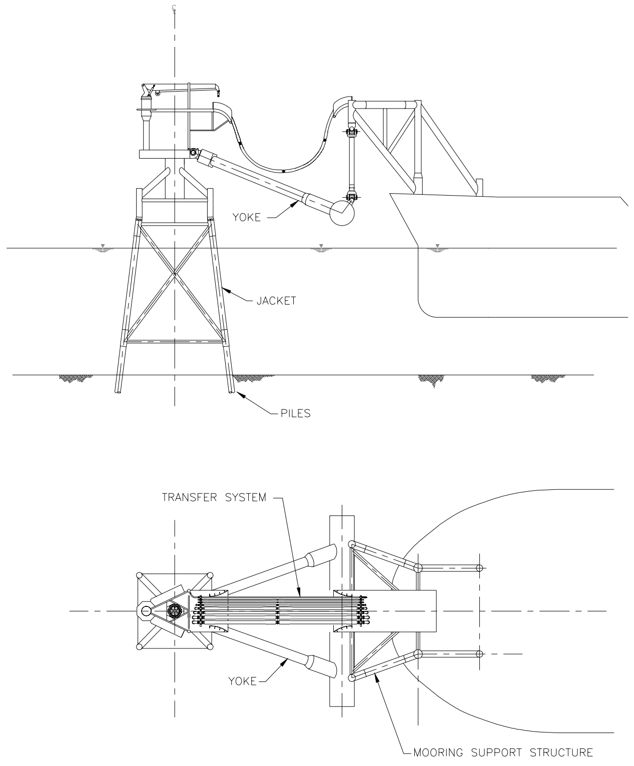

Figure 17: Turret Yoke Mooring in 25 meters of water

Figures 18 and 19 illustrate the restoring characteristics of the tower yoke mooring system for the range of relative elevation expected for this example. Figure 18 represents the restoring characteristics for the minimum water depth and the full load condition, while Figure 19 represents the same for the ballast load condition and the maximum tidal elevation and storm surge. For this example the maximum relative elevation is 11.6 meters with about 4.5 meters due to the tide and storm surge and the remainder due to the draft change at the yoke connection point.

It is seen that the restoring characteristics of the yoke mooring system change dramatically between the cases in Figure 18 and 19, with the system becoming much stiffer and non-linear for the ballast load case. This stiffer system limits the offsets of the vessel at the expense of a significance increase in loads on the tower and U-joints. The maximum vessel offsets tend to occur for the full load condition with its much softer mooring characteristics and larger wave and current forces on the vessel.

The system was analyzed for a number of design cases that included variation in vessel load condition, collinear and crossed environments, and offloading to tankers of opportunity. The maximum offset was estimated to be 14.5 meters and the maximum resultant force on the tower was 1,000 MT. These results also correlate well with model test data.

As discussed in an earlier section of the paper, the total damping of the system is a very important parameter in estimating the response of non-linear shallow water systems. This is important for the tower yoke mooring system as the system is typically very lightly damped, as there is very little contribution from the mooring system (on the order of 1% of critical damping). For this example the total surge damping varies from 3 to 5% of critical depending on the vessel draft and environmental conditions, while the total sway damping varies from 8 to 15% of critical. This is typically half that of a typical external turret mooring. As it tends to occur in water depths where the environmental loading is a maximum, it is very important to ensure that the best possible estimates of loading and damping are obtained and that the design is robust enough to allow for variations from the estimates made.

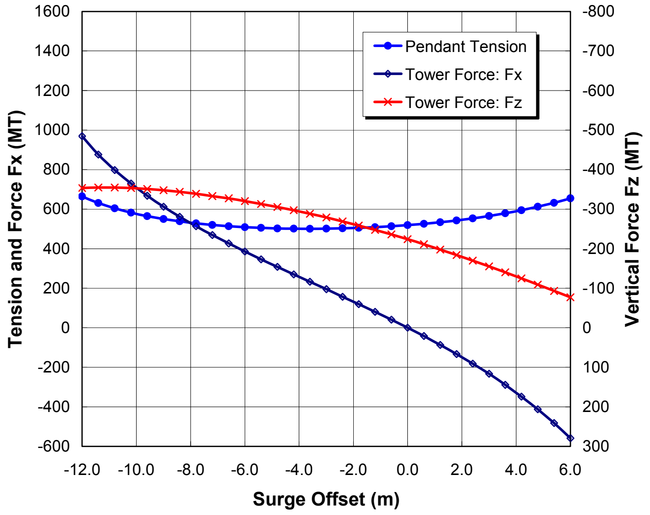

Figure 18: Surge Force-Deflection Curve for Fully Loaded Vessel

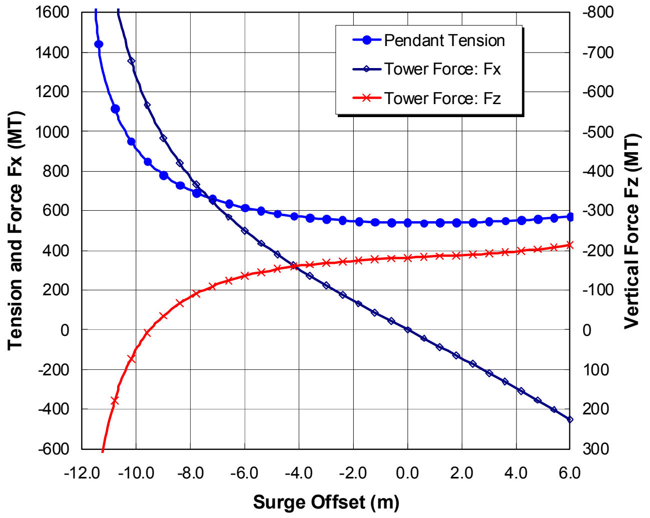

Figure 19: Surge Force-Deflection Curve for Ballast Loaded Vessel

Figure 20 illustrates the sensitivity of the mooring system offsets and loads to small changes in total surge damping. When the damping is varied from 5 to 2.8 of critical damping the total tower resultant force changes by 34%, the vessel offset changes by 27%, and the tension in the pendant increases by 10%.

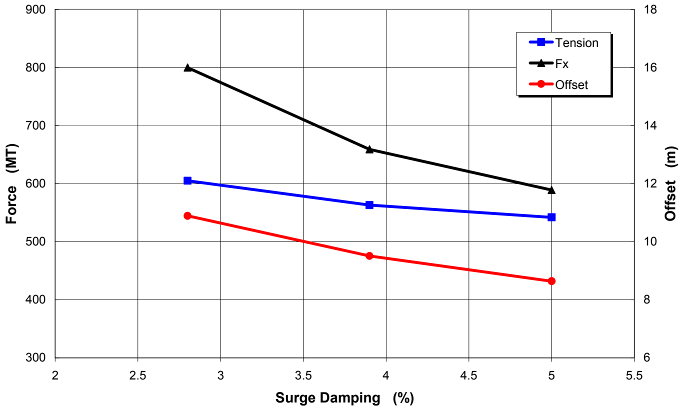

Figure 20: Influence of total damping on mooring response

Riser System Design. As noted earlier an advantage of the tower yoke system is the simple riser-flowline interface. Flowlines and umbilicals to the FPSO are routed to the base of the tower where they can be connected to the various swivels using standard hardpipe conductors. The fluid paths from the swivel to the vessel are made using jumper hoses of unbonded pipe or marine hoses. Electrical and other utilities are transferred using flexible umbilicals. As can be seen in the photograph in Figure 2 and 17 the jumper hoses and umbilicals between the top of the tower and the mooring support structure on the vessel are arranged as simple free-hanging catenaries. The wind loads and vessel / yoke motions are the two major sources of excitation on the jumper hoses. The main design requirements are that there is no contact between the jumper hoses and the yoke and structural components, and that maximum tension and minimum bend radius criteria for the components are not exceeded. Contact between risers is generally permitted after careful evaluation to show that integrity of the risers is not affected.

Summary and Conclusions

The paper attempts to provide the reader with an overview of the complex interaction between environment, seafloor, vessel, mooring and riser systems for shallow water FPSOs. It is not meant to be a complete review of the literature or address all the issues but to provide a framework for analysts not familiar with shallow water hydrodynamics to obtain a rudimentary understanding of the sensitivity of the system to various parameters. The paper has used two commonly used and very different single point mooring systems to illustrate several of these points.

The importance of properly defining the metocean criteria for shallow water single point mooring systems cannot be overemphasized. It is important to ensure that the metocean criteria are derived for the shallow water site and the joint distribution of wave, wind and current properly defined in a form suitable for weathervaning systems. This requires the interface of global analysts with the metocean specialists to ensure that the criteria appropriate for the location and the mooring system being considered.

The paper also draws on existing databases and models to illustrate the influence of the seabed on the wave and current loading on the vessel. It is seen that the loads increase rapidly as the water depth decreases. Combining this with the non-linear stiffness characteristics of the mooring system and the low level of damping associated with the low frequency motions of the FPSO, lead to a dynamic system that is sensitive to variations in loading and/or damping.

The two examples provide a description of typical mooring system restoring curves that demonstrate their non-linear behavior, especially at the extreme excursions of the system. Small variations in offset at these extremes can lead to large variations in tensions and loads. Care should be taken in understanding the characteristics of the mooring system and “tuning” them to be as linear as possible. The examples also show the sensitivity of the system to the level of surge damping with small variations in the order of 1 to 3% of critical resulting in large increases in loads and offsets (up to 25% to 35% depending on the system being studied). The examples emphasize the importance of understanding the sensitivity of the systems being designed in shallow water and the importance of accounting for this in the design.

References

1. Single Point Moorings of the World, 6th Edition, Oilfield Publications Ltd.
2. Jeannin, O. et. al., (1988), “Disconnectable Mooring System for the First Floating Production, Storage, and Offloading Unit in Bohai Bay, People's Republic of China,” *Offshore Technology Conference*, OTC 5750.
3. LeMehaute, B. (1976), An Introduction to hydrodynamics and Water Waves, Springer Verlag.
4. Position Mooring (2001), Det Norske Veritas, Offshore Standard DNV-OS-E301.
5. Principles of Naval Architecture (1988), The Society of Naval Architects and Marine Engineers, 2nd Revision.
6. Oil Companies International Marine Forum (OCIMF) (1994), Prediction of Wind and Current Loads on VLCCs, 2nd Edition, Witherby and Co., London.
7. Shore Protection Manual (1984), Department of the Army, Waterways Experiment Station, Corps of Engineers, Coastal Engineering Research Center, 4th edition.
8. Ortloff, C. R., and Krafft, M. J. (1997), “Numerical Test Tank: Simulation of Ocean Engineering Problems by Computational Fluid Dynamics,” *Offshore Technology Conference*, OTC 8239.
9. Winterstein, S. Ude, T. C., Cornell, C. A., Bjerager, P., Haver, S. (1994), “Environmental Parameters for Extreme Response: Inverse FORM with Omission Sensitivity,” *Structural and Reliability*, pp 551-557, Balkema, Rotterdam.