Spread Moored or Turret Moored FPSO's for Deepwater Field Developments

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ABSTRACT

From a mooring designer's perspective, a key component of the design of a deepwater spread moored FPSO is the integrated design of the mooring system with the vessel hull and topsides, riser and flowline systems, and the field layout. However, recent experience has shown that the mooring system for several deepwater fields have been designed without taking into account all the relevant interfaces, leading to expensive mid-project changes, increased component costs, and impact on schedule and installation.

The objective of the paper is to provide a clear description of the various interfaces and issues that need to be considered when designing and laying out a mooring system to ensure an optimized mooring design for the FPSO. The paper addresses technical issues related to the design of the mooring system, the pull-in system and chain fairleads, and the installation of the mooring system and the FPSO.

The paper is based on the authors experience in designing and installing the mooring systems for two Deepwater FPSOs off West Africa, and two FPSOs off Brazil. The paper will illustrate the design aspects for the mooring system including anchor leg layout and design, design of the pull-in system, issues with installation, identifying the various interfaces between vessel, riser systems, and installation.


MODEC VENTURE II

INTRODUCTION

Deepwater oil fields are becoming more and more common and the use of a Floating (Production) Storage and Offloading systems (FPSOs) provide a mature technology for the production, storage and export of hydrocarbon products from these areas. FPSOs have been installed in a variety of configurations over the past thirty years. In general there are two options for mooring systems, either spread moored or turret moored.

A spread moored FPSO involves a vessel moored by anchor legs from the bow and stern of the vessel in a four-group arrangement. The risers that transport the products to and from the vessel are suspended from “riser porches” on the side of the vessel. This type of mooring system maintains the vessel in a fixed orientation of the F(P)SO in global coordinates.

A turret moored FPSO is designed as a Single Point Mooring (SPM) that allows the FPSO to weathervane about the mooring system, in response to the environment. This weathervaning ability allows the vessel to adapt its orientation with respect to the prevailing environmental direction to reduce the relative vessel-environment angles and the resulting load on the mooring. This also allows for a more optimum offloading orientation than that with a spread moored system. The riser systems are also supported within the turret structure.

This paper compares the two FPSO systems by providing a description of the unique characteristics of the two mooring systems. This paper will not address the actual cost estimate or comparison between the two types of systems. A realistic comparison can only be performed for an actual field development where the basis design parameters are better known. There are many factors which influence the selection of a mooring system. These factors include details of the vessel, the environment, the subsea field architecture, the topsides equipment layout and the oil offloading requirements.

The paper is divided into three sections:

- General comparison between turret and spead moored system
- Design and characteristics of atypical mooring system for Brazil
- Design and charactersistics of a typical spread mooring system for West Aftrica

In conclusion the authors wish to show that in making the decision on which type of mooring system is best suited for a particular application all relevant factors should be considered. Often the decision can be swayed by incorrect application of one or more factors. In general it is possible to design either type of system for most applications, bearing in mind the preferences of the owners/operators.

COMPARISON BETWEEN TURRET AND SPREAD MOORED SYSTEMS

Turret Moored Systems

Two types of turret systems are commonly used for F(P)SOs – the internal turret system where the turret is mounted within the F(P)SO hull, and an external turret system where the turret is mounted on an extended structure cantilevered off the vessel bow.

An FPSO turret system is a compact multi-functional structure that includes many stand-alone sub-systems found on other moored floating systems. The turret integrates the F(P)SO mooring system, the installation equipment for the anchor legs and the risers, the fluid-transfer system including riser support, manifold, pig launching and receiving, metering, chemical injection, and subsea control systems into one compact, self-contained module.

Figure 3 provides an illustration of the internal turret mooring system developed for the Barracuda early production system (P-34) in the Campos basin, offshore Brazil. This turret system was designed for 34 risers in water depth of 835 meters and installed in a converted 50,000 DWT tanker. The figure provides a good illustration of the various sub-systems and their typical arrangement within the internal turret mooring system. Since then FTI has completed an additional 10 turret moored F(P)SO projects.

The mooring system of the internal turret includes the anchor legs, the turret shaft and the bearing system. The turret provides the load-transfer mechanism between the mooring and the vessel and also provides the mechanism for the weathervaning capability of the turret mooring system. The fluid-transfer system includes the support for the risers, the manifold, the injection, and the swivel stack systems that allow transfer of the fluids from the earth-fixed turret and risers to the weathervaning ship-fixed production system. In addition, the turret may include the installation system comprised of winches and sheaves.

The 360-degree weathervaning feature of a turret moored F(P)SO significantly reduces the impact of greenwater on the vessel deck and production equipment and wave-frequency vessel motions, affecting both crew comfort and production plant uptime. As the F(P)SO maintains a heading into the predominant environment, greenwater is generally limited to the area forward of the turret and away from process and other key main deck systems. Also, vessel motions, particularly rolling motions, are typically reduced thus allowing more operating uptime during inclement weather conditions. This weathervaning ability is very important for the offloading operation as the headings of the F(P)SO and the export tanker are both into the predominant sea or winds, thus creating safer approaches and alignments during offloading operations. As the risers are contained within the turret structure, offloading operations are simplified as the F(P)SO hull is uncluttered with risers or exposed mooring lines.

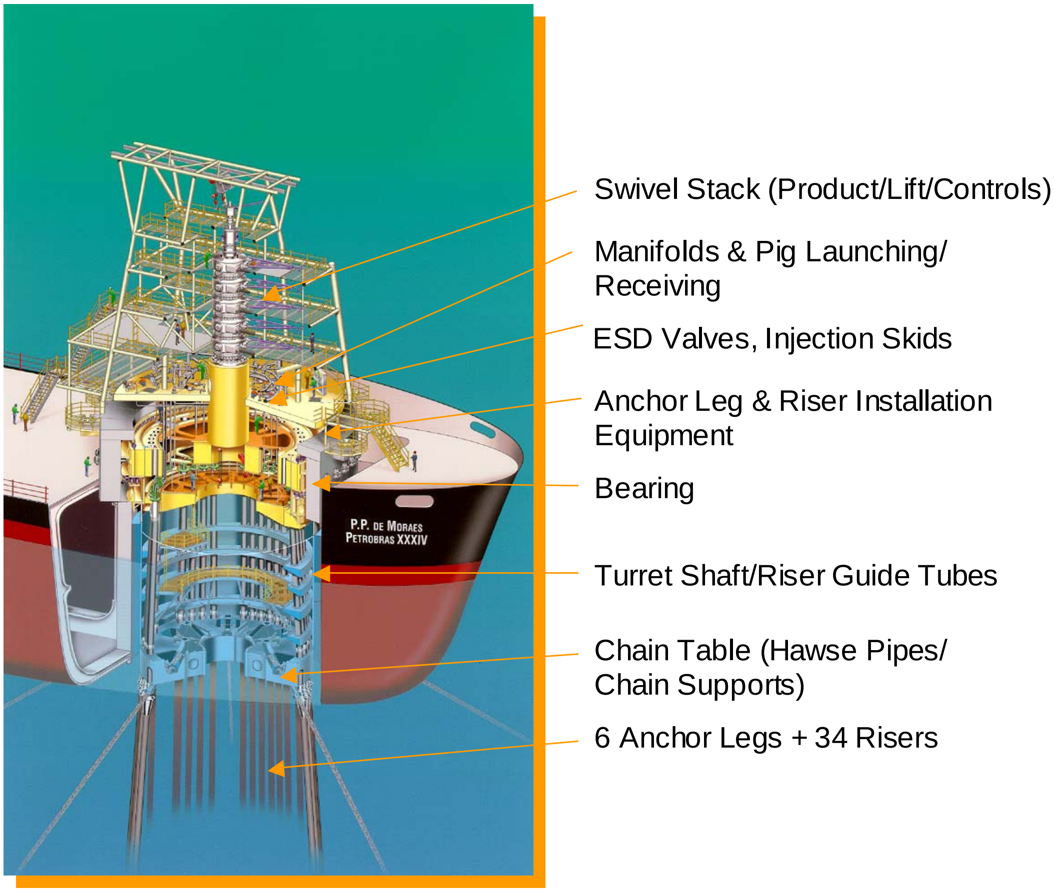

Figure 3: The P-34 Internal Turret Mooring System.

For a turret system, anchor legs may be arranged symmetrically or grouped in multiple sets of three or more legs such that openings between sets allow for varied and more direct riser approaches to their connections on the base of the turret. This "direct approach" may allow for more economical seabed flowline arrangements by eliminating loop routings around anchor leg arrays. In addition, turret mooring systems typically have fewer anchor legs of smaller component size than a mooring system for an equivalent spread moored F(P)SO.

Until recently, internal turrets were assumed to be limited to 40 or so risers before the cost and turret congestion became unmanageable. Now, new and cost-effective turret designs can accommodate up to 100 or more risers in water depths ranging up to 2000 meters or more. Various designs for lower-cost external turret systems permit up to 40 or more risers for deepwater activities.

Spread Mooring Systems

Spread mooring or Multi-Point Mooring (MPM) systems have long been the traditional means of mooring all kinds of ships and barges in open and protected waters. For this type of mooring, multiple anchor lines extend from the bow and stern of the hull and anchor the unit to the seafloor in a fixed or slightly variable heading. Spread mooring systems can be designed for shallow or deepwater stationkeeping, in mild to moderate environments. The performance of the spread moored system is dependent on the prevailing weather and it is considered suitable for regions with a fairly restricted range of weather direction. They are not so effective, however, in harsh or multi-directional environments where changing wind, waves and currents may impose severe loads on the anchoring system and create excessive motions on the unit. It is also important to consider the feasibility of offloading as a function of the day-to-day environment taking into account the approach and offloading operations with the export tanker.

Figure 2 provides an illustration of a typical, large-field, spread moored F(P)SO system. The figure also indicates the various sub-systems identified within the turret mooring system and their typical location on the spread moored F(P)SO. Note how the various sub-systems are distributed about the deck of the F(P)SO. Also note the increasing complexity of the on-deck arrangement of the various F(P)SO systems that require additional interfaces between the various providers of design and equipment. All of these sub-systems must be accounted for in the CAPEX of a spread moored system when compared to that for a turret mooring system.

For deepwater spread moored F(P)SO units, the number of anchor legs required may range between 12 and 20 lines, compared to 6 to 12 anchor legs for a turret moored system.

Riser attachments for spread moored F(P)SO units are commonly located on “porches” installed along the length of the F(P)SO hull. The ability of a spread moored F(P)SO to accommodate a large number of risers (100 or more) provides the operator with additional flexibility with regards for installation, expansion and a more direct connection to individual wells by minimizing subsea manifolding.

For many large spread moored F(P)SOs, the mooring system installation requires separate winches for the forward and aft anchor legs with a system of sheaves to allow access to each fairlead. This adds to the congestion on the deck and becomes a major interface requirement for the topsides arrangement for the ship and production systems of the vessel. The riser system typically requires its own winch and sheave arrangement.

Anchor leg and riser arrangements for the spread moored F(P)SO often impact both the subsea arrangement of the flowlines and the selection of the offloading system. In order to limit the possibility of an anchor leg breaking and falling onto a subsea flowline, the flowlines are generally routed around the seabed anchor arrays so the risers approach the F(P)SO perpendicular to the riser porches. For safer operations, dual offloading systems on the vessel bow and stern to accommodate export tankers during changing environmental directions may be used, or even satellite export systems may be installed that move the offloading activities away from the F(P)SO system. Specialized dynamically positioned export tankers also may be also used for offloading from a spread moored F(P)SO.

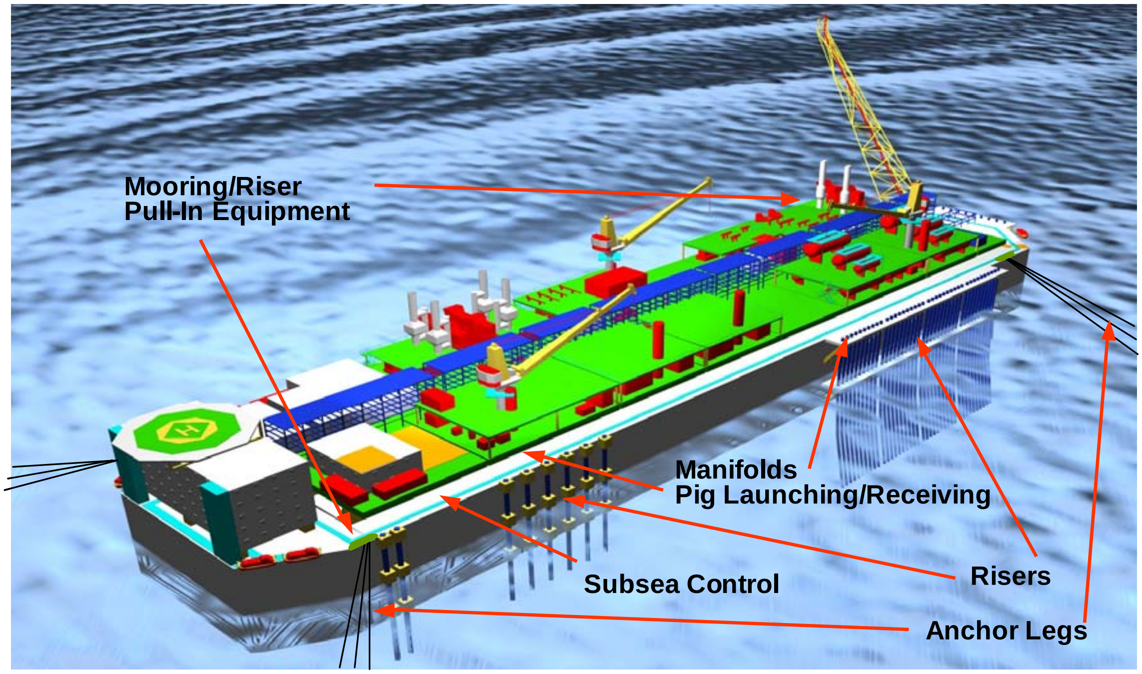

Figure 2: Typical Large-Field New-build F(P)SO System.

For the West African market FTI & MODEC combined have designed and installed 3 spread mooring systems and 2 External Turrets.

Likewise, in the Brazilian arena FTI and MODEC have combined for 2 Internal Turret Moored systems, 2 External Turret Moored Systems and 1 Spread Moored system.

The decision on which type of system to use for each of these projects was partly driven by company preference and partly by technical requirements.

For projects with 100 risers or more, the likely solution will be a spread mooring, whereas for up to 30 risers the turret moored solution will most likely dominate. When making a decision of the type of system it is important to consider both CAPEX and OPEX of the complete system and not just the FPSO itself. The FPSO CAPEX, The offloading system CAEX, Offlaoding system availability and operational constraints must be addressed also.

Possible Offloading Scenarios

An important difference between a turret moored and spread moored F(P)SO system is the reliability and ease of use of the offloading operation. The choice of F(P)SO mooring systems can impact the reliability and equipment used for offloading liquid product from the unit. The offloading technique may be one or more of the following methods and is a function of whether the export tanker is a vessel of opportunity or from a dedicated tanker fleet.

Tandem Offloading: The export tanker approaches forward or aft of the F(P)SO, depending on sea and environmental conditions. It is then "tethered" by a hawser line downstream from the F(P)SO unit. Floating hoses from the F(P)SO are connected to the export tanker's manifold, and the product is transferred between the two units. Typically one to two assist tugs are used to keep tension on the hawser to maintain the tanker relative alignment with the F(P)SO and to prevent the tanker migration towards the F(P)SO during benign or changing sea conditions. This is the most common and preferred offloading arrangement for all F(P)SOs. It is a well-established offloading method in use at marine terminals and F(P)SOs for several decades and utilizes standard OCIMF equipment. In some regions of the world, dynamically positioned shuttle tankers are used that do not require assist tugs to maintain position during offloading. However, they are typically dedicated to a region or group of fields, and this "dedicated" feature reduces the favorable economics associated with the use of "tankers of opportunity" for offloading F(P)SO units. The overall field CAPEX and OPEX also increases substantially because of the investment, operating and maintenance costs associated with the dedicated tanker fleet.

Satellite Offloading: A deepwater CALM buoy or other terminal structure is positioned some distance away from the F(P)SO unit (approximately one nautical mile). Flowlines are connected between the two facilities to allow the transfer of product to the export tanker moored to the terminal. While this distances the offloading operations from the F(P)SO, and provides excellent uptime over the life of the field, it also adds significant cost to the overall project for the installed buoy and flowlines, and the additional power and pumping requirements on board the F(P)SO.

Side-by-Side Offloading: The export tanker is moored abreast of the F(P)SO and hoses or Chiksan loading arms are connected between both vessels to transfer the product. For spread moored F(P)SO units, this offloading method can be complicated as the export tanker must carefully navigate between the bow and stern anchor patterns to avoid collision with the hull or legs or risers (if nearby). This method of offloading is not very common for deepwater field developments because of the inherent risks.

For spread moored F(P)SO systems, side-by-side and tandem offloading creates a high degree of exposure to collision as the F(P)SO remains fixed in position as the export tanker maneuvers about it. For a turret moor F(P)SO system, side-by-side and tandem operations are simplified as the unit's beams are uncluttered with risers or exposed mooring lines, however, the offloading system of choice is the tandem offloading for both tankers of opportunity or DP shuttle tankers. Also, the headings of the F(P)SO and the export tanker are both into the predominant sea or winds, thus creating safer approaches. For safer operations, expensive satellite export systems may be rationalized for spread moored F(P)SO units yet remain a debatable option for turret moored F(P)SO offloading.

Pros and Cons of the Two Mooring Systems

The description of the two mooring systems has highlighted many of the differences between a turret moored and spread moored system in terms of design and performance. Table 1 provides a comparative summary between the two systems that illustrates the differences discussed above.

As discussed earlier, turret moored systems orient themselves to the prevailing environment direction that allows its use in harsh, multi-directional environments with minimized loads and vessel motions. A not so obvious advantage of a weathervaning turret mooring system is that as it adjusts itself to the prevailing environment it is not as sensitive to poor design environmental criteria which is common in areas where new development takes place. A spread moored system is moored in a fixed orientation and thus is more sensitive to global environment intensity and direction. The turret system provides a compact load and fluid-transfer system with a minimum number of anchor legs required. The weathervaning ability helps provide more constant offloading conditions for export tankers, helicopter operations, and discharges from flares. However, the passive weathervaning ability of the turret mooring system requires the location of the turret at the vessel bow that is the location of the maximum vessel motions and thus requires a riser system that is robust enough to withstand the motions at the turret. A turret mooring system is not readily adapted to the addition/modification of riser systems (needs to be designed in to the system), and its design and fabrication requires specialized engineering and manufacturing techniques and knowledge.

Table 1: Comparative Summary of Turret Moored and Spread Moored F(P)SO Systems.

	Turret-Moored	Spread-Moored
Vessel Orientation	360 degree weathervaning	Fixed orientation, can impact flare
Environment	Mild to extreme, directional to spread	Mild to moderate, uni- to fairly directional
Field Layout	Fairly adaptable, partial to distributed flowline arrangements	Prefers flowline arrangement to approach beam-on
Riser Number & Arrangement	Requires commitment, moderate expansion capability	Can be designed for flexibility, additional tie-ins
Riser Systems	Location of turret (bow) requires robust riser design	Adapts to various riser systems, combinations of various types
Stationkeeping Performance	Number of anchor legs, offsets minimized	Larger number of anchor legs, offsets variable
Vessel Motions	Weathervaning capability reduces motions	Dependent on relative vessel/ environment directionality
Vessel Arrangement	Turret provides "compact" load and fluid transfer system	Components spread on deck, requires extensive interfaces
Offloading Performance	FPSO typically aligned with mean environment	Dependent on vessel/ environment orientation

An important aspect to consider with spread moored vessels is the offloading performance of the system over the life of the field. As the vessel orientation is fixed, a tandem moored export tanker has a limited range of relative heading with respect to the F(P)SO when tandem offloading from the vessel, especially in inclement weather, not directly aligned with the F(P)SO orientation. In order to maintain the shuttle within this allowable zone additional tug assistance may be required as compared to a similar turret moored system, or a second offloading station may be required at the other end of the F(P)SO to improve the offloading uptime. The environment mis-alignment with the F(P)SO orientation can also lead to difficulties in approaching and leaving the F(P)SO before and after the offloading of product.

In extreme cases where the use of a spread moored system and multi-directional environmental conditions does not provide the desired uptime for tandem offloading, a satellite offloading station may be installed approximately one nautical mile from the F(P)SO. In deepwater, flowlines are suspended between the F(P)SO and the remote offloading station (typically a large CALM buoy).

Considering the basis of design for the development, the various sub-systems and components can be addressed and a comparison between the two mooring types, including engineering, management, and fabrication/assembly costs can be made.

The capital costs (CAPEX) of the two systems

- Moorings: This includes all systems of the mooring to vessel load-transfer system including anchor leg components, fairleads and chainstoppers, the turret structure, mooring installation equipment, etc.

- Fluid-Transfer: This includes all equipment required for fluid-transfer from the risers to the topsides production stream. This includes the riser porches, manifolding, pig launching and receiving, swivel stack, riser specific installation equipment, etc.
- Hull Modifications: This group includes mooring system specific modifications for the hull, e.g., the turret moonpool, underwater fairlead supports, bending shoes, bilge keels, etc.
- Topsides Systems: This includes equipment specific to topside system cost due to mooring system selection, e.g. metering, chemical injection skids, electrical and hydraulic systems that may be located in a turret system, modifications to topsides to accommodate the selection of either system, etc.
- Offloading System: This includes the specific offloading system components required for each mooring system type. This includes offloading system related equipment on board the vessel and remote offloading systems and associated flowlines if required.
- Installation: This includes all installation costs to installing and hook-up the FPSO to its moorings and remote offloading system if required.
- Services and Administration: This includes all engineering, management, procurement and mark-up costs associated with the spread moored or turret moored specific items described above.

The operational costs (OPEX) of the two systems

- Demurrage: Tanker demurrage time and charges.
- Maintenance and Inspection: This includes all maintenance and inspection requirements for the mooring system specific components including the requirements for a remote offloading system if utilized.
- Offloading Tugs and Pilots: This includes the costs for offloading assistance from support vessels, and pilots required for navigation around the FPSO. The offloading costs are developed to provide a relative offloading OPEX cost as this has been used to ensure comparable offloading performance from both F(P)SOs.
- Offloading Hoses and Hawsers: Replacement costs associated with replacing hoses and hawsers with each system, based on standard industry practice.

Production loss due to excessive vessel motions is computed as a relative cost difference between the spread moored and turret moored systems rather than the actual values for each system obtained from the analysis. This minimizes the high sensitivity of the overall cost estimate to production loss, compared to the CAPEX and OPEX costs associated with the two systems.

The Present Value (PV) of the two systems serves as a method of comparing the total cost of the mooring systems on the same time reference, accounting for inflation and the present value of future expenses. The PV for each case study is based on a 10.5% discount rate computed from the first oil milestone.

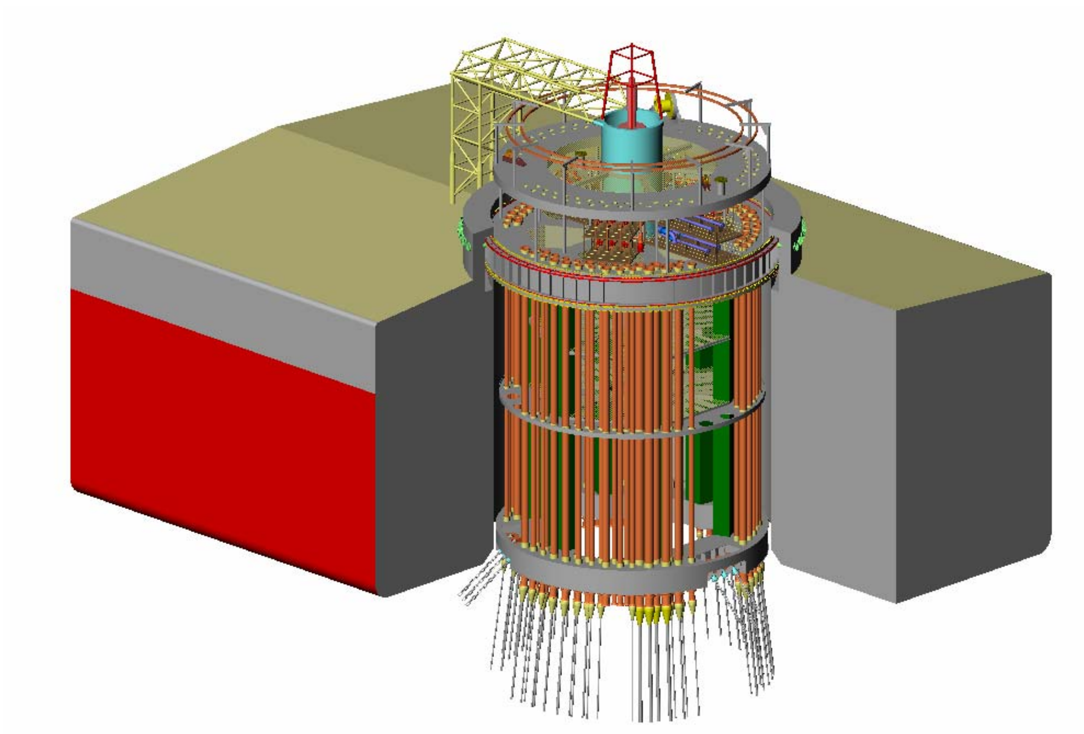

Figure 9: Illustration of a large capacity internal turret for offshore Brazil.

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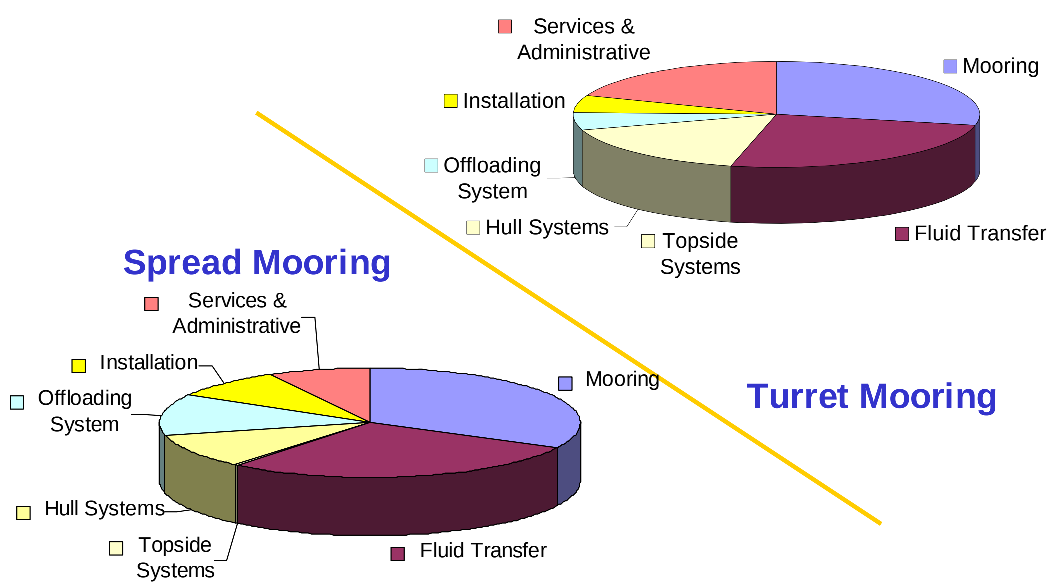

Comparison between a spread moored and a turret moored FPSO in Brazil.

Flowlines

A long standing misconception is the capacity of turret mooring systems to support large number of risers. FMC Technologies has developed large internal turret systems that are capable of supporting over a 100 risers. Because of the reduced number of anchor legs and anchor leg groups required for a turret mooring system, a turret mooring system will have more seabed area available between the mooring lines on the seabed [1]. Recently FMC Technologies proposed an external turret solution accommodating 33 risers for use on the Frade field in 1,000 meters of water in the Campos basin. Figure 1 illustrates the arrangement if risers on an external turret. Both turret moorings and spread moorings are expandable, but require planning for additional risers during the initial construction. In the case of a turret mooring, slots for additional future risers need to be arranged in the turret. In the case of a spread mooring, provisions for additional risers will have to be made in the riser porch structures, at deck level and at or near keel level.

General Layout of mooring system and flowlines

During the initial phase of the project, thought must be given to the way that flowlines are routed on the seabed. Typically, mooring arrangements are determined in a FEED study phase using results from preliminary mooring analysis to determine mooring system characteristics such as the number of mooring lines, the mooring line plan angles and anchor radius. More detailed mooring analysis, in particular the verification of the minimum fatigue life at a later stage may indicate that a much larger chain size is needed to satisfy fatigue life design criteria. The results of a detailed study that investigated the effect of mooring system footprint on the fatigue resistance of the mooring system indicate that these changes could have been prevented if a fatigue analysis had been performed as part of the FEED study [2].

The layout of the mooring lines and flowlines on the seabed can also have a significant effect on the feasibility of the selected riser system. During the detailed riser analysis for a recently installed spread mooring project in Brazil it was found that for the risers to work in a catenary configuration, the vessel offsets needed to be kept below 8% [3]. This offset limitation is below the maximum offset criteria of 10% that is typically given to the mooring designer. Because the mooring design typically precedes the detailed riser analysis by 12 months or more, this can create a situation whereby it becomes desirable to make changes to the mooring design late in the project while the mooring line components are being manufactured.

Vessel Motions

Extreme roll motions are greater for a spread moored FPSO since maximum beam sea condition is a 7 meter significant sea. Since the wind wave and current systems in the Campos basin are not strongly correlated, large angles between vessel and waves can also occur for turret moored FPSOs albeit for reduced wave heights. However, in recent years, Petrobras has increased the design significant wave height to be used for beam sea conditions for turret moored FPSO’s from 3.5 to 5.7 meters. The result of this is that maximum roll angles for spread moored and turret moored FPSOs are getting closer. In the Campos Basin, both spread moored and turret moored FPSO are fitted with extra wide bilge keels (1-1.5meters) to keep extreme roll motions to below 10 degrees. Figure 2 shows a model of an FPSO in Campos Basin beam sea conditions. Because of the significant beam sea conditions (up to a significant wave height of 7 meters with a relatively short spectral peak period) vertical accelerations along the side of a spread moor can be higher than those at the turret location for an internal or even external turret.

A comparison between two recent model test campaigns carried out by FMC Technologies showed that maximum vertical accelerations near the riser hang-off locations on a spread moored FPSO were actually higher (3.2 m/s2) than those measured on for an FPSO with an external turret mooring (2.1 m/s2). In addition, the large beam sea condition can lead to wave slamming issues on the riser balcony along the side of the vessel in the full draft condition. Figure 3 shows wave slamming around the riser porch area observed during FPSO model tests.

Offloading availability

Currently there are far more turret moored FPSOs in the Campos Basin than Spread Moored, but of the last nine FPSO projects in the Campos Basin, five use a spread mooring. From this recent experience with spread moorings it is becoming clear that in the Campos Basin, offloading availability for a spread moored FPSO is lower than for a turret moored FPSO even when one takes into account that the spread moored FPSOs have offloading stations on both the bow and the stern. The difference in operability of the export system between spread mooring and turret mooring is even greater in West Africa where most large FPSOs are installed with a separate single point mooring for the purpose of exporting crude.

Mooring system Design.

One of the main differences between the Campos Basin in Brazil and West Africa is the environment. In West Africa, the largest waves are limited to a narrow 45-degree sector centered around South-Southwest, while in Brazil, severe wave conditions approach the platforms from a 90-degree sector between Southwest and Southeast. The result for a spread mooring system is that in Brazil large wave conditions are encountered at large angles to the bow of the vessel, which result in larger mooring loads. Using a turret mooring system will reduce the relative wave angles for the larger sea states and result in smaller mooring components. From recent project experience it was found that in the Campos Basin, for a given water depth, the mooring system for a turret mooring used only half as many mooring lines (9) as a spread mooring (18), and that at the same time the breaking strength of the mooring lines used on the turret mooring (750 metric tons) was half of those needed for the spread mooring (1500 metric tons).

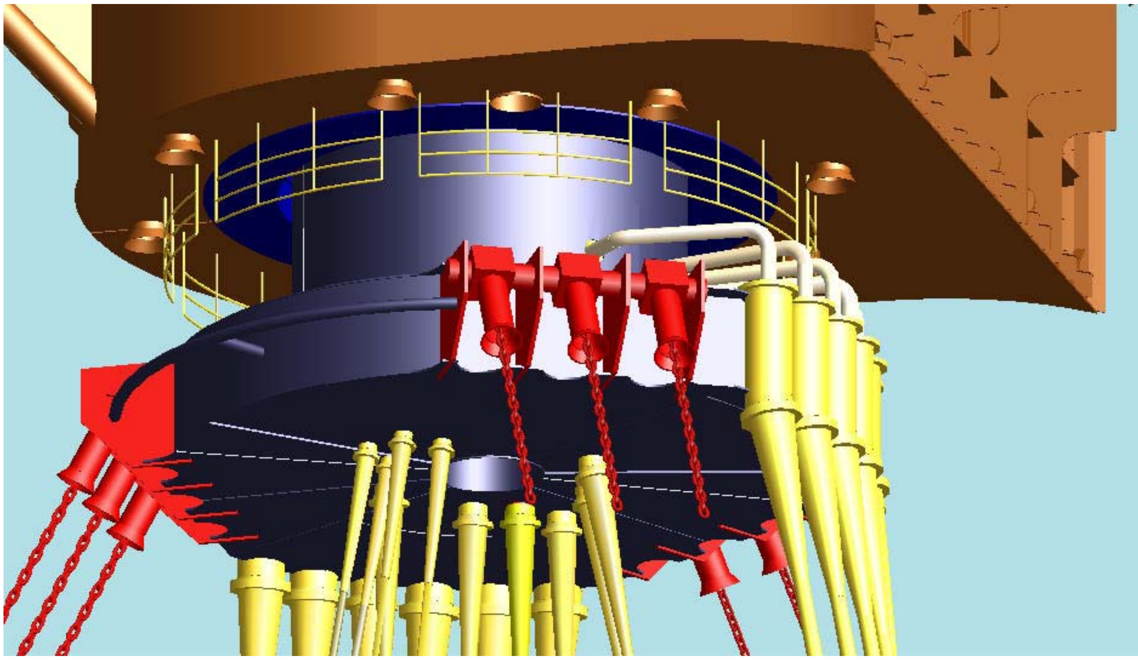

Figure 1 Example of riser arrangement on an external turret.

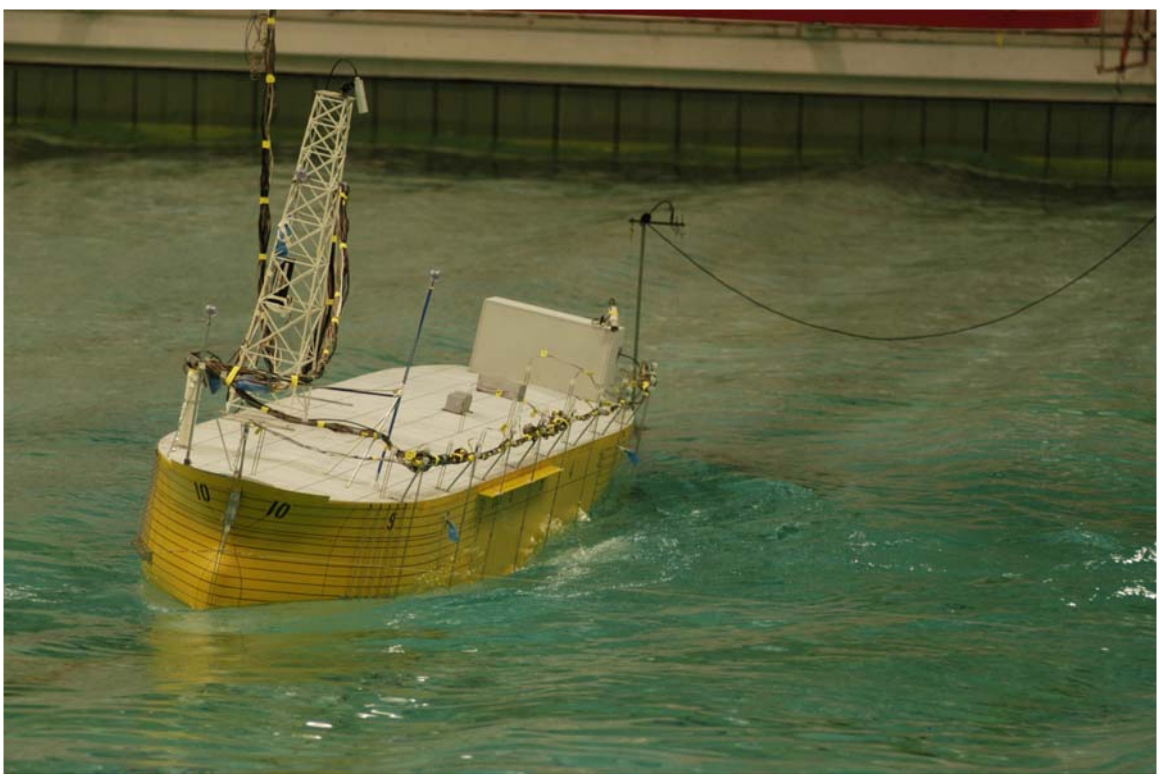

Figure 2. FPSO model test of Campos Basin beam sea conditions

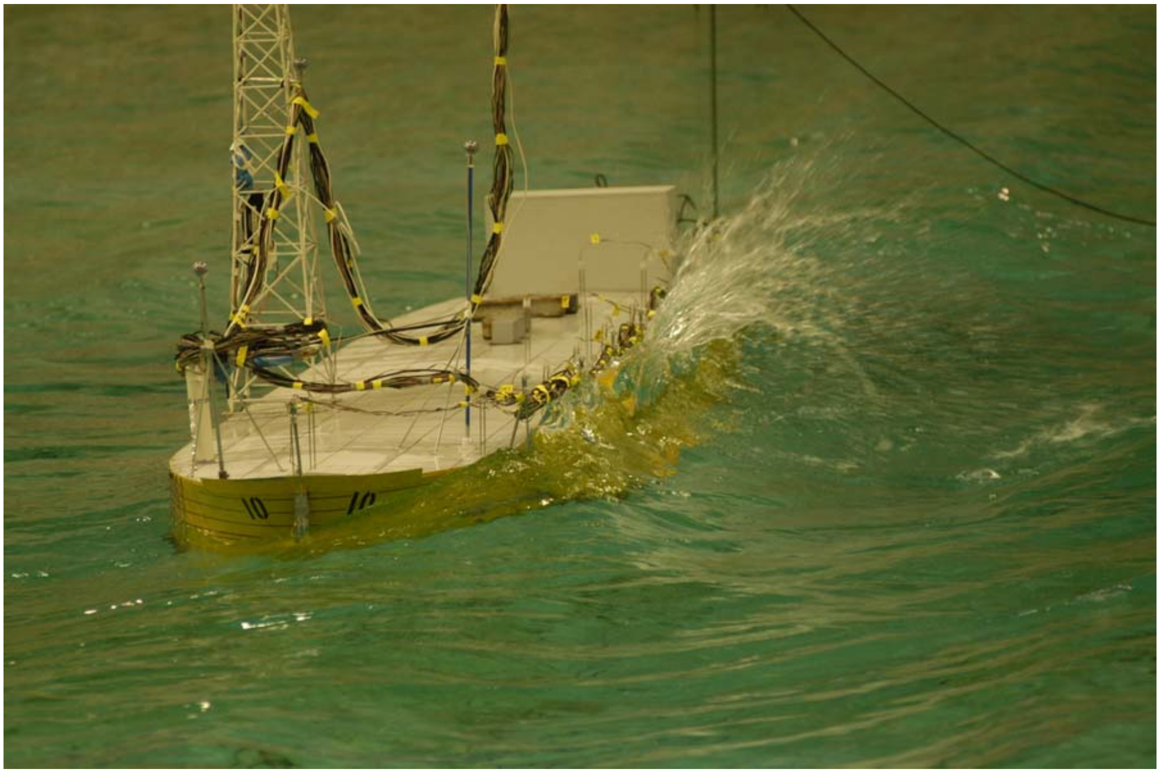

Figure 3. FPSO model test showing wave slamming on riser porch area.

Design and Characteristics of a Typical Spread-Mooring System for West Africa

Spreadmoored FPSOs are popular in West Africa due to the relatively benign and highly directional wave environment, and the typical fields that have been developed. Large FPSOs (typically 150,000 to 250,000 barrels of oil/day) also incorporate an offloading buoy and associated flow lines to provide the desired uptime and reliability for offloading. For smaller FPSO developments (around100,000 barrels of oil/day) a turret mooring system is considered an optimum solution with tandem offloading from the stern of the FPSO. Tandem loading from spreadmoored FPSOs are only considered to be an emergency option or used off very small FPSOs (say up to 50,000 barrels of oil/day) where an average of one to two offloadings are performed a month.

Optimization of the design of a spreadmooring for large West Africa FPSOs requires the integration of the mooring design with major components of the FPSO system. Key interfaces include the vessel hull and topsides, riser and flowline systems, and the field layout. The following subsections detail the impact of the various design parameters on the mooring system:

- Environmental Conditions
- Field Layout
- Performance Requirements
- Integration with Hull and Topsides
- Impact of Risers and Oil Offloading Lines
- Installation & Hook-up

Environmental Conditions

The environment offshore West Africa can be characterized by persistent long-period swells from the SSW with uncorrelated low-intensity wind and current environments. The environment is also characterized by squalls that are of short duration (typically one hour) and very high wind speeds (5 sec gust greater than 30m/s). Squalls typically originate over land and propagate over the ocean, but locally can be incident from almost any direction. These high wind speeds coupled with the very large FPSO systems results in large vessel offsets and thus anchor leg tensions, and typically govern the design of the mooring system from an extreme load and offset perspective. As the vessel is typically oriented with its bow, or stern towards the SSW the loading from the swell on the FPSO is minimized but due to its persistence results in defining the fatigue life of the mooring system.

For the FPSOs with offloading buoys the buoys are typically located North of the FPSO to optimize the approach and departure of the tankers of opportunity. However, the nature of the environment can also lead to large crossed conditions (wind, waves and current from very different directions) and thus result in the tanker orientation being quite varied.

Mooring System Design and Interface with Riser System

Mooring systems for spread-moored FPSOs offshore West Africa typically are designed as grouped mooring systems with fairleads at the corners of the vessel. Typically the number of anchor legs range from twelve to sixteen with three or four anchor legs in each group, approximately 5 degrees apart. The anchor legs typically have a taut or semi-taut configuration and constructed with chain and spiral strand wire or polyester rope. The mooring system is anchored using suction embedded piles or vertically loaded anchors. For water depths greater than 1,000 meters the fairlead to anchor horizontal distance is typically 1 - 2 times the water depth. Typical maximum vessel offsets for an intact mooring system are 5% - 7% of water depth.

The layout of the mooring system during the FEED stage of the project is extremely important as it plays a large role in determining the performance of the mooring and its cost and effectiveness as changes to the mooring layout during detailed design is difficult to accomplish due maturation of the subsea layout. It is quite typical in preliminary engineering to consider a symmetric mooring arrangement with anchor points determined from a simple analysis or rule of thumb, but experience has shown that insufficient attention to the mooring design at this stage can have a detrimental impact on the system at a later stage.

One reason for this is that the mooring design must take into account the riser and oil offloading lines (OOL) loads. Also experience has shown that the anchor legs towards the swell environment (towards the SW) are also susceptible to fatigue damage and that increasing the distance to the anchor (closer to 2 times the water depth) can result in much better mooring performance and overall lower mooring costs.

Due to the weight and length of these OOLs, each OOL exerts a horizontal force on the FPSO that is equivalent to that of an anchor leg. In addition the large FPSOs have a large number of risers attached to the vessel that also exert large horizontal forces on the vessel. Summing up the external forces from the OOLs and risers results in large surge and sway forces, and a yaw moment that have to be counteracted by the mooring system in addition to the environmental loads to maintain the vessel at the desired heading and position.

The asymmetry of the external forces caused by risers and the OOLs attached to one end of the vessel result in the design of an asymmetric mooring system. The mooring asymmetry may either be accomplished by varying the number of anchor legs in a group and/or varying the pre-tension and anchor leg length. One characteristic of such a mooring is that the stiffness is also asymmetric and thus for a given load, vessel offset will vary as a function of direction. The mooring system is typically “softest” when offset away from the offloading buoy as the force from the OOLs is fairly constant with offset. Another unusual characteristic of such an FPSO mooring system is that the static equilibrium position of the FPSO may vary by 10 meters with change in draft from ballast to fully loaded.

These response characteristics are extremely important when transferring design information to the riser analysts and designers. The riser designs for spreadmoored FPSOs in deepwater have very restrictive vessel offset requirements (typically 5% of water depth), especially if steel catenary risers are used. Due to the yaw motions of the spread-moored vessel (especially in squall environments) the design offsets of the vessel may vary by 50% depending on whether it is attached near midships or near the bow/stern. This coupled with the asymmetric stiffness characteristics of the mooring system requires a clear specification of vessel offset as a function of the incident environment. This requires the mooring and riser designers to work closely in the design phase to ensure that consistent environmental conditions and vessel response data is used to design the riser system.

Integration with Hull and Topsides

The anchor leg fairleads can be either keel mounted or deck mounted depending on project construction and operational requirements. The selection of fairlead type can have a large impact on the hull construction. Keel mounted fairleads are more complex and need to be installed in dry dock and the arrangement/number/size must be determined fairly early in the project design cycle to ensure proper integration with the hull. Deck mounted fairleads are typically simpler and are mounted on the main deck with stiffeners to support them and can be installed at any time during the hull/topsides fabrication. The keel mounted fairleads provide clear access on both sides of the vessel while deck mounted fairleads restrict the access to the vessel sides. Keel mounted fairleads may also require guide tubes for the chain from the keel to the main deck.

The fairlead arrangement also impacts the design of the pull-in system that could be a winch, chain jack or combination. For spread moorings (in contrast to turret systems) the pull-in system can take a large amount of real estate on the deck and the design of the pull-in system must consider the topsides arrangement, the location of structural supports and marine equipment on the deck, and other obstructions. The retrieval lines are directed to the various fairleads using a series of sheaves that also take a lot of real estate on the deck and need to be supported. The mooring pull-in system may also be used to pull-in the riser and oil offloading lines and thus requires a fairly good definition of all the risers and their locations.

Mooring System Installation and FPSO Hook-up

Installation of deepwater mooring systems presents numerous technical challenges both in terms of installing the individual anchor legs and in hooking up the vessel. This is further complicated in West Africa due to the presence of persistent swell and the unpredictable nature and intensity of West African squalls.

Unlike other regions of the world where there exist periods where the seas are relatively calm due to the small wave heights and short wave periods, the long period swell results in the installation vessels undergoing relatively large heave and pitch motions that results in increased dynamics during lifting and lowering operations. Most permanent mooring systems in West Africa are anchored using suction piles that may weight 150 – 175 MT. During the lowering operation a vessel heave of 1 meter amplitude can result in the suction pile heaving +/- 4 meters due to the dynamics in the system with large velocities – greater than 1 m/s. This can result in large winch line tensions and can result in instability while setting down the pile as well as permanently disturbing the soil in which it is being installed. For a stable and controlled installation, typical penetration velocities need to be 0.25 m/s or less and require the use of active or passive heave compensation and large vents on the pile top to allow water to discharge during self-penetration without blowing out the soil around the pile.

Another installation challenge is to install the mooring system without inducing twist in to the anchor leg and to ensure no damage to the spiral strand wire or polyester rope which has been a recurring problem on deepwater mooring system installations. Mooring line twist can be minimized if a low rotation rope (and definitely not six-strand) is used on the deployment winch or pair of deployment winches is used to counter-balance the torque. It is also important to ensure twist is minimized during FPSO hook-up and tensioning, as the long-term performance of mooring components under permanent twist is not well understood. Experience has shown that with the right procedures and equipment that the amount of twist in the anchor legs can be minimized to one or less turn every 1000 meters of mooring line length.

Another very important task during the installation of the spreadmoored FPSOs is the hook-up of the vessel to its mooring, especially when considering the persistent swells and high-intensity squalls that may be experienced offshore West Africa. This is even more important if the FPSO is being installed near to a dry tree unit. Up to 6 large bollard pull tugs may be required to position the vessel and it may take approximately 12 - 24 hours to pick up and connect an anchor leg to the FPSO. As indicated above, squalls with wind speeds up to 40m/s can be experienced. In such a squall a FPSO with a large topside facility in ballast condition may experience forces greater than 600 tons. In such circumstances even 6 tugs may not be sufficient tugs to hold the FPSO on station at the design heading. In the situation with a dry tree unit nearby this causes some extra restrictions on maneuvering of the tugs. Prior to connecting any lines it is possible to weathervane the FPSO so as to reduce the squall load and so the risk is relatively low. In a similar manner the FPSO can still be weathervane to an extent with one mooring line connected provided that adequate arrangements are provided to ensure that the mooring line will not "jump" the sheave/shoe, or get damaged. Typically an FPSO to be "storm-safe" for 10-year return period environmental conditions requires 8 – 10 anchor legs attached and tensioned and thus the exposure to extreme weather during hook-up can range from 4 – 8 days. For this duration it is possible that the connected mooring lines will be subject to extreme loads and the vessel to extreme offsets that may result in interference between the anchor legs, positioning tugs and the pre-installed riser/flowline systems. This stage of the installation needs to be properly addressed during design and through installation procedures to ensure a safe installation.

CONCLUSIONS

When comparing the CAPEX costs of a turret mooring system to a spread moored equivalent, it is important to include the various sub-systems inherently present in a turret mooring when determining the CAPEX of the spread moored system. For example, in addition to the mooring system and load-transfer components of a turret, the turret also contains fluid-transfer and control system components like the riser manifolding, pig launching and receiving, chemical injection skids and subsea control systems. In addition, the mooring and riser installation equipment may be included within the turret. All of this equipment is also required on the spread moored system; however, it is rarely included in a comparison to turret mooring system costs. The additional costs required for the mooring support points on the Spread Moored option are often overlooked in the direct comparison. These costs are not insignificant.

In addition to CAPEX , it is important to recognize that turret mooring and spread mooring systems have very difference performance characteristics, both in terms of vessel motions (and thus topsides equipment performance) and offloading. As a turret moored system is a single point mooring system it aligns itself to the environment and provides a means of offloading from the stern of the vessel using equipment and methods well developed over the years of SPM offloading from marine terminals and turret moored F(P)SOs.

Though tandem offloading is also common to spread moored vessels, the fixed orientation of the F(P)SO and the changing environmental conditions makes approach and the offloading operation more difficult. Offloading from a spread moored F(P)SO with moderate to large production rates typically requires an upgrade from the conventional offloading system, possibly requiring two offloading stations (bow and stern), additional tug assistance during the offloading operation, and possibly a remote offloading system with high CAPEX costs, to provide a performance comparable to a turret moored system in most environments.

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