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Design and Installation Challenges for Deepwater Mooring Systems

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Introduction

A large number of new offshore development is occurring in deepwater remote locations using floating production systems. Simple extrapolation of the shallow water experience may not be adequate for mooring systems in the deeper waters. The present paper, based primarily on some recent West Africa floating production storage and offloading (FPSO) project experience, outlines several challenges in the design and installation process to ensure a reliable and cost effective mooring system. The discussion focuses more on the design aspect and touches on some installation issues as well.

The primary focus is on conventional steel mooring system in taut leg configuration, using suction anchors, bottom chain, steel wire rope and top chain. Steel mooring systems have a longer industry history and are considered to be relatively robust in handling. Although synthetic moorings are not discussed specifically, several of the issues raised here are relevant for synthetic mooring systems, too.

Design & Analysis:

The design and analysis of mooring systems for deepwater poses several challenges, some that are obvious and some that are more subtle in nature. The following sections highlight some of the key areas requiring attention.

<u>Metocean Criteria Development</u>

First, there is the challenge of gathering quality data for the site within the required timeframe. Early planning for the data gathering is usually economical and helps reduce unnecessary conservatism in design. Even when good data is available, appropriate criteria development is still challenging for these floating systems.

A good understanding of the system's dynamic response is required to specify the design criteria and identify environmental "extreme cases" to be analyzed. The metocean specialist and the mooring specialist need to work together to develop the response based design criteria. Definition of extreme environment and the associated environment can both be critically important and may have significant influence on the design. For example, a 100-year return wind condition may be defined as one of the extreme environment cases. The associated environment may be the 95% non-excedence wave and current condition that should be applied simultaneously for the design. To appropriately specify the associated environment, the metocean specialist needs to understand the sensitivity of the system dynamic response to both the magnitude and direction of the associated environment. Due to system damping characteristics, the use of the most severe associated environment to go along with the extreme design environment may not be the most conservative scenario for mooring design. Contrary to intuition, in some situations, the absence of the associated environment may produce a higher response.

Mooring design in West Africa poses a set of additional challenges such as the simultaneous presence of the local seas and regional swells and the presence of short duration squalls with rapidly changing wind directions during a storm. The database for squalls is still quite limited and is based on a relatively short observation period. This introduces an uncertainty in extrapolation of 100-year return squall conditions. More data on extreme squalls, including the frequency content of the gusts and their spatial coherence will help us better design FPSO moorings. Joint effort in this area could benefit the entire industry.

Analysis Tools

A reliable and cost effective mooring design requires a combination of an experienced engineering team, availability of appropriate analysis tools, and a project management structure that enables high technical performance. A deficiency in any one of these resources can result in a design that is less than optimum. Assuming that we have a perfect team working under a perfect structure, let us focus on the analysis tools.

Although multiple analysis software tools are available in the market, each has its own limitations. There are choices to be made at several levels. Choices have to be made between a integrated software (for combined hydrodynamics and mooring analysis capability) or separate programs for each task with interfaces. This has significant impact on the design cycle for some systems where system dynamic behavior has strong interactions between the mooring and the floater (e.g. offloading buoys in deepwater). There is also the battle between time domain versus frequency domain analysis. The analyst has to identify what best suits the task at hand and make appropriate allowances for shortcomings in the software. The role of damping from all sources still continues to be an important parameter influencing the slow-drift response. The software used should be critically examined for its treatment of the damping contributions, limitations identified, and suitable allowances incorporated in the design margin.

The complexity of the various extreme conditions and the fatigue conditions to be analyzed often require analysts to switch analysis tools for the different tasks. For example, the fatigue analysis may be more suitably done with a frequency domain software while the squall analysis requires a time domain analysis tool. When such changes are required, benchmarking predictions of different software against each other with some common cases is essential for consistent predictions. Also, any tool should be benchmarked or verified against model tests, before it is accepted for critical design decisions.

Model Tests

Model tests are a valuable tool for assisting the design of complex systems. However, model tests can only shed light on attributes that one has properly modeled, measured and is able to justify with a sound technical basis.

For floating systems, wind tunnel tests for wind and current loads and wave basin tests for motion response and mooring loads are commonly performed. For wind tunnel tests there are few critical areas that need special attention. The building of the scale model for wind tunnel testing is a process that involves judgement on the part of the model builder to make "equivalent approximations" of complex topsides equipment. This is an area that can exhibit considerable variability based on the experience and practice followed by the individual wind tunnel facilities. Typically, the primary members of the modeled structure are well represented. However, when it comes to the secondary members like small piping, spool pieces, and small appendages, the practice seems to vary widely. Careful checks of this modeling process and the underlying assumptions are extremely important. Benchmarking of the test set-up is another area that can significantly add confidence to the test results by identifying potential instrument problems. Using a simple block like a cube to measure the force and correlate it with calculated values is a simple but reliable check. Also, the symmetry of the block can help with some additional checks on the instrumental set-up.

For wave basin tests of complex floating systems, the need for systematic testing of the floater alone, floater with moorings and finally floater with moorings and risers is essential. This provides a building block approach that can be used to perform systematic checks very efficiently. Frequently, the need for economy in the testing budget forces the project to bypass some of the steps and this can make a systematic understanding of various contributing factors almost impossible. Numerous technical challenges are faced in the model test program. These include modeling the full deepwater mooring system, appropriate modeling of viscous forces in a Froude scaling environment, simultaneous modeling of vessel motions and dynamic line tensions. Given the time, resources and oversight, the test facilities can adequately address all the issues to a high degree of accuracy. However, the challenge for the designer is to strike an optimum balance between quality, cost, and schedule.

Prediction of Design Maximum

Considerable scatter exists in the statistical interpretation of dynamic simulations, both from model tests and numerical simulations. Design values selected vary widely from absolute maximum value to average of max value, with biased average of the maximum value falling in between. This is an area where industry needs to better define the design maximum or the "most probable maximum" value. West Africa squalls present another unique challenge by their short transient nature and the need to derive response statistics from a short time history sample. Analysis of multiple squall time series with varying initial conditions is recommended.

Strength Design and Fatigue Design

Traditionally, shallow water mooring systems in most parts of the world (except North Atlantic type environment) are designed to meet strength requirements and typically satisfy fatigue requirements. This is no longer true for deepwater systems. The pretensions are normally higher for deepwater systems and the taut nature of the mooring system results in dynamic tensions that are significantly higher under moderate wave conditions. For deepwater moorings in West Africa, fatigue is beginning to play a dominant role. This is especially true for the mooring chain. The widespread use of studless chain with lower fatigue life has made the problem more acute. Modern mooring designs typically utilize groups of mooring lines to provide redundancy in the event of a line failure. Spread moored systems typically have mooring lines in groups at each of the four quadrants of the FPSO while turret moored vessels utilize three groups of mooring legs. In West Africa environment, fatigue design typically governs one or more of these groups of mooring lines.

The need for accuracy of pretension in the mooring lines is enhanced as inequalities in tension in adjacent mooring lines will result in additional fatigue life reduction on the more loaded line in the group. Sensitivity checks with realistic installation tolerances are strongly recommended especially when the design margins are low. The sensitivity of fatigue damage to pretension stems from the fact that dynamic stress magnitude increases directly with pre-tension, and the fatigue damage is approximately proportional to the cube of the dynamic stress range. Thus, imbalances in pretension in a group can result in reduced fatigue performance.

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Chain Terminations

The mooring designer is faced with some design choices for the top termination for the mooring system. The common choices are fairlead with stopper, direct stoppering with one or two axes of rotational degrees of freedom (i.e. articulated stopper), a hawse pipe and stopper (for turret moored systems) and fixed bending shoe with a stopper. There are significant cost and reliability differences between these various choices. For the articulated stopper, there are several design detail variations. Similarly, with the bending shoe there are choices to be made on supporting surface for the chain (i.e. a curved surface with chain laying in an X-pattern or a grooved surface for the links to be supported without twisting action. The former allows free lateral movement of the chain, but introduces bending stresses and torsional stresses. The latter has a better support for the chain minimizing the stresses on the supported links at the expense of higher bending stresses at the first free link. The curvature of the bending shoe and the details of the chain support surface are extremely important in minimizing bending stress. For any of the above systems, the fatigue performance needs careful evaluation.

The prediction of fatigue behavior of the chain at the stopper/termination brings a new challenge in design detail. The ability to accurately predict tension-bending fatigue with certainty requires serious effort, even on the part of experienced analysts. Also, there is a scarcity of experimental data to verify the tension-bending fatigue analysis. Frequently, the stress enhancement due to bending is used in conjunction with the pure tension-tension fatigue data. This approach has some limitations and really needs to be formally tested. All analyses performed should include the as-built geometry of the proof-loaded chain. In this area, there is opportunity for significantly extending the current understanding and verifying the underlying hypothesis.

Fatigue checks at the anchor end are as critical as the checks performed for the top end of the chain. A majority of the deepwater West Africa systems have semi-taut or taut moorings. Depending on the fixity of the bottom boundary condition, the fatigue at the bottom end could be critical. For the mooring line dynamic tension prediction, the system is analogous to a transversely vibrating string, constrained at the bottom end, with the top end being dynamically excited by a boundary displacement.

Asymmetry Arising from Offloading System

Another interesting characteristic of most deepwater West Africa Spread moored systems is the inherent asymmetry of the mooring system. The common use of an offloading buoy with a suspended oil offloading line (OLL) introduces a large directional load. The analysis model should contain the OLL and the risers. The presence of a floating wellhead platform like a TLP with suspended fluid transfer lines (FTL) to the FPSO introduces additional complexities in the analysis. With some initial investigation the relative importance of the risers, OLLs and FTLs should be determined, and the model expanded to include these, individually or in an equivalent system representation, as appropriate. The resulting mooring system, if optimized, will be highly asymmetrical, primarily to resist the OLL loads. Thus, systems are emerging with unequal number of lines or different sizes of lines in the different quadrants.

Interface Management

The complex system designs are typically divided across several design groups within or across multiple engineering contractor companies. Ensuring the timely flow of technical information at the right level of detail is one of the most challenging tasks, especially across different contractor groups working at different sites, each with its own priorities of cost and schedule. Rework on a schedule-critical project typically is very expensive. Minimizing rework needs a continuous information exchange at all steps. Often, the quality and clarity of information can be the source of the problem when interfacing parties are not conversant with each other's terminology and common analysis practice.

Installation Challenges

Although the industry has had quite a bit of deepwater installation experience, incidents of dropped mooring lines, damaged lines or interfacing structures during installation and similar problems continue to plague the various projects.

Some of the high level challenges in deepwater installation are considerably higher tension values and therefore large pull-in loads, expensive installation vessel spreads demanding an efficient installation procedure, longer times required to perform as-built surveys, and the high cost of fixing a problem or installation related damage. Some of the more detailed challenges are discussed below.

Avoiding Twist In Mooring Lines

Ensuring there is zero or minimum twist introduced in the mooring system during pre-installation or final hook-up of the mooring is essential to its long-term integrity. Presence of twist in the wire rope can result in bird-caging action and premature failure. Presence of twist in the mooring chain can reduce the strength and fatigue performance significantly. Ideally, the mooring line should be completely free of twist at hook-up. Additional safeguards are required to avoid twist being introduced during installation. Some installation time will have to be spent to take out introduced twist. Either of these steps will increase the installation time and hence cost, but are necessary for optimum performance of the mooring system. Use of low-torque pull-in wire, use of a second line for balancing the torque, and introduction of an in-line swivel during pull-in are various methods currently used. The installation contractor's past experience can be a valuable asset. The issue of managing twist should be addressed very early on in the installation planning.

The acceptable level of twist in a mooring system is still a gray area. The long-term behavior of mooring wire and mooring chain in the presence of varying levels of twist cannot be predicted with certainty. There are some analytic tools that the manufacturers have that can be used as rough guidelines but are not benchmarked. For studless chain, experience has shown that the relationship of twist angle versus torque is very sensitive to the precise modeling of the geometry of the link at the crown region. Similarly, reliable data on torsional rigidity of mooring wire rope and pull-in wire rope may not be readily available. This information may be important to predict the anticipated twist. The industry could benefit from some collaborative effort to develop systematic data on torque-twist behavior of both chain and wire rope under various levels of tension. These data will increase understanding of the resulting strength and fatigue life reduction due to twist. The complexity of the problem calls for a combination of analytic predictions benchmarked by laboratory testing.

Tension Accuracy at Hook-Up

This is another area that can easily be overlooked. As mentioned earlier, for taut systems the tension variation between the adjacent lines in one mooring group can result in a severe reduction of the fatigue performance. When the requirement is specified, reliable means of measuring tension during installation is required. Measurement of chain departure angle served reasonably well for shallow water catenary systems. For taut systems, the resolution of the angle measurement may not be adequate. Indirect prediction of tension requires very accurate measurement of all the variables and parameters governing line tension. The more important parameters include: mooring chain and wire length, unit weight of chain, wire and connectors, elasticity of the chain and wire, water temperature, water depth including tide, draft and trim of the vessel, exact location of the anchor, number of links embedded in the soil, and the prevailing weather. Verification of the top shackle height below the water surface (predicted versus observed value) has been successfully used as a check on some recent projects. However, more reliable direct measurements would be desirable. The verification of the installed mooring line tension is something that needs to be thought through early in the installation planning cycle.

Avoiding Installation Damage to Wire Rope

In our recent experience we have seen several problems with damage to wire rope during installation. The damages have occurred on both sheathed and unsheathed spiral strand wire ropes. Some of the damage incidences occurred during the unspooling operation from the installation reel. In another case, the damage was caused by other installation gear. Fortunately, neither of these incidents caused any serious damage. However, an adequate assessment was required, and in one instance, a remedial action is being worked for additional corrosion protection in the region of the damaged sheathing. Assessment of the damage and remedial action can be costly for these systems in deepwater. A replacement line and the installation cost can easily reach several million dollars.

Conclusion

Though the industry has moved forward into deepwater with several installed systems there still is considerable room for improvement in several areas of design and installation. The challenge to both operators and engineering contractors is to design economic systems that are safely installed without unpleasant surprises in the field, and are reliable in-service. The cost of fixing a problem late in the design stage, or in the field during installation, is extremely high. This expensive fix can only be avoided by very rigorous planning, diligent review of design and installation planning phases, and careful management of design and installation interfaces.