

SLOR vs. SCR for Deepwater Applications

Technical Appraisal

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ABSTRACT

This paper provides a technical appraisal of the use of Single Line Offset Risers (SLORs) and Steel Catenary Risers (SCRs) in deepwater applications. It addresses the main design issues associated with both types of riser, and provides an overview of the typical response of both riser systems with regards to extreme storm loading, wave induced fatigue and VIV (vortex induced vibration). Based on the general trends, the technical design approach required for each riser type is established.

KEY WORDS:

SLOR; SCR; Freestanding Riser; Deepwater.

INTRODUCTION

Deepwater developments often require a Floating Production, Storage and Offloading vessel (FPSO) to facilitate oil storage, and as a result large non-heave optimised structures are selected which are unsuitable for top tension riser systems. In addition, the water depths, temperatures and pressures associated with some of these developments present challenges beyond what can be economically achieved using large diameter flexible pipes.

Hence the riser system selection is often a choice between Steel Catenary Risers (SCRs) and Single Line Offset Risers (SLORs).

The SCR benefits from being a simple design, however the dynamic response of the riser is sensitive to design alterations and can lead to unacceptable fatigue lives and fabrication difficulties. The SLOR, on the other hand, requires a fair amount of component design effort, but the system dynamic response is much reduced, leading to greater confidence in the overall design.

Drawing on first hand experience gained from a number of real life applications of both SCR and SLORs in deepwater developments, this paper presents a technical appraisal of the two riser systems, with particular emphasis on the design issues typically encountered for each type of riser. It addresses the global response exhibited by each riser

type under extreme storm loading, long term fatigue loading and VIV (vortex induced vibration), and identifies the driving factors behind each response.

Ultimately the riser system selection is often influenced by other factors beyond what may be considered the best design solution, however this paper will focus on the technical aspects of the riser design and defines the design approach required for both the SLOR and SCR solutions.

RISER DESCRIPTIONS

SLOR

General Arrangement

There are a number of variants to the SLOR design; one of them is described below.

The SLOR consists of a single vertical steel pipe connected to a foundation pile at the seabed. The system is tensioned using a buoyancy can, which is mechanically connected to the top of the riser. The riser pipe runs through the bore of the buoyancy can, which is located between 50-100m below the mean water level (MWL). This arrangement minimises the effects of waves and surface currents on the riser, whilst maintaining access for inspection and ease of jumper installation. At the top of the buoyancy can is a gooseneck assembly, to which a flexible jumper is attached which links the SLOR to the vessel, thus essentially decoupling the freestanding riser from the vessel motions.

The riser base may typically be offset from the vessel by around 200-300m, depending on the water depth and the vessel excursions. The length of the flexible jumper is typically between 1.4 and 1.6 times the riser base offset, with a departure angle at the vessel of between 10-15 degrees.

A sketch of the SLOR arrangement is provided in Fig. 1.

Foundation System

A typical SLOR foundation consists of a pile (either a suction pile, or drilled and grouted), to which the riser is connected via a high integrity

connector. The riser may have a rigid base connection, or may incorporate a low stiffness elastomeric flexible joint to reduce local bending moments.

Lower Riser Assembly

The lower riser assembly consists primarily of the lower offtake spool, and the lower taper joint. The offtake spool is a component with an internal flow path that exits from the side of the spool. Attached to the side of the spool is an induction bend. A base jumper is attached to the end of the induction bend by either a horizontal or a vertical connection system.

Attached to the top of the offtake spool is the lower taper joint. This is a high specification component designed to control the bending at the base of the riser where it is connected to the stiff offtake spool body.

Buoyancy Can

The SLOR is tensioned by an air or nitrogen filled buoyancy can. A central pipe runs through the centre of the can and acts as the main structural element in the buoyancy can. Internal bulkheads are used to divide the can into sub-compartments.

The riser pipe is attached to a load shoulder on the top of the buoyancy can, and thus the upthrust generated by the buoyancy can is transmitted directly to provide tension in the riser string.

Keel Joint

At the base of the buoyancy can, where the riser exits from the central structural pipe, a keel joint arrangement is used on the riser to control the bending moment transferred into the riser string due to offsets and motion of the riser. The keel joint arrangement is similar to that used for some production risers on dry tree units, however it can be simpler as there is no requirement for riser axial motion (stroke) to be accommodated.

The keel joint consists of two tapered riser sections joined back to back. Positioned between the two tapered sections is a keel centraliser which acts as a guide for the riser against the buoyancy can. The outer diameter of the keel centraliser is slightly smaller than the ID of the central core of the buoyancy can.

Gooseneck Assembly

The gooseneck assembly provides fluid off-take from the freestanding riser to the flexible jumper. It comprises an induction bend and is structurally braced back to a gooseneck support spool at the base of the assembly to react the loads generated on the assembly by the flexible jumper.

For production risers, where access to the riser bore may be required, a re-entry mandrel can be attached at the top of the gooseneck through which access can be achieved.

The bends in the gooseneck, offtake spool and base jumper are typically configured as 3D or 5D radius bends. These can allow the passage of pigs, and prevent flow restrictions. For production risers, the bends may require an erosion allowance or cladding depending on the content of the production fluid.

Flexible Jumper

A flexible jumper is used to transfer fluid between the riser and the vessel. Bend stiffeners are used to restrict the bend radius of the jumper at the vessel and gooseneck termination points. The properties of the flexible jumper and bend stiffeners are dependent on the individual riser service, insulation and pigging requirements.

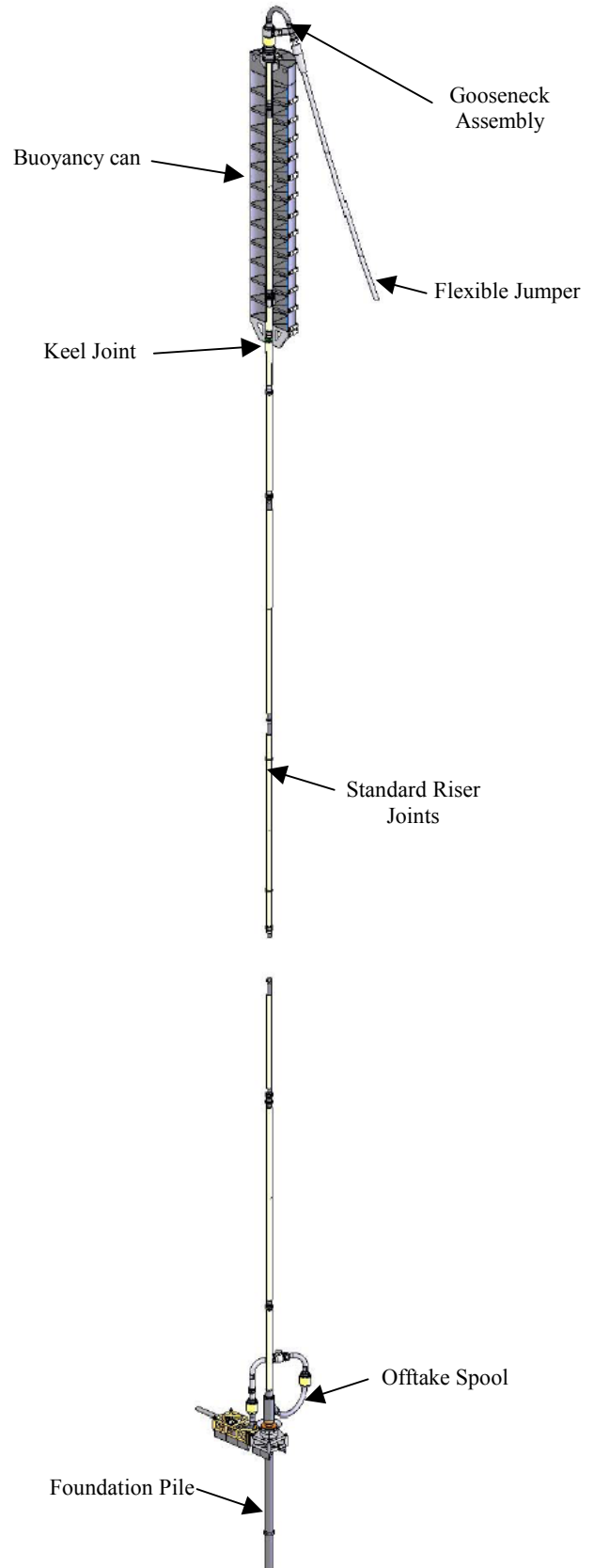


Fig. 1 – SLOR General Arrangement

SCR

The SCR is a mechanically and structurally simpler system than the SLOR. It consists primarily of a steel pipe, freely suspended from a floating platform, and allowed to free hang to form a simple catenary. At the seabed the riser gradually touches down over a region of riser, with a significant portion of the riser lying on the seabed.

At the vessel, the SCR may be attached via a flexible joint or taper joint, with the flexible joint generally required for barge or FPSO type structures where vessel motion is more significant. The primary variable for the riser is the top angle (or departure angle) of the riser from the vessel. The top angle is defined by the length of the riser, and the orientation of the hang-off porch on the vessel. Increasing the riser top angle typically increases the tension in the riser, and reduces the bending in the riser at the touchdown point (TDP). However, increasing top angle also increases the bending stress at the top of the riser at the connection to the vessel, and can result in a high vessel payload.

At the seabed the riser may terminate at a manifold some distance from the TDP, or may continue directly into a pipeline system. In some cases a riser anchor may be required to secure the riser at the end termination, however this is dependent on a number of factors including system loading, soil conditions and pipeline layout.

A sketch of a typical SCR configuration is presented in Fig.2.

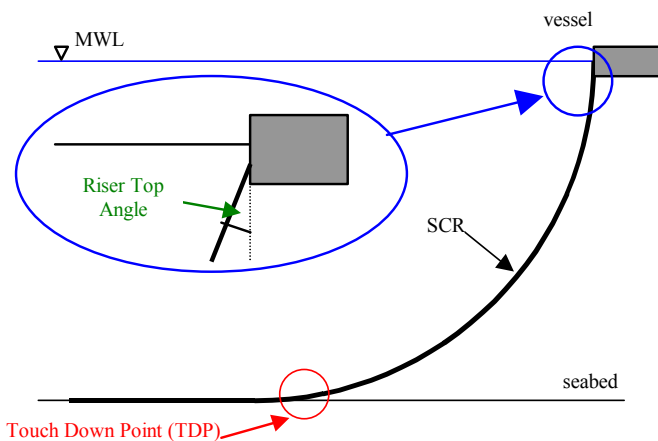


Fig. 2 – Typical SCR General Arrangement

RISER RESPONSE AND DESIGN DRIVERS

The dynamic responses of both the SLOR and SCR riser systems are presented in the following sections. Riser analysis for both SLOR and SCR riser type is conducted in accordance with API and DNV riser design codes [API-RP-2RD, 1998 & DNV-OS-F201, 2001]. Soil interaction and foundation assessments are conducted in accordance API code [API-RP-2T, 1987]. Fatigue assessments are conducted based on DNV and DOE codes [DNV-RP-C203, 2001 & DOE, 1985].

Extreme Storm

SLOR

The extreme storm response of a SLOR is largely quasi-static. As the riser and buoyancy can are located away from the wave zone and surface current regions, the direct environmental loading on the system

is low. The flexible jumper connecting the riser to the vessel also dissipates 1st order vessel motions, such that at the attachment point of the flexible jumper to the gooseneck the dynamic component of the loading is small.

The riser response tends to be driven largely by vessel offset, which may deflect the riser in the direction of the offset, resulting in an increase in loading at the gooseneck and also at the riser base. This can be accommodated by local strengthening of the gooseneck and lower riser assembly. High loading may also be experienced where the riser exits at the base of the buoyancy can, and hence careful design of the tapered keel joint is required.

Where the flexible jumper is attached to the vessel and the gooseneck, bend stiffeners are used to control the rotation between the jumper and the vessel / riser connection.

A typical plot of the von Mises stress along the riser length under storm loading is presented in Fig.3. From the plot, it is seen that along the majority of the riser string, the stress shows a gradual linear increase towards the top of the riser, which is mainly due to axial tension and hoop stress in the riser. At both ends of the riser however bending loads are seen in the system, but are accommodated using locally thickened or tapered components to control the curvature.

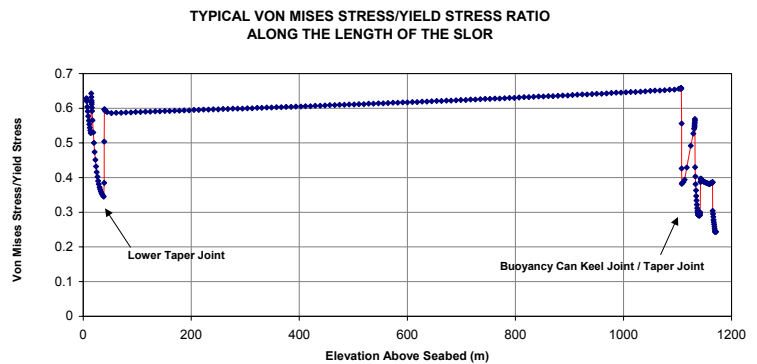


Fig.3 – Typical von Mises Stress in SLOR under Max Operating Storm

SCR

The extreme storm response of an SCR can often be driven by vessel heave. Where an SCR is subjected to significant vertical motion at the vessel attachment, compression may occur at the TDP. This is due to the lagging response of the riser near the TDP, where the upper section of the riser descends faster than the lower section of the riser. The heave response of the SCR can be significantly affected by the riser weight and drag, and hence for highly insulated production risers this can cause difficulties. In certain cases a weight coat may be applied to the riser, however this also increases the overall drag diameter.

The vertical motion of the riser may also result in the occurrence of heave induced VIV, which further increases the hydrodynamic drag over the lower sections of the SCR.

A plot of the displacement of the TDP region of an SCR subject to severe vessel heave is presented in Fig.4. Each line represents the position of the SCR at one second intervals. From the plot, it can be seen that as the SCR lowers, a buckle appears just above the TDP as the riser is compressed.

Riser TDP Area Snapshots at T+6s to T+12s

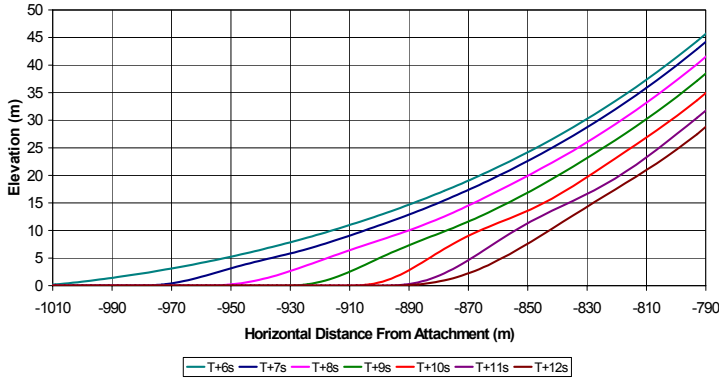


Fig.4 – Displacement Plot of SCR Subject to Severe Heave Motion

A timetrace of the bending moment and tension forces in an SCR subject to similar heave is presented in Fig.5. From the plot is clearly seen that as the riser enters into compression, a severe spike in the bending moment plot occurs. This can result in high stresses in the riser at the TDP which may result in overstressing.

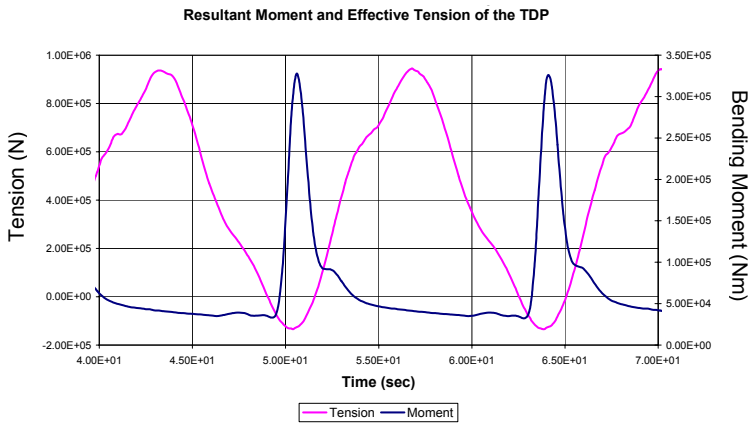


Fig.5 – Timetrace of TDP Tension and Bending Moment Response Under Severe Heave

Due to the non-linear response of an SCR under such loading conditions, it is often necessary to conduct extensive random sea analyses to establish the likelihood of overstressing, considering a range of sensitivity parameters such as hydrodynamic drag coefficient, wave period and vessel draft etc. If it is predicted that under certain circumstances the riser may be overstressed, an elasto-plastic assessment of the riser pipe is required, and the impact on the fatigue response of the plastically deformed region assessed.

Another area of uncertainty regarding SCR extreme storm response is soil interaction. Trenching of the riser may have an impact on the riser response, particularly under vessel offsets transverse to the direction of the trench, where effects such as 'riser hinge' may occur. Other effects such as riser embedment, soil suction and the impact of seabed friction are also difficult to quantify, and thus lead to uncertainties regarding the SCR response.

Wave Fatigue

SLOR

The configuration of the SLOR ensures that it is not responsive to wave loading. The long term dynamic loading on the SLOR is therefore very low, with the majority of dynamic motion associated to 2nd order drift motions of the vessel which gradually alter the configuration of the flexible jumper, and thus the loading on the riser.

A plot of the wave fatigue life along the riser length for a typical SLOR is presented in Fig.6. From the plot it is seen that the life along the length of the riser is very high, even for a DOE F2 class weld, however fatigue 'hot spots' do occur at certain critical locations. These locations are at the lower taper joint, and at the top and bottom of the buoyancy can. To achieve the required life at these locations, local thickening of joints, or the use of tapered joints is required. In addition, it is essential that welds are either avoided, or only high quality welds are used, and that stress concentrations are minimised through good design practice.

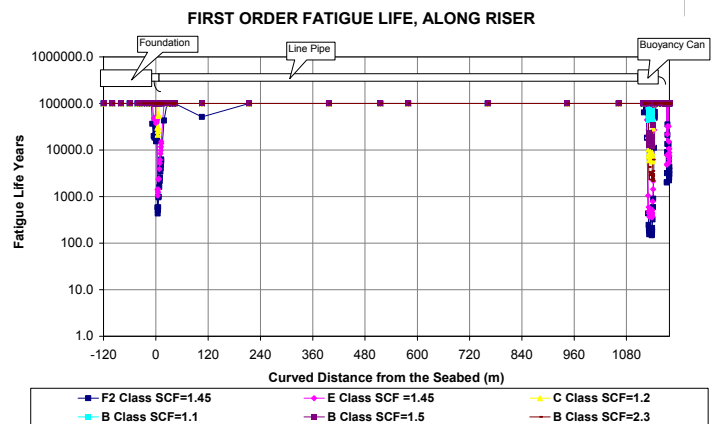


Fig.6 – Typical SLOR Wave Induced Fatigue Response

SCR

As the SCR is directly connected to the production vessel, the riser is far more susceptible to wave fatigue due to the direct application of the vessel motion to the riser. As a result, the fatigue performance of the system can also be strongly influenced by the hang-off location on the vessel, with risers located away from the vessel centerline subjected to more severe vessel heave.

A typical wave fatigue response plot of an SCR is presented in Fig.7. showing two distinct peaks in fatigue damage. The first occurs at the attachment point of the SCR to the vessel, which is due to the fluctuation in bending moment at the flexible joint connection. However this can often be controlled through the use of a thick walled extension piece between the bottom of the flexible joint and the first weld to the riser pipe.

The second peak occurs at the TDP. This peak is due to the continual lift off and set down of the riser on the seabed which produces significant stress cycling in this region of the riser. This can often result in high fatigue damage being incurred along this section of the riser.

To improve the assessment of the TDP damage, it is often necessary to conduct additional analyses such as increasing the number of wave loading cases, and to consider environmental directionality. This can

reduce the conservatism of the fatigue damage estimate but can result in long run times. Other effects such as damage spreading can also be considered, this takes into account the variation in position of the TDP due to effects such as vessel draft variation and mean vessel offsets. Damage spreading can provide reasonable improvements in the TDP fatigue response; however, to be used it requires confidence that the mechanisms that produce the damage spreading will occur regularly and reliably.

To improve the fatigue response in this region, thickened riser sections, or high quality onshore welding may be specified. However due to the length of the TDP region being subjected to high damage, and the potential installation tolerances, the region over which the high fatigue resistance measures are required is often long.

The TDP response is also sensitive to the seabed properties, and seabed stiffness can influence the fatigue damage. However an accurate assessment of the seabed properties over the location of the TDP is difficult to predict, and the location of the seabed samples obtained may not reliably reflect the seabed properties at the actual installed position of the riser.

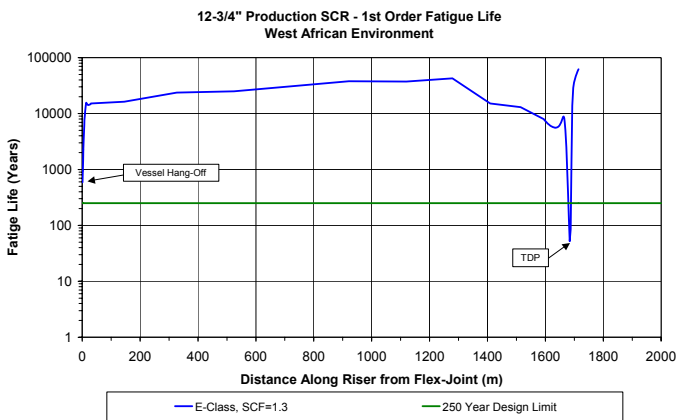


Fig.7 – Typical SCR Wave Induced Fatigue Response

Vortex Induced Vibration (VIV)

SLOR

The VIV fatigue response of a SLOR is largely similar to the wave induced fatigue response, with generally low damage along the majority of the riser length, but with damage peaks at the riser base and at the interfaces of the riser and the buoyancy can. The critical region for VIV damage tends to occur just below the interface of the riser with the buoyancy can, where the VIV response of the large diameter buoyancy can produces the greatest displacement of the riser system. A plot of a typical VIV response is presented in Fig.8.

As for the wave induced fatigue response, it is necessary to design the components at the locations of the peak fatigue damage such that they are capable of withstanding the predicted stress cycling, using tapered or thickened riser joints and high quality welding. Generally components can be designed with adequate fatigue performance, and the use of strakes is not necessary.

To further improve the VIV fatigue response it is also possible to tune the mode shapes of the riser to avoid a particularly damaging VIV response for critical current profiles. This can be achieved through a moderate adjustment of the riser tension, however the extent to which the base tension can be adjusted is limited by practical considerations.

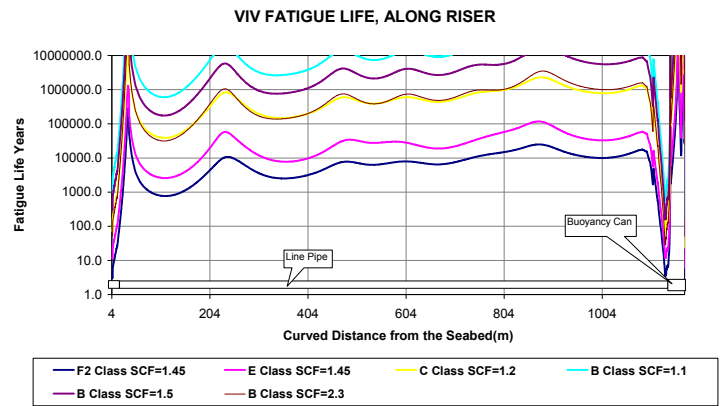


Fig.8 – Typical SLOR VIV Fatigue Response

SCR

The VIV response of an SCR generally follows a similar trend to the wave fatigue response, with a damage peak at the TDP location, and the damage gradually dropping off towards the top of the riser. A typical plot of VIV damage over the riser length is presented in Fig.9. Due to the difficulties associated in achieving an acceptable weld fatigue performance at the TDP (as discussed in the SCR wave fatigue section), it is often necessary to apply strakes along a section of the SCR. However extensive strake coverage can cause other problems due to an increase in hydrodynamic drag and installation handling difficulties. Damage spreading may also be required to be considered to achieve acceptable life, however this is more complex to apply for a VIV response as variation in the riser configuration can alter the VIV behaviour.

The extent of the VIV damage at the TDP can also be sensitive to the seabed stiffness used in the analysis, which as previously discussed can be difficult to determine with accuracy.

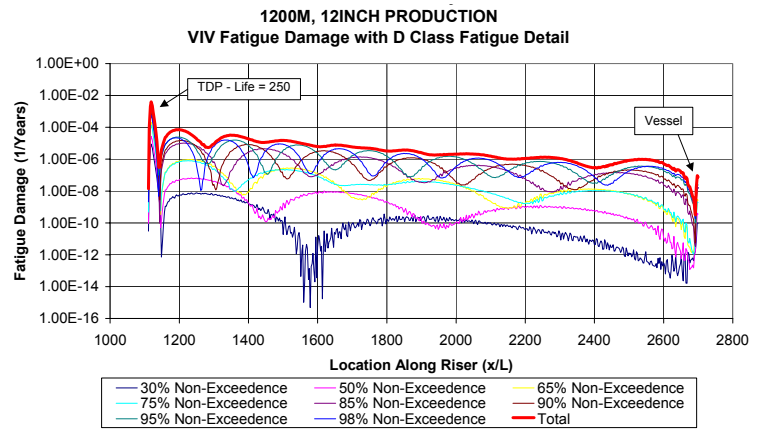


Fig.9 – Typical SCR VIV Fatigue Response

Clearance

SLOR

Riser interference is highly dependent on factors such as field layout and vessel offsets, and hence it is very difficult to define an overall clearance response for a specific riser type. However, it is often noted that clearance problem tend to arise between riser systems, umbilicals and mooring lines which move differently.

Difficulties can be experienced when a SLOR is positioned close to a mooring line, flexible riser or umbilical which are configured in a catenary configuration. Due to the significant differences in configuration and stiffness of these systems, the relative differences in deflections under extreme vessel offsets can result in interference.

However, while the use of a common riser type, and general improvements in field layout can avoid such problems, it is possible to tailor the configuration of a SLOR to avoid specific interference problems occurring. By adjusting parameters such as the base tension, the offset between the vessel and riser base, the elevation of the buoyancy can or the length of the flexible jumper, the interference problems can be minimised.

As interference considerations can have an impact on the riser configuration, it is generally required to conduct an interference assessment at an early stage of the riser design.

SCR

For an SCR, the minimum separation requirement at the vessel hang-off is largely driven by current loading, with vessel offsets having a limited impact as the risers tend to move together. Interference problems at this location tend to be more of a concern for situations where SCRs of differing diameters and weights are located close together. For these cases the riser deflection due to current loading can be quite different for risers of varying diameters. In addition, where a large diameter riser shields a smaller riser, wake reduction effects can also be a concern

At the seabed, as the current velocities are often much lower, the minimum separation is driven by vessel offsets, and effects such as trenching can have a significant impact. The case where one riser becomes 'stuck' in a trench, while the neighbouring riser is free to move is typically the driving case for the minimum riser separation requirement at the TDP.

To resolve interference problems, other than moving the hang-off location of the risers on the vessel, the only other parameters available to adjust are the azimuth angle or top angle of the riser at the hang off point. Adjustments to the azimuth angles of the risers can be made, provided that there is sufficient seabed space, without significantly affecting riser response, however due to the riser shape, the separation of the upper sections of the risers does not increase significantly. More significant improvements can be achieved through adjusting the riser top angles, however this has a significant impact on the riser response and hence may not be feasible for an already marginal riser system.

Installation

SLOR

The SLOR lends itself to installation either using a J-lay tower, or drilling derrick, with the riser joints being passed vertically into the derrick prior to being connected at the drill floor. The handling and connection of the buoyancy can to the riser is often the most challenging aspect of the installation, however this can be achieved either by lifting the buoyancy can over the riser string, or hauling the buoyancy can underneath the vessel and running the riser string through the buoyancy can, with the choice of methodology being dependant on the vessel configuration and crane capacity. Due to the vertical installation of the SLOR, fatigue damage accumulation is not generally a consideration, and the bending stress acting on the riser joints as they are suspended in the rotary table is typically limiting installation factor.

SCR

The installation of an SCR is essentially a continuation of the flowline

installation. As such the installation is typically conducted using either J-lay or S-lay techniques from a conventional lay barge, however smaller diameter SCRs may also be installed by reeling. Following the installation, the riser is set-down on the seabed, or handed over to the production vessel. During the installation process, the accumulation of fatigue damage in the riser can be of concern, in particular for the TDP region of the SCR. This is most critical as the riser is passed over stinger during S-lay installation, where the riser system can experience high cyclical bending loads. Hence a fatigue assessment of the SCR installation may be necessary in order to establish the duration that the riser should be allowed to remain on the stinger before it accumulates excessive damage.

DESIGN APPROACH

Based on the riser system responses as outlined in the previous sections, it can be seen that the design of a SLOR or an SCR system requires different approaches. The following section describes the typical design approach required for each riser type.

SLOR

The design of a SLOR typically involves an upfront global analysis of the riser, consisting of an optimisation of the riser configuration, layout and base tension. Following the selection of the riser configuration, global storm and fatigue analyses are conducted in order to define the functional loading on the critical riser components, and to define the fatigue details and SCFs required for such components.

The detailing of a number of critical components is then required, including the taper joints, gooseneck, offtake spool and base jumper. In addition, the buoyancy can is also required to be designed such that it is capable of producing the required upthrust, and that it is structurally sound and capable of withstanding both the differential pressures and the loading from the riser itself.

While a reasonable degree of effort is required in the detailed design of these components, the SLOR benefits from the fact that the overall system design is robust and is relatively insensitive to many parameters. This allows a relatively conservative design approach to be adopted for the upfront global riser design, with allowances for parameter sensitivities and design changes included in the overall system. In addition, due to the robust design of the riser, the same, or largely similar designs can be repeated for a number of SLORs, thus enabling the components to be designed in a single design cycle, and ultimately allowing fast track designs to be achieved.

SCR

For an SCR, the design activities focus largely on global riser response analysis, with very few component analyses needed. Typically the design process begins with riser pipe wall sizing, followed by a riser configuration assessment. The configuration assessment is a key stage in the riser design, and should be used to gain an early understanding of the overall riser response and its sensitivity to key parameters. Should the configuration analysis show that the riser is likely to exhibit a marginal response under certain loading conditions it is of great importance that the key parameters which influence this response are fully defined before extensive storm or fatigue analyses are conducted. In addition, the configuration analysis should also be used to ensure that the most appropriate riser configuration is selected, in particular the departure angle, such that it does not become necessary to alter the configuration during the detailed storm and fatigue analyses which can lead to extensive re-work.

Following the configuration assessment, extreme storm, wave fatigue, VIV and interference analyses are conducted. The extent of these analyses is generally defined by how marginal the riser response is. Typically an initial conservative assessment of the riser response is made, followed by increasingly detailed and in-depth analyses being conducted as required until a satisfactory solution is found. Where changes in the overall riser configuration are required to achieve a satisfactory response for one condition (e.g. adding strakes to improve VIV response), it is necessary to re-analyse the new riser configuration under other loading conditions (e.g. to assess the impact of the increased drag due to the strakes on the extreme storm response). Hence it is necessary to identify the most critical aspects of the riser response at an early stage, and define the required solutions, prior to commencing the detailed analyses on other riser responses.

Following the global analysis, some component detailed design is required for items such as the flexible-joint, hang-off receptacle, anodes, and riser anchors or on bottom stabilisation systems if required. Further work may also include the definition of weld fatigue testing programs to verify the suitability of the specified weld procedure under the load ranges predicted at the critical riser weld locations.

CONCLUSIONS

From the experience gained through the design of both SLOR and SCR riser systems it has been seen that the SCR lends itself very well to deepwater developments in benign environments such as Indonesia or those using heave optimized vessels such as Spars or TLPs. For these developments, the loading on the riser system is relatively low, and thus the SCR can perform well within its capabilities. The design cycle for such a system is relatively straight forward, and requires limited component detailed engineering.

However, where environmental loading is more severe, and if non-heave optimized structures such as barges, semi-submersibles or FPSOs are employed, the SCR design can be far more taxing. These developments often tend to push the SCR towards its limits, and hence far more detailed and complex analyses are required such as elasto-plastic analyses and extensive fatigue assessments to consider effects such as soil interaction and damage spreading. In addition, when the designs are marginal, the ability of the riser system to accommodate variations is limited, and hence extensive re-work can be required if alterations in design parameters occur during the detailed design phase. The SCR can also be subject to design uncertainty regarding some key parameters such as seabed properties and the as-installed riser configuration. These parameters may have a significant impact on the overall system response, and hence the riser must be designed to accommodate the expected range of variation. This can be difficult for an already marginal riser system.

To overcome these difficulties and uncertainties alternative riser configurations can be considered, including systems such as a Lazy-Wave SCR. The response of a lazy wave SCR is significantly less dependant on soil interaction than that of a simple catenary SCR, and hence any uncertainties associated with soil conditions and trenching are less critical for such a design. However, it is noted that a lazy wave SCR may be subject to other problems such as large deflections under extreme current loading and installation difficulties due to the buoyant sections of the riser. In addition, a lazy-wave SCR design has not been sanctioned for use on a development to date.

The design of the SLOR involves a greater emphasis on detailed component design than for the SCR, while the extent of the global analysis required can be reduced. The location of the buoyancy can

below the wave zone, and the use of the flexible jumper to decouple vessel motions from the riser body greatly reduces the system dynamic response, producing a robust riser design, and allows the SLOR to be used on developments subject to severe environmental loading and with non-heave optimised vessels. In addition, the elevation of the buoyancy can is able to be adjusted such that it is not located in a region of high current which can be critical for developments subject to extreme currents such as loop currents. The robust design also allows the riser to be conservatively analysed, and allowances for design changes and uncertainties to be included upfront in the design process, thus giving greater confidence in the overall system design than for an SCR.

It is acknowledged that the design of both SLORs and SCRs are also dependent on the limitations of certain components in the riser system such as the flexible jumper for a SLOR, or the flexible joint for the SCR. Both of these components can be limited by parameters such as pressure, temperature and diameter, and many recent developments are pushing the limits of the current technologies. This is particularly true for the SLOR, which can feasibly be designed for very high pressures and large diameters, but may ultimately be limited by the capabilities of the flexible jumper.

While the selection of a riser system for a development is influenced by many factors, the technical suitability of a riser type for a particular development should always remain a primary consideration. SCRs can be designed to be acceptable for many of the new West African and Gulf of Mexico developments, however it should be noted that in some cases the designs are approaching the limit of feasibility. While this is not necessarily a problem, it does mean that the efficiency of the design process is reduced, and the ability to accommodate variations in design parameters is compromised. Although the SLOR requires a greater degree of detailed component engineering, this is often only required for one riser, with the design then duplicated for other risers. This produces a robust and flexible design, allows the risers to be designed with confidence, and avoids the need to undertake a complex analyses that require an accurate definition of design input parameters.

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