The Grouped SLOR - Design & Implementation

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Nigeria Oil and Gas, Abuja
Feb. 2007
ABSTRACT

Large deepwater developments typically have a complex and congested seabed layout immediately adjacent to the production vessel. This is due to the large number of risers and umbilicals often required to meet production and export requirements and the spatial constraints imposed by mooring lines and vessel offsets. This poses significant constraints on the riser design to achieve an acceptable riser arrangement whilst ensuring that clashing and interference is avoided.

The freestanding hybrid riser, in both the bundle and single line arrangements, is a configuration that has been widely used in West Africa. It has been selected due to its excellent fatigue performance, the decoupling of the vessel motion via jumpers and the ability to be pre-installed, thus taking this activity off the critical path. However, both the bundled hybrid riser and the Single Line Offset Riser (SLOR) have field layout problems: The bundled riser, whilst able to efficiently incorporate 10-12 lines in a single structure, poses practical problems at the bottom and top ends where connections need to be made to flowline and flexible jumpers respectively. Due to the large number of lines terminating in a small envelope the problem is how to acceptably route flowlines and their associated jumpers, whilst accommodating pipe expansion, movements and installation tolerances and further compounded by thermal and other flow assurance issues. Similarly at the top end, the offtake of dynamic flexible jumpers to the vessel can be challenging to achieve an acceptable arrangement that both facilitates installation and prevents clashing during operation.

The field layout challenge presented by the SLOR is primarily as a result of its large deflections as a result of current loading. This requires each SLOR to have a large spatial clearance with the adjacent SLOR, mooring line or umbilical. So whilst the SLOR facilitates easy access, at the top and bottom end, for connection of jumpers the maximum number of SLORs that can be accommodated within a given field layout is often limited and insufficient to meet initial and future project requirements.

This paper provides an introduction to the Grouped SLOR, a riser solution that is developed specifically with a view to optimize the riser/vessel interface and seabed layout. It uses a buoyant frame to guide the freestanding risers which constrains all risers to move collectively and this effectively eliminates the risk of clashing. As the riser spacing can be greatly reduced compared to a conventional SLOR, the arrangement allows seabed real estate to be optimized without losing the many benefits of the freestanding riser concept.

The Grouped SLOR is discussed and compared with current riser solutions from component level, up to the technical and operational advantages of the system and on to its application in a typical West of Africa deepwater development.

INTRODUCTION

2H Offshore has had tremendous success with its standalone hybrid riser concept, the SLOR. Operators have successfully fabricated and installed the SLOR, as well as its pipe-in-pipe variant, the Concentric Offset Riser (COR) in deepwater developments offshore Africa and recently offshore Brazil. The SLOR offers an attractive solution due to its excellent fatigue performance and ability for pre-installation, thus taking it off the critical path.

Recently, new developments with larger riser counts and the need for tiebacks to existing developments have been identified and these requirements pose significant problems as previously outlined. The problem is further compounded by use of turret moored FPSO which further decreases the available riser porch spacing, as shown in Figure 1.
In order to meet the riser requirements of large offshore developments, 2H Offshore have developed the Grouped SLOR concept, a variant of the SLOR and COR design which incorporates a guide frame connecting between 2 or more risers (typically 4-6) constraining them to move collectively and ensuring positive separation.

This concept is shown in Figure 2 and Figure 3 where the frame assembly can be seen in more detail.

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**OVERVIEW OF THE ORIGINAL SLOR DESIGN**

The original SLOR arrangement consists of a rigid steel riser pipe extending from the mudline to a buoyancy can situated 50-100m below the mean water line. The buoyancy can provides upthrust which applies tensile loading to the riser pipe and generates an overpull at the mudline of between 50 and 150Te. The gooseneck and flexible offtake can be located either above or below the aircan depending primarily on installation strategies. The aircan can be connected to the riser either using chain or a flex element or if the offtake is above the aircan the riser pipe can be routed through the bore of the aircan and terminated at the upper bulkhead.

The SLOR is generally situated 100-500m away from the vessel or turret depending on depth. Connection between the two is achieved using a flexible jumper via a steel gooseneck assembly connected to the top of the riser pipe. This can be seen in Figure 3. The flexible jumper is then connected to the vessel through an I-tube assembly with adequate bend stiffeners to minimize fatigue damage.

The bottom assembly of the SLOR is connected to a foundation pile (suction, driven or drilled) and terminated with an offtake assembly that facilitates connection to the flowline with a rigid jumper. Connection to the foundation pile is achieved via a roto-latch (or other articulation) or a stress joint.

The COR design follows a similar design to the SLOR except the design incorporates a pipe-in-pipe configuration. The outer annulus is then used for gas lift purposes and as such the COR is only usually used for production risers. To achieve this, the upper assembly is modified to incorporate a smaller gooseneck with access to the annulus so that gas can enter the COR via a flexible jumper attached to the vessel and inject into the production flow at the base of the riser through a gas lift crossover forging.

These SLOR and COR arrangements have already been successfully utilized on projects in West Africa with further applications planned in the coming years.

**GROUPED SLOR – OVERVIEW**

The Grouped SLOR, which has been referred to as an open bundle hybrid, configures a large number of lines in close proximity but without clashing and maintaining a practical distance between each riser to facilitate installation, inspection and maintenance, including removal and reinstallation if necessary.

A typical Grouped SLOR arrangement is illustrated in Figure 4.

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**FIGURE 2 – GROUPED SLOR (6-RISER ARRANGEMENT)**

**FIGURE 3 – GROUPED SLOR FRAME DETAIL**
Grouped SLOR Arrangement

The individual SLOR design is similar to the standard freestanding arrangement, with the riser pipe running through the central bore of the aircan (as shown in Figure 5). The main modification is the elongated large diameter upper stem between the top of the aircan and the gooseneck connector. This is used to guide the riser at the guide frame elevation. The riser pipe is terminated at the top of the stem and it is at this point that the aircan upthrust is transferred to the riser string.

The aircans are typically 5-6m in diameter, with a centre-to-centre spacing of 2 diameters when connected with the frame, giving a 1D air gap between them. The length of each aircan depends on the water depth and required overpull, but for a mid-depth development with 150Te SLOR base tension, the aircan length will vary from 10-25m depending on riser purpose and diameter.

To aid installation, the gooseneck is designed to be removed and attached after the SLOR and guide frame have been installed. This allows the flexible jumper to pass over the top of the guide frame, optimizing the allowable space and increasing the overall stability of the system.

A section of the SLOR aircan with stem attached is given in Figure 5.

Guide Frame

The guide frame is the component that differentiates the Grouped SLOR from the standalone SLOR design.

The guide frame is fabricated from steel tubulars in a truss arrangement to make it relatively lightweight and easily installable using a light duty vessel. For the 4-SLOR group configuration shown in Figure 4 the frame is approximately 45m long, with a central bolted connection such that the frame can be handled in 2 sections if required.

Connection to the seabed is achieved using spiral strand steel tethers connected to either end of the frame. These are splayed out below the frame to resist frame rotation and are connected to the mudline using suction piles via a length of chain connected to the tethers and terminated at the top of the piles. The chain aids installation as it allows the height of the frame and level of the frame to be modified to account for inaccuracies from pile installation.

Although the frame tubulars provide buoyancy when installed, additional buoyant tanks are welded to the top of the guide frame at either end of each half. The tanks,
which can be sealed air tanks or syntactic foam filled, are configured such that typically 50Te of overpull are maintained at the base of each tether at all times. The buoyancy tank arrangement allows the frame to be towed out to the field in two halves if required.

The risers are held within the frame using a receptacle with gates bolted onto the front of the frame. These include a central opening which allows two arms to swing open to accommodate the riser guide stem, these are then swung closed using an ROV and locked using a pin.

The riser stem slides within the receptacle relative to the frame to account for vessel movement, temperature and pressure effects, and also different stages of the installation process. The inner surface of each receptacle is equipped with an ultra-high molecular weight polyethylene (UHMWPE) bearing pad to resist wear over the duration of the field life.

Since the receptacles are bolted to the frame, they can be easily replaced if required without disturbing the adjacent risers.

A schematic of the frame is shown in Figure 6, with a detailed view of the riser receptacle in Figure 7.

![Schematic of the frame](image1)

The majority of the SLOR and Grouped SLOR components share their design with well proven Spar and top tensioned riser designs.

The keel joint and keel ball operate in the same way as the keel joint at the base of a spar truss where large bending loads are found, and the aircan itself is designed in the same way as a spar TTR with the stem running through the aircan, albeit slightly scaled down.

Further similarities are seen in the frame receptacle assembly, where the sliding of the wear stem mirrors the upper stem design of a spar riser and also the interaction of the riser with the spar truss heave plates.

**ANALYSIS**

**Finite Element Analysis**

Grouped SLOR structural analysis shows that the system is more stable than a standalone SLOR or COR, which have already been proven to be excellent in fatigue and operational performance. The maximum displacement of the guide frame is typically less than 2% of the water depth, and the greatest bearing load on the guide frame is typically less than 10Te. This is well within the bearing capacity of the UHMWPE wear pads.

The Grouped SLOR response depends greatly on the arrangement of the SLORs within the frame and their service conditions. It is therefore recommended that pairs of risers with similar requirements are installed opposite one another. For example, if a field has two 10in production risers, and a 10in gas injection and 10in water injection riser, it would be preferable to put the two production risers in the middle of the frame, and the two injection risers on the outside, or vice versa, such that the frame loads are relatively balanced. The relative stiffness of the risers along with the weight of their flexible jumpers then settles the frame into its static position.

**Computational Fluid Dynamics (CFD)**

The hydrodynamic stability and proximity of the riser air cans to one another within the group are critical in ensuring the system remains stable. In light of this, CFD analysis was conducted to ensure the hydrodynamic coefficients used in finite element analysis are appropriate. The CFD analysis results confirmed that the maximum drag coefficient experienced by the air cans is less than 2.0, assuming an infinitely long air can. In reality the air cans are typically a maximum of 6 diameters in length and therefore the end effects reduce this maximum value (as confirmed during tank testing detailed below). Snapshots of the CFD analysis are given in Figure 8, along with the drag parameters obtained in Figure 9.

The flow interaction and vortex-induced loading measured from CFD analysis concludes that air can spacing of one diameter gives the best response in terms of VIV activity, galloping and use of space. Due to the simplistic design and relative low-cost of the guide frame, the air can spacing can easily be increased for developments where high extreme currents are seen.

![CFD analysis snapshots](image2)
MODEL TESTING

In order to confirm the hydrodynamic response of the aircan arrangement, scaled tow tests were conducted at MARIN’s test center in Holland.

The tow tests were conducted for a range of current velocities typical of a development in the Gulf of Mexico or offshore Africa with aircan spacing ranging from 0.5 diameters to 2 diameters representing full scale spacing of 3m to 12m respectively.

Tow testing results indicated that as a result of aircan end effects and the variability of the aircan lengths, the maximum drag coefficient likely to be experienced is approximately 1-1.5 with an aircan spacing of 1D. This is less than the value of 2.0 used for finite element analysis. Finite element analysis confirmed that in order to generate clashing between the aircams, the required drag coefficient for a spacing of 1D is 16.0.

It can therefore be concluded that the SLORs within the group remain stable under extreme current activity with no chance of clashing.

Further system tank tests are likely to be conducted in the near future to confirm the response of the entire system to wave and current loading.

A photo of the tank testing arrangement is given in Figure 10.

FABRICATION

The majority of the Grouped SLORs components are welded and thus can be fabricated on-shore prior to installation. The aircan, frame and bottom assemblies in particular offer substantial fabricated assemblies and offer commercial benefits as local fabrication sites can be used. This is of particular benefit to developments off Africa, where politics and the requirement for local content can be an important driver.

INSTALLATION

The Grouped SLOR installation procedure has been developed in conjunction with Subsea7.

Foundations

The single suction pile required for each SLOR foundation, and the two smaller suction piles required for each guide frame, can be installed from an anchor handling vessel. The foundations are positioned such that the SLORs splay out at the seabed, increasing the 5m or so spacing at the frame to approximately 25m spacing at the seabed. This increases rotational stability as well as allowing for suction pile relocation if required (analysis shows that the group is not compromised if a riser base needs to be repositioned).

Frame Installation

The frame can be installed prior to or after the SLORs are installed. The frame can be towed out from an anchor handling vessel or lifted off the back of a barge.

Once the frame is in the water, the tethers and lead chain are attached and a ballasting chain is attached between either end of the frame and the vessel crane. The descent of the frame is controlled using the length of
chain released until the required depth is achieved and an ROV is used to connect the chain to the suction pile. Since the buoyant tanks are sealed, there is no requirement for additional ROV intervention and the ballast chain can simply be released from the frame.

**SLOR Installation**

The SLOR (or COR) can be installed using either J-Lay, reel-lay, or towed out. For J-lay and reel-lay, the bottom assembly is welded to the bottom of the riser pipe, then the riser is either welded in double joints and run in, or reeled off a spool until the aircan keel joint is reached. This is then welded onto the riser pipe and subsequently the final riser joints and wear stem connection.

The riser is then hung off to the side of the moonpool and the aircan and wear stem are flanged together. The riser is subsequently threaded through the aircan stem and connected at the top to integrate the two assemblies.

In order to land the SLOR onto the pile at the mudline, two methods can be employed. The first method involves allowing the aircan to free-flood as the riser is lowered, supporting the riser on the vessel crane until it is within the proximity of the suction pile connection. A pull-down assembly can then be used to latch the SLOR into the pile, and subsequently an ROV pumps inhibited nitrogen into each aircan compartment, driving out the water and increasing the tension within the riser pipe until all of the compartments are filled and the required base overpull is reached.

If the vessel crane capacity is not high enough to support the weight of the riser and flooded aircan, a number of compartments can be designed to withstand the collapse loads incurred at its operating depth. These compartments remain air filled for the duration of the installation and are equalized using ROV once installation is complete. The additional buoyancy generated then assists the installation process.

In order to descend the riser whilst these compartments are aired-up, a chain can be connected to the top of the aircan and also to the vessel crane. By trimming the length of chain released, the descent of the riser can be controlled until it is latched at the base, after which an ROV is used to fill each compartment and equalize the pressure differential in the air-filled compartments before finally releasing the crane.

At this stage, the SLORs and frame are freestanding, as shown in Figure 11. The separation is dependant on the water depth. To reduce the risk of clashing between the frame tether and SLORs a separation of 10% of the water depth or greater is recommended - this has the benefit of allowing greater riser splay to be achieved with deeper waters.

Using a winch or chain in conjunction with a guiding channel on top of the frame, each SLOR is then pulled into the frame and an ROV is used to assist the guidance of the riser stem into each receptacle gate. The ROV then closes each gate and inserts a pin to lock it closed.

The ease of installation of the SLORs into the frame allows for safe removal of risers if servicing is required. This defines one of the major advantages of the Grouped SLOR compared to a hybrid tower, where lines embedded in buoyancy are not readily serviceable and additional lines must be considered for redundancy, adding weight. In the case of the Grouped SLOR, risers can be removed from the frame and unlatched at the base at any time during their operating life and replaced. This offers additional benefits during field decommissioning, since each riser can be removed in one piece and dismantled on shore.

**Flexible Jumper Installation**

Once each SLOR is installed in the frame, the flexible jumpers are installed. The pre-installable benefit of the Grouped SLOR is then apparent. By installing each SLOR and frame and creating the Grouped SLOR arrangement without the flexible jumper, the system can all be put in place prior to the arrival of the FPSO, thus taking the riser off the critical path.

The gooseneck with flexible jumper connected is finally lowered using a vessel and an ROV to activate the connector. The flexible jumper is then reeled out and passed to the FPSO where it is pulled in to the I-tube and terminated. The final Grouped SLOR arrangement is illustrated in Figure 12.

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FIGURE 12 – FULLY INSTALLED GROUPED SLOR

The Grouped SLOR design offers significant FPSO weight and operational benefits compared to other free hanging arrangements. The FPSO is only required to support the weight of the flexible jumper as the riser is self-supporting, thus increasing the available FPSO deck capacity. The de-coupling of the vessel with the riser via a flexible jumper also results in increased riser stability during storms or other events that increase the vessel motions.

MONITORING

The behavior and operating state of the Grouped SLOR system can be monitored at low cost using load sensors and inclinometers.

Since the air can wear stem remains in compression during operation, the level of strain in the stem member can be monitoring for fluctuations and reductions, indicating a loss of tension and possible air can leakage.

By mounting load sensors around the perimeter of the stem, the strain differentials can also be used to monitor the bending loads in the stem, providing an indication of the fatigue imposed on the system and also the offset of the frame.

Furthermore, inclinometers mounted on the guide frame can monitor the loss of a frame tether or depressurization of a buoyancy tank - giving an indication of the integrity of the system and if necessary allowing repairs to be carried out expeditiously.

Due to the proximity of the Grouped SLOR to the vessel, the monitoring system for an entire group can be connected in parallel and data can be sent back to the vessel using an acoustic modem on the riser frame and receiver situated just below the water surface at the FPSO.

The topside monitoring system is detailed in Figure 13 and the Grouped SLOR sensors and data-relay system is shown in Figure 14.

FIGURE 13 - TOPSIDE MONITORING SYSTEM

FIGURE 14 - GROUPED SLOR MONITORING SYSTEM

CONCLUSION

The Grouped SLOR riser system provides a well developed and attractive riser solution for fields where space is limited, but high productivity is paramount. It offers all the benefits of the freestanding SLOR, whilst incorporating the multi-line advantages of the hybrid bundle without adding to the complexity of the subsea

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layout, improving both flowline routing and the capacity for future tie-ins.

The combination of design flexibility and operational and fatigue performance makes the Grouped SLOR a potential solution to any medium-depth to ultra-deep development.

ACKNOWLEDGEMENTS

2H Offshore wish to acknowledge Subsea7 for their assistance in the development of the installation procedure for the Grouped SLOR and their funding of the tank testing of the aircan arrangement.

2H Offshore also thank MARIN for their expertise and assistance with the arrangement of the tow testing program.

2H Offshore is a specialist engineering company serving the deepwater oil and gas industry. 2H Offshore, an Acteon company, provides deepwater riser engineering from conceptual design through product supply to life of field integrity management. This “design | supply | manage” approach is the hallmark of 2H and makes it a complete riser provider.