Grouped SLOR Deep Water Riser System and Installation Assessment

S. Hatton, N. Dale - 2H
J. Mair, D. Karunakaran, D. Lee - Subsea 7

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Daniel Karunakaran, Dan Lee, Subsea 7
Stephen Hatton, Nick Dale, 2H Offshore Engineering Ltd
John Mair, Subsea 7

Abstract

The growing trend of deep and ultra deepwater developments necessitates the use of risers that will give good stress response and fatigue performance, and be able to optimise field architecture to accommodate complex and congested seabed layouts. In order to achieve this, Subsea 7 and 2H Offshore have developed the Grouped SLOR™, a hybrid riser solution which captures the above stringent riser requirements and maintains maximum operability in deepwater developments at water depths greater than 700m.

The Grouped SLOR consists of individual free standing risers, SLOR™ and/or COR™ grouped together by a buoyant guide frame tethered down at either ends to suction piles. Connection between the vessel and the SLOR™ or COR™ is provided by a flexible jumper from a gooseneck located at the top of the riser assembly.

The paper describes the technical development, key features of the riser system, and the design and analysis work carried out. It also focuses on the various methods of installation, namely towing, J-laying and reel laying of the Grouped SLOR. The results obtained from the analyses, i.e. riser stress response, fatigue and loadings, along with computational fluid dynamics of the air can assemblies, are discussed to prove feasibility of the system and to gain confidence in the installation strategies.

Introduction

Grouped SLOR™ is an ‘open bundle’ riser solution developed specifically to optimise the riser/vessel interface, production vessel approaches and seabed layout[1]. It uses a buoyant truss frame to guide the freestanding risers, constraining all risers to move collectively, and thus eliminating the risk of clashing.

The Grouped SLOR has great potential for large deepwater developments, which typically have a complex and congested seabed layout immediately adjacent to the production vessel. This is due to the large number of risers and umbilical often required to meet production and export requirement, 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 are avoided. In addition, the fatigue requirements, stringent insulation and gas lift requirements (use of concentric riser system) greatly favour the use of Grouped SLOR.
One of the benefits of the Grouped SLOR system is the flexibility of installation. The riser buoyant guide frame and its associated components (e.g. buoyancy tanks, tethers, etc.) can be towed out or transport by barge, and preinstalled on site prior to receiving the riser system. The SLOR (including COR) system can be subsequently installed by either towing, J-laying or reel laying. Once the individual SLOR/COR is installed in the guide frame via the receptacle, the flexible jumper is installed. The jumper can either be clamped onto the SLOR/COR while waiting for the arrival of the production vessel or “hook up” to the vessel by pulling it into the I or J-tube and terminated.

**Grouped SLOR Concept**

SLOR and COR are trademarks of 2H Offshore Engineering Ltd (2H), and Subsea 7 is in collaboration with 2H to develop and launch the Grouped SLOR so that they can offer it as a SURF (subsea umbilical, risers and flow lines) solution for deepwater field developments.

2H has had tremendous success with its standalone hybrid riser design, the Single Line Offset Riser (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/COR offers an attractive solution due to its excellent fatigue performance and ability for pre-installation, thus taking it off the field development critical path.

Recently, new field developments with larger riser numbers and existing developments with the need for additional tiebacks have been identified, and these requirements pose significant problems for SLOR/COR systems due to clashing issues. The problem is further compounded by use of turret moored FPSO which further decreases the available riser porch spacing as shown in Figure 1.

![Turret Moored FPSO with SLOR™](image)

In order to meet the riser requirements of large offshore developments, Subsea7 and 2H have jointly developed the Grouped SLOR concept. This is 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 as depicted in Figure 2. Details of the Grouped SLOR arrangement riser guide frame assembly are illustrated in Figure 3.
SLOR and COR Design

The SLOR arrangement consists of a rigid steel riser pipe extending from the mudline to an air can situated 50-200m below the mean sea level depending on environmental loading conditions. The air can provides up thrust which applies tension to the riser pipe and generates an over pull at the mudline of between 50Te and 150Te depending on water depth. The gooseneck and flexible off-take can be located either above or below the air can depending primarily on installation strategies. The air can can be connected to the riser either by chain or a flex element. Alternatively, if the off-take is above the air can the riser pipe can be routed through the centre of the air can and terminated at an upper bulkhead.

The SLOR is typically situated around 100m away from the vessel or turret depending on water depth. Connection between the two is achieved using a flexible jumper via a steel gooseneck assembly connected to the top of the riser pipe as illustrated in Figure 3. The flexible jumper is then connected to the vessel through an I-tube or J-tube assembly with bend stiffener.

At the base, the SLOR is connected to a foundation pile (suction, driven, gravity or drilled) and terminated with an off-take assembly that facilitates connection to the flowline with a rigid spool. Connection to the foundation pile is achieved via a roto-latch (articulation joint) or a stress joint.

The COR design follows a similar design to the SLOR except that the design incorporates a pipe-in-pipe configuration. The outer annulus is used for gas lift purposes, and as such the COR is usually used for production risers. 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. COR is extremely useful if the development requires a gas lift riser adjacent to the production riser. COR can also be used to meet stringent thermal requirements having a high thermal mass and excellent insulation capability achieving long cool down durations.

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

Grouped SLOR Design

The Grouped SLOR consists of a number of risers in close proximity which eliminates clashing issues, whilst maintaining a practical distance between each riser to facilitate installation, inspection and maintenance, including removal and reinstallation if necessary. The individual SLOR/COR is connected into the guide frame assembly via the receptacle as shown in Figure 6.

Grouped SLOR Arrangement

The individual SLOR/COR design is similar to the standard freestanding arrangement, with the riser pipe running through the central bore of the air can, as shown in Figure 4. The main modification is the elongated large diameter upper stem between the top of the air can and the gooseneck connector, similar to that used on a SPAR riser. This stem interfaces with the guide frame via a bearing assembly. The riser pipe is terminated at the top of the stem transferring the air can up thrust to the riser string resulting in tension on the riser.
The air cans are typically 5 to 6m in diameter, with a centre-to-centre spacing of 2 diameters when connected with the frame, giving a 1 diameter air gap between them. The length of each aircan depends on the water depth and required over pull but for a mid-depth development with 150Te SLOR base tension, the aircan length will vary from 10 to 30m depending on water depth, 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, optimising the allowable space and increasing the overall stability of the system.

![Figure 4 Grouped SLOR Aircan Assembly](image)

**Riser Guide Frame**

The guide frame depicted in Figure 5, is the component that differentiates the Grouped SLOR from the standalone SLOR/COR design. It is fabricated from steel tubular in a truss arrangement to minimise its in water weight and maximise its stiffness. It is installable using a light duty vessel or simply towed to site. For the 4-SLOR group configuration shown in Figure 3, the frame is approximately 45m long with a central bolted flange connection, such that the frame can be handled in 2 sections if required.

Connection to the seabed is by spiral strand steel tethers connected to either end of the frame. These are splayed out below the frame to provide stiffness to resist rotation during operation. The tethers 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 as shown in Figure 10. The chain aids installation as it allows the height of the frame to be easily adjusted during installation to account for inaccuracies from pile installation.

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Although the frame tubular provide buoyancy when installed, additional buoyant tanks are attached to the top of the guide frame at either end of each half as illustrated in Figure 5. The tanks, which are sealed air tanks or syntactic foam, are configured such that typically 50Te of over pull are maintained at the base of each tether at all times.

The risers are guided within the frame using a receptacle with a swinging gate which is bolted on to the front of the frame as depicted in Figure 6. 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, temperate 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.
**Riser In-Place Analysis and Model Testing**

Finite element (FE) analysis is performed to confirm the stability and arrangement of Grouped SLOR configuration. Computational fluid dynamics (CFD) is also carried out to confirm that the hydrodynamic coefficients employed for the FE analysis are appropriate. A model test campaign was carried out to confirm the CFD results and the hydrodynamic response of the air can arrangements under extreme current loading conditions.

**In-Place Analysis**

FE analysis on the Grouped SLOR shows that the system is more stable, with lower displacements 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 under normal operating condition is typically less than 2% water depth for deep water environment (800m) and increases to 6% water depth for ultra deep water environment (2000m). This reduction is due to the difference in geometry configuration from 800m to 2000m and will not be an issue as the guide frame is typically 100m away from the vessel.

The greatest bearing load on the guide frame is less than 10Te for a water depth of 2000m, which is well within the bearing capacity of the UHMWPE wear pads. For a lower water depth of 800m, the maximum bearing load is around 6Te.

The guide frame rotation for a deep water development of 2000m under normal operating condition is less than 1.5 degree. Considering the most unstable installation configuration, whereby only one SLOR is installed, the rotation increases to around 25 degree, however this will not affect the stability of the frame. Lower frame rotation is expected for a shallower water depth development.

The Grouped SLOR response depends greatly on the arrangement of the SLOR/COR within the frame and their service conditions. It is therefore recommended that pairs of riser with similar requirements are installed opposite one another. 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 ensures that the frame remains balanced and stable at all times.

**Computational Fluid Dynamics**

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 (Cd) 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 7, along with the drag parameters obtained in Figure 8.
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 vortex induced vibration (VIV), wake effects and galloping. 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 observed.

![CFD Velocity Vectors Around Air cans](image)

**Figure 7** CFD Velocity Vectors Around Air cans

![CFD Analysis of Air Cans, Mean Transient Drag Coefficients](image)

**Figure 8** Mean Air can Drag Coefficients

**Model Test**

In order to confirm the hydrodynamic response of the air can arrangement, scaled tow tests were conducted at MARIN’s test center in Holland. The tow tests shown in Figure 9 were
conducted for a range of current velocities typical of a development in the Gulf of Mexico or offshore Africa with air can 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 air can end effects and the variability of the air can lengths, the maximum Cd likely to be experienced is approximately 1 to 1.5 with an air can spacing of 1 diameter (D). This is less than the Cd value of 2.0 used for finite element analysis. Finite element analysis confirmed that in order to generate clashing between the air cans, 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 possibility 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.

![Figure 9 Grouped SLOR Tow Model Test](image)

**Installation Assessment**

To confirm the flexibility and feasibility of installing the Grouped SLOR system by towing, reel laying and J-laying, Subsea 7 has carried out detailed installation strategies as depicted in Figure 10 and Figure 11, coupled with installation analysis as illustrated in Figure 13 to Figure 15. The results confirm that the three methods of installation are feasible with stress and fatigue within allowable limits. The analysis results also define the installation window, rigging arrangements, and vessel and crane requirements.
Figure 10  Installation of Grouped SLOR Frame

Figure 11  Mating SLOR/COR with Buoyant Frame
**Foundation Installation**

The single suction pile required for each SLOR foundation and the two smaller suction piles required for each guide frame can be installed from either Subsea 7’s vessel or a local support 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 stability as well as allowing for suction pile relocation if required. The 25m spacing allows for ease of installation of flowline PLETS and rigid jumper spools and avoids the congestion typically associated with hybrid riser bundles where the riser base is heavily congested.

**Guide Frame Installation**

The guide frame complete with buoyancy tanks, riser stem receptacles and tethers as depicted in Figure 5 will either be towed out to site or lifted off at the back of the barge.

The foundation piles, typically suction piles, for the tethers are preinstalled using installation vessels by transporting to site and upending as shown in Figure 12.

Once the guide frame is at the required position, it is lowered into the water by the main crane (if it is brought in by barge). The tethers, lead chain, ballasting chain and other necessary riggings are subsequently attached on the guide frame from the installation vessel and tug boat, in preparation of lowering the frame to the specific depth (typically between 50m to 200m below mean sea level). The descent of the frame is controlled using the length of the ballasting chain until the required depth is achieved, and an ROV is used to connect the tether with chain attachment to the suction pile as illustrated in Figure 10. 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.
**Towing of SLOR/COR**

The towing method is divided into three operations, i.e. surface tow to the field location, followed by removal of the buoyancy modules as depicted in Figure 13, and finally the upending operation in stages, with the final stage illustrated in Figure 14.

The surface tow operation requires either one or two tug boats depending on environmental conditions and tug boat limitations. It has the main advantages of assembling, inspection, checking and testing the complete SLOR or COR system on the spool base (or assembling base) before loading out. This significantly reduces the overall cost on installation by saving on vessel time, riser assembling, welding and testing as compared with J-lay and reel lay. Subsea 7 has the added advantage of bundle towing knowledge which will add confidence to the project. The additional fabrications, such as buoyancy modules and piggy-back blocks, all of which being recyclable, will also be highly favourable in terms of the local content contractual agreement.

The disadvantages of this method of installation are the tug boat, rigging and buoyancy module requirements, and the location of the spool base relative to the installed field location. Planning of tow route access has to be carried out and clearance obtained from the port authority.

![Figure 13 Surface Tow Operation Followed by Removal of Buoyancy Modules](image-url)
J-Laying of SLOR/COR

Subsea7’s Seven Seas installation vessel will be employed for J-laying the SLOR/COR system by lowering the riser system through the moonpool using the abandonment and recovery (A&R) wire. Cross-haul operation is subsequently carried out to transfer the riser system to the side of the vessel by utilising the main crane and auxiliary crane as shown in Figure 15. Supply boat is required to bring the pipes and components onto the vessel.
The riser assembly will be constructed by welding the double-joint pipes and associated components. Welding, field joint coating, non destructive test (NDT), anode attachment, etc. are carried out on the vessel, which will impact the installation time. Installation of the COR system will add to the complexity of this method of construction.

The main advantage of J-laying is that the installation field is not restricted to the location of the spool base, which may influence the riser stress and fatigue. No route access is required from the port authority. The main disadvantages of this method of installation are the time taken and associated cost to assemble the riser system.

Analysis carried out shows that optimisation of the riser system to obtain an effective tension of the order of 90Te for the COR system is required to avoid snatch load (compression) on the A&R wire.

**Reel Laying of SLOR/COR**

The reel lay operation is carried out using the Seven Oceans installation vessel, similar to a steel catenary riser (SCR) installation operation, except with the attachment of complex components like bottom and top assemblies, air cans, etc. with the help of a support vessel.

The pipelines are assembled on the spool base and reeled, complete with field joint coating, non destructive examination (NDE), qualification assessment and checks and other pre-commissioning requirements.

Reeling assessment has to be carried out to ensure that the pipe wall thickness is within the allowable based on the project’s agreed specifications. No problems are envisaged for reel laying the SLOR. However, for COR (effectively a pipe-in-pipe configuration) system, additional precautions will be necessary to ensure the limits of the straighteners and tensioning system are not exceeded.

The main advantage is that assembling and reeling of the riser pipes can be carried out in a controlled manner, thereby reducing the risk of damaging the pipes and field joint. Fatigue is not envisaged to be an issue. There will be high usage of local content and manpower in the assembling and reeling the riser. The disadvantages are the deck storage space for the SLOR/COR components and the additional time taken to attach the upper and lower assemblies compared to a tow-out installation.

**Flexible Jumper Installation**

Once each SLOR or COR is installed in the guide frame via the receptacle, 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 production vessel (typically FPSO), thus taking the riser off the critical path.

The gooseneck complete with flexible jumper is then 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 or J-tube and terminated. The final Grouped SLOR arrangement is illustrated in Figure 2 and Figure 3.
The Grouped SLOR design offers significant FPSO payload reduction 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 and fatigue life, and reduced riser stress during extreme storm events.

**Installation Analysis**

Installation analysis is carried out based on irregular wave analysis with a significant wave height of 2.5m with varying wave periods. Different wave directions are analysed to help in defining the appropriate vessel headings.

**Towing**

Towing analysis carried out on the SLOR and COR indicates that the maximum riser stresses are less than 150 MPa with dynamic tension on the tug boat of around 20Te. The fatigue damage experienced during the tow operation is around 4% for the SLOR and 1% for the COR, based on an F2 fatigue details with a stress concentration factor (SCF) of 1.4, which are within the allowable 10% in accordance with DnV Standards[3,4].

The maximum riser stress obtained during the upending operations is less than 320MPa for both SLOR and COR, which is less than the allowable of 80% yield stress (based on typical API X65 steel grade). The maximum dynamic tension on the tug boat is less than 100Te.

**J-Laying**

J-laying operation initially carried out via the moonpool of the Seven Oceans, indicates that the abandon and recovery (A&R) line has to maintain a minimum tension of 40Te and 90Te for SLOR and COR respectively to avoid snatch loading. The resulting maximum von Mises stresses are around 60MPa for SLOR and 80MPa for COR, which are significantly less than the allowable.

The subsequent cross-haul operation for the SLOR indicates that the maximum riser stress is around 200MPa with corresponding auxiliary wire and crane wire experienced a dynamic tension of less than 30Te. The maximum riser stress experienced by COR is around 100MPa with a dynamic tension of less than 25Te obtained for the auxiliary wire and crane wire, which are therefore acceptable.

**Reel Laying**

Reel laying analysis indicates that SLOR and COR can be installed water filled without compromising on the capacity of the reel lay vessel’s (Seven Oceans) tensioners. However, for water depths greater than 2500m, it is recommended to install the riser empty.

The results of the analysis indicate that minimal stress is experienced during the reel laying operation. Critical stage of installation occurs during the connection of the aircan to the top assembly of SLOR/COR with a tether chain using a tug boat in close proximity to the reel lay vessel. The maximum tension tensions on the A&R wire and tug boat tensions are around 300Te and 30Te respectively. The riser did not experience significant stress due to the “hinge” connection of the aircan to the riser top assembly using a tether chain of around 45m.
**Flexible Jumper**

The flexible jumper complete with gooseneck and bend stiffener can be installed either by Subsea 7’s vessels, namely Skandi Neptune or Seven Seas. Analysis carried out indicates that the minimum bend radius (MBR) obtained does not compromise the allowable MBR, with minimal compression of less than 1Te. The dynamic tension on the crane is within its capacity.

**Conclusion**

The Grouped SLOR system is a well developed arrangement and provides an attractive riser solution to fields where space is limited, but high productivity is paramount. It offers all the benefits of the freestanding SLOR/COR, whilst incorporating the multi-line advantages of the hybrid bundle without adding to the complexity of the subsea layout, improving both flowline routing and the capacity for future tie-ins.

The combination of design and installation flexibility, stability, and operational and fatigue performance makes the Grouped SLOR a potential solution to any deep to ultra-deep development. In addition the high usage of local content and manpower favours the local content contractual agreement, making it the ideal riser solution for deepwater applications offshore West Africa.

**Reference**

4. DnV Rules for Planning and Execution of Marine Operations, Chapter 4, 1999.