Deepwater Risers – Historical Review and Future Projections

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Abstract

The objective of this paper is to present the historical development of installed riser systems from the earliest offshore installations to the current state of the art and into the future.

The paper describes the main driving forces during the riser design process and presents the evolution of riser technology in a range of different regions and describes the influencing factors behind each development and the propagation of technology around the world. Using graphical visualizations of an extensive dataset of installed riser systems, the paper breaks down the global trends in riser by type, size, water depth and market dominance.

Introduction

For any deepwater offshore development the riser system is a fundamental and technically challenging part of the project. Not only are the risers inherently dynamic, but lack of access and limited options for maintenance during the field life mean that usually the risers need to function and maintain their integrity throughout the whole life of the field. Even the general details of the riser design are generally defined quite late in the field development. Only after the geotechnical, geophysical and flow-assurance studies have been completed, as well as the FPSO capacity and type been defined does attention switch to how to connect the two together using a technically adequate and cost-effective riser system. As offshore developments have progressively moved into ever greater water depths and harsher environments, combined with increasing well pressures and temperatures, resolving that question has become an ever present and increasingly complex design challenge.

One could be forgiven for assuming that there would be "standardized" designs for risers in similar regions and water-depths, but whilst there is some truth in that idea, the riser solutions for offshore developments frequently show a surprisingly wide range of differences between projects, even for those in close proximity geographically. The differences are typically the result of the culmination of a number of driving forces, be these technical, commercial, political, schedule, contract strategy, operator preference or local content driven, to name but a few. There is no such thing as the "best" riser design, only the one which is most applicable to that development under those driving conditions – and at the specific time that the decision was made. This paper aims to describe those driving forces and review the range of different riser
designs geographically and how they have been influenced by these driving forces. Finally, the paper will make predictions on the future of riser design and the influencing factors involved.

**Principal Riser Types**

Although there are many diverse variations of riser design, for simplicity this paper will focus on the four most common types as shown in Figure 1.

![Figure 1—Four Main Riser Types](image)
These can be summarised as:

- **Unbonded flexible risers**: continuous lengths of pipe made up of a number of metallic and polymeric layers allowing pressure containment and tensile strength combined with relatively low bending stiffness. These pipes can be installed in several different configuration types, the most common of which are illustrated in Figure 1. They are produced and installed in continuous lengths by reel lay, although they may be made up of several sections of pipe joined by intermediate connectors at points along their length. They are typically smaller in diameter than rigid lines due to pressure and manufacturing considerations.

- **Top Tension Risers**: Vertical steel lines normally joined by threaded connections, used on dry tree production facilities on motion optimised vessels such as TLPs or Spars. The riser is tensioned either from the vessel with tensioners or independently by long buoyancy cans constrained within the wellbay. This type of riser has to be capable of resisting the full tubing pressure in case of a tubing leak as the well control (tree) is located at the top of the riser in the wellbay.

- **Steel Catenary Riser (SCR) and Steel Lazy Wave Riser (SLWR)**: Steel pipe sections welded into continuous lines and hung from the supporting vessel in a catenary configuration to connect wet tree developments to the production facility. Risers in this configuration can experience high levels of bending and fatigue at the hang-off and touchdown locations. Top tension, fatigue and storm performance can be improved by including buoyancy modules to support the line in a lazy wave configuration (SLWR).

- **Free-standing Hybrid Risers (FSHR, Bundled Tower, Buoyancy Supported Risers)**: Certain project requirements may use a hybrid system consisting of a combination of unbonded flexible pipe and rigid steel pipe. These may be a vertical rigid line or bundle supported by a buoyancy can, in the case of FSHRs or Bundled systems, or SCRs supported by a submerged pontoon in the case of the Buoyancy supported riser concept (BSR). Connection with the host vessel is made via unbonded flexible pipe jumpers that enables the steel riser response to be decoupled from vessel motions. Such systems produce excellent fatigue performance, but may be expensive to engineer, manufacture and install due to the large number of components installed.

**Design Drivers**

When considering design drivers for any riser system, it should be remembered that every development is different. A driver which is critically important for one development may not be for another and vice-versa. Consequently, it is not possible to compare the importance of each driver, only state the influences they may have on any given project and at what point in the design process they are likely to appear.

As illustrated in Figure 2, the final design will be driven both by the specific requirements of the development and the physical limitations of existing riser pipe. Whilst it is beyond the scope of this paper to describe any aspect in detail, the following sub-sections expand on these aspects for any given development.
Reservoir Characteristics
The properties of the reservoir itself are naturally a key input to the design process. Not only do they define the characteristics of the fluids to be conveyed by the riser system, but also the properties of the reservoir tend to be fixed, at least at the start of production, and must be designed around as changing them is not an option.

The reservoir will define the type of fluid the production risers will need to transport and whether that fluid is at high pressure, which will require thicker walled pipe, or corrosive, which will affect the selected material properties of the pipe. The fluid temperature and the presence of wax and hydrates will also define thermal insulation requirements. Other considerations regarding the flow of the fluid and whether engrained sands will cause corrosion, gas bubbles that cause slugging, or whether the fluid viscosity will require gas-lift or active heating are all defined by the reservoir.

The extent of the reservoir will define the number of wells and risers required, and also the best locations to place the wells and or manifolds, as well as defining the strategy for use of dry or well trees.

Production Vessel
The development location will define key aspects such as the water-depth and environmental loads the vessel will be located in. These influence the mooring system design and maximum offsets, as well as the dynamics of the vessel, which will be heavily influenced by the hull shape. Regions prone to hurricanes or icebergs may have requirements that allow the vessel to disconnect. The reservoir size, fluid properties, location and access to offloading lines will define storage and surface processing requirements as well as the payload requirements of the vessel.

Finally, as a particularly expensive and long-lead time, the decision needs to be made whether to start a new build or purchase an existing vessel on the market which may be adequate for the proposed development. Purchasing an existing vessel can produce economic gains in getting to first oil quickly, but the vessel is unlikely to be perfectly suited for the requirements of the reservoir.

Operator Aspects
Different operators have different preferences when it comes to riser design solutions. Previous experience, both good and bad, plus the number of employees within the company who have direct experience
with particular riser types also influence any decision. Knowledge of the key technical aspects such as whether to allow intermediate connections in flexible risers can exclude or include technologies for certain developments depending on the operator. Novel and unproven technologies consequently can face many additional difficulties in being sanctioned where previous experience and knowledge is limited.

Project timeframes and first oil targets may also exclude systems which will take a long time to produce, even if more expensive or technically superior.

Finally, contracting strategies regarding pricing and political influence can also have direct influence on the riser system chosen. Global oil prices also affect the decision as to whether to develop the field or not.

**EPIC Contractor Aspects**
Any riser system design ultimately needs to be installed and the installation phase has significant cost implications which depend partly on the types of vessel required from installation contractors. Some developments only require riser designs that can easily be installed by smaller and lower cost installation vessels, whereas others, particularly developments in deep water, require larger, more expensive vessels with greater tensioning and lifting capacities.

At the bid stage the different installation contractors will offer prices based on their specific fleet of vessels, their previous experience on similar projects and the combined knowledge and technological offerings of any consortium partners – which may also lead to alternative designs. Geographical presence and access to shore facilities also play a major role.

**Location**
Different countries not only have different offshore environmental conditions based on their location, but also different geopolitical goals, drivers and infrastructure.

For example, developments in the North Sea tend to be in shallow water whereas the Brazilian offshore market is almost entirely deep and ultra-deep-water. Gulf of Mexico developments need to be designed for hurricane conditions whereas the environmental conditions West of Africa tend to be benign.

The maturity of the oil industry and political conditions in a given country also influence the availability of access to trained personnel and equipment suppliers. Areas such as the North Sea and Gulf of Mexico can draw on a wide range of suppliers which are not as abundant in areas such as West Africa. In order to develop the local industry, governments may also apply local content and importation restrictions which may also radically influence different factors of the riser design.

**Environment**
As previously mentioned, the offshore conditions vary from region to region and directly affect the dynamics of the vessel the risers will be connected to. The directionality of the waves and currents, as well as their intensity can have a strong influence on the type of host vessel to use, and consequently the fatigue and extreme storm performance of the riser system.

Finally, the collapse resistance of the lower riser and flowline is driven by the maximum water depth the riser will be installed in.

**Rigid Steel Riser Capabilities**
Rigid risers are the most technically understood design and tend to be by far the cheapest solution per meter of pipe. Design and manufacture of rigid pipe is also well understood and relatively low cost, and inspection and repair are relatively straight-forward. Rigid pipe must be carefully designed to accommodate long term fatigue and extreme loading and may require flexjoints, titanium taper joints, buoyancy modules to induce a lazy-wave shape, or upset-ends to produce adequate performance. Installation payloads tend to be high and if the transported fluid is corrosive then internal coatings of corrosion resistant alloys may be required.

As rigid pipe must be manufactured in sections and welded together, the manufacturing and installation
process can be lengthy, but in the past decade the ability to reel steel pipe has enabled the installations cost to remain competitive with the flexible pipe alternatives.

**Flexible Riser Capabilities**
In comparison to rigid steel pipes, unbonded flexible pipes, made from steel and polymer layers, are considered to have good fatigue and strength performance. Although the manufacturing and design process is complex and expensive, as they are made in continuous sections they can be made and stored in reels at a fast pace once the factory is set up. Their adaptability to adjustments in the field layout and riser design throughout the design process is another advantage. In general, flexible pipes have greater limitations in regard to high temperatures and pressures in comparison to rigid solutions.

Flexible riser systems also tend to have high payloads and require additional protection in corrosive environments.

**Composite Riser Capabilities**
Whilst not yet in common use, the industry is starting to turn to composite pipe solutions for particularly challenging applications where traditional steel or flexible pipes are extremely challenging. Whether the principle composite material is carbon-fiber or glass-fiber, or whether it is an integral pipe or used as a material in the flexible pipe manufacturing process, composite risers have excellent performance in fatigue, strength, corrosion resistance, are very light weight and have a relatively simple manufacturing process. The materials are however expensive, and a lack of field proven applications restrict their market where cheaper and more widely used alternatives can still be proved to be viable.

**Development of Riser Design and Configurations**
The effects of the different design drivers mentioned above have produced a range of different riser design solutions which are detailed in this section. Note that the trends discussed are taken from a proprietary database of worldwide projects, which whilst comprehensive, may be missing some developments, and therefore the plots should be considered qualitatively.

**Historical Milestones**
**Figure 3** is a graphical representation of most offshore developments. The horizontal axis for shows the year of installation from 1981 to 2017 and the vertical axis shows the water depth the host vessel was installed in. The points are colored by riser type and solid lines join the maximum installed depth of each riser type over time. **Figure 4** shows the cumulative number of installed lines globally over time and their respective market shares.

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Early Shallow Water Developments. Focusing on the early offshore developments in the period from 1981 to 1994, developments were in water depths no greater than 300m and unbonded flexible risers were used almost exclusively. Their flexibility and ability to accommodate large dynamic motions of the production vessel in relation to the water depth make them the ideal solution for such developments. Typically, the host vessels were semi-submersibles or FPSOs in very shallow waters.

The First Top Tension Risers. Perceiving the requirement for a vessel type that could operate in a range of water depths and be stable in the harsh environments West of Shetland, Conoco Philips commissioned the Hutton TLP system which was installed in 1984 in 147m water depth. The Hutton TLP hosted the world's first Top Tensioned Risers, twenty-four 9-inch production risers and a single 9-inch export riser. The Hutton TLP remained the only Top Tensioned Riser System, until the Snorre Field was installed in 1992 in 335m
Progression into Deepwater. 1992 heralded the age of developments in water depths greater than 500m with the installation of the P-20 semi-submersible in 625m in the Marlin field offshore Brazil using unbonded flexible pipe. Subsequently, continued developments in flexible riser design produced unbonded flexible risers capable of use in ever greater water depths. Within only 5 years of breaking the 500m water depth barrier, several developments were being installed in water depths of 1000m.

Development of the Steel Catenary Riser. When the first SCR was installed by Petrobras on the P-18 semi-submersible in 910m water depth, it was not for lack of a suitable flexible solution but to test the riser concept for export lines on other upcoming projects. Once proven as a concept, SCRs were installed in ever greater water depths in a range of TLPs and Spars in the Gulf of Mexico. In only 6 years from the first SCR installation in 910m in 1994, SCRs were being installed in water depths of 1463m by the year 2000. Being cheaper to manufacture than unbonded flexible pipe, available in larger diameters and able to withstand high pressures, SCRs make a cost-effective option for large diameter export lines for most developments that do not utilize a FPSO.

Hybrid Systems. As discussed previously, hybrid systems combine both rigid and flexible pipe in their design, combining the cost and strength benefits of steel pipe in extreme water depths, and the fatigue performance and flexibility of unbonded flexible pipe in shallower water depths.

The first bundled hybrid riser operating with a floating vessel was designed by Cameron and installed in 1988 in the Green Canyon field, Gulf of Mexico. The riser was installed from the submersible production unit and located directly below it. Steel riser sections were mechanically joined and the riser weight in water was neutralized by buoyancy modules. This riser was later relocated to the Garden Bank field in 1994. Both fields ended up producing sand; the riser was decommissioned and not used again and is not shown in Figure 3 for that reason.

Figure 5—The Girassol Hybrid Riser Concept

The hybrid concept reappeared 2001 when a bundled flowline and riser solution was used on the Girassol development in Angola in 1400m water depth. The main driver for the use of bundled hybrid solution was that the Girassol reservoir is located relatively close to the seabed and the produced oil is at a relatively low temperature. With wells scattered over a large area and relatively long flowlines in water temperatures of around 4°C at the sea-floor, a high degree of thermal efficiency was required to ensure that the production fluid did not cool to a level where hydrates would form during shutdown conditions.

The level of thermal efficiency required could only be found by using an insulated bundled flowline and vertical riser section supported by a buoyancy can.

Another advantage of the design was that it could largely be manufactured using standard fabrication techniques, which were readily available in Angola, providing extensive local content. One disadvantage of the design however is that the whole production of the field runs through a single riser with difficult access for maintenance. Failure of a single component could result in a shutdown of the entire field.

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Since Girassol, a small number of hybrid risers have been installed in various locations around the world. Although expensive to manufacture and install, their ability to combine large diameter pipe with reduced vessel hang-off loads and high fatigue performance make them a strong contender for export lines. The most recent hybrid riser system installed was the Kaombo FSHRs in 2018.

**Ultra-Deepwater and Beyond.** Since breaking the ultra-deep barrier of 1500m in 2002, working solutions have been found for each of the riser types discussed in ever and ever greater water-depths. The current depth record is held by the Stones SCRs in 2900m water depth, in the Gulf of Mexico, using a steel catenary riser in a lazy wave format – first used by Shell in Brazil on BC-10 in 2009.

The use of a rigid line in lazy wave format provided several key benefits for use in such an extreme water-depth. Firstly, as the development would use an FPSO as the host vessel, a disconnectable turret solution was required to allow the FPSO to disconnect and leave the area in the event of a hurricane event. Consequently, a riser system was required with sufficient flexibility to accommodate both the connected and disconnected conditions and also not apply excessive hang-off loads on the buoy unit. The riser pipe also needs adequate thickness to provide collapse resistance in the extreme hydro-static pressure encountered at 2900m water depth. Using a steel pipe solution in a lazy wave configuration accommodates all these requirements with adequate fatigue performance when connected to a dynamic FPSO.

**Corrosion Resistance.** An additional consideration for riser design of all types is the capacity of the pipe to have sufficient corrosion resistance to transport the production fluid without corrosion due to compounds such as H\_2S or CO\_2 in the production fluid. When unprotected, carbon steel is highly susceptible to corrosion from H\_2S or CO\_2 if inhibitors have not been used. Whilst expensive, Corrosion Resistant Alloys (CRAs) and composite solutions such as carbon-fiber and glass-fiber solutions can provide excellent passive corrosion resistance.

![Figure 6—CRA Lined Pipe](image)

Corrosion resistance is a particular challenge of the pre-salt fields offshore Brazil, which can have elevated levels of both H\_2S or CO\_2. The first CRA clad SCRs were installed on the Roncador Field in 2013 in Brasil.

**Vessel Type**

As mentioned previously, the vessel type selected for the development can play a significant role in what type of riser system is used as some riser types are more conducive to certain types of vessel and metocean conditions and existing infrastructure for specific regions may also preclude certain types of vessel. Figure 7 shows the proportion of different vessel types by geographic region. The predominance of FPSOs in all regions but North America is noticeable, where Spar and TLP solutions, and more recently semi-submersibles, are far more common as they provide reduced vessel motions during the hurricane conditions often experienced in the Gulf of Mexico. Access to a well-developed network of export pipelines also means that only minimal topside storage requirements are necessary.
When examining the split of riser types with respect to the host vessel, Figure 8 shows the percentage distribution the type of host vessel the different riser types have been attached to. The data is partially skewed by the capacity of the host vessel and the number of risers installed, but it is shown that Top Tension Risers are only used on Spar and TLP type vessels, with the exception of some small early production systems. TTRs are not a good fit for the larger dynamic motions of FPSOs and semi-submersibles, and the deck layout of these vessels is also not suitable for dry tree systems. SCRs have been installed on all vessel types almost equally, whereas hybrid risers have almost exclusively been installed on FPSOs, with a single case of an export line attached to a semi-submersible. Flexibles have mainly been used on FPSOs and semi-submersibles, with a small number of lines attached to Spars and TLPs.

**Geographic Differences**
The split of different riser types geographically is shown in Figure 9 below. The tree-map at the top represents the split of installed risers by geographic region, while the lower section shows the range of water depths that each type has been installed in per region.
The plot shows clearly that the region with the largest number of installed risers is South America, generally Brazil, and that 90% of the risers in that region are flexibles. This makes Brazil clearly the largest flexible pipe market in the world with flexibles having been installed in both shallow and ultradeep water depths. A small number or SCR/SLWRs, TTRs and hybrid risers have also been installed, but the market is clearly dominated by flexibles.

In contrast, the flexible market in the region with the second highest number of risers, North America, generally the Gulf of Mexico, is dominated by rigid solutions of either TTR or SCR/SLWR design, and in deeper waters than any other region. Flexible risers have only a very small market share in this region.

Asia, and Europe are also dominated by flexibles and TTRs as the water depths tend to be shallow and not conducive for using SCRs.

Africa shows many flexible riser installations, and by far the highest number of hybrid risers. This is partly as a result of their ability to be constructed in-country, providing a high component of local content.

**Size Differences**

The distribution of riser diameters used in all developments in the database is shown in Figure 10 and colored by riser type. Because of the many other factors in riser selection already described in this paper, it is hard to draw many distinct conclusions from this plot, however the pressure containment limitations of large diameter flexible risers are evident by their absence in diameters greater than 12inches, in water depths greater than 500m water depth. There is a clear absence of flexible pipes in the quadrant of the graph which...
shows larger diameters in deeper water-depths. The largest diameter risers used to date are 24 inch steel lines which have been used on a number of developments in the Gulf of Mexico, such as Thunder-horse.

Figure 10—Distribution of Installed Risers by Size and Water-depth

Codes and Standards, Regulatory Considerations

The development of regulations to which riser system design must comply has accompanied the rapid technological changes seen by the industry. Early requirements for offshore risers lacked specifics as to the design requirements other than ensuring that the systems were safe and fit-for-purpose. Designers of the first systems frequently followed design processes such as those defined in API Q1 (American Petroleum Institute) which ensured the suitability and safety of the early designs. Without formal codes the early designs tended to be made by large operators with sufficient budgets for specialist engineers and R&D programs which could fund the extensive design work required. As these designs became field proven and test results became published, standard design best practices and design codes started to emerge.

With an-ever increasing number of offshore developments in increasingly difficult environments, regulatory bodies started to increase the number of requirements to ensure safe standard practices across the industry.

Whilst each country has its own regulatory body, many refer to and require the use of industry standards and guidelines developed by organizations such as the American Petroleum Institute (API), the International Organization for Standardization (ISO), the American Bureau of Shipping (ABS) and Det Norske Veritas (DnV). In some cases regulators have taken recommended practices and incorporated them into law. Consequently, it is important to be familiar with the governing requirements of any development before entering the design stage. Third party verification by an agency such as ABS, DnV or BV may also be a requirement to ensure that the design codes have been rigorously followed.

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Future Developments

As discussed above, the wide and varied number of influencing factors on different field developments makes making even broad predictions on future concepts notably complicated as the number of possible variations, drivers and requirements for each individual field are legion.

For the Gulf of Mexico, FPSOs are likely to remain unlikely and few TLPs are planned at the moment. Developments tend to be heading for semi-submersible vessels, and with the deeper, higher pressure and higher temperature wells encountered in the region, thick-walled SCRs are likely to continue to dominate the market, or SLWRs if SCRs are shown to have inadequate fatigue performance.

In Brazil, flexible risers connected to FPSOs are still likely to be a favored solution for most fields, however the corrosive properties of many of the pre-salt wells are likely to mean the CRA-Clad SLWRs will be ever more common for the production lines. These lines may be replaced by corrosion resistant flexible lines if these can be field proven and produced at an acceptable price.

In Asia, the push towards deepwater developments will likely maintain the use of disconnectable turret moored FPSOs, with SLWRs and SCRs with some flexible riser use.

The African market is likely to remain to be largely flexible solutions to FPSOs, but still with a large number or free-standing risers due to the local content opportunities this riser type produces.

With the development of ever more powerful computing tools, such as artificial intelligence (AI), neural networks and advanced data management systems, conservatism in analysis and real-time fatigue data logs can be produced to reduce any conservatism in the analysis to a minimum. Such technologies can therefore be used to prove the applicability of systems which may have otherwise been considered unfeasible using older analysis techniques.

The use of steel, either in rigid pipe or as wires in a unbonded flexible has its limits however, and a step-change in the materials used is likely to be required for developments in particularly harsh or deep conditions. Composite materials such as carbon fiber and glass fiber have excellent properties which make them well suited to such developments, and as these technologies become more and more field proven and the industry becomes more familiar with their use, prices should fall and it seems inevitable that use of composite components or composite pipe will take hold in such developments.

Summary

This paper touches on the main design drivers that apply during the riser design process. Whilst many key drivers relate to physical and technical limits which must be met, economic and political factors also play a significant part in the design process. Whilst there is significant overlap in the applicability of different designs, the combination of these factors has resulted in a diverse split of riser designs geographically. Whilst the push into ever deeper water depths has slowed in recent years, it can safely be assumed that records will keep being broken and novel ways of applying technology to riser design will keep being developed. As the limits of existing flexible and rigid pipe design are met, composite solutions will likely start to break into the market in these most challenging conditions.

Abbreviations

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<td>ABS</td>
<td>American Bureau of Shipping</td>
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<td>API</td>
<td>American Petroleum Agency</td>
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<td>BSR</td>
<td>Buoyancy Supported Riser</td>
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<td>DnV</td>
<td>Det Norske Veritas</td>
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<td>FSHR</td>
<td>Free-standing Hybrid Riser</td>
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<td>ISO</td>
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<td>SCR</td>
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References