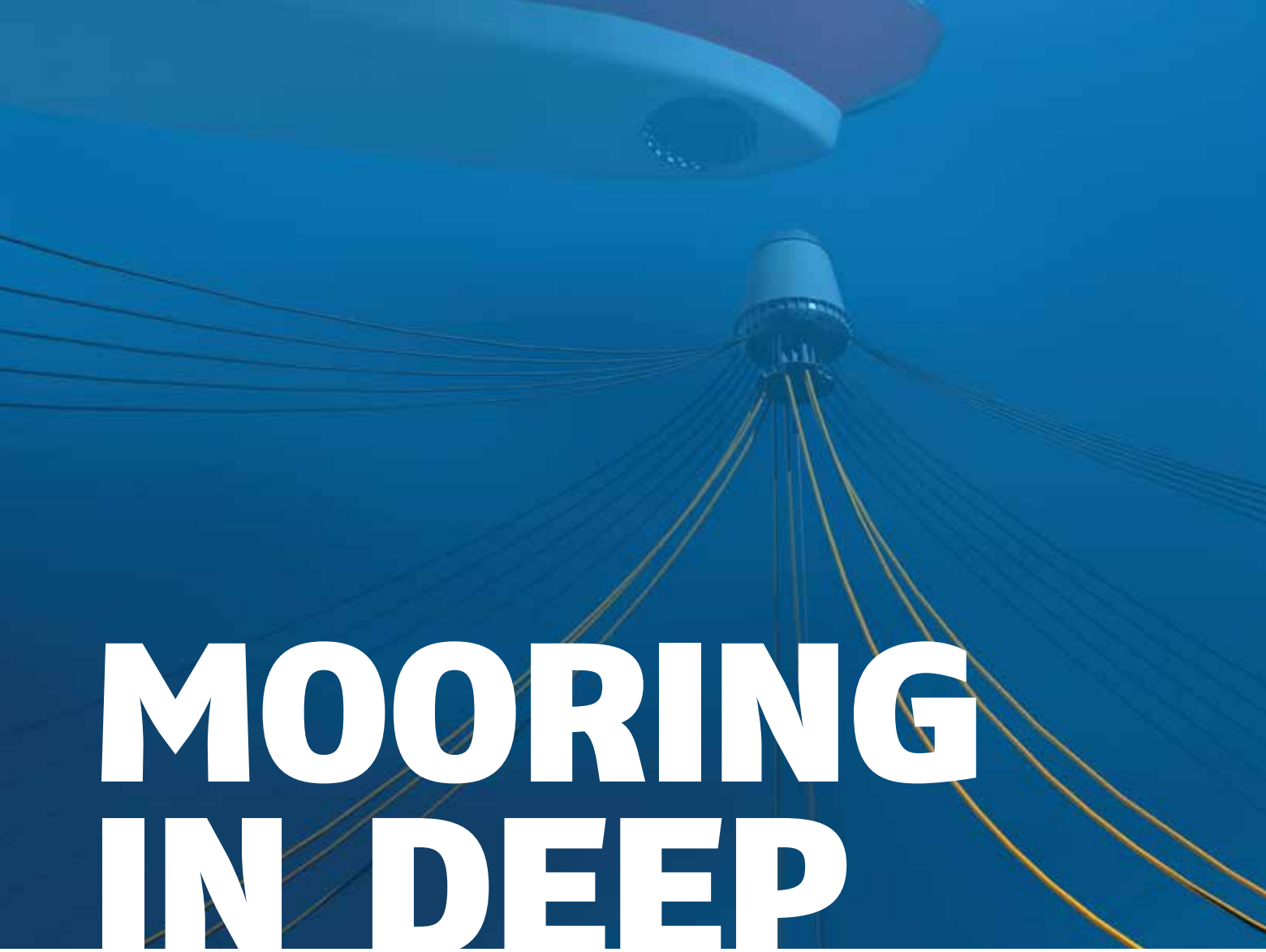


MOORING IN DEEP WATER

Reliability, safety, cost, and environmental factors all affect how an FPU is connected to the seabed

By Andrew Newport

Floating production units (FPUs) need to remain on station, within certain limits, to protect the integrity of the riser system that connects the subsea wells or pipelines to the FPU. There are various types of riser systems and configurations that can be used, but all have limitations in the excursions they can accept to avoid rupture or long-term fatigue damage. Maintaining the excursions of an FPU within acceptable limits is the main function of the mooring system.

FPUs in shallow water are generally ship-shaped units, either floating production storage and offloading systems (FPSOs), or the simpler floating storage offloading systems (FSOs). FPSOs typically receive unprocessed fluids from subsea wells; separate

Mooring legs and risers connected to a buoy that can be disconnected from the FPSO to allow the vessel to sail to safety.

and treat the oil, water, and gas; and store the oil in the vessel's cargo tanks for offloading to shuttle tankers. The water is either cleaned and discharged overboard, or re-injected into the reservoir. Similarly, the gas is conditioned and compressed, and either exported via a pipeline, or re-injected into the reservoir. FSOs, by contrast, receive pre-treated oil from another facility, which is then stored in the FSO's cargo tanks and periodically offloaded to shuttle tankers.

There are two principal types of mooring systems for FPSOs and FSOs: turret moorings and spread moorings. Turret moorings are a form of single point mooring in which a geostationary turret is moored to the seabed, and the FPU is connected to the turret by a bearing system. This arrangement allows the vessel to weathervane around the turret to adopt the position of least resistance to the prevailing wind, waves, and current, and thereby minimize the load on the mooring legs and vessel hull.

In contrast, spread moorings incorporate mooring legs at the bow and stern of the vessel, preventing the vessel from weathervaning. As a consequence, spread moored systems can be deployed only in regions with directional weather or with benign environmental conditions. In general, an associated offloading buoy is required to avoid the possibility of shuttle tankers drifting into the FPU during approach or during offloading as the prevailing weather direction changes.

In the large majority of cases, FPUs rely on a passive mooring system for stationkeeping, although a small number of turret-moored systems combine mooring legs with dynamic positioning (DP) systems. In these systems, the DP is used to control the heading of the vessel to reduce mooring loads, increase natural ventilation of the process facilities on deck, or to improve crew comfort.

The mooring legs of FPUs in shallow water, whether turret moored or spread moored, are generally composed of chain. The weight of the chain is used to provide a restoring force as the unit drifts off station under the action of wind, waves, and current. The mooring legs are arranged in groups, or bundles, and hang from the FPU in a catenary arrangement. The grouping of mooring legs provides clear corridors between the bundles, which are used to route flow lines and risers to the FPU. This arrangement helps avoid clashes between the mooring legs and risers, and minimizes exposure to damage of the subsea facility if a mooring leg fails and falls to the seabed.

As the unit moves off station, mooring legs are lifted on the weather side of the system, and laid down on the lea. This results in an imbalance in the suspended weight of the mooring lines, which generates a restoring force, acting to pull the unit back onto its station. If required, the restoring force can be increased by increasing the linear weight of the mooring leg. This is most commonly achieved by increasing the diameter of the mooring chains, but the effect also can be achieved by fixing discrete clump weights along the length of the chain, or having a double chain segment in the mooring leg.

While this approach to stationkeeping is effective in water depths up to about 300 m, the use of weight alone to control excursions becomes ineffective at greater depths, and the suspended weight of the mooring legs becomes excessively high. As a result, alternative types of mooring system have been developed and deployed for FPUs in deeper water.

Alternatives as depth increases

Although there is some variation in the definition of terms, deep water is generally applied to water depths in the range

Artist's impression of the spread-moored FPSO *Ilhabela* in a water depth of 2,140 m. This unit is due to start production in second quarter 2014.

of 400 to 1,500 m, with depths in excess of 1,500 m being termed ultra deep. As FPU operations have moved into these increased water depths, alternatives to chain-based catenary mooring systems have been developed. For ship-shaped FPUs, taut mooring systems based on the elastic response of steel wire ropes and synthetic ropes have been deployed. The legs of these systems stretch as the FPU moves off station, generating a restoring force without the large change in mooring leg geometry that is characteristic of catenary systems. Taut mooring systems are lighter than chain systems and are able to limit excursions within the capabilities of the riser systems more cost effectively than could be achieved using catenary systems. The legs of taut moorings are still grouped into bundles to provide corridors for routing of flow lines and risers.

Synthetic rope, notably polyester, offers a lighter solution than the use of wire ropes in taut mooring systems, having a very low weight in water. When first deployed during the 1990s, there was concern that polyester ropes would slacken and lose their pre-tension due to creep and the bedding-in of the rope construction. However, experience has shown that the issue of bedding-in can largely be overcome by pre-stretching the rope during installation, and although some creep occurs in service, this has proved to be manageable. In practice, very few polyester mooring systems have needed re-tensioning during their operating life.

In taut mooring systems, a short section of chain is used to connect the steel wire or synthetic rope to the anchor point, avoiding abrasion of the rope through contact with the seabed. This section of chain also can be increased in length to provide a catenary section at the bottom of the taut mooring leg. This semi-taut configuration reduces the loads on the FPU for small excursions, and also reduces the uplift imposed on the anchor point, leading to more economic anchor point designs.

Permanent versus disconnectable

For the majority of FPUs operating in deep water, mooring systems are designed to be permanently connected, from initial installation to decommissioning of the system. However, there is a requirement for the Gulf of Mexico (GOM) for FPSOs to be capable of disconnecting from their mooring system to be able to sail to safety in the event of a hurricane. This requirement is

The legs of taut moorings are still grouped into bundles to provide corridors for routing of flow lines and risers.

imposed to avoid the potential pollution risk from oil stored on board FPSOs.

For such deep water disconnectable systems, the mooring legs can be connected to a buoy that can be released by the FPSO, enabling the vessel to leave the station in a controlled manner. In such cases, the lightness of synthetic rope does offer an advantage over wire ropes, reducing the payload on the buoy once it has sunk below the sea surface and reduced the pre-tension.

Design criteria

Any FPU mooring system must maintain excursions within acceptable limits, and also possess adequate strength to withstand the imposed loads. The majority of mooring systems have been designed against the 100-year return period storm condition, limiting excursions and ensuring the mooring has adequate strength with an appropriate safety factor against failure. The safety factor applied under the 100-year conditions actually aims to ensure that the mooring system can withstand the 10,000-year return period storm without failing. A shortcoming of this approach is that the ratio of 100-year to 10,000-year return period storms varies for different geographical regions, implying that the factor of safety applied to the 100-year return period design case should also be specific to the region if a consistent reliability is to be achieved globally. As a consequence, there is an increasing trend to directly check the mooring design for the 10,000-year return period conditions to ensure that the mooring achieves the intended reliability.

All permanent mooring systems are designed with a degree of redundancy, whether for shallow water or deep water applications. The majority of operating systems have been designed to enable continued operation with the failure of any single leg—that is, a single leg failure is a design case and is treated as a component failure rather than a system failure. In this approach, after failure of a single leg, there remains an adequate factor of safety against failure for the remaining intact legs.

Originating from the regulations for permanent moorings in the Norwegian sector of the North Sea, designs that can accommodate two broken legs also have been deployed on several FPUs. This approach reflects a concern that if one mooring leg has failed, adjacent legs, which have the same design and have experienced similar loading, may also be at the point of failure. At present there is no consensus in the industry as to the necessity for this requirement, and its application is still limited.

In addition to withstanding the extreme design loads, mooring systems must have adequate fatigue resistance to enable them to operate for the design life of the FPU. In general, the fatigue lives of wire ropes and synthetic ropes are long, and can achieve factors of safety well in excess of the requirements of the design codes. However, systems composed primarily of wire or synthetic rope still use a section of chain at the top of

The turret-moored FPSO *Espirito Santo* operating in a water depth of 1,780 m.

Suction piles being prepared for installation.

Anchor Points

A key element of any mooring system is the design of the anchor points that secure the mooring legs to the seabed. The holding capacity of any anchor depends upon its design, the anchor embedment depth, the direction of loading, and the soil properties at the location.

In shallow water, the most common types of anchor points are drag anchors, gravity bases, driven piles, and drilled and grouted piles. These designs can provide high lateral load capacity, making them a good solution for anchoring catenary mooring systems where the mooring leg arrives on the seabed horizontally.

In deeper water, where taut mooring systems are employed, the anchor points experience both vertical and horizontal loading, which precludes the use of drag anchors due to their poor vertical holding capacity. Piles are still an option for deep water applications, but their installation complexity has generally limited their use to anchoring TLPs, and gravity bases have proved uneconomic.

For taut mooring systems in deep water, vertically loaded anchors (VLA) or suction piles are most commonly employed.

VLAs are essentially plates that are installed in a similar manner to drag anchors, but after embedment the anchor shank is reoriented to align with the mooring leg, resulting in a large vertical holding capacity. There are a number of variants on this design, including the use of a bridle instead of a solid anchor shank, and designs that can be embedded by penetration under gravity rather than by drag embedment.

Suction piles, which are the predominant design for deep water anchor points, are a form of cylindrical caisson that is open at the bottom and closed at the top. The pile penetrates to a limited depth under self-weight, and then water is pumped out of the pile to reduce the internal pressure. This results in a relatively higher external water pressure, which drives the pile further into the seabed.

Once installed, the suction pump is removed, and the top plate of the pile can be left open. The pile will then behave as a conventional pile, relying on the action of skin friction to resist uplift. The alternative, which is more common, is to seal the top plate, mobilizing the interior under pressure to increase the pile's vertical holding capacity.

the mooring leg to enable the required leg pre-tension to be achieved by adjusting the length through a chain stopper.

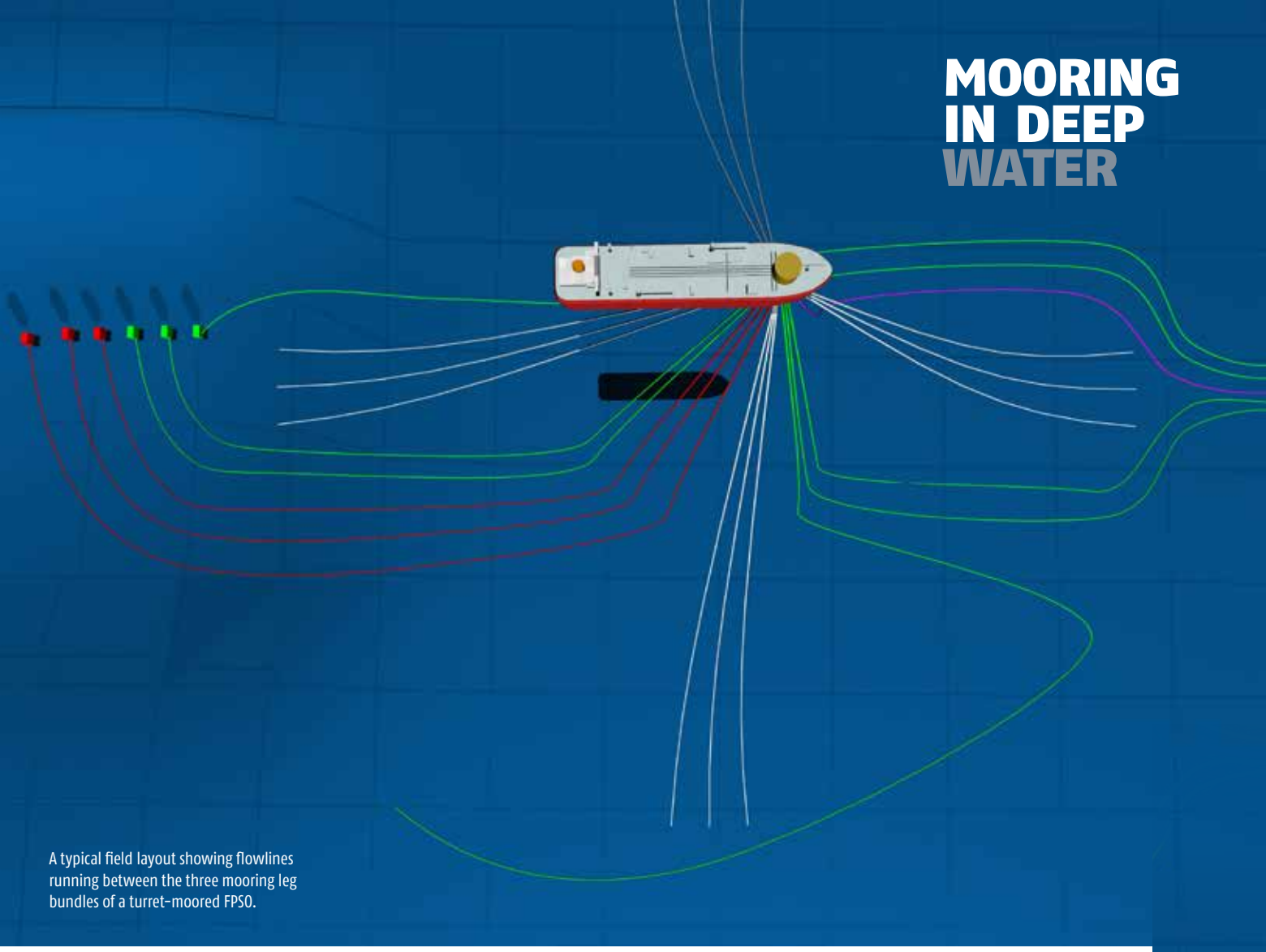
This top section of chain is particularly sensitive to fatigue, experiencing the phenomenon of out-of-plane bending (OPB) fatigue as well as the tension-tension fatigue experienced by the rest of the mooring leg. The industry was alerted to OPB fatigue following the failure of three mooring legs on the Girassol deep water off-loading buoy in 2002. These failures occurred less than one year after the installation of the buoy. Subsequent investigation revealed that the last chain link on the chain stopper was bending in its weak plane before it started to slide over the adjacent link. The interlink rotation is inhibited in part by the high pre-tension associated with deep water systems, with the consequence that there is a practical limitation on the magnitude of pre-load that can be used if excessive fatigue damage is to be avoided. This limitation can increase the number of mooring legs that would otherwise be needed so as to maintain excursions within acceptable limits without using excessive pre-load.

The industry was alerted to OPB fatigue following the failure of three mooring legs on the Girassol deep water off-loading buoy in 2002.

Alternatives to ship-shaped FPUs

As water depths have increased, alternative FPU forms also have been developed, principally spars and tension leg platforms (TLPs). Production semisubmersibles (semi-subs), which had been used to a limited extent in shallow water, also were developed for use in deep water.

The mooring systems for semi-subs and spars are similar to those used for spread moored ship-shaped FPUs, but TLPs are moored by clusters of vertical tethers, which are tensioned by the excess buoyancy of the TLP hull. These tethers are composed of high-strength steel tubulars, which are designed as elements of structure rather than following the design methodology of



A typical field layout showing flowlines running between the three mooring leg bundles of a turret-moored FPSO.

mooring components. The tension leg mooring system allows horizontal movement under environmental loading, but prevents vertical movement of the hull. This results in a stable platform that can support rigid risers, enabling the use of surface-mounted Christmas trees.

At present, the deepest mooring for an FPSO is for the Petrobras Cascade and Chinook project in the GOM, in 2,500 m (8,200 ft.) of water. The Shell Perdido spar, also operating in the GOM, is moored in a water depth of 2,450 m (8,000 ft.), almost matching the depth of Cascade and Chinook. In contrast, the deepest TLP is the ConocoPhillips Magnolia, again located in the GOM, but in only 1,432 m (4,698 ft.) of water. This is around the effective economic limit for TLP tendons, and it is unlikely that TLPs will be installed in deeper water in the future.

In 2015, the Shell Stones FPSO is due to be installed in the GOM in a water depth of 2,900 m, becoming the deepest operating FPU of any type.

Future trends

The installation of FPUs in increasing water depths naturally lags behind exploratory drilling in deeper waters. The latest generation of drillships has the ability to drill in water depths of 3,657 m (12,000 ft.), but the deepest water in which drilling has occurred so far is 3,174 m (10,411 ft.), offshore India's east coast. (See "Designing the Next Drillship," beginning on page 40 in this issue, for more information on the challenges faced by these vessels.)

Based upon present drilling trends, and the historical lag between exploration drilling at increased depth and the installation of production systems, it is unlikely that FPUs will be installed in water depths greater than 3,000 m (9,483 ft.) before the end of the decade.

The majority of short-term deep water development will be centered on offshore West Africa, Brazil, and the GOM, but developments also are expected in less traditional areas including offshore Southeast Asia, Europe, and Australia. This continuing activity, and the development of deep water fields in regions with harsh environmental conditions, will continue to challenge the deep water mooring industry to design innovative mooring systems that provide safe, reliable, and cost-effective solutions for future FPUs. **MT**

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