5.2.1 Introduction

Over the years different types of offshore structures have been designed for a multitude of purposes. There is no doubt, however, that the development of hydrocarbon exploration and production provided a vital boost to their spread. The need to transfer drilling rigs and production plants offshore, and the resulting need to design and build support structures, the difficulties of building platforms capable of withstanding increasingly extreme environmental conditions have led to offshore research and engineering becoming one of the most interesting and innovative branches of technological development.

The first offshore drilling activities took place during the late 1930s in the Gulf of Mexico. The first offshore production platforms of modern design were installed from the 1950s onwards, but it was in the early 1970s that a genuine boom took place in the offshore industry. The 1980s saw the consolidation of development technologies for moderately deep waters, following the exploitation of almost all easily accessible large fields. In the 1990s attention moved to the potential for developing small fields, which could only guarantee small economic returns. Hydrocarbon exploration focused mainly on very deep waters, thus triggering the development of innovative technologies with the aim of constructing production platforms at ever increasing depth.

Generally speaking, an offshore platform has the primary function of allowing the production of hydrocarbons from the subsurface, with minimum treatment and maximum respect for safety and environmental protection. These are then transported to plants on the coast for definitive treatment prior to commercialization. Due to the high costs of offshore construction, facilities in open waters must be simplified and reduced as far as possible. The requisite facilities are thus kept to a bare minimum, and, during the construction phase, offshore construction work are as limited as possible by maximizing onshore prefabrication.

Over the years, technological advances and the constant quest for innovative solutions have led to the development of different types of structures to support production facilities. The main factor influencing development typologies is the depth of water in which the platforms must be installed. We have already dealt with offshore drilling rigs (see Chapter 3.4); this chapter will provide a detailed description of offshore production platforms. We will first examine the most common development typologies for moderately deep waters; we will then briefly outline development strategies for small reservoirs and the technical expedients adopted for economically profitable exploitation; finally, we will discuss development typologies for very deep waters, describing the structures which have been used in recent years, and those which are proving themselves to be most promising for the future.

5.2.2 Development in shallow waters

Generals

An offshore unit in shallow waters generally consists of a structural platform, able to support drilling rigs, wells and wellheads, processing plants for the primary treatment of hydrocarbons, support and safety facilities, and accommodation for workers. In relatively shallow waters, no more than 300-400 m
deep, platforms are generally fixed structures, which stand on the seafloor, to which they are rigidly anchored. However, it is impossible to use rigid solutions at greater depths; under these conditions the platforms must be free to oscillate in response to environmental loads.

Below we will describe in detail the facilities present on an offshore platform, and the structural typologies most frequently used to build fixed platforms. It should be remembered that the discovery of large new fields in moderately deep waters has become a genuine rarity in recent years. The only potential for development in shallow waters is represented by the ability to exploit small, geographically dispersed, hydrocarbon reserves whose development would not be economically viable, or would involve excessive risk, were suitable technological solutions not adopted.

**Fixed platforms**

Fixed platforms generally consist of a support structure which rests rigidly on the seabed and supports the production plants (topside), keeping them at a sufficient distance from the surface of the water to avoid them being hit by waves (Fig. 1).

Given the relatively shallow waters in which these platforms are installed (a maximum of 300-400 m but normally less than 200 m), fixed platforms can generally be easily linked via subsea pipelines to terminals along the coast, where the hydrocarbons are collected. As a result, these platforms do not usually need storage facilities. The hydrocarbons produced by the wells flow through the primary treatment plants on the platform, and then pass continuously through subsea pipelines to onshore gathering stations. Here they undergo further processing, bringing them to the required conditions for the final refining and commercialization phases.

**Surface production facilities (topside)**

The development of an offshore field requires the following topside facilities: a) drilling rigs and/or workover rigs; b) wellheads, placed at the tops of the wells to control the flow of hydrocarbons from the seabed to the surface; c) processing plants for the hydrocarbons produced and, where necessary, facilities for the injection of gas or water into the reservoir; d) utility systems to support primary processing; e) safety and emergency facilities; f) pumping or compression systems to propel the oil and gas to gathering stations along the coast; g) control systems for operations and relevant control rooms; h) technical rooms and laboratories; i) accommodation and common rooms for workers; j) flares to allow gas to be burned in case of emergency; k) equipment for moving materials; l) transport systems for workers.

These different components may be unified and integrated on a single platform (Fig. 2), or hosted on independent structures, generally linked by bridges allowing the passage of workers, piping, and electrical and instrumentation wiring. Which of these two alternatives is selected depends on the depth of the seabed and the size of the plants. Several platforms of modest size allow for greater flexibility and are inherently safer; they also simplify the design, construction and installation process as compared to that required for a large integrated platform. From the point of view of safety and the flexibility of construction the optimal solution is to host worker accommodation, processing and support plants, drilling rigs and flare on separate platforms. However, as depth increases, so does the impact of costs on support structures: at depths over 100 m, these structures are so expensive that facilities must be concentrated as far as possible on a single platform.
In the case of integrated platforms, the general layout is governed by safety issues: processing plants, drilling rigs, utilities, accommodation and control rooms are therefore kept as far as possible in separate areas. Accommodation and control rooms are placed as far away as possible from the potentially high-risk processing and drilling zone. Utilities, which are much less dangerous, are concentrated in the area between the processing and drilling zone and the accommodation area.

Environmental conditions also influence the configuration of topside facilities: the flare is located as far away as possible from the accommodation area, and to the lee side of it with respect to the prevailing winds. The orientation of the platform itself is designed to expose the smallest possible area of the support structures to waves and currents.

All the facilities are supported by steel structures on several levels, connected by columns and diagonal girders. For reasons of expenditure, both structures and facilities must be prefabricated onshore as far as possible. This entails the need to build complete modules, which are as large as possible at onshore construction yards; these can then be transported and installed offshore. The size of these prefabricated units therefore depends on the availability and lifting capabilities of the crane barges used for offshore installation. Until the second half of the 1980s, even large platforms were built by prefabricating modules of mass no greater than 1,500-2,000 t onshore; these were installed singly and connected together offshore, thus wasting a considerable amount of time and money. From the late 1980s, the development of a new generation of crane barges for installation has allowed for the construction of integrated modules of enormous size and weight (up to around 12,000 t). This minimizes the number of offshore lifting operations, and thus drastically reduces the time required to complete the platform and start up its facilities.

A modern topside structure includes a main module (deck), which is prefabricated onshore and installed offshore directly onto the support structure, which keeps it at a sufficient distance from the surface of the water (see below). Depending on the size of the platform, the deck may have four, six or eight main columns, which transfer the load to the structure upon which they rest. If not all the facilities can be contained within the deck due to the weight restrictions mentioned above, we need to construct other modules which are installed on the main module.

Accommodation for workers (up to 100-150 people on large platforms) and common rooms are generally built as an independent module, given their different typology, more architectural than engineering. The accommodation module is also constructed in steel, with external cladding in load-bearing corrugated metal sheets. The helideck used for the transport of workers is usually built on top of the accommodation module, of which it forms an integral part.

The flare, needed to burn gas in emergencies or when the production is started up, is also usually built as an independent module, with a metal framework structure of triangular or square section. This framework is so long that the flare has to be transported to the installation site resting horizontally on a barge, and then installed vertically on the platform. It is therefore impossible to prefabricate the flare as an integral part of the production module, even were the total weight to allow this.

The drilling and, if necessary, workover rig is also an independent module, which can be removed after operations end and reused to develop other fields.

**Drilling and workover rigs**

Production wells can be drilled using rigs hosted directly on the production platform or, in shallow waters, using special jack-up drilling vessels, which operate directly above the platform. The jack-up is a vessel consisting of a hull and framework legs. It is towed to the drilling location, where its legs are lowered until they rest on the seabed; the hull is then lifted until it reaches operating height.

To reduce the amount of time required for development, it is often preferable to carry out
pre-drilling before the platform is installed. The wells are drilled through a structure previously installed on the seabed (template), which is used as a guide during the drilling phase. At depths of less than 100 m, pre-drilling is carried out using a jack-up rig. At greater depths, we must use floating rigs of semisubmersible type. These consist of a metal deck hosting the drilling rigs; the deck is supported by four, six or eight columns of large diameter, which in turn rest on submerged pontoons. While sailing, semisubmersible units have a limited draft (6-8 m), whereas in operating mode they can be submerged, reaching drafts in the order of 20 m, thus notably increasing stability. Where the seabed is suitable for fixed platforms, semisubmersible drilling rigs are moored using a system of anchors, chains and steel cables. In deep waters, however, they are kept in position using computer-controlled thrusters, which refer to satellite positioning systems.

When pre-drilling ends, a pair of docking piles are installed next to the wells drilled through the pre-installed template structure. These piles act as guides during the subsequent installation of the production platform above the pre-drilled wells, to ensure that the structure is positioned within extremely tight dimensional tolerance limits.

After the installation of the platform has been completed, the pre-drilled wells are completed with light facilities, also used for workovers. These are usually modularized, allowing them to be easily removed from the platform when operations end, and where possible reused to develop other fields. When the wells have been completed, we install the wellheads, and then connect these to the processing plants.

The wells from the seabed to the surface and the wellheads

The hydrocarbons from the reservoir are channelled from the seabed to surface plants through conductor pipes, supported by the same structure which supports the topside.

Once the well has been completed, a wellhead or christmas tree is installed at the top of each conductor; these allow us to alter the direction of flow from vertical to horizontal, to channel the hydrocarbons towards treatment plants, to close the well and regulate the flow. The wellhead consists of a series of valves, operated manually or using appropriate devices. The wing valves, usually gate valves, are used to open or close the well, whilst the flow is regulated using valves with adjustable calibrated orifices (choke valves) which are far more resistant to abrasion. After installation, each wellhead is connected to a manifold into which the reservoir fluids from the wells are channelled before processing.

Processing plants for the hydrocarbons produced

The high cost of offshore units means that treatment carried out on the platform must be kept to a minimum, reducing the corrosiveness of the hydrocarbons to allow their transport to gathering stations along the coast. Any further treatment required will be carried out here; on the platform we only carry out treatment involving the separation, dehydration, and heating or cooling of reservoir fluids.

Separation allows us to separate gases from liquids (crude oil, condensates and water). During this process, any sand dragged along with the fluids, which may cause erosion can also be removed.

Dehydration allows us to remove the water contained in crude oil or natural gas, in order to avoid the formation of hydrates during transport through the pipeline; these solidify when the fluid cools and risk causing obstructions. The most frequently used method involves bringing the hydrocarbons into contact with a pure glycol solution. Facilities for the separation of water from crude oil also remove other impurities present and collect the petroleum vapours contained within it separately.

The fluids produced are heated and cooled in accordance with varying processing requirements and the properties of the products to be treated.

At times, after a few years of production, we may need to inject water or gas into the reservoir to maintain reservoir pressure at an acceptable level. In these cases, the platform also hosts facilities for re-injection through purpose-drilled wells or depleted production wells (see Chapters 5.3 and 5.4).

Utility systems for primary processing

In order for the hydrocarbon treatment plants to function, and for the platform to operate with the requisite safety and reliability, it must also include a series of utility systems. These facilities are:

- Power generated unit to power all the electrical equipment on the platform. This usually consists of several turbines running on both gas and diesel oil (normally natural gas produced from the reservoir; gas oil during start-up or if production is halted).
• Treatment plant for the gas used to power the turbines.
• Plants for the injection of chemicals, under the form of corrosion inhibitors, into the export pipeline (e.g. methanol, usually injected every time the platform is started up).
• Glycol regeneration unit for the glycol used to dehydrate gas; as it exits the dehydration column, the regeneration unit separates the glycol from the water, and recovers it.
• Diesel oil distribution system: the diesel oil is stored in tanks and used to power turbines, emergency generators, fire pumps and other motors.
• Unit which supplies compressed air to all the field equipment and other utilities on the platform.
• Refrigeration units: the need to cool processes and support facilities is met by using refrigerating water which circulates in a closed loop, and is cooled in seawater exchangers.
• Seawater collection and distribution plant: seawater is pumped to the platform by submerged pumps installed inside tubular caissons at a depth of a few tens of metres. Seawater is used as a coolant in exchangers, to feed desalination and purification plants, and during drilling operations.
• Desalination and purification plant: this water is then distributed to worker accommodation, utilities, laboratories, the drilling rig and the emergency showers needed for instant decontamination of personnel.
• Plants to collect discharges from equipment and waste water.
• Treatment plant for the water separated from reservoir fluids during processing: this water is treated to recover the hydrocarbons remaining in it after the primary separation process; the recovered hydrocarbons are fed into the production system, whereas the water is discharged into the sea after treatment to limit the pollutants it contains as far as possible.
• Sewage treatment plant to treat sewage from worker accommodation and utilities.
• Nitrogen generation plant to power some specific utilities.
• Biocide liquid distribution plant, used to prevent organic growth inside the pipes of fire-fighting systems.

**Safety and emergency systems**

Safety systems significantly condition offshore units; those normally used on platforms are as follows:

• Emergency generator system: consisting of one or more generators powered by diesel oil, which become operative if the primary generator systems fail.
• UPS (Uninterruptible Power Supply) system: consisting of a series of batteries to power vital platform systems which become operative if both the primary and emergency generators fail.
• Shut-down system: which shuts down production in case of accident.
• Detection system, which uses a series of sensors placed throughout the platform to detect the beginnings of a fire, smoke or gas leaks, and thus activate alarm and protection systems.
• Active fire-fighting systems: these use water, foam, carbon dioxide and inert gas, and protect the entire platform; the water is pumped directly from the sea, whereas the other substances are stored in tanks.
• Passive fire-fighting systems, consisting in the application of appropriate materials resistant to high temperatures on all those parts of structures and facilities at risk of prolonged exposure to fire in case of accident, and whose collapse could prejudice the safety of the entire platform. Additionally, the well and processing zone is generally isolated from other areas of the platform with explosion-proof walls.
• Personnel evacuation systems: generally life boats and life rafts, suitably distributed around the platform.
• Security and protection systems for workers: these are located at strategic points around the platform, and include life-jackets, gas masks, showers for use in case of contact with dangerous substances, etc.
• Alarm systems: these consist of acoustic and visual devices which are switched on automatically in case of emergency.
• Telecommunications systems: these allow workers on the platform to communicate internally and with the outside world to request help in case of emergency.

**Oil and gas pumping or compression systems**

Often, after treatment carried out on the platform, the pressure of the hydrocarbons produced is insufficient to propel them onshore through subsea pipelines, and we need to increase it. For gas especially, pressure is usually initially sufficient to avoid the installation of compressors to propel it...
onshore; however, over the years, pressure tends to decrease as a result of continued production, and it later becomes necessary to install compression systems.

The platform also hosts the devices (pigs) which are propelled through the entire pipeline by the fluid pressure, allowing it to be cleaned, and the conditions of the pipeline to be inspected. The pig is inserted through sidelines in the main pipeline (pig trap), with trap doors for the insertion or recovery of the pig.

**Control system and control rooms**

The production and processing plants, and support and safety systems are constantly monitored by a data capture and processing system run from a control room which represents the heart of the platform. From the control room, operators can work on the entire platform, using control panels which show the functioning of the platform in a schematic way using graphic displays; these also allow operators to intervene remotely.

The functioning of the platform is monitored uninterruptedly 24 hours a day, usually by two groups of operators who work on different panels: one group works on the processing plants and utilities systems, whilst the other monitors the electrical generator and distribution systems.

The monitoring and data capture system constantly records operational data from all the appliances. Their working history can thus also be used to plan and record maintenance work on the platform.

**Technical rooms and laboratories**

Alongside the control room, platforms usually host other technical rooms: one or more electrical rooms, where the electrical distribution switchboard, batteries and transformers are installed; a room containing the refrigeration units for air-conditioning plants; a work shop for minor repairs or maintenance work, and laboratories to carry out chemical and physical analyses of production fluids.

**Accommodation and living quarters for workers**

Platforms are generally manned. Workers (up to 100-150 people on large platforms) are housed in a specific area of the platform, which for safety reasons is as far as possible from wells and processing plants. Accommodation and common rooms are generally grouped together in a special module on several floors. Alongside the cabins for personnel, this also hosts other common areas such as: offices and meeting rooms, infirmary, radio and telecommunications room, kitchens, storeroom, laundry, canteen, recreation rooms, TV rooms, gym, etc. The accommodation and common rooms, served by an air-conditioning and ventilation unit, are slightly pressurized to prevent the entrance of any toxic gases, which may leak from facilities in case of accident.

**Flares**

A unit is needed to collect the discharges from the various processing plants (hydrocarbon and natural gas vapours), and dispose of these. The gas to be eliminated is sent to a burner placed at the far end of a metal framework, known as the flare; its length, depending on the maximum amount of gas which can be burned, may easily reach a hundred metres. The flare is oriented so as to be downwind of the prevailing winds.

**Equipment for moving materials**

Materials are moved onto the platform using cranes, placed so as to serve the entire upper deck surface of the topside. Access for the cranes to the lower decks is ensured by the presence of suitably positioned cantilevered loading bays. The cranes, which can lift several tens of tonnes, are used to load and unload materials onto or from the transport vessels which supply the platform. Materials are moved around the platform on monorails serving all critical areas; less heavy materials can be moved using transport trolleys.

**Personnel transfer systems**

Platform workers are usually transported by air using helicopters. More rarely, and only in geographical locations where weather conditions allow this, workers may also be transported by sea; in the latter case, the platform is equipped with a jetty to moor the transport vessels and the equipment needed for mooring. In any case, all platforms have a helicopter pad placed on the roof of the accommodation module, in order to guarantee fast evacuation in case of medical emergencies or accidents.

**Support structures**

The modules hosting surface facilities must be supported by adequate structures resting on the seabed, which serve the following main purposes:
• To maintain the topside at a sufficient distance from the surface of the water to avoid waves hitting the facilities.
• To transfer their own weight and that of the facilities above to the seabed.
• To transfer the loads caused by environmental factors such as waves, currents, winds and earthquakes to the seabed, resisting rigidly.
• To resist and transfer to the seabed the loads caused by potential collisions with ships.
• To support the conductors which link the wellheads at the surface to the wells and thence the reservoir.
• To support vertical sections of any subsea pipelines (risers) which rise from the seafloor to the production plant at the surface.
• To support those parts of surface facilities which interact with seawater, typically water intakes and discharges.
• To support the conductors inside which subsea tubes rise to the surface; these may be power or fibre optic cables, or other flexible tubes of small diameter which carry hydraulic control fluids to the subsea pipeline shutoff valves, allowing these to be controlled from the platform.
• To support berthing and mooring facilities for ships used to transport workers.

Two typologies are widely used to construct the rigid support structures for surface facilities in depths of water up to 200-300 m (and in some extremely rare cases up to 400 m). The most common is certainly a steel lattice structure (jacket), designed to be as narrow and light as possible; this structure transfers loads to a system of foundation piles. The second typology, by contrast, is massive and heavy, and is generally made of reinforced concrete; this structure supports the topside by resisting environmental loads through gravity alone.

**Steel lattice support structures (jacket)**

The jacket is a steel lattice structure constructed from tubular members. This structure usually consists of four or eight legs of large diameter, generally designed to diverge from the vertical by a few degrees so that the base of the structure is larger than its top, thus enabling it to transfer loads to the seabed more effectively (**Fig. 3**).

The legs are connected to one another by a series of tubes welded both vertically and horizontally to form a three-dimensional lattice structure. The diameters of the legs depend on the size and weight of surface facilities, and the depth of the seabed, and is generally in the order of a few metres. The other tubular members forming the framework are smaller, but still about a metre in diameter.

The structure’s mass also depends on the size of the facilities, and above all on the depth of the seabed upon which it is to be installed. It may range from a few thousand tonnes in depths of water under 100 m, to 20,000-30,000 t for depths in the order of 200 m, up to as much as 40,000-50,000 t (giant jackets) in depths over 300 m.

All the vertical members descending from the topside which must be supported by the jacket (see above) are inserted inside guides or welded to fixed supports held up by suitably positioned elements of the framework.

Jackets are built onshore in construction yards. Except in those rare cases when they are of very limited size they are constructed in a horizontal position and, once finished, are loaded onto a barge for transport to the offshore installation site. Usually the weight of the structure is such that it cannot be lifted into place; the jacket is therefore launched in a horizontal position, up-ended in the water, and then sunk and positioned definitively with the help of a crane barge. All these intermediate phases of
installation require the jacket to be equipped with a series of structural features with a merely temporary function; to allow it to be loaded onto the barge and subsequently launched in open waters the jacket must have two parallel skids running almost its whole length. These allow the structure, when in a horizontal position, to slide along parallel tracks placed both on the wharf at the onshore construction site and on the transport barge.

Once launched in open waters near the final installation site, the jacket must be able to float. Some large buoyancy tanks, attached to the main structure and made of steel plate suitably reinforced with internal rings, must therefore be included. A controlled staged flooding of the buoyancy tanks during the phases of up-ending and positioning on the seabed is then carried out. After installation has been completed, the buoyancy tanks are removed to reduce the surface area exposed to waves and currents. To reduce the size of the buoyancy tanks, the tubular members forming the structural framework are also made watertight; the legs of the jacket are divided into compartments equipped with valves, and these too are flooded sequentially during the phases of up-ending and approach to the seabed.

Once it has come to rest on the seabed, the jacket is supported by a temporary foundation, designed to support the weight of the structure before the foundation piles are installed. This temporary foundation, or mud mat, consists of a reinforced metal plate of appropriate size, welded to the elements of the framework forming the lower floor plate of the jacket, at the seabed level. Since the marine environment exposes the steel structure to significant corrosion, the upper part of the jacket, subject to the action of waves, is given an appropriate number of coats of paint. The remaining submerged part of the structure is shielded by a cathodic protection system using sacrificial anodes in aluminium alloy (which has a lower electrochemical potential than steel), suitably placed along all structural elements.

As already mentioned, the definitive foundation of the jacket consists of piles, which must transfer to the seabed all environmental loads and those deriving from the facilities above. The piles are steel tubes of large diameter, and are driven into the seabed with the help of hydraulically operated subsea pile hammers before the topside modules are installed. Where the seabed is extremely hard, we may need recourse to drilling. The depth to which the piles are driven into the seabed depends on the loads they must support, and the properties of the ground, and may easily exceed a hundred metres.

For small jackets with modest surface facilities in shallow waters, the piles may be driven through the main legs of the structure. When the number of piles required is larger than the number of legs, and the depths of water greater, the piles are driven through sleeves placed at the base of the jacket and joined to the legs in such a way as to transfer the loads of the structure to the foundations. Structural continuity between piles, sleeves and jacket is ensured by a ring of concrete poured at the end of piling operations, to fill the hollow space between each pile and its sleeve.

The jacket is usually also equipped with a number of utility systems allowing the staged flooding of watertight compartments during the installation phases, and the concrete to be poured to connect the piles and the structure. This staged flooding is carried out by opening the valves installed in each watertight compartment; these can be operated manually or using pneumatic systems.

The concrete is generally pumped from the surface to the various sleeves through another system of tubes and valves. In order to prevent the concrete escaping as it is poured, the space between the pile and the sleeve must be sealed at the base of the pile sleeve using rubber rings (grout packers); these are inflated with nitrogen once pile driving has terminated.

**Gravity support structures**

Unlike jackets, gravity support structures do not need foundation piles to transfer the various loads to the seabed, but simply rest on the seafloor using the force of gravity to maintain stability. Whereas jackets are built to be as narrow and light and insensitive to the loading of waves and currents as possible, gravity structures depend on their mass and base dimensions for resistance and stability.

To guarantee the required stability whilst not exceeding the load-bearing capacities of the seabed on which the structure rests, we need to construct an extremely massive base with large dimensions. Consequently, gravity structures are usually made of reinforced concrete. In this case, the topside is supported by cylindrical columns of large diameter, usually four in number. These columns, below the area subject to wave loading, are set into a large base
consisting of cells created with concrete walls (Fig. 4). Since the size of the structure allows it, many installations of this type are also used to store the crude oil produced, by virtue of tanks constructed inside the cells of the base. There is thus no need to transport the crude oil onshore through subsea pipelines, since it can be collected by tankers directly from the offshore production site.

A gravity support structure is built in a yard with a large dry dock. When construction work has finished, the dock is flooded so that the structure, whose base is watertight, can float. It is then towed out of the dock to a sheltered area of sea near the construction yard. Here a crane barge can install the topside modules on the substructure. Once the modules have been installed, these can be connected together, and test the functioning of facilities. The ability to complete the installation of facilities in a sheltered area near the coast, thus protected from adverse weather conditions, allows for an optimal use of time, and represents one of the advantages of this type of solution. The entire platform is then floated to the offshore installation site, where it is flooded and sunk in a slow and controlled way. In order to increase its mass, and thus the stability of the structure, some of the cells in the base are filled with inert materials once installation is complete.

The gravity solution in reinforced concrete has been used for some large fields in the North Sea, such as those along the Norwegian coast, with the platform being constructed inside the deep and very sheltered fjords. It has been extremely difficult to use this typology in other geographical contexts. In a few isolated cases, steel gravity structures have been built. Attempts have also been made to build hybrid structures, with a concrete base and upper steel framework, but none of these solutions have been particularly successful.

One possible alternative application for this typology is represented by the need to exploit reservoirs in arctic waters: only a gravity structure in extremely massive reinforced concrete can withstand collision with an iceberg, or the compressional loads resulting from the formation of pack ice. For these purposes, the reinforced concrete base has a cylindrical or truncated conical shape. In any case, gravity platforms represent a possible specialized typology, with advantages only in special contexts.

Foundations

Pile foundations represent the most commonly used typology for the construction of rigid platforms, and are generally coupled with framework structures (see above).

A recently adopted alternative to pile foundations involves constructing steel cylinders about ten metres in diameter, open at the base and closed at the top. These are placed at the four bottom corners of the jacket and integrated into the structural framework so as to protrude a given number of metres beneath the lowest level of the structure (Fig. 5): when the jacket is positioned on the seabed, the cylinders penetrate the upper layers of the seafloor due to the weight of the structure. After this initial penetration is complete, a pump system depressurizes the space inside the cylinders by sucking out the water, so that the cylinders can slowly sink into the seabed, driven by the pressure difference between interior and exterior.

As far as gravity platforms are concerned, on the other hand, as we noted earlier no special foundation
systems are required. The vertical compression loads are distributed over such a large load-bearing area that local pressures are limited, and the weight of the structure is so high as to balance any overturning moments.

Design of the facilities

Engineering the development of an offshore field, and in particular of a rigid platform, takes place in distinct stages, each with a well-defined aim.

Preliminary design and feasibility studies

Once we have discovered the field, evaluated its production capabilities and analysed the properties of the hydrocarbons, the first engineering phase begins. This involves drawing up a preliminary design and feasibility study, with the aim of defining the most suitable solution. During this first stage, cost estimates are made in order to evaluate the economic return on investments. More specifically, this first stage involves the following activities:

- Preparation of functional specifications defining the geographical location of the platform, the processing typology with the necessary systems and subsystems, the typology of the main support structures, and supplying a rough estimate of the mass and size of facilities and structures.
- Definition of surface facilities (primary processing systems, support and safety systems, the interface with gathering systems for the fluids produced by the wells and the interface with systems to export the fluids after treatment), and preliminary sizing of major plants.
- Definition of safety and environmental protection requirements (identification of safe temporary

Design of the facilities

Fig. 5. Jacket with a foundation alternative to piles (Eni-Saipem).

refuge areas and escape routes, and active and passive protection systems), and evaluation of the acceptability of environmental working conditions in terms of noise, vibrations and the presence of toxic substances.

- Definition of drilling package, well completion and workover systems.
- Definition of platform support structures and estimate of the mass of the topside structures, support structure, foundations, flare, accommodation and helideck.

It should be stressed that designing an offshore installation is heavily influenced by the prefabrication methods used in onshore yards, and by the methodologies used for offshore transportation, installation, completion and start-up. The design process should therefore take into account all possible problems and constraints, attempting to identify the optimum compromise.

Once the preliminary design stage has been completed, a preliminary estimate of investment expenditure is prepared with operating costs and, where necessary, decommissioning costs, thus obtaining the cash flow. This allows us to carry out an economic analysis with the aim of evaluating the economic profitability of the project over time. If the results of the economic analysis are positive, the necessary go-ahead, on the basis of the development plan chosen, might be obtained.

Collection of environmental data

The second stage involves collecting all necessary environmental data.

We therefore carry out in-depth geomorphological studies to define the exact conformation and depth of the seabed on which the platform is to be installed, and geotechnical investigations to assess the mechanical properties of the ground. Geotechnical studies require core samples to be taken in the subsurface to considerable depths if we intend to use a pile foundation, with tests aimed at determining the mechanical properties of the various layers. We also measure some of the properties of the seawater, such as the temperature and salinity at various depths, if these are not already available from databases. The meteorological conditions which the platform will face (winds, waves and currents), are obtained from statistical data for the area already available in the literature, or extrapolated using simulations with mathematical models.
Basic design

After gathering all the basic data needed for design, both with reference to the properties of the hydrocarbons to be produced and environmental and geotechnical parameters, the third phase begins. This involves defining all aspects of the drilling rig and processing plants, support facilities, safety systems, structures, etc.

Diagrams of energetic flow and of the materials are prepared, and the necessary process analyses to establish the characteristics of the hydrocarbon treatment plant are carried out, while the size of the plants and the materials used to build them is determined. In the same way, the characteristics and the size of utility systems are determined.

The well drilling and completion systems is then defined by preparing specifications for these, and drawing up general criteria for health and safety, the environment and acceptable risk; specifications for active and passive safety systems are prepared, and plans for the classification of hazardous areas, safety and rescue systems, and for escape routes are defined.

General layouts of the offshore complex, floor plot and elevations of facilities, appliances and main pipelines, plans of maintenance and distribution systems and utilities, plans of fire barriers and explosion-proof walls, are then prepared. Specifications for next detailed planning and the classification of the piping required are developed; specifications for piping materials, paints, cladding and insulation are drawn so as to be ready for subsequent requests for quotes from suppliers. After determining the specifications for the design of machinery and equipment, and carrying out the necessary studies, all the appliances required are defined, identifying their dimensions, capacity and mass, and drawing up specifications for subsequent requests for quotes from suppliers; specifications for the containment of noise and vibrations are also drawn up.

This is followed by the preparations of basic specifications for the electrical system, defining the electrical layout of the platform, carrying out basic calculations and drawing up a preliminary list of electrical loads; layout for switchboard rooms, substations and cabins are prepared and the properties of the relevant equipment are defined, drawing up specifications and data sheets needed for the subsequent request for quotes from suppliers. Layout for the routes taken by the main cables are then studied and optimized. Design specifications for instruments, automation and telecommunications are drawn up, and the characteristics of the equipment needed (control, safety, alarm and telecommunications systems, control and safety valves, measuring and control apparatus, etc.) are defined and used for subsequent quotes from suppliers; layout for instrumentation systems, control rooms and cabins, telecommunications systems and the main routes taken by cables are also prepared.

After establishing the project criteria and preparing design specifications, all the analyses required for the sizing of the main structures are carried out. These analyses must take into consideration all the loads, including temporary ones, to which the structures will be subjected during construction (loading onto barges for transport, transportation, offshore installation) and later during the operational life of the platform. Specifically, for deck structures and topside modules account must be taken of: a) static behaviour during the life of the platform, considering its various configurations (addition or removal of appliances, presence of temporary well workover equipment, etc.); b) behaviour during earthquakes; c) behaviour of transport vessels during loading and transportation phases; d) the phases of loading, transportation and offshore installation by lifting; e) fire resistance, to determine the extent of protective coating systems on the main structures; f) response to accidents such as explosions or the dropping of suspended loads; g) vibrations caused by rotating machinery.

Similarly, for support structures such as the jacket, exposed to waves and currents, we must take account of: a) the static behaviour of the structure subject to all the loads deriving from both the topside and the environment; b) the response to seismic loads; c) structural fatigue, extremely important due to the cyclical nature of hydrodynamic forces; d) the structural behaviour of the foundations; e) the behaviour of vessels during loading and transportation operations; f) behaviour during launching, for jackets launched from barges; g) behaviour during lifting, for jackets installed by crane barges; h) behaviour during up-ending and sinking and temporary stability after the structure has been placed on the seabed, before the completion of piling; i) the installation of foundation piles; l) accidents such as collision with ships and suspended loads dropped from the topside; m) cathodic protection system.
Once the design of the main structures is completed, the size of the most important secondary structures (such as staircases, walkways, grids, the main supports for appliances and pipes, supports for risers, J-tubes, caissons, etc.) must be determined and specifications to be used for the purchase of materials are to be prepared. Finally, layout for the buildings and the relevant structural and architectural drawings are developed, while specifications for air-conditioning and ventilation systems, and for electrical systems and utilities are drawn up.

**Detailed engineering**

At this point the final detailed design phase begins. This represents the definitive refinement of the previous phase, and aims to engineer all the facilities required, up to the issue of purchase orders for materials and equipment, and the preparation of the technical drawings required by yards for construction. During this phase, all the definitive calculation reports required for the project to be approved and certified, procedures for the construction, transportation, installation, commissioning and start-up of the platform and write the operating manuals are drawn up. Finally, all the drawings made during the detailed engineering phase are handed over to the construction yards.

**Construction**

For reasons of expenditure, the building of offshore structures and facilities must be completed as far as possible onshore, before they are transported to location in open waters and installed in their final configuration. The size and mass of the prefabricated units that can be finished onshore depend on the availability and capacity of the barges used for transportation and later for installation. This must be taken into consideration when modularizing a platform.

The structures to be prefabricated onshore are of considerable size and mass. Construction yards must therefore stretch over a large area, and the ground must be consolidated to guarantee high load-bearing capacities. They must also have suitable lifting equipment and a wharf able to support large loads, and to berth and moor the large barges onto which the structures are loaded.

**Topside construction**

Generally, the topside structure consists of a main module (deck), which is installed offshore directly onto the support structure. The facilities are built inside a steel structure of several storeys, connected to one another by columns and diagonal girders. If all the facilities cannot be contained within the deck, due to the limitations dictated by the transportation and installation phases, we need to build other modules, which are prefabricated separately and then installed on the main module.

Regardless of the specific construction sequences adopted by individual yards, the following two rules should be followed to optimize time and expenditure: work as much as possible inside covered sheds, in order to reduce the risk of inactivity due to adverse weather conditions; carry out as many activities as possible at ground level and on several fronts to reduce costs and allow us to proceed with several activities simultaneously. Consequently, it is essential to identify the largest possible number of subelements which can be prefabricated under cover, and then devise an installation sequence allowing the prefabricated components to be assembled as far as possible at ground level.

In accordance with these guidelines, the construction of a deck, or a typical module containing facilities, usually follows a sequence resembling that described below:

- Preparation of the areas of the yard needed for the various phases of construction.
- Installation of slipways (concrete blocks on which steel guides are installed), on which the deck will first be assembled and then skidded during loading onto the transport barge.
- Assembly of the loose structural elements received from the steelworks, prefabricating complete structural subunits of such a size that they can be constructed under cover (structural frameworks forming the complete floor plates of all the elements, vertical structural components such as columns and diagonal girders).
- Transfer of structural subunits to another shed.
where sandblast and painting of the surfaces is carried out.

- Assembly and painting of loose piping elements (pipes, bends, flanges, etc.), to form the prefabricated piping spools to be installed subsequently, whilst simultaneously prefabrication is undertaken.
- Prefabrication in the workshop of cable trays and their supports.
- Assembly of structural subunits, to create the framework for the various floor plates of the deck: each structural level can be assembled at ground level upside-down, thus allowing the installation of structural supports for piping and cable trays, mainly suspended beneath the framework (vertical columns and diagonal girders between one storey and another can also be welded to the framework while it is upside-down on the ground).
- 180° rotation of the first floor plate and subsequent installation in its final position on the slipways (Fig. 6).
- Installation of facilities on the first level framework; once this operation has been completed, the appliances are lifted and installed in their final positions on the floor plate.

- Mounting of prefabricated piping elements, installation of valves and connection of piping spools to appliances (Fig. 7).
- Installation of the second floor plate and its appliances, and so forth for subsequent levels (Fig. 8).
• Laying of electrical and instrumentation cables on the cable trays when welding work is almost complete, so as to minimize the risk of them being damaged.
• Systematic check that all components of the platform have been completed, and initial testing of the functioning of facilities (commissioning); this will be completed offshore, after installation has been finished and before the platform is started up.
• Mounting of temporary equipment needed for offshore installation, such as lifting slings.

Once finished, the deck (or module) must be loaded onto a barge for transportation to the open water installation site. The loading operation is usually carried out by sliding the structure along the slipways, using a system of hydraulic jacks. The barge is moored into position, and must be ballasted following a carefully designed sequence, in order to constantly compensate for the transferral onboard of the load, and changing tides. Suitable steel box girders are installed to create a bridge between the slipways on the wharf and those on the barge.

Construction of the support structure: jacket
The structural framework of the jacket is built in onshore construction yards following the same principles adopted for the topside: in other words, attempting to maximize prefabrication under cover and ground level assembly. The jacket consists of a three-dimensional frame made of tubular steel members welded to one another.

As already mentioned, depending on the dimensions of the topside and the depths of water in which it is to be installed, this structure generally consists of four or eight legs of large diameter linked by a series of tubular members, welded together to form both vertical walls and horizontal floor plates.

Small jackets, for installation on undemanding seaboards and in geographical areas where environmental conditions are not particularly severe, may be constructed by welding the tubular members directly to one another and to the main legs, thus welding only from the outside.

For large jackets, the joints between the tubular members are subjected to considerable static and dynamic loads and fatigue, and the connecting welds must therefore be continued inside the tubular members. The joints are therefore prefabricated units, made up of an inner tube of larger diameter, to which the tubular members which end in the node are welded (Fig. 9). This allows us to weld both along the external circumference and inside each member. Given their complex geometry, a result of the large number of elements which meet in each node, these joints are subjected to thermal treatment at high temperatures after prefabrication, to release the stresses caused by weld shrinkage. The tubular members forming the framework and which link together the prefabricated joints are created by the circumferential welding of several base elements (ferrules); each ferrule in turn is made in a workshop by rolling steel sheets of suitable thickness followed by longitudinal welding.

Other elements which can be prefabricated under cover are: a) the structural units containing conductor guides; b) the box girder sections forming the slipways along which the jacket is slid for loading onto the transport barge and later for launching in open waters; c) the mud mat structures forming the temporary foundations for the jacket before piling; d) the buoyancy tanks which ensure that the jacket can float during its installation; e) the sleeves which act as guides for the piles; f) the walkways and other small structures.

The walls of the jacket are generally built in a horizontal position, in the open and in a very large area of the yard; this area must be suitably prepared by installing slipways on which the jacket is assembled, and along which it will slide during loading onto the transport barge. The nodes and prefabricated tubular members are welded together on the ground to create the vertical walls of the framework.

For four-legged jackets, two opposite walls are constructed contemporaneously at ground level facing one another, so that when rotated through 90°, they stand parallel to one another. Most of the tubular members forming the floor plates which link the walls of the framework are welded to one of the two walls while it is still at ground level. After assembling these two opposite walls, they are then through 90° using a series of crawler cranes. The two walls are then connected by welding the members...
forming the floor plates, already connected to one of the two walls. The remaining diagonal girders linking the two walls are installed and welded at altitude. The anodes, risers, tanks, tubes for cementing and for the ballasting of watertight compartments during installation, and all the other structures supported by the jacket are welded to the walls of the framework as far as possible while these are still on the ground.

For eight-legged jackets the central block is constructed first; the external walls are then built at ground level, facing the central block. After completing ground level assembly, the two external walls are rotated through 90°, and joined to the central block. After completing the framework, the buoyancy tanks, assembled beforehand, are lifted and installed at altitude. The successful use of this building methodology depends on the ability of the prefabricated units to meet extremely stringent control and dimensional tolerance criteria. When the jacket is finished, it is loaded onto the barge (Fig. 10). The loading operation, as for the topside, involves sliding the structure along the slipways, whilst the barge, moored perpendicular to the wharf, is gradually ballasted following a carefully devised sequence.

**Construction of support structures:**

**gravity platforms**

For gravity structures, especially those in reinforced concrete, the procedure is completely different. These structures are built in their final vertical configuration in large dry docks. They are built from the bottom up, with the progressive installation of the reinforcement and slip forms and ramp bridge deck, followed by concrete casting. Once construction is complete, the dry dock is flooded, allowing the structure to float. The platform is then towed out of the dock by tugs and floated to a sheltered area near the construction yard where the topside modules are lifted into place by a crane barge.

**Transport and installation**

Onshore prefabrication introduces a series of issues linked to the need to transport structures of large size and weight from yards on the coast to the installation site, and then install these in open waters.

**Transport and installation of the support structure: jackets**

The vessel generally used to transport jackets from construction yards to the offshore installation site is a steel lighter, or barge, generally designed and constructed for this purpose. Given their considerable size, jackets are usually built and then transported in a horizontal position on the barge; only in those rare cases where the structures are designed for waters only a few tens of metres deep can they be built and transported in a vertical position.

Once placed in transport configuration after the loading operations, the jacket is rigidly connected to the structure of the barge, which is then towed by one or more tugs to the offshore installation site. The crane barge needed for installation operations is brought here simultaneously. As soon as weather forecasts are favourable, the installation operation begins by removing the elements connecting the barge and the jacket. Usually the structure must be placed in the water with an operation known as ‘launching’, since the jacket can be lifted directly off the barge only in those rare cases when its weight is compatible with the maximum lifting capacity of the installation vessel.

The launching operation is extremely delicate: the barge is first ballasted so that it leans a few degrees towards the stern. The jacket is then pushed by appropriate hydraulic jacks to overcome the friction between the slipways and the guide girders on the barge. At this point the structure begins to slide freely due to gravity, thanks to the inclination of the vessel. The jacket then continues to slide until it definitively leaves the barge. In some cases the jacket’s buoyancy tanks are designed and positioned so that the jacket can rotate autonomously until it is in a vertical position after entering the water. Usually, however, the jacket floats in the water in a horizontal position after launching. It is therefore needed to up-end it by differentially flooding the buoyancy tanks and other watertight compartments built into the structure’s legs. The launching and up-ending operations are carefully planned in minute detail, so as to ensure that the
structure is always stable, and does not exceed the minimum distance from the seabed.

After launching and up-ending, the jacket floats in a vertical position, with its base about ten metres above the seabed. The final positioning manoeuvre follows: the crane grabs the jacket using suitable slings, the flooding of watertight compartments is completed, and the crane gently lowers its hook, allowing the jacket to sink until it rests on the seabed in its final position. In order to guarantee that the jacket is correctly positioned, it is constantly monitored during the final phases of installation using an acoustic system which continuously identifies the structure’s position with respect to a reference system previously installed on the seabed.

When final positioning is complete, the jacket is supported by its temporary foundation. The crane is unhooked, and the crane ship is prepared to install the foundation piles. The piles, too, are prefabricated onshore, and transported offshore lying horizontally on a barge. The barge is brought alongside the crane ship, and each pile is up-ended and installed by the crane inside the sleeves on the jacket. Each pile is then driven by a pile hammer until it reaches the depth specified by the project. After pile-driving, the piles need to be cemented in place: the cement mortar is pumped from the crane barge into the gaps between pile and sleeve, through tubes previously placed along the jacket structure. Once the cement has set, the structural link between the foundation piles and the structure is complete.

All the phases of installation require underwater observation of the various manoeuvres which occur beneath the surface of the sea. For this purpose we use submarine robots (ROV, Remote Operated Vehicle), manoeuvred from the ship’s bridge with remote control systems. The ROVs are placed in the water when operations begin, and allow us to see, using underwater television cameras, the touchdown of the jacket, installation and pile-driving. In some cases, the ROVs are equipped with manipulators, and can also be used to manoeuvre the valves for cementing.

The installation sequence ends with the removal of the temporary structures used only for the offshore installation operation, such as: buoyancy tanks, temporary platforms to support the lifting slings and the hydraulic control systems used to operate the subsea valves required for flooding and cementing operations. Until a few years ago, these removal operations required teams of divers, who had to work under saturation conditions due to the depths, thus forced to spend days afterwards in a hyperbaric chamber built on board the installation vessel. Technological developments, and the need to work in increasingly deep waters, has allowed the design of special ROVs. As well as allowing for the observation of operations, these can also work underwater, thanks to mechanical arms and manipulators. Today, divers are used only for work in shallow waters, whereas operations at depth are mainly carried out by underwater robots.

Transport and installation of support structures: gravity structures

Given their enormous size and weight, gravity support structures cannot be transported by barge, but must be floated. After leaving the dry dock, the structure is attached to a sufficient number of tugs, which transport it, floating in a vertical position, to a sheltered area not far from the construction yard. Sheltered from the danger of adverse sea conditions, the topside modules are then installed, lifted by a crane barge from their transport barges and positioned on top of the support structure. Once the installation of the modules is complete, these are connected together, and the functioning of facilities is tested. The complete platform is then towed to the offshore installation site.

After reaching its destination, the structure is slowly sunk by the gradual and controlled flooding of the watertight compartments built into its base. The tugs, arranged around it in a circle, keep it under control until touchdown has occurred. Its position and orientation are monitored as described for jackets.

Once the structure has come to rest on the seabed, all the watertight compartments are flooded to increase stability. To further increase its weight, some purpose-built compartments at the base of the structure are filled with inert materials.

Transport and installation of the topside

The deck and the modules containing topside facilities are transported from the construction yard to the offshore installation site on special barges, as we have seen for jackets transportation. The considerable masses to be transported require the construction of grid structures to spread the loads over the deck of the transport vessel, at the points where the topside rests. After completing loading operations, elements are installed to ensure that the structures remain integral with the barge during transport. The barge is then
towed to the offshore site, where the vessel used for installation is already in place. When weather forecasts are favourable for the coming hours, the barge is moored to the crane barge.

Over the past decades, significant developments have taken place in the construction of installation vessels. New vessels have appeared on the market equipped with cranes of high capacity and high stability hulls, which can also operate under conditions when the sea is not perfectly calm. The most powerful vessels have a pair of cranes which work in tandem, and semisubmersible hulls which considerably increase their draft during operations, thus allowing them to remain extremely stable and relatively unaffected by wave motion.

The lifting slings, pre-installed at the construction site, are linked to the crane’s hook (or hooks, with two cranes lifting in tandem), and the connecting elements are removed and the crane can lift the load. When the structure is completely free, the barge is unmoored, and towed away from the operation zone. The crane barge, with the load suspended from its hook, subsequently approaches the substructure (jacket or gravity platform), onto which the deck or module is to be installed (Fig. 11). When the vessel is in position, operations to lower the deck onto the substructure begin; to ease correct positioning, the design includes purpose-built conical sleeves or guides which allow the installation of the structures to be completed within the requisite dimensional tolerance.

The installation vessel generally works while anchored to its mooring system, consisting of anchors and steel cables. Modern ships of higher capacity also have a dynamic positioning system which allows the vessel to maintain a predetermined position with respect to a satellite control system autonomously, by activating and orientating propeller thrusters. This speeds up installation operations, since the vessel can operate without being moored.

After completing the installation of the deck, and any further modules forming the topside, it is necessary to link the substructure and the deck, and the deck and the other modules. Between the deck and the substructure it is necessary to weld the legs and join together corresponding pipes. Connecting the deck to the other modules is more difficult, especially when the processing plant is divided between several modules. As well as the welds, required to guarantee structural continuity, it is needed join up all the pipes and install all the electrical and instrumentation cables which pass between the modules. This phase is the most critical, since it is extremely expensive and time-consuming. The primary objective of a good project is thus to reduce these post-installation operations to a minimum, with an optimal subdivision of platform systems between the various modules. The availability of crane barges of ever greater capacity has also allowed us to design and construct increasingly integrated topsides over the years. Once all the work needed to connect the modules to one another has been finished, the topside facilities are complete and ready for the subsequent commissioning and start-up activities.

An alternative installation methodology to lifting which allows us to overcome the limitations resulting from the maximum capacity of crane barges is the float over. This procedure involves transporting the deck on a barge which is narrower than the space between the structure’s legs, so that the legs are outside the external sides of the vessel. The barge must be towed and positioned inside the previously installed support structure, so that the legs of the deck are in

![Fig. 11. Installing the deck: lifting with a crane barge (Eni-Saipem).](image)

![Fig. 12. Installing the deck: positioning on the support structure by float over (courtesy of ARUP Energy).](image)
line with the legs of the structure on which they will come to rest (Fig. 12). At this point the topside structure is lowered until it comes to rest on the support one. The structure is lowered using sand jacks, and by ballasting the barge. After completing the mating operation, the barge continues to be ballasted until it is completely free of the structure above, and can thus be towed away from the platform. This apparently simple operation is in fact extremely delicate, and heavily affected by weather conditions, which must be absolutely favourable. However, it does allow us to construct extremely large integrated topsides.

5.2.3 Development of marginal fields

Characteristics

Most large offshore hydrocarbons basins have now entered the phase of maturity, having been in production for several decades; at the same time, new discoveries of large fields in shallow waters have become an absolute rarity. The technological solutions which will be discussed briefly in this section aim to exploit small geographically dispersed hydrocarbon reserves in shallow waters, whose development would not be economically viable, or would entail excessive risk, were some specific expedients – which have become available only in recent years – not used. Since reservoirs of this type are characterized by being on the borderline of development viability, they are described as marginal, dependent on the levels of oil and gas prices, development costs linked to the properties of the field to be produced, and the level of economic risk which the operator is able to sustain. Generally speaking, marginality is linked to two basic factors: the small amount of hydrocarbon reserves in the reservoir concerned, and its distance from other existing installations. Development potential depends on our ability to contain expenditure as much as possible, and the need to reduce to a minimum the time required for the transition from the engineering phase to the operational phase.

The time factor is crucial for the development of a marginal field: each year of delay in the start of production reduces the field’s economic value. Consequently, once it is decided to develop a marginal field, this must be done as quickly as possible, and the production period must be as short as possible in order to allow a rapid return of the initial financial exposure. Another factor characterizing marginal fields is the greater uncertainty of our knowledge of reservoir properties, given the economic impossibility of undertaking expensive data collection campaigns.

The technological solutions used to develop a marginal field must therefore allow us to: minimize the expenditure and time required for development by identifying simple solutions, as standardized as possible, which reduce the need to treat the hydrocarbons offshore to the minimum; reuse production facilities for another field once the reservoir is depleted, since investment expenditure often cannot be repaid by their use on a single platform.

Development typologies

There are three basic typologies for the development of marginal fields, which meet these conditions: small fixed platforms, which are light and unmanned, with a minimum of topside facilities; subsea production systems linked to floating treatment plants; subsea production systems linked to existing platforms.

Fixed platforms

On small fixed platforms, clearly advantageous for very shallow waters (maximum 50 m), the topside must be as light as possible. Consequently, treatment and support facilities must be reduced to a minimum.

Thanks to the simplification of facilities, operations can be controlled remotely from another platform or from the shore. There is thus no need for a human presence, and therefore for accommodation, on the platform. Some of the technological expedients allowing us to minimize the number of facilities to be installed are: the use of multiphase fluid pumping technologies, allowing water-oil emulsions to be transported in pipelines, and thus avoiding the need to separate these on the platform; the reduction to a minimum of electricity consumption, allowing us to use alternative energy sources such as photovoltaic cells or wind generators; the simplification of the firefighting system, made possible by the lack of a human presence on the platform. Simplifying facilities also allows for considerable structural reduction, and thus a further decrease in the total mass of the topside, easing the construction, transportation and installation phases.
and thus significantly reducing the time and expenditure required.

Supporting substructures also benefit from the lightness of the topside module. These are constructed in steel, in the shape of either a four-legged framework or a tripod with only three legs. In very shallow waters, the substructures may consist of only a single steel column of large diameter (3-5 m), on which we install the production topside, and inside which the well conductors and the export pipelines are placed (Fig. 13).

To guarantee an economic return on investments, we must be able to reuse the structures on other fields. Their design must therefore take into account possible future use, and allow them to be easily removed and reinstalled with minimal modifications.

**Floating platforms**

In deeper waters it becomes preferable to use floating treatment plants linked to subsea production systems; this is also the solution most frequently adopted for the development of large fields in deep waters (see below). For reasons of cost, production facilities are generally housed on converted oil tankers, which also allow the storage of the crude oil produced. The crude oil is periodically transferred to tankers moored near the floating platform, and then transported to onshore treatment plants.

The subsea production system consists of a steel structure (template) installed on the seabed and anchored with foundation piles. The structure is initially used as a guide for the drilling of wells. When drilling has been completed, the production module is installed on the template; this contains the subsea wellheads, a manifold to collect the fluids produced, and the control system for the wellheads. The production module is then protected by a framework structure which prevents potential damage to facilities caused by fishing or objects dropped from the surface.

The tanker converted into a production facility is anchored near the subsea template. The risers are then installed; these are the pipelines which allow the hydrocarbons to rise to the surface facilities from the wellheads (see below). Given the limited depth of the seabed, the risers must be made of flexible materials, so as to work with modest radii of curvature and the dynamic motion of the vessel to which they are linked without being damaged.

![Fig. 13. Development of marginal fields: simplified support structure (Eni-Saipem).](image)

**Fig. 14. Development of marginal fields: subsea production system connected to an existing platform.**
Other flexible cables of small diameter (umbilicals) link the surface vessel to the wellheads on the seabed; inside these are the electrical control cables and the small tubes which transport the fluids needed to manoeuvre the valves on the wellhead and any chemicals needed during the start-up of the wells.

**Existing platforms**

When the marginal field is near an already producing platform, we can avoid using a floating treatment plant by linking the subsea production systems to the existing platform using one or more pipelines to transport the reservoir fluids and an umbilical to control the subsea systems (Fig. 14). In this case, we usually need to modify the existing facilities on the platform to increase their treatment capacity. Since the reservoir fluid is transported without prior treatment and is highly corrosive, the pipeline cannot be made of simple carbon steel, but must be made of special corrosion resistant steel, or carbon steel plated inside with suitable alloys. Furthermore, to avoid the pipeline being blocked by the formation of waxes or hydrates on its walls when the untreated reservoir fluid cools to below given temperatures, we need to provide it with external thermal insulation. For all these reasons, the pipeline becomes extremely expensive, and it is economically viable to develop the marginal field in this way only if the subsea wells are installed no more than a few kilometres from the existing platform.

**5.2.4 Development in very deep waters**

**Generals**

The drastic decrease in discoveries of new fields on the continental shelf, and thus in shallow or moderately deep waters, has led offshore petroleum exploration towards very deep waters. The difficulties faced in designing and installing production platforms at depths ranging from 300-400 m up to over 2,000 m are easily understood. From a structural point of view it is impossible, and economically untenable, to extend the typological solutions adopted for shallow waters to these great depths. We must abandon the support structure which rigidly resists the loading of waves and currents; whilst the platform must remain anchored to the seabed, less rigid structures must be used, allowing for considerable displacements, and consequently adaptation to wave motion.

If we have a surface production platform which is not rigidly connected to the seabed, however, this introduces the problem of bringing the fluids to the surface inside pipelines which are sufficiently flexible to withstand the stresses caused by large displacements and the direct action of waves and currents.

Great depths also mean high hydrostatic pressures and low temperatures. To obtain a high degree of thermal insulation insulating materials with low density and thermal conductivity must be installed on the pipelines. However, low density materials are also poorly resistant to high pressures, thus making it necessary to find new technological solutions combining thermal insulation with resistance to high pressures. From an operational point of view, floating drilling rigs, able to maintain their position and operate without needing to be anchored had to be designed. As far as the construction of production facilities is concerned special vessels for the installation of structures and pipelines, and to carry out subsea operations at great depth needed to be built.

Here we will first describe some typological solutions suited to very deep waters. These, whilst guaranteeing considerable elasticity, low oscillation frequencies and thus adaptability to the dynamics of wave motion, nevertheless keep the displacements of surface facilities within values allowing for the installation of surface wellheads and the use of traditional completion and workover technologies, similar to those used on rigid platforms. We will then see how, in some cases, the flexibility of this system and thus its displacements are such that this solution cannot be adopted; in this case the surface treatment plants must be coupled with production systems with subsea wellheads and non-conventional well completion systems. Finally, we will briefly describe the different types of risers, in other words the pipelines which allow the transfer of reservoir fluids from the seabed to surface facilities in very deep waters.

**Platforms in deep waters with surface wellheads**

**Compliant tower**

Conventional platforms in moderately deep waters are so rigid that the structure’s natural oscillation period is lower than that of the most powerful waves, thus avoiding phenomena of resonance. To apply the same principle at great depths (with equally high rigidity), we would need structures of such enormous size and weight that they would be impossible to build, as well as economically unviable.

The compliant tower was designed to resolve this problem. This is a platform similar to a conventional platform, with a metal framework support structure of jacket type, but very narrow and with far lower rigidity, and thus with natural oscillation periods much higher than those of conventional rigid platforms, even
higher than those of the most powerful waves. In this way we avoid dangerous phenomena of resonance thanks to oscillation periods higher than those of waves, rather than lower as is the case for conventional rigid platforms.

The structures and topside facilities are identical to those on a conventional platform, including drilling technologies and access to wells from the surface. The support consists of a steel framework structure of square section, similar in type to a jacket (see above). Its low rigidity is obtained by keeping the section of the framework very narrow in relation to the depth of water, and above all by creating a joint in the structure which forms a hinge whose rotations are controlled by resistant members that act as springs.

This structural hinge may, for example, be built at a certain distance from the base of the structure. In this case, the framework is constructed in two sections: the lower base section is a rigid structure identical to a conventional jacket, whose foundations are created using piles in an equally conventional way; the upper section, much taller, has a square cross-section of constant size along its entire height, and rests on the lower section (Fig. 15). The four legs of the upper section end in pins, which, during offshore installation, are inserted into the legs of the lower section; the two sections are linked by concrete casting to seal the gap between pins and legs. The structural hinge is built into the lower part of the upper structure (tower). The rotations of the upper part of the structure around the hinge are controlled by eight steel tubes (two per corner) which run most of the way along its length. When the tower oscillates in one direction, the tubes on the opposite side come into traction, and act as springs which return the tower to a position of equilibrium. The great advantage of this solution lies in the fact that the same technologies and structural typologies are used as for conventional platforms. The structures are built and installed in the same way as rigid platforms (see above).

As far as transportation is concerned, both sections of the structure are transported by barges to the installation site. The lower structure is launched, up-ended and installed on the seabed with the help of a crane barge suited to operating at great depths. The foundation piles are then driven in and cemented. After completing the installation of the lower structure, the upper structure is in turn launched and up-ended by sequentially flooding the watertight compartments inside the legs, and then positioned above the lower structure. After hooking up the two structures, concrete is cast to join the two sections. The several day period required for the concrete to set is highly critical: since the upper structure is in a condition of partial stability, this phase of installation must be undertaken in good weather conditions, and with favourable forecasts for the entire duration of the operation. After completing the installation of the tower, we proceed to install the deck and any other topside modules, lifting them with a crane barge as we have seen for platforms in shallow waters. During the design phase, we should take into consideration problems linked to the large displacements (especially very high fatigue, and the wear caused by constant relative movements and friction between the steel pipes and their guides). Platforms of this type have been built on seabeds about 500-600 m deep. At greater depths, however, the solutions described below are used.
**Tension Leg Platform (TLP)**

In the platform known as a Tension Leg Platform (TLP), the hydrocarbon treatment plants are housed on a special floating hull with excellent stability, which is kept in position by a system of vertical tendons anchored to the seabed (Fig. 16).

The hull is made of steel, and consists of four vertical columns of large diameter (about 20 m), stiffened by internal longitudinal and circumferential ribs. The columns, placed at the corners of a square whose sides may be up to 80 m long, are connected at the top to a structural platform, designed to support treatment facilities and occasionally drilling equipment. Facilities and living quarters are built inside steel modules to be installed above the hull, as for rigid platforms (Fig. 17). The wells are preferably pre-drilled using a drilling rig suitable for great depths, and then completed from the top of the TLP.

In this case we are dealing with a semisubmersible hull; once it has been ballasted in operating conditions it has a very high draft, allowing it to remain extremely stable despite the loading of wave motion. Since only the columns cut through the surface of the water, this considerably reduces the loading exerted by waves on the structure. Protection from corrosion is ensured by the presence of sacrificial aluminium anodes on underwater parts, and by painting the areas exposed to the atmosphere near the waterline and the internal ballasting compartments. The hull is anchored to the seabed with 12-16 tubular steel tendons whose diameter is lower than a metre, attached to the structure near the base of the columns (3-4 tendons per column). These tendons are fixed to the seabed with foundation piles, which are driven into the ground to a depth sufficient to guarantee resistance to the high tractions released by the tendons. Thanks to the action of the tendons, maximum movements are contained within limits enabling us to use well completion technologies and wellheads similar to those used on conventional platforms in shallow waters.

The difficulties in designing a TLP are mainly linked to the correct simulation of the loading of wind, waves and currents on the hull, the accurate evaluation of the system’s dynamic response, and thus the motion induced, the tensions in the tendons, and the minimal distance of the deck from the wave crests. To refine the design and optimize its size, we should always carry out trials on models in a tank. In particular it is essential to achieve optimization of the pretension in the tendons, obtained by selecting a suitable value for the hydrostatic lift on the hull. The pretension must be high enough to ensure that the tendons always remain taut regardless of operating conditions, but at the same time must not be excessive, to avoid the hull becoming oversized. Once we have optimized the pretensions in the tendons and the height of the hull, these determine the choice of the diameter of the columns and the

![Fig. 16. Tension Leg Platform (TLP).](image-url)
size of the pontoons linking these at the base. It should be remembered that the tendons and all elements subject to cyclical loads must be carefully designed against fatigue. During the design process we should also optimize the horizontal dimensions of the hull, taking into consideration the layout and safety requirements for hosting surface facilities.

The hull of the TLP and the modules containing facilities are constructed at onshore yards equipped for building conventional rigid platforms. Transportation is then effected: for this purpose a special vessel is used which, using a ballasting system, can immerse its deck so as to allow the hull of the TLP to float freely on its base pontoons when it is to be launched. The hull must then be transported near the site where it is to be installed and the topside modules integrated. Transport may occur on the vessel onto which the hull has been loaded, or the hull may be allowed to float freely immediately after loading, and then be towed. Transport using a barge is more expensive, but much faster.

The construction, transportation and installation of the topside modules are carried out as for rigid platforms, in particular gravity platforms. The modules containing facilities may also be installed while the hull is temporarily anchored near the yard in a sheltered area of sea. The tendons are prefabricated onshore in sections of length under a hundred metres, and then transported offshore where they are assembled using mechanical mating systems as they are lowered into the sea in a vertical position. The foundation piles are prefabricated onshore, and transported offshore as for the foundation piles of a jacket.

Offshore installation requires the presence of a crane barge. The first stage of this process involves installing and driving the piles using a subsea pile hammer suited to great depths. After the piles have been installed, we begin to assemble the tendons in parallel on the two long sides of the crane barge. In the meantime, the TLP is towed to the installation site. The completely assembled tendons are left hanging from the sides of the crane barge, awaiting the arrival of the TLP. The TLP is then moored to the crane barge, and the tendons transferred one by one and hooked into place at the base of the columns of the hull. The tendons are then lowered from the TLP until they can be inserted into the relevant slots on the tops of the piles or on the foundation template. The tendons are hooked to the piles with the help of submarine work vehicles controlled from the surface (ROVs). Once the tendons have been hooked into place, the ballast water is pumped out of the TLP’s hull to bring the tendons

![Fig. 17. Tension Leg Platform (TLP): hull and topside.](image1)

![Fig. 18. Mini-TLP.](image2)
into tension in accordance with project specifications. The installation of the TLP can now be considered complete.

This type of platform represents a viable solution, and has already found a practical application in offshore fields at depths ranging from 500 m to about 1,200 m. However, it does not allow the crude oil produced to be stored, so export pipelines are needed. Alternatively, the TLP can be used alongside a storage vessel (FSO, Floating Storage Offloading vessel) and a loading buoy to which the tankers connect to load the product. Both these units must be permanently moored near the TLP, and linked to one another and with the TLP using pipelines, which are generally flexible, for the transfer of products. Recently a type of TLP has been built with a hull of completely different design from that described above, and which represents a good alternative especially for topside facilities of modest size and weight (Fig. 18). This type of platform, known as a mini-TLP, has a hull consisting of a single central column supporting the deck and its facilities. Three pontoons radiate out from the base of the central column. The tendons (six in total) are connected to the ends of the pontoons.

**Spar platform**

A different floating production system for deep waters is the Spar (Fig. 19). The hull of the Spar consists of a cylindrical tower structure about 25 m in diameter and 200-250 m high, which floats in a vertical position thanks to a special arrangement of watertight compartments. The structure is of conventional naval type, in steel reinforced by circumferential ribs and transverse and radial bulkheads. The bulkheads serve to subdivide the hull into various watertight or floodable compartments, allowing it to float as desired. The inner central part of the tower is hollow, enabling it to hold the production risers which carry the hydrocarbons from the wells to the wellheads at the surface, and thence to treatment plants. Each riser is kept taut by a buoyancy tank which is also installed inside the hollow centre of the tower. Once the tower has been positioned and ballasted in operating conditions, it floats vertically with a draft equivalent to over 90% of its length.

The watertight compartments which provide the necessary hydrostatic lift are concentrated in the upper part of the hull. At the lower end, other watertight compartments are built to keep the tower floating horizontally during the transportation and installation phases. These are later flooded, allowing the hull to adopt its vertical operational position and compensating for any offset in the centre of gravity of the structure and its topside facilities. Protection from corrosion is ensured by the presence of aluminium sacrificial anodes on the lower parts, and by painting areas exposed to the atmosphere near the water line, and the internal ballasting compartments. To prevent the vortex shedding generated by the passage of currents along the cylindrical surface of the tower causing unwanted phenomena of dynamic oscillation, spiral strakes are installed on the outer surface along its entire length, similar to those which can be seen on factory chimneys.

The production plants and living quarters are contained in one or more topside modules installed on
top of the tower, and built inside steel frames, as for the topsides of rigid platforms. The wells are pre-drilled using a drilling rig suited to deep waters, and then completed from the top of the tower.

The Spar is anchored with a mooring system consisting of a series of cables arranged in a circle around the tower and tethered to the seabed using piles, or suction anchors. A suction anchor consists of a cylinder about 5 m in diameter and ten metres tall, open at the base and closed at the top, to which the chain at the end of the mooring cable is attached. The cylinder, once resting on the seabed, is driven into the ground by creating a pressure inside which is lower than external pressure. This is done by extracting the water using a system of subsea pumps placed on the top of the cylinder itself. The mooring lines are steel cables, ending with sections of chain at both ends, and stretched so as to increase their rigidity and thus reduce the tower’s movements.

The design of the hull depends on modes of transportation and installation, and on operating conditions. Appropriate trials on models in tanks are carried out to test the results of theoretical simulations. In order to define the optimal pretension to be applied to the mooring cables, the mooring methodologies and an evaluation of the dynamic response of the system are important. Fatigue checks are essential to determine the size of the local structures to which the moorings are connected. The mooring system is designed to keep the tower in position even under the worst possible weather conditions.

Construction involves subdividing the tower into a given number of sections. The sections are then aligned and welded together in open air. Due to its excessive length, the structure is usually built and transported in two sections whose size and weight is such that they can be prefabricated inside covered workshops. These can be finally assembled in the water, by joining together the two sections of the tower floating horizontally at the quay of a yard near the final installation site, or on land in a dry dock. Construction procedures for topside modules are identical to those seen earlier for rigid platforms.

Offshore installation takes place in two distinct phases, both requiring the assistance of a crane barge and remote-controlled underwater work vehicles (ROVs). During the first phase, the moorings are installed. Each mooring pile is lowered to the seabed with its mooring line already attached, and is driven into the ground by a subsea pile hammer suited to working at great depth. If suction anchors are used instead of piles we proceed in the same way. The second phase of installation begins by transporting the tower from the assembly yard to the offshore installation site. The tower is towed by tugs, floating horizontally. After reaching the installation site, the watertight compartments allowing the tower to rotate through 90° are progressively flooded until it reaches its definitive vertical position. The end of each mooring line is then recovered from the seabed to the deck of the crane ship, and transferred to the Spar. Once all the lines have been recovered, they are tightened until they reach the tension values specified during the engineering phase.

At this point the module or modules containing production facilities are installed, using methods identical to those seen earlier for rigid platforms. The final operation is to lift the buoyancy tanks from the transport barge and install these in the central part of the tower; the production risers are later attached to these (see below). This type of platform represents a valid solution for deep waters, and has already found practical applications in a large number of cases in depths up to 1,700 m.

Recently, a platform named Truss Spar was designed and built; this represents a development of the Spar (Fig. 20). The Truss Spar differs from the Spar in the lower part of the tower, which consists of a steel framework instead of a cylindrical hull. The watertight compartment at the base of the tower,
required during horizontal transportation and to up-end the tower, is now obtained by installing a parallelepiped at the base of the frame. At the various levels of the framework are floor plates, which allow an improved damping of vertical movements. The advantages of the Truss Spar over the classic solution are as follows: 
a) a saving of structural steel and thus reduction of construction costs; 
b) reduced total height of the tower; 
c) vertical movements reduced thanks to the presence of floor plates acting as dampers; 
d) lower loading of currents thanks to the framework which replaces a substantial portion of the cylindrical section; 
e) fewer vibrations caused by vortex shedding.

**Floating production units coupled with subsea production systems**

There is another class of floating production systems which represents an alternative or addition to the production systems discussed earlier. Unlike those examined previously, these do not allow the completion of the wells from the surface and the installation of surface wellheads; these units must therefore be linked to subsea production systems and wellheads. These units are vessels which are either semisubmersible or have conventional hulls, on board which the production facilities are installed. In this case, the wells, either individual or grouped on a template installed on the seabed, are pre-drilled before the installation of the production unit, and then completed with subsea wellheads. The subsea production system is created as for the development of marginal fields in shallow waters, to which we refer for a detailed discussion (see above).

The floating production unit is moored in a central position with respect to the subsea wells, to which it is then joined by rigid or flexible pipelines which carry the reservoir fluids from the wellheads to surface facilities (see below). Other flexible tubes of small diameter (umbilicals) link the subsea production systems to the surface units; these contain the electrical cables and hydraulic fluids required to control the wellheads from the surface and any chemicals needed during the start-up of the wells.

**Semisubmersible units**

A production unit of semisubmersible type (Fig. 21) is identical in structure to the semisubmersible drilling rigs (see above). Under operating conditions, the unit is ballasted until it reaches a considerable draft, and therefore high stability and reduced motion due to wave loading. The disadvantage of this type of hull is that it has no storage capacity; pipelines for the export of products are therefore needed, which are difficult to make and very expensive for deep waters. Alternatively, the production unit may be used in combination with a storage vessel (FSO) and a loading buoy, moored near the semisubmersible production unit.

**Floating hull**

The advantage of using a vessel with a conventional hull is precisely that it has large holds in which to build storage tanks. In this case, the production unit is also used for storage (FPSO, Floating Production Storage Offloading vessel), and it is sufficient to hook it up to a loading buoy to ensure the export of the fluids produced (Fig. 22). In this case the hull may come from a converted tanker or be tied to a storage vessel (FSO) and a loading buoy, moored near the semisubmersible production unit.
purpose-built. Purpose-built hulls are generally made of steel, although some are made of reinforced concrete. In any case, the treatment plants, support and safety facilities and living quarters are installed on the main deck.

An FPSO is shaped like a conventional ship, and thus has a preferential orientation with respect to waves, currents and winds. The most effective way of mooring an FPSO is to use a rotating turret, to which the mooring cables are attached, and around which the vessel can rotate through 360°, thus keeping the bow into the wind and significantly reducing the load on the moorings (Fig. 23). Only where the production unit must be installed in an area where intense wind and waves come from a single quadrant can the vessel be moored in a fixed position, with mooring cables at the bow and stern, and with the bow facing in the direction of the prevailing winds. If a rotating turret is used, it can be installed outside the FPSO’s prow by means of a cantilevered structure or located inside the vessel. The external solution is more convenient if the turret is being installed on a converted tanker, whilst internal installation is preferable if the vessel is purpose-built: since the turret can be installed in an area closer to the centre of rotation of the ship’s motion, the turret is subjected to lower loads. In any case, the turret is a highly critical and expensive component of this system, because in addition to the mooring cables, the production risers must also be joined to the same rotating system, and the transfer of fluids to the manifold on the vessel must be guaranteed without the danger of leaks due to ruptures.

The mooring system is an equally important component of a floating production system; there are various alternative solutions. A conventional mooring with a catenary cable system loses rigidity in deep waters and thus causes the ship to move considerably, as well as requiring extremely long cables with high weight, which are therefore very expensive. In order to increase rigidity whilst simultaneously reducing the length of the cables, it is preferable to use a mooring system with shorter cables that must therefore be extremely taut. Traditionally, a mooring line consists of a steel cable with sections of chain at both ends, and with the lower end joined to the anchor. If shorter cables are used, the relatively lower length of the mooring lines and the high loads to which they are subjected exert significant vertical loads on the seabed anchoring system. In this case, traditional anchors must be replaced with piles or suction anchors, as we have described above for the mooring of the Spar (see above).

As far as the mooring cables are concerned, cables have recently been manufactured in synthetic fibres, with the production of increasingly light and resistant prototypes. Polyester fibre in particular has revealed itself to be a good alternative to steel cables for use in very deep waters: however, the disadvantage of these cables is that they are less resistant to abrasion, and potential surface cuts; in this case, too, the ends must be made of chains.

Designing the hull presents the problems typical of ship design, whilst that of the treatment plants follows the same criteria adopted for rigid platforms. Indeed, the procedure is often less complex, since the deck areas available for installation are larger, and there are thus fewer constraints on facilities. In this case, too, for safety reasons the layout of facilities is governed
by the attempt to segregate the dangerous processing areas and flare in an area as far away as possible from living quarters, generally with utility systems in between. This is easier for facilities on FPSO’s, thanks to the length of the vessel: accommodation is located at one end (bow or stern), with the processing area and flare at the other end. If the vessel is purpose-built, the accommodation is placed at the bow (in the more secure windward position), whereas in converted tankers accommodation is kept in its original position at the stern. Due to rolling and pitching motions, special attention must be devoted to the design of processing plants, and to fatigue-assessment; if the vessel is converted, the fatigue check must also take earlier use into account.

As far as construction is concerned, building an FPSO does not present particular problems. The hull, both for converted tankers and newly constructed vessels, is built in a traditional shipyard. The treatment plants, on the other hand, are built as the typical modules of offshore platforms, and thus in a different yard. Once finished, the hull is sailed to the quay of the yard where the facilities modules have been constructed, and moored. Here the modules are installed and integrated on the deck. Once integration is complete, and we have checked that the facilities are fully functional, the vessel can leave the yard and be towed to the offshore installation site. The mooring system is installed and rested on the seabed before the vessel arrives. As soon as the production unit reaches the installation site, the moorings are recovered, and attached one by one to the vessel, as seen for the Spar platform (see above).

We then install the production risers and umbilicals with the devices to control the wellheads, which are layed from an appropriate vessel (see below), and linked to the ship and the subsea production system. The problem of exporting the crude oil produced and stored in the holds of the FPSO is resolved by placing a loading buoy next to the production vessel. The buoy is moored near the FPSO and linked to it by flexible or rigid steel pipelines; the buoy also has a mooring line and a flexible tube, to the end of which the tankers which come to collect the crude oil are connected.

The flexible pipelines which transfer crude oil from the FPSO to the buoy are highly complex and expensive since, to resist the high pressures and loads, they are made by superimposing numerous layers of special plastic materials, alternating with metallic spiral armour. The solution using rigid steel tubes is much cheaper, but presents considerable problems due to the high dynamic loads and fatigue caused by the relative motion between FPSO and buoy. To reduce these effects, the rigid tubes cannot be installed with a natural catenary configuration, but must follow a special w-shaped configuration, obtained by installing buoyancy modules along the middle section.

**Risers**

In deep water developments, the substantial distance between the seabed and production facilities, and the fact that these facilities are themselves hosted on non-rigid structures and are thus subject to significant displacements, cause considerable problems in the construction of the pipelines (risers) which transport the reservoir fluids from the wells to the surface.

As already mentioned, the displacements of TLP and Spar platforms as a result of waves and currents can be kept within limits allowing the installation of surface wellheads and the use of vertical steel risers. These limited displacements can be absorbed by the length of the pipeline and the flexibility of the steel without the need for special materials or geometrical configurations, required for floating production systems.

During production, the vertical risers act as guides for the succession of tubing elements, which carry the hydrocarbons from the reservoir to surface facilities; they also function as containment facilities if leaks occur within the tubing. During well workover and reservoir stimulation activities, the riser also functions as a guide for the equipment which must be lowered into the well from the surface.

Each riser links a well to its wellhead at the surface, and consists of a steel pipe about 25 cm in diameter, thick enough to resist the pressure and stresses induced by the static and dynamic loads to which it is subjected. The riser is installed directly from the platform, using a traditional drilling derrick, and joining together prefabricated sections of pipeline. The first tube is lowered into the water, and this is then joined to the second using a special threaded joint, the pair of tubes is lowered, and the third tube joined to the top, and so forth until the entire pipeline is complete. When it reaches the seabed, the pipeline is joined to the head of the pre-drilled well using a special connector. Due to high bending stresses and fatigue the lower part of the riser, near the connector, is made of special materials such as titanium alloy special flexible joints can also be used.

Each riser must be kept suitably taut both to support its own weight and to control its dynamic behaviour; tension is exerted from the surface using devices attached to the platform hull or steel buoyancy tanks surrounding the top of the riser. The weight of the riser in water may nevertheless be reduced by
installing buoyancy modules made of special polyurethane foam around some sections of the pipeline. To reduce the loads due to the movements of the platform, the tops of the risers are not rigidly attached to the structure but using purpose-built devices that allow relative movements. The wellheads must then be joined to the manifold which channels the fluids produced to the treatment plants through flexible pipes.

The solution using vertical steel risers, however, cannot be adopted for floating production systems, in other words semisubmersible platforms or FPSOs; in these cases the displacements of the hull due to waves and currents cannot be absorbed by the flexibility of the vertical steel risers, the wellheads cannot be installed on the surface, and we must therefore use subsea production systems. The risers must have geometries and be made of materials which ensure that they are sufficiently flexible to absorb without damage the considerable displacements at the top, and, at the same time, resist high fatigue. The main solutions are as follows: a) flexible risers; b) rigid steel risers; c) vertical steel risers grouped inside a tower not supported by the production hull (riser tower); d) independent vertical steel risers not supported by the production hull.

In all cases, thermal insulation is needed to maintain the temperature of the reservoir fluids above given minimum values, to prevent hydrates or waxes forming and being deposited on the walls of the pipeline.

**Flexible risers**

The first floating production systems were constructed to exploit marginal fields in shallow waters. Here, given the limited length of the pipelines, flexible risers were needed. With the increase in deep water applications, this solution was also extended to great depths. It is necessary to develop a pipeline which, though resistant to high internal and external pressures, can adopt modest radii of curvature without being damaged. To this end, the wall of the tube is formed of a series of concentric layers: a first internal layer, in contact with the fluid, is a thin sheet of stainless steel; outside this are alternating layers in special polymers and spiral steel armour (Fig. 24). Given the complexities of manufacturing, production costs are extremely high.

Thanks to its flexibility, this type of riser can be installed with a catenary configuration, with the upper end suspended from the production facilities and the lower end resting on the seabed until it is joined to the subsea production system. The greatest problems are linked to the difficulties of guaranteeing that the product lasts for the entire life of the platform.

Especially critical from this point of view are fatigue and the movements which generate abrasion between the different layers of the tubing.

The tube is manufactured in special yards on the coast. Risers of limited length and small diameter can be wound onto purpose-made reels, which are then transferred onto the installation vessel. For very deep waters, and therefore considerable lengths, the flexible pipeline is loaded directly on board the vessel, wound around large diameter drums of vertical axis. The installation vessel carrying all the flexible pipelines can then sail to the offshore site, where the risers are laid extremely quickly, by unwinding the reel or the drum around which they are wrapped.

Despite high production costs, this type of riser has given good practical results. The benefits of rapid installation and the consequent savings in terms of time and money are countered by the fact that the installation vessel in most cases has to load the product directly at the production site, which is often at a considerable distance from the offshore installation site. Although flexible pipelines have lower thermal conductivity than non-insulated metal pipelines, they are not particularly suited to applications where a high degree of thermal insulation is required.

**Rigid risers**

To reduce the cost of flexible pipelines, technological solutions have been developed over the past decade for the construction of rigid steel risers. Designing and installing a rigid riser is far more complex than a flexible riser, particularly if the installation site is in a geographical area where environmental conditions are especially severe. In particular, we need to take into consideration the
dynamic response of the pipeline, subjected to the motion of the vessel to which it is attached and to the loading of waves and currents. The least expensive configuration is a simple catenary, which can be used in very deep waters and in sites where environmental conditions are fairly favourable. In this case the weight of the pipeline is entirely supported by the hull to which it is connected with a special flexible joint. At the lower end, the riser is placed on the seabed for a section sufficient to ensure that the pipeline remains attached to it thanks to the frictional force between pipe and ground. The contact point between the pipe and the ground moves freely according to system dynamics. The bottom end of the riser is then linked to the subsea production template using a section of pipeline, which is usually flexible, flanged at both ends. Where it is not possible to use a simple catenary geometry, due to particularly severe weather conditions or an insufficiently deep seabed, we need to use a ‘wave’ configuration. In this case, the natural catenary of the riser is modified at a given depth, by installing buoyancy modules along the pipeline which force the riser to adopt a wave configuration, and then continue with a catenary until it reaches the seabed. The configuration thus obtained allows the pipeline to have a dynamic response, so that it is subjected to lower loads (Fig. 25).

Resistance to fatigue is another highly critical aspect of the design of rigid risers. Fatigue is caused by three factors: wave motion, the motion of the vessel, and the vibrations induced by the vortex shedding created by the passage of currents. As far as vortices are concerned, we need to install helical strakes on the upper part of the riser (most exposed to currents), to prevent vortex shedding. The most critical parts of the riser in the context of dynamic loads and fatigue are those near the link to the hull and those near the point of contact with the seabed; at these points, very thick steel and particularly careful welds should be used. Using titanium alloy for the entire riser, thanks to its properties of resistance and high elasticity, would allow us to reduce the thickness of the pipeline considerably, and a corresponding saving of materials. However, this solution has not yet been adopted given the high costs of titanium, and the complexities of welding techniques.

As far as installation is concerned, three different methodologies are used, each of which in turn conditions onshore manufacturing techniques: laying from an installation vessel, using the method known as J lay; laying from an installation vessel, using the methodology known as reel lay; floating transport and up-ending at the installation site.

The J lay methodology is considered the most secure, although it is more time-consuming: the pipeline is constructed offshore by welding together sections of tube previously assembled in sections whose maximum length is about 50 m. The first section of pipeline is inserted into a tower on the installation vessel, and is then lowered into the sea in a vertical position, keeping the top above water, to allow a second section of pipeline to be inserted into the tower. At this point, the top of the first section and the bottom of the second section are welded together; the two joined sections of pipeline are in turn lowered into the water, allowing us to install the third section, and so on until the riser is complete. Once the laying operation is finished, the head of the riser with its elastic joint is placed in the water by lowering a cable linked to a winch. A second cable linked to a winch on the production vessel recovers the head, which is then inserted into a slot in the hull.

In the reel lay methodology, the pipeline is entirely prefabricated onshore, and then wrapped around a wide reel on the installation vessel. Although the reel has a large diameter, the pipeline suffers considerable plastic deformation during the reeling operation. When the vessel reaches the installation site, the reel rotates, releasing the pipeline, which is lowered into the water. The pipeline, deformed by loading, must then be straightened by imposing an opposite deformation. The need to introduce these plastic deformations makes this procedure quite risky for the installation of risers, since their effect on fatigue resistance has not yet been fully evaluated.

In floating transportation, the riser is completely prefabricated at an onshore yard, as near as possible to
the offshore installation site. The complete pipeline is then launched directly from the yard, by sliding it along purpose-built roller systems and exerting traction from the sea using tugs. Once in the water, the riser can be transported using a series of tugs. Upon reaching the installation site, the pipeline is sunk completely, and the head is then recovered by a powerful winch on the production vessel. This methodology is very risky since the behaviour of the riser during transportation is difficult to predict. High costs are also incurred by the need to create a special area of the yard for prefabrication and to construct a large number of temporary buoyancy modules able to resist high hydrostatic pressures, and which must be disconnected from the pipeline before its final installation.

As far as thermal insulation is concerned, rigid risers can be treated on the surface with coatings resistant to high pressures; however, it is necessary for the low thermal conductivity requirements not to be particularly restrictive. In the case of catenary rigid risers, the possibility of using pipe in pipe, the most effective technological solution currently available to guarantee high thermal insulation, is as yet unproven. The pipe in pipe consists of a double concentric pipeline: the inner pipe has the task of resisting the pressure of the reservoir fluid; the outer pipe must resist the extremely high hydrostatic pressures caused by great depths. Insulation is guaranteed by inserting material with excellent thermal insulation properties in the gap between the two pipes.

**Riser tower**

The motion of the production vessel has an enormous influence on the dynamic behaviour of the risers connected to it. The riser tower provides a solution allowing us to decouple as far as possible the production vessel’s motion from that of the riser. In this case, the steel risers which carry the reservoir fluids from the subsea wells to the surface are collected inside a cylindrical tower, also made of steel, hinged to a base foundation (Fig. 26). The tower is kept in a stable vertical position by the hydrostatic lift of a large watertight cylindrical tank connected to its top; it therefore does not need to be supported by the production vessel. The foundation consists of a cylinder of large diameter which acts as a suction anchor (see above). The height of the riser tower is slightly lower than the depth of the seabed on which it is installed, so that the top of the buoyancy tank remains submerged at a sufficient depth from the surface to avoid the effects of wave motion. The connection between the risers and the production vessel is guaranteed by installing a bundle of flexible tubes which, in a catenary configuration, link the flanges on the vessel’s side to the corresponding flanges at the tops of the risers, at the head of the tower. Thanks to this configuration, the motion of the tower and the vessel are relatively independent, since the two systems are linked only by highly flexible elements. The fact that a considerable number of risers are grouped inside a single tower also allows us to obtain a high degree of thermal insulation. We can install special insulating foam with very low thermal conductivity values inside the tower, in the gaps between the tubes.

Due to the dimensions of this structure (which may be considerably above 1,000 m in length), the tower, including all its internal risers, must be constructed onshore, near the coast and perpendicular to it. Once complete, the tower is launched by sliding it along special rollers and exerting traction from the sea using tugs. It is then floated a few metres below the surface of the water; after reaching the installation site it is slowly up-ended by flooding the tubes inside,
disconnecting the temporary buoyancy modules and keeping the upper end connected to a tug. After up-ending is complete, the base of the tower is attached to its foundation, installed previously. We then install the buoyancy tank, which is placed in the water by a crane barge, allowing its watertight compartments to flood freely. Finally, the flexible tubes connecting the risers and the production vessel are installed. Pipelines, rigid or flexible, are placed on the seabed to connect the subsea wellheads to the flanges of the corresponding risers at the base of the tower and thus allow the hydrocarbons to flow into the risers.

The riser tower, as well as resolving the problem of rigid risers attached directly to the vessel, also has the advantage that it can be constructed and installed independently from the production vessel, whose construction is particularly critical in terms of time. The installation of the riser tower, subsea production systems and the pipelines connecting these to the tower can occur before the production vessel reaches the installation site. The only activity needing to be undertaken after mooring the vessel is the installation of the flexible tubes connecting it to the tops of the risers.

The negative aspects of this solution are the difficulties of onshore prefabrication and limited flexibility with respect to possible evolutions in the development of the field. Grouping the risers inside a single structure introduces considerable inflexibility with respect to any modifications required during later phases of development, or potential maintenance work.

**Independent vertical risers not supported by the production vessel**

A development of the riser tower concept involves installing the vertical steel risers individually, rather than grouped inside a tower. Each riser is hinged to its own base foundation, is kept taut by its own buoyancy tank and is connected to the production vessel by its own flexible tube (Fig. 27). This solution has all the advantages of the riser tower, and at the same time eliminates its negative aspects. The fact that the risers are installed independently offers maximum flexibility, since the risers associated with the drilling of future subsea wells can be installed when they become necessary, without requiring any advance operations. The paths followed by the connecting tubes to the subsea production systems are also simplified, since these do not all have to converge towards the base of the riser tower, but simply reach the base of their own risers. Nor do we need a large onshore prefabrication area, since individual risers can be constructed offshore, using the J lay method for laying pipelines in deep waters (see above).

The solution using independent vertical risers is also suitable for cases where a high degree of thermal insulation is required since the pipe in pipe concept can be used for the riser tubes (see above).

The only potentially critical aspect is represented by the risk of interferences and collisions between the risers, caused by their independent motion. A large number of studies, simulations and trials using models have nevertheless led to the conclusion that the risers tend to move in synchrony with each other, thus avoiding the risk of interference. The first application of this solution has been installed for a seabed about 1,300 m deep.

**Bibliography**


Edei J.C. et al. (1999) Fabrication of the Baldplate compliant


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