44.1 Introduction

Understanding offshore construction operations requires some familiarity with the type and form of the structures involved. For readers who are not familiar with such structures, section 44.2 briefly describes their general form and function.

Offshore structures are dominated by oil and gas production facilities as exploration for hydrocarbons extended from land to shallow waters and moved to deeper and more hostile environments such as the North Sea.

Other types of offshore structures include cargo and offloading terminals, offshore wind turbines, ocean thermal energy facilities, military and defence-related structures and some novel floating structures for leisure or other purposes.

The construction and installation techniques vary depending on the types of structures involved, but in this chapter some typical examples, mostly related to the oil industry, are introduced and give a good representation of the methods and activities involved.

Construction methods for both steel and concrete structures are described. Reference is made to the general factors affecting the techniques with particular reference to cost, safety and practicality of operations.

Offshore operations involve a well-planned programme of work and project organization with effective control and management. This subject is briefly discussed to demonstrate its importance in a multidisciplinary operation of great complexity.

Finally, reference is made to codes and regulations and operations involving inspection, maintenance and repair of offshore structures.

It is hoped that the reader will gain a general understanding of offshore construction techniques and their impact on various fields of engineering by the examples given.

The subject has been addressed purely as an introduction to this topic and readers who are interested in extending their knowledge further have access to numerous publications including those mentioned in the bibliography at the end of this chapter.

44.2 Offshore structures

The oil industry only began to move offshore in the late 1940s. Offshore operations were first carried out in the US, where a gradual move could be made from the swamps of Louisiana. Exploration results there indicated that the oil area extended offshore into the shallow waters of the Gulf of Mexico. The mobile jack-up drilling unit was originally developed for this region.

44.2.1 Jack-up rigs

The jack-up unit is a barge fitted with movable legs (Figure 44.1). The unit can be towed or self-propelled from site to site with the legs in an elevated position. Once at a drilling location, the legs can be lowered to the sea-bed and the barge can 'jack' itself up the legs so that it comes out of the water, clear of any anticipated wave action, ready for drilling. When the well is finished, the operation is reversed to make the barge ready for moving to its next location. The length of the legs determines the water depth in which the jack-up can be used, but they are commonly designed for use in up to 75 m of water and occasionally as much as 105 m. Reasonably calm weather is required when the units are being jack-up and down.

In order to enable offshore drilling to be carried out in the deeper waters (e.g. in the Gulf of Mexico), semisubmersible and drill-ship drilling units were developed.

44.2.2 Fixed platforms

Once exploration drilling has confirmed the existence of an oil or gasfield, appraisal drilling is usually required to show if it is large enough to be developed commercially. Field development calls for the drilling of a series of production wells and the installation of equipment to control the production. The usual method is to install a fixed platform and to drill deviated production wells from it. Deviated wells are drilled inclined from the vertical and in a direction away from the platform to reach parts of the reservoir as far away from the platform as possible. Sometimes satellite wells are drilled up to 10 km away and tied back to the platform by pipeline. Both steel and concrete platforms have been used in the North Sea in a variety of designs. The first fixed platforms installed in UK waters were relatively small uncomplicated steel structures for the southern North Sea gasfields in water depths up to 45 m. These have become dwarfed by those subsequently installed in the northern North Sea oil- and gasfields, in water depths of up to 180 m. These have overall heights of around 275 m from the sea-bed and are able to withstand storm waves 30 m high and winds of 240 km/h.

A steel platform consists of a framework called a 'jacket' on which a deck is mounted (Figure 44.2). The jacket is fabricated onshore and towed out to sea on its side, either afloat or on a large barge. On reaching its location, it is carefully up-ended and secured by piles driven into the sea-bed. Once this has been completed, the deck is installed and modules containing the drilling, production and accommodation facilities are added.

Concrete platforms vary considerably in design and consequently in method of construction (Figure 44.3). Normally, a buoyant base is built in a dry dock and floated into progressively deeper water as the structure is built up from it. This requires sheltered, deep water close to shore. The weight of a concrete platform is several hundred thousand tonnes greater than a steel platform. A concrete platform is frequently designed with chambers for oil storage. When completed, with a superstructure containing drilling, production and accommodation facilities, it is towed out by a number of large tugs to its location. It is then ballasted down until it rests on the sea-bed where it remains secure under its own weight. Concrete platforms are consequently called gravity platforms. All the fixed platforms are, therefore, bottom-supported structures.

Another approach developed for deeper waters is the guyed tower (Figure 44.4). The platform deck is supported by a lightweight steel compliant tower, held upright by guy lines radiating outwards. This type of platform has been used for a field in the Gulf of Mexico.

44.2.3 Floating platforms

Because of the very large cost of fixed platforms and the possibility of finding oil in waters which are so deep that fixed platforms would neither be technically feasible nor economical, considerable attention has been given to developing oilfields by other methods.

One approach is to use a floating production platform. However, it is necessary to restrict lateral and vertical movements to a minimum, so as to avoid unacceptable loads on the high-pressure vertical pipes known as 'risers' which provide the link between the platform and the wells on the sea-bed.

The semisubmersible rig is a floating platform with the deck supported by vertical columns on submerged pontoons which provide its buoyancy (Figures 44.5 and 44.6). By varying the quantity of ballast water in the pontoons, the rig can be raised or lowered in the water. The lower the pontoons lie beneath the water the less they are influenced by wave action. This reduces vertical movement and allows drilling or production to continue.
Figure 44.1  A typical configuration of a jack-up rig

Figure 44.2  A typical configuration of a conventional fixed steel jacket (platform)
Figure 44.3  A configuration of a gravity-base concrete platform

Figure 44.4  A typical configuration of a guyed tower
in rough seas. A semisubmersible rig is normally held in position by up to twelve very large anchors. The design of the latest semisubmersible rigs enables them to drill in UK waters at depths of 450 m and over, all the year round, despite the exceptionally high waves experienced in winter. Semisubmersible platforms can also be designed as production facilities equipped with process equipment.

Anchored semisubmersible units used for drilling or built with production and accommodation facilities are in use around the world. Another floating technique is the use of a tension leg platform (TLP) which is a semisubmersible type of unit, held in place by tensioned cables anchored to the sea-bed immediately beneath each corner of the platform. The platform is ballasted down while the cables are attached and then deballasted, bringing the cables under tension. The platform moves like an inverted pendulum, with very little heave. See Figure 44.8.

Other techniques include the use of specially built ship-shaped vessels, converted tankers and floating concrete platforms.

### 44.3 Stages of construction

Offshore construction can be categorized into five main stages: (1) fabrication; (2) launching; (3) tow-out; (4) installation; and (5) hook-up and commissioning.

#### 44.3.1 Fabrication

In this section, construction of steel structures is discussed in order to highlight the main tasks involved. Construction of concrete structures is covered in section 44.5.

Fabrication of steel jackets is generally carried out in land-based fabrication yards which have access to waterways, or the open sea. Such facilities are in some ways similar to those in the shipbuilding industry with dry docks and slipways allowing the vessels to be eventually launched upon completion.

Size and weight of structures vary considerably and as a result, some can be fabricated in only a limited number of yards which have suitable facilities with sufficient draught along the waterways for their transport.

Some typical sizes and weights of the jackets are:

1. Steel jacket, Thistle A, North Sea: jacket weight 31 396 t, water depth 161 m.
2. Steel jacket, Brent A, North Sea: jacket weight 14 225 t, water depth 140 m (Figure 44.7).
3. Steel jacket, Indefatigable CD, southern North Sea: jacket weight 536 t, water depth 29 m.

The world's tallest existing platform is the Cognac steel jacket
platform with a height of 385 m. However, the Bullwinkle platform, which is of a similar design to the Cognac, will be 492 m tall when installed in 1988. This platform will then be 49 m taller than the world's tallest building. This record will no doubt be broken again in future years.

Limited dimensions and handling capacities of fabrication yards and dry docks may result in the need to fabricate the structures in more than one piece. In addition, parts of the platform may be fabricated separately in other yards. The parts will then be brought together and mated under separate operations. Deck structures of jackets and modules are often fabricated and assembled separately. These modules, which could weigh from under 50 t to a few thousand tonnes are transported and are lifted and installed on the deck of the platforms, using crane barges, when the deck is installed. As an example, the total topside weight of the *BP Magnus* platform, which consists of a multistorey deck 75 m square and 32 m high, is in the order of 31 000 t.

To minimize cost, the maximum possible work on fabrication, assembly, testing, inspection and installation of various components is carried out inland. Costs of offshore construction operations are significantly higher than the land-based work and are therefore limited to essential tasks which cannot be carried out in any other way.

For fabrication of steel structures, welding tubulars ranging from 300 mm to 2 m diameter or more, and with varying thickness of up to 80 mm is involved; an example is the *BP Magnus* platform in which two of its four legs each has a diameter of 10.5 m. Welding such large structures requires efficient automatic welding techniques with quality control and stress-relieving in many cases.

Fabrication of nodes consisting of several tubular members of different sizes is one of the most complex parts of the welding operation. Techniques of casting nodes have been developed which enhance their load-carrying capacities by eliminating high welding stresses and streamlining and strengthening the joint structure. The design of tubular joints is discussed in a publication by the Underwater Engineering Group of the Construction Industry Research and Information Association (see Bibliography).

Covered fabrication facilities are available to allow work to be independent of weather conditions.

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*Figure 44.6* A dynamically positioned semisubmersible drilling rig in operation
Steel structures are fabricated in sections which can be accommodated and handled in the yard. Close tolerances are required to enable mating with other sections. Inspection and quality control become integral parts of the fabrication operations, as these structures are required to withstand high loading conditions with theoretical fatigue life equivalent to 10 times their service life.

Failures of welds resulting from bad workmanship, unpredictable loading conditions and poor tolerances have provided lessons to the industry, resulting in bringing about improvements in welding techniques, more extensive nondestructive testing and attention to detailing of structures.

Large-size structures are generally fabricated and assembled on pre-installed trestles and rails to enable the next stage of the operation, which is launching and tow-out, to take place.

### 44.3.2 Launching

When fabrication is complete on land, the structure is transferred to waterways for towing and transportation to its offshore destination. The method of launching depends on the size and weight of the structure and the facilities used for its construction.

#### 44.3.2.1 Load-out from quays

Lighter structures, or those which, because of the draught limitations of the waterways, are fabricated on quays, are moved on to flat-top barges (moored against the load-out quays) for transporting to sea. Limitations of cranes in fabrication yards to handle weights ranging from a few hundred to several thousand tonnes require the completed structures to be transported slowly on rails or bogies and loaded on to the barges. Alternatively, they can be supported on pads, each of which floats on a cushion of water or oil, using the principle of hydraulic or air flotation. Reduction in friction, as the result of pads floating on water or oil cushions, enables the structure to be winched on to the barge with relatively small pulling loads.

Modular trailers with over 700 wheels and capacities of up to 12,000 t or more have been used for this purpose. Bogies also enable the load to be distributed to levels within the load-bearing capacity of the quayside which is often below 5.5 t/m².

The barge-loading operation requires powerful ballasting facilities on barges so that they maintain their level against the quayside under changing tides and gradual transfer of the load on to their flat decks.

Barges with sufficient deck capacities need to be fitted with
44.3.2.2 Load-out from dry docks

Load-out from dry docks requires flooding of the docks allowing the structure to float. Limitation in the draught in the dry docks often requires the operation to take place within the limited period of high tide. The floating structure is towed out of the dock by tugs for transport to sea.

44.3.2.3 Launching from slipways

The completed structure rests on a number of rails which extend along the slipway into water, similar to the method used in the shipbuilding industry. The structure is freed from its trestles for launching, and is gradually winched and allowed to move into the water until it floats. This technique is particularly suitable for structures which are too heavy to be transported on barges, or have excessive draught and need to be fabricated and loaded-out in yards closer to the open sea. The BP Magnus, a self-floating jacket and piles weighing 42 000 t, was launched in this way from the Highland Fabricators’ yard in Scotland in 1982.

44.3.3 Transportation at sea: marine operations

Transportation of structures, whether floating or transported on flat-top barges, is carried out by a number of tugs. The tugs position themselves in a ‘star’ formation, providing the power and controlling the movement of the structure along its predetermined path.

Suitable weather windows are required to ensure the safety of the structure during transportation. The speed of the tow is limited to a few knots and, depending on the distance, may take anything from several hours to a few days. At the destination and prior to its installation, intensive survey and inspection of the sea-bed, subsea template and other structures is made.

Back-up facilities are mobilized, and trial runs are undertaken to ensure that the final crucial stages of the operation pass without difficulties.

At this stage, support vessels carrying power, personnel, equipment, divers and inspectors are at the site to carry out the highly controlled and co-ordinated operation of setting the structure in its final position. Sonar systems and satellites are used to monitor the position of the structure and help to hold it in a position within the small allowed tolerances, which vary from a few metres for the first stage of station-keeping to a few millimetres for the final setting stage into the support structures or templates.

44.3.4 Installation

44.3.4.1 Installation of the main structure

The method of installation varies and depends on the type of structure. For floating, bottom-supported, steel jackets a controlled up-ending operation is carried out followed by further ballasting; the structure is then lowered on to the sea-bed.

Maintaining structural safety and stability during the up-ending operation is crucial. This stage is therefore a well-investigated and tested operation during which the movement of the structure is also helped by lines from tugs and crane vessels.

Structures transported on barges may be lifted either by heavy-lift crane barges and lowered on to the sea-bed, or submersible barges may be used if they remain afloat. Submersible barges can, by a process of ballasting, have their draught increased until the structures they carry float freely and are towed clear.

An alternative method is to launch the structure directly from a barge equipped with a launching frame at its stern.

Crane barges are used to drive piles around the legs of the jackets; piles are guided by pre-installed sleeves around the legs. Pile-driving techniques now allow the use of underwater pile hammers with high driving capacities of 200 tonf and beyond.

Piles driven for the BP Magnus jacket are a typical example of the support system, being 100 m long with 2.1 m diameter and 63 mm plate thickness. The 36 piles have been driven by two of Menck’s (MHU 1700) underwater hammers, delivering a striking energy of 170 tonf. Each pile has been designed to take loads of up to 6000 t.

The techniques explained in this section are examples of installing fixed jackets. The installation of other types of structures such as templates, articulated columns, floating structures such as semisubmersibles, and TLPs are all different, with differing levels of complexity.

In the case of TLPs (Figure 44.8), for example, installing and tying the tethers to their templates on the sea-bed is a complex and lengthy operation. It can be carried out from the platform itself or, alternatively, by pre-installing the tethers using crane barges and finally mating and tying them to the main structure as a second operation, has been shown to be more economical.

44.3.4.2 Installation of secondary components (topside)

For installing other components or parts of a production platform such as the deck structure and some subsea components, heavy-lift cranes are used. Fixed jackets could have deck structures weighing several thousand tonnes which are transported separately on flat-top barges. The deck is lifted by one or two cranes and is installed on top of the support structure.

Various modules, part of the hydrocarbon production facilities on the deck, and each weighing from a few hundred to a few thousand tonnes, are also transported separately and, using a crane barge, are installed on the deck.

Early installation of all modules on the deck is not often feasible because of weight limitations of barges and stability problems during transportation at sea.

In the BP Magnus platform, the total topside payload of the structure was 31 000 t divided into 19 modules each weighing up to 2200 t, some 40 to 50 m long.

44.3.4.3 Installation of secondary components (subsea)

For installation of subsea modules such as templates or manifolds, often accurate positioning and mating with existing subsea structures are required. In such conditions, a guidance system is required in addition to cranes to control their lowering and positioning. Tensioned guide wires combined with guide posts are examples of the methods used for the controlled lowering and positioning of the modules subsea. The guide wires are tensioned by winches from the installation vessel and the lines are tied subsea to the guide posts. The component which is being installed is equipped with funnel-shaped guidance sleeves which are engaged on to the guide wires and which enable the unit to be lowered to its position guided by the tensioned lines.

All operations are closely monitored by divers or remotely operated vehicles (ROVs) carrying underwater television cameras.

44.3.5 Hook-up and commissioning

The term ‘hook-up’ refers to the operations which link the various components and parts of the offshore facilities when they are all installed.

Tying the subsea pipelines to the platform risers, installing and tying umbilical lines, cabling and pipework to complete the
The manpower required for such an operation offshore could run to over 1000 men for major projects. Temporary accommodation and transportation offshore are required for such a large number of people who may stay in accommodation vessels moored close to the platform. Part of the operation is sensitive to sea state and may result in significant delay (downtime) in completion. Selection of suitable vessels which can operate safely close to the platform at more severe sea states, although more costly, is more economical in the long run for severe environments such as those in the North Sea.

44.4 General factors affecting construction techniques

Selection of suitable techniques for fabrication and installation of offshore structures are influenced by many factors which include:

1. Material (steel, concrete or hybrid structure, and other new materials).
2. Economic factors such as the need to bring the field to partial production early and improve overall cashflow.
3. Cost.
5. Water depth.
7. Constraints imposed by regulatory authorities, such as vessel operation constraints, pollution control, navigation restrictions, etc.
8. Existence of suitable fabrication yards/dry docks with sufficient space and load capacity and available draught in the waterways for transport of the structures.
9. Socio-political factors which may influence selection of yards and even the type and form of structures.

In addition, with the development of novel techniques and new equipment and tools, traditional methods have been replaced by new methods and are likely to continue changing.

The introduction of high-pressure flexible lines, subsea trenching crawlers for trenching and laying pipelines, dynamically positioned vessels capable of maintaining position at more severe sea states, ROVs, crane barges with heavy lifting capacities of 8000 t or more all influence not only fabrication and installation techniques but have played major roles in changes to the form and design of the structures.

The handling capacity of crane barges enable bigger modules to be built onshore and provide a reduction in the cost of offshore hook-up operations. The use of underwater high-capacity hammers has allowed the sizes of piles to be increased, resulting in reductions in numbers and, therefore, savings in material costs and offshore operation costs.

Some of the developments and trends have been described in publications listed in the bibliography.

44.5 Concrete structures

44.5.1 Types

Concrete structures, by their nature are, in general, bulkier and heavier than those constructed in steel and involve different construction techniques.

In order to understand and appreciate the differences, it is helpful to refer to a number of major concrete structures and their functions, as listed below.

1. Concrete gravity platforms (resting on the sea-bed with no piling involved).
(2) Floating concrete structures (semisubmersible, TLPs or ship-shape structures).
(3) Arctic caissons.
(4) Concrete pontoons, supporting various types of structures.
(5) Articulated buoyant columns.

In this section, construction of concrete gravity platforms is discussed to demonstrate the tasks involved.

44.5.2 Major requirements
For all such structures the prime considerations are:

1. Suitable facilities and locations for their construction.
2. Offshore construction (if applicable), mooring and support facilities.

The weight and size of concrete gravity structures increased substantially as their application to deeper waters of 100 to 300 m was introduced, and resulted in the construction of structures weighing in excess of 800 000 t with topside loads of over 30 000 t.

The Brent platform in the North Sea consists of a cellular base of 90 m square and 54 m high. The four towers rise some 107 m above the base to support a deck with a total area of around 39 000 m² and weighing 31 000 t (Figure 44.9).

The platform displaces 436 300 t of water. Construction to deck level required over 257 000 t of concrete and 15 000 t of reinforcing steel.

Construction of such large platforms in existing dry docks has been impractical because of the limitation in the size and weight capacity of the docks and the draught available for tow-out. For these reasons the practice has been to construct dry basins with access to deeper waters and to construct part of the base to a height at which the available water depth allows flotation, tow-out and transportation.

Construction of such a basin at Ardoyne required the removal of some 900 000 m³ of material.

Limitations in water depth of 10 to 15 m in many coastal areas and waterways leaves only a few locations suitable in the UK for such operations. Norway with its sheltered deep fjords, however, offers good surroundings for construction of concrete structures. Stability requirements during transport dictate the depth to which the floating structure should be submerged. Such requirements acknowledge the need for a deep sheltered site where the partly completed base can be moved, and be moored, and where the remainder of the construction work offshore can be completed. It should be remembered that draughts of 100 to 150 m are often required for major platforms.

44.5.3 Concrete construction
High-grade sulphate-resisting cement concrete (grade 50 or more) is used for offshore construction work. Durability in hostile sea environments requires high grades of cement, aggregate and good workmanship. The large quantities involved pose supply and storage problems. Concrete production plants with high output capacity in excess of 100 m³/h are often required. This can be achieved by using more than one plant to ensure continuity of supply during breakdowns.

Concrete is pumped, or moved by trucks, within the site. For offshore construction, several pumps are used, each with capacities in excess of 300 m³/h. The concrete production plants can be located on pontoons, moored against the platform. Long pumping distance often requires the addition of plasticizers and retarders to the concrete.

Slipforming is the common method of placing concrete, with rates in excess of 50–100 mm/h for the caissons and higher rates of 100–200 mm/h for the main towers. Slipforming of inclined surfaces has also been developed and has proved to be practical.

Thicknesses of concrete slabs and walls vary from 500 mm to a few metres. The ducts are introduced within the thick members to help in the dissipation of heat to cope with the high heat of hydration.

Both reinforcing bars and prestressing tendons similar to those used in land-based structures are used.

For the Brent offshore platform, 1000 jacks of 3 t capacity were used and required 1100 m³ of concrete to achieve a 1 m lift. The base slab required 20 000 m³ of grade 50 cement concrete. Several tower cranes with the capacity of 10 to 15 t were required for concreting and handling reinforcement and formwork.

The effects of creep and temperature changes require thorough investigation for both construction and service life when, during oil production, parts of the cellular base space are used for storage of crude oil at temperatures of 30 to 40°C above the surrounding sea-water temperature.

44.5.3.1 Deck installation
Following completion of the concrete platform it is ballasted-down to enable the deck structure to be lifted and positioned on the towers by heavy-lift crane barges. Other modules for the deck are brought into their positions and installed. It is also

Figure 44.9 One of the concrete platforms under construction by McAlpine Sea Tank at Ardoyne Point, for use in the Brent field
sometimes possible to ballast-down the platform until only a few metres of the towers are above water. The deck may then be transported on pontoons, each with a clearance to enable the deck to be moved over the towers. By gradually deballasting the platform, the deck can be aligned with the towers.

Winches installed on the towers are used to perform the final pulling stages of the deck over the towers, and the final few millimetres of the positioning is completed with the help of jacks.

This operation requires delicate control of the platform and the deck, continuous monitoring of the movements and a powerful ballasting system to cope with the ballasting rates required.

44.5.3.2 Towing to the final position
The significant draught of the structure is often in excess of 100 metres; it is therefore necessary to select and survey a towing route in order to ensure that sufficient water depth exists along the total distance. The effect of current, waves and wind are studied to ensure tugs have sufficient reserve power to cope with towing under specified adverse weather conditions. Towing speed can be as low as 0.5 kn, increasing to 2 to 2.5 kn in safer passages.

Navigation, towing and monitoring of the operation may require a crew of from 30 to 50 men.

When the structure reaches its destination, tugs in star formation hold it in position while, by gradual ballasting, the structure is lowered on to the sea-bed.

44.5.3.3 Foundation considerations
In addition to the common requirements for load-bearing, long- and short-term settlement, stability and keying against shear forces, it is important to note that, owing to the action of waves, loads on the foundation are cyclic and affect the drainage of the soil underneath both in the short and long term. The direct effects of waves on soil, particularly in shallow waters of up to 50 m, could also be significant. Variations in pore pressure depend, among other things, on the densities of the oil to be stored.

Problems of scour around the perimeter of the base require careful consideration. Various methods, varying from dumping stone to the installation of manmade mattresses filled with grout, sand or stone, have been used with varying degrees of success.

44.6 Construction in the arctic
Oil in arctic zones was first discovered in the MacKenzie delta and Arctic islands in North America. Further studies in the US in the late 1970s showed that there were substantial potential resources offshore in the Arctic zones, particularly in the Bering, Beaufort and Chukchi Seas.

The first field was developed in water depths of 1 to 20 m. Future discoveries in the lease sale areas involved operating in depths of 20 to 50 m.

Structures suitable for such relatively shallow depths but extremely hostile environments are therefore different from the conventional offshore structures. The environmental conditions, particularly the presence of ice packs, play dominant roles and are worth mentioning.

44.6.1 Environmental conditions
The expected maximum wind and wave conditions in arctic areas of immediate interest are less severe than those of the North Sea. The 100-year expected maximum wave height is in the range of 12 to 15 m for water depths of 15 to 30 m. Storm surges in excess of 6 m are, however, significant for the design of arctic structures.

Ice criteria dominate the design of the structures. The main features of the arctic ice are:

(1) First-year ice. The thickness of ice formed within 1 year could be up to 2 m, depending on the area.

(2) Multi-year ice. This is the ice which has lasted more than one melt season and has resulted in the build-up of an ice sheet into a thickness of 6 m or over, with a diameter of 3 to 5 km being typical.

Collision of two large sheets of ice may result in the formation of pressure ridges several metres above the water level as ice mountains and their coves could extend several metres into the soft sea-bed.

Multi-year ice-floes could travel at velocities of up to 2 m/s and their impact with any structure would result in an effective total load of several thousand tonnes, depending on the form of ice and details of the structure.

Ambient temperature reaches a low of -50°C.

So far as ground conditions are concerned, the new features particular to arctic zones are permafrost and gas hydrates. The permafrost table could vary from a few feet below the mud line to several metres. Gas hydrates are ice-like pockets of natural gas which fit into the structural voids in the lattice of water molecules.

Freezing and thawing of soil columns are other features which affect ground conditions to support gravity base structures.

44.6.2 Types of arctic structures
The most common types of structures considered as arctic platforms for drilling or production of hydrocarbons are: (1) artificial islands; (2) hybrid islands; (3) cone structures; (4) tower structures; and (5) floating structures.

44.6.2.1 Artificial islands
Since early 1970s, a number of artificial islands have been constructed in water depths of 1 to 20 m. Most of these islands are in the MacKenzie delta, in northern Canada. The construction method has varied from over-the-ice construction to dredging the loose soil and filling with dredged sand and armour stone. Armouring is particularly the cause of high cost because of lack of quarry stone in the nearby areas.

Artificial islands are attractive economically for shallow waters below 10 to 20 m depth. For depth ranges of above 10 m, other types could become more economical.

Ice pads are another type of structure which consist of layers of ice formed on top of one another by pumping water from the lower depth of water to the surface of the ice-pack. The thickness of each layer is in the order of 6 m. The ice-pack covers the entire water depth forming a platform for the operation.

44.6.2.2 Hybrid islands
They include caisson-retained islands in which sand-filled barges or ship hulls form the central core of the island and rest on beams which extend 4 to 5 m below the water level. The benefit of this type of island is the reduction in volume of fill and short construction time.

44.6.2.3 Cone structures
The most common types of island developed are cone-shaped
structures. Cone-shaped gravity platforms vary in form and shape and are constructed of steel, concrete or a hybrid of steel and concrete structures. The outer walls are inclined to break ice on impact in the most effective way. The main structure of the cone consists generally of cellular form.

44.6.2.4 Tower structures

Other types of platforms are braced-steel structures and concrete gravity platforms with cylindrical towers. These structures are suitable for areas with light ice conditions.

44.6.2.5 Floating structures

Floating structures vary in form and include ship-shaped structures, floating concrete caissons and conical floating platforms. Most structures in this category are suitable for deeper waters and arctic areas where ice surveillance and management is practical and economical. These structures are basically moored to the sea-bed with several mooring lines.

44.6.3 Construction

With temperatures down to −50°C, the presence of ice floes and limited open water restrict the working season to 1–3 months. Construction operations are costly and, for both economic and practical reasons, most structures are designed to be constructed in easier conditions and are towed to location for installation.

Construction of artificial islands using arctic dredgers has proved possible. Use of support vessels, ice-breakers for towing and management of ice-packs, and tugs enable the platforms to be fabricated in several sections and be brought together for final mating and setting on location.

Concrete cone structures with total displacement in excess of 500,000 t are fabricated in segments, using conventional techniques of concreting. Similar to concrete platforms used for other offshore locations, limitations in draught for towing the structure dictate the location for fabrication and the construction techniques.

Ice loadings on arctic cone structures are not known precisely but could vary in intensity from 1000 to 2000 kN/m² global loading and to 12,000 kN/m² local pressure. These require concrete structures to withstand high punching shears as well as high bending and shear forces. The structures are therefore heavily reinforced with high-strength temperature-compatible steel as well as prestressing tendons.

Concrete has been shown to gain strength with time in low-temperature conditions. This includes compressive strength, tensile strength, bond strength, impact resistance and modulus of elasticity. Application of concrete for arctic structures is therefore a viable solution.

Low temperature and presence of ice have been used as an aid for construction purposes, e.g. ice roads several kilometres long and 10 to 20 m deep. These roads stretch into the sea and form access routes to artificial islands. Artificial ice-platforms for drilling in high arctic areas are another example.

Offshore construction in hostile arctic areas has therefore led to the development of novel ideas and use of special equipment suitable for such conditions. Arctic engineering has become a specialized field involving the development of material, equipment and better understanding of environmental loads such as ice loads and soil conditions.

44.7 Fabrication/construction facilities

Major facilities suitable for fabrication and construction of offshore structures are: (1) land-based fabrication yards; (2) dry docks; (3) slipways; and (4) offshore floating facilities.

44.7.1 Fabrication yards

Land-based yards are close to waterways with loadout quays for transporting the structures to sea. Main features of such yards are:

1. Covered areas for weather-independent work such as steel-rolling, fabrication, assembly and painting.
2. Cranes with sufficient reach and capacity.
3. Quays with surface load capacity of 50 to 150 kN/m² to cope with heavy loads of several thousand tonnes.
4. Access to deep water and open sea for towing out structures.

Such facilities are often required to be approved by certifying authorities to ensure that they provide conditions needed to meet the necessary standards of workmanship and quality control. Fabrication yards are used primarily for fabrication of steel jackets, deck structure of the platforms and a variety of modules for installation on the decks of offshore structures.

44.7.2 Dry docks

Dry docks for fabrication of offshore structures are, in general, larger structures than those used for shipbuilding. These facilities are equipped with cranes and other support facilities required for fabrication or construction of large and heavy structures, which are outside the capacities of the fabrication yards, and can be floated out for transport to offshore locations. The dimensions of Kisirkorn dry dock, Scotland, are 180 × 170 × 11.5 m deep. This facility, with its deep-water mooring site and various fabrication and paint shops, is a typical example of the dry dock suitable for fabrication of large steel jackets.

44.7.3 Slipways

These facilities are similar to shipbuilding slipways and allow the fabrication in land-based environments. When the construction is completed, the structure is loaded-out on rails on to the water in a similar manner to launching a ship. Purpose-built slipways, with direct access to open seas, suit large-size structures which are outside the handling range of available fabrication yards and dry docks.

44.7.4 Offshore fabrication platforms

Large floating pontoons made of steel or concrete have been developed and moored offshore as fabrication yards. The use of such platforms is justified when other conventional facilities are not available, or there are specific restrictions such as depth of water for transport to the sea.

Those countries involved in the oil industry, such as the UK, France, Norway, Holland, the US, have developed and, at times, maintained such facilities with government assistance.

44.7.5 Back-up facilities

A vital key to success is the use of suitable equipment for efficient and cost-effective execution of work. Speed of operation, completion of work on time and achievement of high standards of workmanship demand that the most up-to-date equipment is available for these purposes. Well-equipped covered areas, automatic welding equipment, nondestructive testing facilities, all backed-up by computer services, are examples of what are needed.
A host of equipment and services is needed offshore to carry out the various stages of fabrication, mating, transport and installation of structures. The following is a list of some of the major facilities required.

1. Heavy-lift crane barges with capacities ranging from a few hundred to over 12,000 t. Some semisubmersible crane vessels available at present have two cranes with total lift capacities of up to 10 to 12,000 t.

2. Support vessels for specialized work, such as diving support vessels, inspection vessels, and vessels for carrying power and control equipment.

3. Accommodation vessels or semisubmersibles as offshore hotels for engineers, inspectors and fitters.

4. Remotely operated vehicles for subsea operations.

5. Tugs for towing or station-keeping floating structures.

6. Anchor-handling vessels.

Involvement of such vessels and associated equipment is a costly stage of the installation operation because of the high daily rates involved in their deployment.

44.8 Analysis

Analysis is by no means restricted to the behaviour of the completed structures in their installed condition. The structures either as part or complete units are subjected to loads different from their normal service condition during fabrication, launching, tow-out and installation.

Static and dynamic loading conditions are involved which require analysis for various purposes, including:

1. Checking stresses (local and global).

2. Static stability of the floating structure at various stages of installation.

3. Dynamic behaviour and stability of the structure subjected to wind, wave and current loads.

4. Load cycles experienced during transport and installation and their effect on the fatigue life of the structure.

5. Deflections and deformations of structures, particularly pipelines and risers during installation.

6. Behaviour of the guidance systems, such as tensioned guidewires, if used for lowering and locating components subsea.

7. Behaviour and response of floating structures and vessels which are used during the installation operations.

For analysis of the conditions listed here, computer programs have been developed and are used for both static and dynamic analysis. There are, however, many cases where computer programs and techniques are insufficient and model tests are needed to verify predicted behaviours of structures.

Model-testing in water tanks is an example of the type of tests carried out for the oil industry.

44.9 Schedule of work: cost factor

Fabrication, assembly and installation of the various components and modules, as well as the main platform structure, are all complex multidisciplinary tasks. The work often involves acquisition of some long lead items which need to be ordered and manufactured well ahead of time.

So far as the offshore operations are concerned, many facilities such as heavy-lift crane barges, support vessels and tugs, are required. These require mobilization, modification and installation of equipment.

A well-detailed programme of work is required in order to carry out all such tasks. Complex civil engineering projects are no exception, and readers familiar with the programmes of work involved in conventional civil engineering will appreciate the additional complexity of offshore construction.

In offshore work, sensitivity to weather and seasonal sea conditions, involvement of high-cost facilities, such as heavy lift cranes, support vessels and the like, create a demand for thorough planning of the operation.

Bar charts and critical path analysis techniques are used to develop the following key areas of the operation:

1. Duration of each operation.

2. Order of work to be carried out and identification of critical activities.

3. Equipment and facilities required, together with specifications for performance.

4. Materials needed.

5. Site/plant requirements.

6. Requirements and restrictions imposed by regulatory authorities.

7. Manpower requirements.

8. Tendering and selection of contractors and subcontractors.

9. Quality assurance and quality-control requirements.

10. Route survey and selection for transport.

11. Co-ordination of work.

12. Planning for completion and transport of various modules.

13. Approval and certification for all stages of the operation.

14. Management system and cost control.

Complex offshore structures often take more than a year to complete and cost several million pounds in capital expenditure. The high rates of cost involved in deployment of these facilities and the use of skilled personnel mean that delays or miscalculations are likely to incur high cost penalties.

The total capital cost of developing offshore hydrocarbon fields varies significantly depending on the depth of water, complexity of the structure and the production system involved, typical costs being, for example, £500 million for the Fulmar field and £1250 million for the Magnus field. These compare with multimillion pound civil engineering projects such as the Thames Barrier at £430 million (1976 price level).

The cost of the development of the oilfields includes drilling, pipelines, production and export facilities. The capital cost of the platform and the construction and installation operations are therefore only one part of a large capital investment in the development of a hydrocarbon field.

44.10 Codes and regulations

There are many codes which apply to the design and fabrication of offshore systems. Specific codes related to the design of offshore structures have been issued by various authorities in the UK, the US and other countries, such as Norway. There are also regulations relating to marine and other offshore operations, some of which are specific to particular countries or areas.

The facilities require to be certified as fit for the purposes specified for offshore structures, whether for production of hydrocarbons or other purposes. The certificates confirm the safety of the operation, safety of the crew, structural and environmental requirements.

There are organizations which assess and issue such certificates. These bodies have set out guidelines and rules with reference to codes and acts which are to be followed. Adherence to such codes and regulations is essential and is one of the
requirements for all stages of the project development, from conceptual design to commissioning.

The major certifying authorities are:

1. American Bureau of Shipping (US)
2. Bureau Veritas (France)
3. Det Norske Veritas (Norway)
4. Germanischer Lloyd (W. Germany)
5. Lloyd's Register of Shipping (UK)

The codes and guidelines cover a broad area ranging from environmental conditions, loads to be considered, allowable stresses, stability, fatigue requirements, methods of analysis, lifting operations, corrosion protection, material specification, fabrication and associated quality control and testing and installation operations.

There are codes and guidelines issued by a number of organizations in the UK including the Department of Energy, Lloyd's Register of Shipping and the British Standards Institution.

In the US, the codes issued by the American Petroleum Institute, the American Bureau of Shipping, the American Concrete Institute, the American Society of Mechanical Engineers and the American National Standard Institute are the main guidelines.

The following is a shortlist of some of the codes and regulations currently in use.

1. American Petroleum Institute API RP2A: Recommended practice for planning, design and constructing fixed offshore platforms.
3. Det Norske Veritas: Rules for the design, construction and inspection of offshore structures.
5. Lloyd's Register of Shipping: Code for lifting appliances in a marine environment.

44.11 Organization and management of offshore projects

Interdependency of design, construction and installation techniques plays an important part in the development of offshore structures. Integration of multidisciplinary tasks at all stages demands well-organized management, co-ordination and control of the work.

44.11.1 Project requirements

Like many other complex projects, the main groups or organizations involved are: (1) the client(s); (2) the designers and consultants; (3) the contractors and subcontractors; (4) suppliers of materials and components; (5) inspectors and approving authorities; (6) finance organizations; and (7) insurance companies.

Management requires a project execution plan and an organized team to carry out the tasks of planning, organization and manpower control, contract administration, quality control, expediting, cost control and liaison and co-ordination.

44.11.2 Project organization

Management can be carried out with varying emphases on decision-making, delegation and construction. The matrix would therefore be different for each approach. The most common approaches for the form of project organization are:

1. Owner project management.
2. Owner partial involvement plus project services contractor.
4. Prime contractor.

44.11.2.1 Owner project management

In owner project management, the owner parcels out various parts of the work to contractors and subcontractors and manages the entire work directly using his own project team. This approach requires a vast team of engineers and planners from the owners who do not often have such a pool of experts.

44.11.2.2 Owner project services contractor

In the project services contractor approach, the owner still has an active role in the management and decision-making processes but selects a contractor to carry out all or most of the project management services.

44.11.2.3 Management contractor

In the management contractor approach, the management contractor acts on behalf of the owner and carries out all management tasks with the main work being contracted out to selected engineering, procurement and construction subcontractors. The owner's role in this case is top-level management and surveillance of the management contractor using his selected project team.

44.11.2.4 Prime contractor

In the prime contractor approach, work is carried out on a 'turnkey' basis by a contractor on a design/construct basis. The contractor is, in this case, responsible for the management and execution of the work, which he may undertake partly himself while subcontracting many other parts of the work to other subcontractors.

In addition to the above approaches, there are cases where combinations of these methods are used. Each approach has its benefits and weaknesses. Selection of the right approach depends on the capabilities of the owner to manage the work, the type of project, country and location.

The number of project managers, planners, engineers, construction inspectors and contract, purchasing, estimating, safety and administration staff varies significantly, and runs from a few hundred to a few thousand depending on the project and method of management. The team operates in various locations, i.e. the central office, land-based sites and offshore sites.

The project management of the Fulmar field in the North Sea involved an in-house team of 95 and a site team of 170 people.

44.12 Inspection, maintenance and repair

The emergence of certification for offshore structures has meant that requirements have been established for inspection, maintenance and repair at regular intervals during the life of the platform.

The inspection of offshore structures presents difficulties because they are being placed in ever deeper and more hostile and turbulent waters. A steel platform can weigh 25,000 t or more and have a total weld length of over 1 km, distributed over some 900 weld points. Templates, manifolds, wellheads, christ-
mas trees, risers, pipelines, flowlines and loading facilities all require regular inspection.

A typical inspection routine for an offshore structure would include the following:

1. General inspection.
3. Debris survey and mapping.
4. Sea-bed, scour and structure stability inspection.
5. Corrosion damage inspection.
6. Cathodic protection potential surveys.
7. Anode inspection.
8. Still photography and photo formatting.
10. Nondestructive testing inspection which may include:
   (a) magnetic particle inspection (crack detection);
   (b) eddy current inspection;
   (c) ultrasonics;
   (d) AC-PD methods;
   (e) Harwell ultrasonic torch technique;
   (f) radiography;
   (g) vibrodetection; and
   (h) photogrammetry.

Once a defect has been located, there are numerous repair possibilities to consider depending on the type of structure. Steel structures are generally repaired by cutting out the defective area and re-welding or by strengthening, using grouted clamps. Reference should also be made to Chapter 42 for further information on inspection and repair underwater. Typical operations involved in the repair of offshore structures are as follows.

44.12.1 Underwater cutting
There are four underwater cutting processes generally in use: (1) oxy-arc; (2) thermic cutting; (3) gas cutting; and (4) shielded metal arc. Of these, oxy-arc is probably the most widely used. Shielded metal arc can cut steels resistant to oxidization and corrosion and nonferrous materials, and is useful where no oxygen is available. Oxy-hydrogen cutting is performed with a torch rather than with a cutting electrode and an experienced operator can achieve a very neat cut in thick metal. Thermic cutting will burn through almost any material, including reinforced concrete.

44.12.2 Underwater welding
There are three underwater welding techniques:

1. **Dry hyperbaric welding.** Using either the semiautomatic or manual metal arc-welding processes, the weld area can be enclosed in three ways: (a) full-sized habitat; (b) mini habitat; and (c) portable dry box.
2. **One-atmosphere welding.** This technique uses an underwater chamber in which the environment is maintained at one atmosphere. The dry hyperbaric welding and one-atmosphere welding are the same except that dry hyperbaric welding is conducted under pressure.
3. **Shielded metal arc wet welding.** Basically the same equipment is used as for surface welding, but with insulated cable joints and a torch with waterproof electrodes.

44.12.3 Grouted clamps
Grouted clamps are used to strengthen nodes and braces on existing steel platforms. The clamps are bolted together and then filled with grout. They have been extensively used to repair defective nodes on older North Sea platforms.

44.12.4 Concrete repair
A discussion of methods of repair for concrete structures is given by the Underwater Engineering Group of CIRIA (see Bibliography). Techniques for inspection, maintenance and repair operations vary depending on the water depth and many other features of the platforms. Divers are used to perform some of these operations in shallow waters within the range of their safe operation which, in most cases, is up to 15 m. In deeper waters, remotely operated vehicles or remotely operated equipment is used.

Many techniques for remote inspection and maintenance operations have been developed recently. These have resulted in the need to modify details of the structures so that such operations can be carried out successfully. Design and construction methods are therefore influenced by inspection, maintenance and repair requirements during the platform's service life. These operations, apart from having to be practical, need to be safe and economical as, in most cases, the costs of divers, service support vessels and other equipment for offshore use are very high, compared with inspection, maintenance and repair operations for land-based structures.

44.13 Cathodic protection
Cathodic protection is the most commonly used corrosion protection method for steel offshore structures. It is normally used in combination with an insulating or protective coating, where the coating forms the first line of defence. Where the coating is damaged, however, corrosion can occur and cathodic protection is used to provide protection at such locations.

Cathodic protection uses either sacrificial anodes or impressed current to make the structure cathodic. This causes an electrical current to flow from the anodes, through the electrolyte, to the cathode (the structure) thereby opposing the natural electrical current arising from the flow of electrically charged ions away from the surface that is corroding.

In a sacrificial anode system, the current can be generated by the use of sacrificial anodes, such as zinc or aluminium. These will corrode instead of the structure, by virtue of their stronger anodic reaction with respect to the environment. They corrode at known rates, which means that their life expectancies can be estimated and maintenance replacement programmes specified so that new anodes can be installed before the older ones are entirely used up. A large platform anode can produce around 4 A d.c. at about 25 V. The current is transmitted over only relatively short distances.

The current alternatively can be generated by an impressed current system where an outside electrical power supply (e.g. a transformer rectifier) supplies a current to an auxiliary anode of some highly resistant material, such as platinum-coated titanium. An electric field is established which inhibits current flows out of the protected metal. Typical operating power for a single impressed current anode may be around 50 A, 20 V d.c. so that high power levels can be achieved with only a few anodes and long distances can be covered.

44.14 Removal of platforms
Most North Sea fixed platforms have planned lives of 20 to 30 years. A few platforms will therefore be decommissioned in the 1990s with a bunching of decommissioning dates between 2000 and 2010. The latest estimates put the decommissioning cost of all the 250 existing platforms at about $20 bn.

There are no set laws regarding the removal of offshore platforms at present. A consultative document recently issued by the UK Department of Energy envisages complete removal of platforms to a depth of 50 m in the southern North Sea, partial removal providing a minimum clearance of 55 m below
the surface in the central North Sea and partial removal to a water depth of 75 m in the northern North Sea.

This is expected to be challenged by the US and the Soviet Union, whose strategic concerns are to minimize the hazards for submarine navigation and require total removal.

Only a few small offshore platforms in the shallow southern North Sea have been removed to date at relatively low cost. The major removal problems will be associated with the 40 or so large platforms located in the central and northern North Sea which are located in water of 100 m or more. While most of these platforms are steel jackets weighing up to 40 000 t, there are also 18 large concrete gravity-based structures with base weights of up to 800 000 t and topside weights of up to 50 000 t.

Suitable dumping sites for the platforms have been investigated by government and offshore contractors. In the US and Japan, the creation of artificial reefs in shallow waters, which could enhance the fish population, have been considered.

However, oil companies are presently trying to increase the life of existing platforms by bringing new fields on stream using subsea completions or unmanned platforms and linking them back to the existing platforms.

Several detailed studies have been carried out to develop cost-effective and safe techniques for removal of such large structures. Many of these techniques involve using some of the methods established for handling such structures during their installation. The methods involve removal of the topside equipment and the deck structure by floating crane barges and the use of underwater explosives to cut the steel structure from its piled foundation.

Acknowledgements

Goodfellow Associates wish to acknowledge contributions to this chapter by M. M. Sarshar, H. D. Parker, L. E. Clarke and R. E. Lawrence.

Bibliography


