Handbook of Bottom Founded Offshore Structures

Part 2 – Fixed steel structures

by Jan Vugts

with substantial contributions from
Frank Sliggers
Rupert Hunt
Maarten Ripping
Kees van Zandwijk

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info@eburon.nl
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Cover design: Square Circle Partners, Heemstede, and Textcetera, Den Haag.
Cover photo: Tow-out of Shell’s Bullwinkle structure on Heerema’s launch barge H851 through the Corpus Christi Ship Channel on 27 May 1988.
The Bullwinkle platform is the tallest fixed platform in the world. It stands in a water depth of 412 m and contains 60 slots for drilling wells. The giant support structure weighs approximately 50 000 tons and was built in one piece at the yard of Gulf Marine Fabricators in Ingleside, Texas. The structure is anchored to the seabed by 28 piles of 2.1 m diameter. The barge H851 was specially built for its transportation from the yard to the Gulf of Mexico and its launch on location in the open sea.
Photo from ‘50 Years Offshore’ (Reference [2.3-1]), Shell International – Photographic Services.

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Preface

The Handbook of Bottom Founded Offshore Structures consists of two parts. Part 1 deals with general features of offshore structures and the theoretical background for analysing their behaviour in the natural environment of the open sea. While emphasizing structures that are bottom founded, considerable parts of the material in Part 1 are more generally applicable to offshore structures of all types. It was published in December 2013. Part 2 focuses on fixed steel structures, especially those of space frame configuration. However, it also includes chapters on two special types of structure that are bottom founded, but are quite flexible and dynamically sensitive and do not belong to the subgroup of fixed structures: jack-ups in the elevated mode and compliant towers. It was foreseen that Part 2 would follow in about a year after Part 1; unfortunately, circumstances have delayed its appearance until September 2016.

While Part 1 was entirely written by myself, and reflects 25 years of experience with offshore structures in Shell, floating and fixed, nearly 10 years of teaching the subject at the Delft University of Technology, and some 20 years of active participation in the preparation of the ISO 19900 series of standards, Part 2 also includes valuable contributions by other contributors: some former Shell colleagues and some engineers from Heerema Marine Contractors; see the Acknowledgement.

The Handbook aims at different requirements of 3 groups of potential users:

- by providing educational material for students of master level courses in offshore engineering;
- by being a reference work for practising engineers in the offshore field to refresh or deepen their knowledge of a certain subjects in the execution of their job;
- by providing material for self-study for anyone who joins the offshore trade later in his or her professional career, or who has missed out on a relevant subject in prior education.

The origin and background to the preparation of the Handbook are described in the preface to Part 1, which is repeated below.

Preface to Part 1
Offshore engineering is a broad and relatively young branch of engineering, comprising an intricate mixture of several more traditional disciplines with many enhancements and extensions of its own. It spans from oceanography and hydrodynamics, via structural and geotechnical engineering, to fatigue of materials, structural dynamics and stochastic processes. While there are many excellent textbooks on traditional disciplines, the mixture with specific aspects for applications to offshore engineering problems is hard to come by. Naturally, there also is a significant body of special offshore engineering literature, most

of it in the form of conference papers and trade journal articles. However, the majority of this literature either has a distinct project or commercial bias, or probes rather deeply into a narrow specialist area. Neither of these is fit for educational purposes. Consequently, when I joined Delft University of Technology in 1992 as professor of offshore engineering there was no suitable educational material to support an integrated university course.

This situation did not really surprise me. During my preceding 25 years in industry with a large oil company (Shell) I had seen and participated in enormous progress in all technological areas. In many respects these years were pioneering years. The exploitation of oil and gas resources in ever deeper water and more demanding environments (among which the challenges presented by the North Sea in the 1970s and 1980s) demanded significant developments in offshore engineering technology, as well as in fabrication and installation equipment. There existed a climate of active research and development by in-house studies, joint industry projects, and studies commissioned from third parties. The pace of development was so rapid that practising engineers and theoreticians alike were continuously stretched, and there never was time for consolidation and an integral recording of expertise and methods. Engineers in industry grew up with the rapidly developing knowledge base, and within many companies there were effective training programmes to guide and supervise young engineers entering the field. While the results and global insights obtained from these studies were in the 1990s generally in the public domain, they were scattered and often not well known.

Given this situation I began to produce some lecture notes for my students at TU Delft to try and fill the dearth of educational material that existed at the time, and probably still today. These notes were produced in a period characterized by a chronic lack of time and were fragmented and incomplete. At my retirement from TU Delft in 2001 the desire to improve and complete the notes and collect them in a book remained. However, the book should be aimed at a wider audience and contain comprehensive material that could serve as a reference book for practising engineers; parts from it could then be selected as material for training of offshore engineering students.

The central skill in the ‘art of engineering’ is the modelling of a problem with which an engineer is confronted. Once a well-formulated model is available, specialist assistance may be sought for its solution, but even the best knowledge of analytical or numerical tools is not of much help in formulating a problem adequately. This is particularly important at a time when computerisation increasingly invites a mechanistic application of sophisticated software, while the underlying concepts and theories are poorly understood. Achievement of the skill requires that engineers command three interrelated elements, i.e. firstly discipline knowledge in several different fields at an adequate level for the job, secondly specialisation of this knowledge to offshore engineering, and thirdly integration of the various contributions towards practical applications.

Therefore, in the Handbook I have chosen to focus on basic aspects of the global behaviour of structures, with added discussion on the nature of a problem and its appropriate modelling. The objective being to promote understanding of how and why structures behave as they do, as well as familiarisation with modelling principles and the theoretical tool box that is available to investigate their behaviour, rather than presenting ready-made recipes. Awareness of the numerous details and petty facts of structures, as well as tailoring of knowledge and solutions towards specific applications will follow rather naturally in engineering practice.

Since my time at the university some important further developments have taken place. From the mid-1990s the industry has undergone major reorganisations with a severe loss of experienced engineers and in-house engineering expertise. At the same time the continuous and rapid growth of computing power increasingly brought even more sophisticated software programs on the market (most of which are general and not specifically aimed at offshore engineering) with promises of hitherto unprecedented possibilities to resolve design and analysis problems. However, a major drawback of the computer age is that insight in the underlying principles of the behaviour of offshore structures in their natural environment gets less attention and is in danger of getting lost. Problems are increasingly tackled by ‘pressing computer buttons’ by users who no longer have adequate background and understanding of the complexities involved. Users tend to lack appreciation of the interrelationships between parts of the overall problem and associated solution procedures, without which proper modelling followed by evaluation and interpretation of the computational results is impossible. This strengthened the call for a broadening of the Handbook’s scope by emphasizing understanding of the global behaviour of structures at sea, the models to describe this and the theoretical tools to solve practical problems.

Another recent development is the significant efforts by the industry to produce international standards under the auspices of ISO, the International Organisation for Standardization. Standards for the design and assessment of offshore structures of all types and materials are collected in the ISO 19900 series. These standards incorporate comprehensive material on applicable methods and how these should be used in worldwide applications, but they are no replacement of text books. From the very beginning in the early 1990s until 2010 I have been closely involved with the preparation of these standards. The Handbook provides useful background and cross-references to them where appropriate.

The Handbook focuses on offshore structures, with special attention to bottom founded structures. The reason for the latter is simple. The Interfaculty Offshore Technology programme in Delft in the 1990s included three offshore lecture courses: one on bottom founded structures, one on floating structures and one on subsea installations and pipelines. My chair was in the Civil Engineering Department and I taught bottom founded structures; floating structures were dealt with by the Department of Marine Technology, while subsea installations and pipelines were taught by visiting staff from industry. Bottom founded structures are a subset of the family of offshore installations. They comprise fixed structures (steel and concrete), compliant towers, guyed towers, jack-ups in elevated condition, and recently also support structures for wind energy. While the public limelight these days is on floating and subsea developments in ultra deep water, fixed structures form the overwhelming majority of the entire offshore population; that was so in the past, is still the case at present and will be so in the future. Their treatment requires thorough discussion of the natural environment in which all offshore structures exist, as well as many general aspects that are equally applicable to other types of structure. And as I have always aimed at treating subjects in the broader context of offshore engineering in general, the material in the Handbook has wider relevance and applicability than for bottom founded structures alone. This is further accommodated by the decision taken to split the Handbook into two parts. Part 1 is more generally oriented towards models and contains the theoretical bases of the tool-box to solve them, while Part 2 more specifically discusses basic aspects and behaviour of fixed structures by presenting simplified methods from first principles that can be executed by spreadsheet or even by manual calculations. This is highly educational and provides the insight that is indispensable for the application of sophisticated computer programs. Regrettably, even in retirement time proved to be a precious commodity and it has taken until now to complete Part 1.

Part 1 comprises 9 chapters as follows:

1. The first 3 chapters put offshore engineering on the map as a young engineering field.
   Chapter 1 describes what offshore engineering is in the context of this Handbook, how it originated and how it developed since the Second World War. It also puts the background in and interactions with other major engineering fields in perspective.
   Chapter 2 tells the history of developments in standards by the industry, by regional authorities and by international organisations, and presents the status of international standards for offshore structures.
   Chapter 3 concludes by giving an overview and classification of the various types of offshore structures.
2. Chapter 4 introduces models and modelling as the critical first step in an engineering effort to solve practical problems. The modelling process is illustrated, main model attributes are identified, and the selection of the most suitable type of model for practical applications is described.
3. Chapter 5 describes the offshore environment of wind, current and waves in which all offshore structures exist, together with relevant models for these environmental features and for the actions on structure caused by them.
4. The last 4 chapters provide a consistent knowledge base for offshore engineering applications. Basic discipline knowledge of the three most relevant engineering disciplines for offshore structures (hydromechanics, applied mechanics and soil mechanics) can be found in many textboooks. Such basic knowledge is assumed to be known and is not duplicated in here. The emphasis is on an integral treatment of offshore engineering problems. However, the literature on some theoretical subjects may

not be readily known, or is not easily accessible to practising engineers and offshore engineering students. These subjects are therefore discussed in some detail. This applies to structural dynamics (Chapter 6), random processes (Chapter 7), fatigue (Chapter 8) and structural reliability (Chapter 9). Foundation issues are not discussed in Part 1.

Preface to Part 2

Part 2 focuses on fixed steel structures of space frame configuration. Chapter 1 provides a link to Part 1 of the Handbook and presents an overview of the material treated in Part 2. Therefore only a few significant points are highlighted here.

The full life cycle of a fixed structure is covered by Chapters 2 to 10, which comprise:

- a discussion of design aspects, from conceptual design to preliminary member sizing and design checks;
- simple methods for the analysis of a structure's mechanical behaviour, quasi-statically and dynamically, and its fatigue performance *in situ*;
- the assessment of strength and fatigue capacity of (tubular) members and joints;
- a discussion of its fabrication on shore, transportation to and installation at the offshore site, including their relationships and interactions with design;
- an introduction to and overview of structural integrity management during its lifetime;
- an introduction to and overview of its eventual decommissioning and removal.

Part 2 also includes an extensive discussion of foundation engineering (Chapter 5), from a description of the properties of soils and how these can be determined, via the mechanisms of load transfer between soil and foundation elements, to foundation design and installation. A comprehensive treatment of foundation issues for offshore structures like this chapter is not easily found elsewhere. The theoretical aspects of this chapter may have fitted better in Part 1, but their combination with an overall treatment of all aspects involved has definite benefits. The chapter is an excellent addition to the other subjects covered in both parts of the Handbook.

In view of the aim to promote understanding and insight in a structure's mechanical behaviour, Part 2 presents simplified modelling and analytical/numerical methods for the determination of global structural response to environmental excitation. The methods are transparent, and generally have a better ability to visualize what actually happens.

Chapter 6 discusses global dynamic response of fixed structures in the ocean with methods that can be executed by spreadsheet calculations. In this manner the fundamental aspects and the complexities of dynamic response are illustrated. As time varying environmental excitation is random, often contains non-linear influences and occurs around a non-zero mean, it is argued that dynamic and fatigue assessments need to focus on response *ranges* rather than on response *maxima* (*extremes*).

For structures with a relatively low natural period compared to the range of periods in wave excitation the response is stiffness controlled and can be analysed by adding a relatively small load set of mass inertial forces to the wave actions. As phase differences between wave actions and the associated inertial forces are then small enough to be neglected, wave actions and inertial forces can simply be added algebraically, after which a normal quasi-static structural analysis can take place. For structures with higher natural periods the response is to varying degrees partly stiffness controlled, partly damping controlled and partly inertia controlled. This can be analysed analogously by a generalisation of this method of including an additional load set representing mass inertial forces. However, the phase angles between wave excitation and the resulting mass inertial forces can now no longer be neglected and need to be properly taken into account. The adding of wave actions and mass inertial forces thus becomes a phasor (vectorial) addition instead of an algebraic addition. It is demonstrated that this has a significant impact on the associated dynamic response. The method clearly illustrates the complexities of global dynamic response of a framed structure in the open sea and demonstrates beyond doubt that representation by the dynamic amplification factor of a single degree of freedom system is totally inadequate for obtaining reliable action effects for design purposes.

By way of example, the method is applied to a hypothetical structure in very deep water and to a monotower support structure in 29 m water depth in the North Sea, such as often used for a wind turbine. The monotower is investigated in some detail in random seas, using a new formulation for Morison wave loading on a monotower. The static and dynamic base shear and overturning moment at the sea floor are compared with finite element calculations by the Bladed program. The linearized spectral random calculations are very instructive in clarifying and understanding the monotower's response, quite contrary to the random time domain simulations with the Bladed program.

In Chapter 7 the monotower is also used as a simple structure for a practical example application of a fatigue assessment in a North Sea scatter diagram, in accordance with the procedures described in Part 1.

Finally, it is worth mentioning here Chapter 11 on self-elevating platforms or jack-ups. This chapter contains a comprehensive treatment of this special type of structure, which is difficult to find in the open literature. Chapter 11 goes a long way to filling this gap.

Prof. dr. ir. J.H. Vugts
The Hague, August 2016.

Acknowledgement

The production and publication of the Handbook have been financially supported by Delft University of Technology, De Oude Bibliotheek – Academy in Delft, Heerema Marine Contractors and Shell Projects & Technology. They did so by guaranteeing the purchase of a number of copies. Heerema also showed an interest in contributing to Part 2 in areas in which they have special expertise, notably the fabrication, transportation and installation of structures, including the engineering and installation of their foundations. The support of these four parties is gratefully acknowledged.

A number of people have cooperated with me in the preparation of Part 2. All cooperators did so on a voluntary and unselfish basis. Four of them need to be specially mentioned: Frank Sliggers, Rupert Hunt, Maarten Ripping and Kees van Zandwijk; each one of them contributed (at least) a whole chapter to Part 2. Besides this, Frank has been my right-hand man and has assisted me throughout the preparation of Part 2. The associations of these four men with the subject matter and with me personally may be summarized as follows:

> Frank Sliggers is a former Shell colleague, who after retirement followed in my footsteps as an associate professor with the Offshore Engineering MSC course in Delft.
> Rupert Hunt is also a retired former Shell colleague, who is currently associated with Halliard Consulting.
> Maarten Ripping and Kees van Zandwijk are engineers and senior advisors with Heerema Marine Contractors.

Their contributions are very valuable additions to Part 2. The nature and content of their contributions have been agreed in mutual consultation and I take full responsibility for the material thus included. I have thoroughly reviewed all contributions and edited them in order to create the greatest possible uniformity in form, style and wording throughout this Part.

Brief descriptions of significant contributions are given below.

Versions of Chapters 2 (Design) and 3 (Quasi-static behaviour) already existed in a previous draft of the Handbook that was used as lecture notes in Delft around the year 2000; these chapters were jointly reworked by Frank Sliggers and me. Frank also initiated and essentially produced Chapter 9 (Inspection, maintenance and repair) as well as Chapter 10 (Decommissioning and removal). Chapters 2 and 10 were additionally reviewed by some Heerema engineers, who made valuable comments that were duly incorporated. Furthermore, Frank was co-author with Maarten Ripping in preparing Chapter 8 (Fabrication, transportation and installation); see below.

A version of Chapter 4 (Member and joint design checks) also already existed in the draft Handbook with lecture notes. However, this version preceded the publication of ISO 19902 and was therefore still based on API RP2A LRFD. Another former Shell colleague, Mike Efthymiou, reviewed the then existing chapter, made some additions and helped me to upgrade it to reflect ISO 19902.

From the very start of Part 2 it was agreed that Kees van Zandwijk of Heerema Marine Contractors would prepare Chapter 5 (Foundations). Before finalizing the chapter his draft was thoroughly reviewed by Fugro, who made many useful suggestions that added to the chapter's completeness and practicality. Fugro's contribution is gratefully acknowledged.

In a similar manner it was agreed from the start that Maarten Ripping, also of Heerema Marine Contractors, would take the lead in writing the chapter on fabrication, transportation and installation. He was later joined in this effort by Frank Sliggers. Together they produced Chapter 8, the draft of which was again reviewed and commented on by Heerema engineers before it was finalized.

The scope of Chapter 11 (Self-elevating platforms or jack-ups) was planned by Frank Sliggers and myself, giving due consideration to the scattered material included in the early Handbook with lecture notes. A complete draft of the chapter was subsequently prepared by Rupert Hunt. All three of us have considerable background in respect of jack-ups. Rupert then prepared the final chapter in close cooperation with myself.

Other, more incidental contributions are referred to and acknowledged at relevant places in the text.

I am extremely grateful to all contributors.

Jan Vugts
August 2016.

Contents

1 Introduction

1.1 General

This two-part Handbook is concerned with offshore structures, and mainly but not exclusively with the group of bottom founded offshore structures. Part 1 [1.1-1] contains:

- a general introduction to offshore engineering (what it is, how it did arise, its relationships with other engineering fields);
- a brief history of offshore oil and gas developments, which is the birthplace of offshore engineering as it exists today;
- an overview of the development of offshore engineering standards, with emphasis on the recent (this century) ISO 19900 series of standards for structures;
- a classification of the various types of offshore installations used by the offshore oil and gas industry for different purposes;
- an introduction to models and the art of modelling in order to find appropriate solutions for technical problems;
- a treatment of some important theoretical subjects for (self)study, to support education at master level courses, or for use as a reference for practising engineers; the subjects cover:
  - the offshore environment in which all structures exist and the associated environmental actions (environmental loading) on structures, with emphasis on the wave environment in a natural sea;
  - the dynamic behaviour of structures, from the fundamental aspects that are common to rigid body motions and structural dynamics, to the vibrations of slender structural components and bottom founded structures as a whole;
  - theoretical and practical aspects of random processes and response analyses in random seas;
  - key features of the fatigue process and fatigue assessments;
  - general aspects of structural design and assessment, including a discussion of structural reliability assessments.

Experience has shown that the theoretical subjects in Part 1 are difficult to fathom and often present problems for offshore engineering students and practising engineers alike, while the considerable body of associated literature is often difficult for them to access. These subjects have therefore been brought together in Part 1, where they are discussed against the background of offshore engineering requirements and applications. They are treated there and explained in some depth in order to promote sound understanding, thus enabling users to establish validity and limitations of the modelling and analysis of real life problems. The subjects are presented with attention to mutual relationships between them and are sufficiently self-contained to provide an engineer with adequate knowledge for advanced offshore engineering applications, without a need for the consultation of more specialized literature in other than rather special cases.

Naturally, the general topics and the theoretical subjects covered in Part 1 have much wider applicability than for bottom founded structures only.

This Part 2 of the Handbook deals more specifically with bottom founded structures, notably in respect of their design and mechanical behaviour on location. The group of bottom founded structures comprises fixed structures, compliant towers, guyed towers and jack-ups in elevated condition. The fixed structure is the traditional workhorse of the industry; the overwhelming majority of fixed structures are steel structures of space frame configuration with a pile foundation. These structures are the main focus of Part 2. Fixed structures can be subdivided into jacket structures and tower structures, which differ in the concept of their pile foundation and the interaction between the space frame and the foundation piles. This is explained first in Chapter 2 (sections 2.3, 2.4 and Annex 2.C), and then in detail in Chapter 3 with the associated consequences for their quasi-static behaviour. Other fixed steel structures are monotowers, free-standing caissons and braced caissons. Monotower structures are less often used by the oil and gas industry, but are of considerable interest as support structures for wind mills. Monotowers behave markedly different than space frame structures, especially with regard to their dynamic behaviour and their monopile foundation. The dynamic behaviour of monotowers is discussed more specifically in Chapter 6 (section 6.4 and Annex 6.B); monopile foundations are considered in Chapter 5 (section 5.5.3.6) as a special type of deep foundation. All caisson type structures are a form of monotower structure, but are not further discussed in the Handbook.

Nearly all gravity based structures are concrete structures (see Part 1, section 3.5). These form an entirely separate class of fixed structures and are not covered by this Handbook. However, some aspects of gravity foundations are discussed in Chapter 5 under the general treatment of shallow foundations.

Jack-ups in elevated condition are in several respects very similar to fixed steel structures, but there are also important differences in structural behaviour. Additionally, they are much more dynamically sensitive than fixed structures. Chapter 11 is entirely devoted to jack-ups. Compliant bottom founded structures are steel space frame structures that are intended by design to accommodate the large horizontal excitation due to wind and waves flexibly by allowing a fair degree of (rigid body) rotation and bending, thus mobilizing mass inertial forces towards a state of dynamic equilibrium. Special aspects of compliant structures are discussed in Chapter 12.

Besides design for and analysis of the mechanical behaviour of bottom founded structures and their foundations *in situ*, this Part 2 also deals with other phases of a structure's life cycle. Chapter 8 addresses fabrication, transportation and installation of steel structures, with their impact on and interaction with design aspects. Chapter 9 presents general considerations on (structural) integrity management during a structure's service life. Lastly, Chapter 10 reviews decommissioning and removal of structures at the end of their life.

1.2 Types of bottom founded structures and their definitions

Various types of bottom founded structures are defined in the ISO 19900 series of offshore structures standards. For information and convenience relevant definitions in ISO 19900 [1.2-1], ISO 19902 [1.2-2] and ISO 19903 [1.2-3] are presented below:

braced caisson
monotower where the lower part of the monocolumn is supported laterally by one or more inclined braces between the column and one or more foundation piles
[ISO 19902:2007]

compliant bottom founded structure
structure which is supported at its base by foundation piles or by another non-superficial foundation system and which is sufficiently flexible that applied lateral dynamic actions are substantially balanced by inertial reactions
[ISO 19902:2007]

fixed structure
structure that is bottom founded and transfers all actions on it to the seabed
[ISO 19900:2002]

fixed concrete offshore structure
concrete structure designed to rest on the sea floor
note Sufficient structural stability can be achieved through its own weight, or in combination with suction in skirt compartments, or founding of the structure on piles into the seabed. It includes the mechanical outfitting of the structure.
[ISO 19903:2006]

free-standing caisson
monotower where the structure consists, over its full height, of a single vertical column that continues into the seabed as the foundation pile
[ISO 19902:2007]

jacket
fixed structure with leg piles and axial force transfer from the structure and topsides into the piles at the top of the structure
[ISO 19902:2007]

jack-up
mobile offshore unit that can be relocated and is bottom founded in its operating mode
note A jack-up reaches its operational mode by lowering legs to the sea floor and then jacking the hull to the required elevation.
[ISO 19900:2002]

monotower
fixed structure in which the whole structure, or at least the upper part of the structure, consists of a single vertical column (tubular or framed) that carries the topsides

> *note* Where only the upper part of the structure is a single vertical column, the lower part of the structure consists of tubular members or frames that connect the vertical column to the foundation piles or to another non-superficial foundation system that supports the monotower at its base, such as bucket foundations.
> *[ISO 19902:2007]*
>
> **steel gravity structure**
> fixed structure that is held in place against environmental actions solely by the weight of the structure and any contained ballast, together with foundation resistance resulting from its weight and lateral resistance from any skirts
> *[ISO 19902:2007]*
>
> **tower**
> fixed structure that is supported by foundation arrangements at the base of the structure
> *[ISO 19902:2007]*

Foundation systems are not specifically defined in the ISO 19900 series of standards, with the exception of the following two foundation elements:

> **bucket foundation**
> foundation of a cylindrical shell open on one end and installed by suction
> *[ISO 19902:2007]*
>
> **skirts**
> structural components constructed in concrete and/or steel that extend from the foundation downwards and penetrate into the seabed
> *note* Skirts are used to increase the capacity of the foundation to resist vertical and horizontal actions and improve erosion resistance. Skirts can also be needed to form compartments facilitating the under-base grouting.
> *[ISO 19903:2006]*

1.3 Aims of the Handbook and related contents of Part 2

The Handbook is aimed at offshore engineering students, who can use it as a textbook/manual for master level courses, and at practising engineers for whom it serves as a refresher and reference book, but who can also use it for self-study of aspects with which they are not very familiar.

As summarized at the beginning of this chapter, Part 1 provides relevant theoretical material in some notoriously difficult areas, intended to improve knowledge and understanding of its applications in modelling and problem solving. This knowledge and understanding is in some danger of getting lost in an era where ‘pushing the button’ of sophisticated computer applications tends to become the norm. Instead of uncritically adopting the outcome of computer calculations, the material in this Handbook should encourage reflection and critical evaluation of the models used, as well as an assessment of the associated strengths and weaknesses of their solutions.

In Chapters 2 to 10, this Part 2 presents and familiarizes readers with methods used in the ‘making’ of fixed steel structures, from conception to removal. Additionally, special aspects of two unique types of bottom founded structure, jack-ups and compliant towers, are discussed in Chapters 11 and 12, respectively. Part 2 further provides readers with sufficient background to understand certain requirements in standards or codes of practice; this background is usually not given in the standards themselves. The Handbook does not present the basics of structural steel design, nor contains elaborate technical detail of steel design. For these purposes specific textbooks and (inter)national standards should be consulted; an overview of offshore structures standards is given in Chapter 2 of Part 1.

Consequently, the Handbook is not and is not intended to be an all-inclusive design guide of fixed steel structures. It is not a replacement of, nor a supplement to existing standards and codes. For special subjects such as, for example, design of boat landings, helidecks, seafastening, lift points or vessel collision with structures, engineers should consult relevant guides and standards for these topics. Also structural design of topsides is not covered herein. Design of pipes that, in addition to being structurally adequate, should satisfy functional requirements, such as conductors, risers, caissons and sumps, are similarly beyond the scope of the Handbook.

Rather than presenting detailed ‘recipes’, Part 2 discusses concepts and attempts to stimulate thinking and critical evaluation of the ‘making’ of fixed steel structures; of their design, fabrication, installation, maintenance and eventual removal, and especially of how and why these structures behave *in situ* as they do. To this end Part 2 presents:

- differences between structures on land and at sea, considerations for conceptual design, selecting a preferred configuration, preliminary determination of main dimensions and initial member sizes (Chapter 2);
- a discussion of the modelling of actions (applied loads) on fixed structures, the quasi-static force flow through a structural frame, support reactions at the foundation, interaction between frame and piles; from these simple, but instructive models relatively simple equations are derived that permit ‘back of the envelope’ type calculations of foundation reactions and main contributions to individual leg and brace forces, which are illustrated in two examples (Chapter 3);
- a discussion of the set-up and application of checking equations for the strength and stability of tubular members and tubular joints, as well as of the stress concentration factors with which the local stress distribution in tubular joints can be described for fatigue assessments (Chapter 4);

- a description of the properties of soils and how these are determined, a discussion of foundation options, load transfer between foundation elements and the soil, and the design and installation of foundations of fixed structures (Chapter 5);
- a discussion of the dynamic behaviour of space frame structures and monotowers, and how this behaviour can be described and better understood (Chapter 6);
- an example of a probabilistic (spectral) fatigue assessment, applied to the monotower from Chapter 6 (Chapter 7);
- a general discussion of the fabrication, transportation and installation of steel space frame structures (Chapter 8);
- some considerations on inspection, maintenance and repair (Chapter 9);
- a review of decommissioning and removal aspects of structures (Chapter 10);
- the history, main components, operational features and site-specific assessment of self-elevating platforms (jack-ups) (Chapter11);
- special aspects of compliant towers as a special class of bottom founded structure (Chapter 12).

1.4 Terminology and notations

Terminology, definitions of variables and their notations usually differ from textbook to textbook and from one standard to another, which can be a great source of confusion. In this Handbook we will generally follow ISO 19902 [1.2-2], which is a modern offshore structures standard. Therefore we will also adopt the terminology and the general rules for notations used in this standard.

For a discussion about terminology in ISO 19902 and their background reference is made to Part 1 [1.1-1], Chapter 2, section 2.5. Definitions are important for proper understanding, and users of the Handbook should familiarize themselves with them; therefore they are encouraged to read this section in Part 1. For the convenience of readers of this Part 2, the most relevant general definitions of terms used in the ISO 19900 series and in the Handbook are summarized below.

Definitions related to the structure:

platform

complete assembly including structure, topsides and, where applicable, foundations

structure

organized combination of connected parts designed to withstand actions and provide adequate rigidity

structural component

physically distinguishable part of a structure

example Column, beam, stiffened plate, tubular joint, or foundation pile.

structural system
load bearing components of a structure and the way in which these components function together

structural model
idealization of the structural system used for design or assessment

topsides
structures and equipment placed on a supporting structure (fixed or floating) to provide some or all of a platform's functions
note 1 For a ship-shaped floating structure, the deck is not part of the topsides.
note 2 For a jack-up, the hull is not part of the topsides.
note 3 A separate fabricated deck or module support frame is part of the topsides.

The performance of a structure is verified by limit states, design situations and design criteria:

limit state
state beyond which the structure no longer fulfils the relevant design criteria

design situation
set of physical conditions representing real conditions during a certain time interval for which the design will demonstrate that relevant limit states are not exceeded

design criteria
quantitative formulations that describe the conditions to be fulfilled for each limit state

Design or assessment of a structure is executed using basic variables that describe actions, load arrangements, load cases, action effects, resistances and strengths:

basic variable
one of a specified set of variables representing physical quantities which characterize actions, environmental influences, geometrical quantities, or material properties including soil properties

action
external load applied to the structure (direct action) or an imposed deformation or acceleration (indirect action)
example An imposed deformation can be caused by fabrication tolerances, settlement, temperature change or moisture variation.
note An earthquake typically generates imposed accelerations.

load arrangement
identification of the position, magnitude and direction of a free action

load case
compatible load arrangements, sets of deformations and imperfections considered simultaneously with permanent actions and fixed variable actions for a particular design verification

action effect
effect of actions on structural components
example Internal force, moment, stress or strain.

resistance
capacity of a component, or a cross-section of a component, to withstand action effects without failure

strength
mechanical property of a material indicating its ability to resist actions, usually given in units of stress

All variables must be given quantified values; these values are indicated by specific names that should be used correctly and should not be confused:

representative value
value assigned to a basic variable for verification of a limit state

characteristic value
value assigned to a basic variable associated with a prescribed probability of not being violated by unfavourable values during some reference period
note The characteristic value is the main representative value. In some design situations a variable can have two characteristic values, an upper and a lower value.

nominal value
value assigned to a basic variable determined on a non-statistical basis, typically from acquired experience or physical conditions

design value
value derived from the representative value for use in the design verification procedure

extreme value
value of a parameter used in ultimate limit state checks, in which a structure's global behaviour is intended to stay in the elastic range
note Extreme values and events have probabilities of exceedance of the order of 10^{-2} per annum.

abnormal value
value of a parameter of abnormal severity used in accidental limit state checks in which a structure should not suffer complete loss of integrity
note 1 Abnormal design situations are used to provide robustness against events with a probability of exceedance typically between 10^{-3} and 10^{-4} per annum by avoiding, for example, gross overloading.

note 2 Abnormal values and events have probabilities of exceedance of the order of 10^{-3} to 10^{-4} per annum. In the limit state checks, some or all of the partial factors are set to 1.0.

nominal stress
stress calculated in a sectional area, including the stress raising effects of the macro-geometrical shape of the component of which the section forms a part, but disregarding the local stress raising effects from the section shape and any weldment or other fixing detail
note Overall elastic behaviour is assumed when calculating nominal stresses.

Some other relevant definitions are:

design service life
assumed period for which a structure is to be used for its intended purpose with anticipated maintenance, but without substantial repair being necessary

exposure level
classification system used to define the requirements for a structure based on consideration of life safety and of environmental and economic consequences of failure
note The method for determining exposure levels are described in ISO 19902. An exposure level 1 platform is the most critical and exposure level 3 the least. A normally manned platform, which cannot be reliably evacuated before a design event, will be an exposure level 1 platform.

fit-for-purpose
meeting the intent of an International Standard although not meeting specific provisions of that International Standard in local areas, such that failure in these areas will not cause unacceptable risk to life-safety or the environment

reliability
ability of a structure or a structural component to fulfil the specified requirements

return period
average period between occurrences of an event or of a particular value being exceeded
note The offshore industry commonly uses a return period measured in years for environmental events. The return period in years is equal to the reciprocal of the annual probability of exceedance of the event.

The notations in ISO 19902 are derived from the general rules for notations in all ISO standards, but care remains required. The general rule for the notation of applied actions (loads) and internal forces (action effects) is the capital symbol F, with a suitable subscript or subscripts to indicate specific actions or forces. The rule for the notation of corresponding actions (forces) per unit length or per unit area is the lower case symbol f, with the same subscript(s) as F. This applies, for example, to wave induced actions (wave loads) per unit length; a Morison type local wave load on a member at location (x, y, z) and at time t is denoted by $f(x, y, z; t)$ in N/m.

The rule with regard to lower case f also has an impact on stresses. Stresses are forces per unit area and can therefore be indicated by f. However, tension, compression and bending stresses in a structural component are commonly denoted by the Greek symbol σ, while shear stresses are commonly denoted by the Greek symbol τ. This existing and wide-spread practice is permitted by the ISO rules and was also adopted in ISO 19902. Thus, in ISO 19902 both f and σ, τ are used for stresses, but there is a distinct difference by the introduction of a convention: the symbol f is used for stresses that represent resistances (strengths) of components, while σ and τ are used for stresses that are actually experienced as a result of applied actions (loads). This convention thus provides a useful distinction between the two different stress notions in checking equations; see Chapter 4.

Symbols are generally explained in the text where they occur, while an extensive list of symbols is included in the Appendix.

1.5 References

[1.1-1] VUGTS, J.H. *Handbook of bottom founded offshore structures, Part 1 – General features of offshore structures and theoretical background*. Eburon, Delft, 2013. ISBN 978-90-5972-796-0.

[1.2-1] INTERNATIONAL ORGANISATION FOR STANDARDIZATION. *ISO 19900 Petroleum and natural gas industries – General requirements for offshore structures.* 1st edition December 2002.

[1.2-2] INTERNATIONAL ORGANISATION FOR STANDARDIZATION. *ISO 19902 Petroleum and natural gas industries – Fixed steel offshore structures.* 1st edition December 2007.

[1.2-3] INTERNATIONAL ORGANISATION FOR STANDARDIZATION. *ISO 19903 Petroleum and natural gas industries – Fixed concrete offshore structures.* 1st edition December 2006.

2 Design

2.1 General introduction

This Part 2 of the Handbook deals mainly with a subset of bottom founded structures, namely fixed steel offshore structures. It aims at presenting users with methods for the design, analysis and construction of these structures, and to provide them with sufficient knowledge to understand the design requirements and design checks included in standards and codes of practice. In this context the early preparation of a chapter on design creates a dilemma. On the one hand it is logical to start a treatment of bottom founded structures with a discussion of how these structures are designed, before dealing in some detail with how a structure once designed behaves in its natural habitat. However, on the other hand the design of a structure requires considerable familiarity and knowledge of underlying subjects and processes to enable a meaningful discussion. It is akin to the question of the chicken and the egg: what is best done first? As explained in Chapter 1, in the Handbook the choice has been made to present the knowledge on several subjects that a designer should master in Part 1 [1.1-1]. Therefore a good background in these subjects is here assumed, allowing treatment in this chapter to be at a higher overview level. For more detail or depth on a subject reference will frequently be made to the relevant treatment in Part 1. However, where it is indispensible for the course of the discussion it can be unavoidable to include a summary or to repeat some material.

An offshore platform comprises topsides, (support) structure and foundation. The design of an entire platform requires a structured approach to ensure that sound decisions are made and appropriate options are selected for a well-balanced design. The three parts of the platform interact and influence design choices. For fixed steel structures structural design of the topsides is mainly governed by the number and disposition of the supports provided by the structure underneath; besides this the design of the topsides is largely independent of the structure and its foundation. More support points enable lighter topsides, with associated benefits for offshore installation, and improve topsides safety through increased redundancy. However, more supports mean more legs and a heavier structure. Weighing the advantages and disadvantages needs careful attention at the very start of design. The topsides thus have a marked impact on the dimensions, the configuration and the load-carrying capacity of the structure supporting them. The design of the topsides themselves is only briefly addressed in this Handbook. The other two parts, the structure and the foundation, interact strongly as will be described.

This chapter provides an introduction to the design of the support structure and the foundation. Their conceptual design with the determination of the principal dimensions and an optimal configuration of the structure, taking due account of functional requirements and other relevant considerations, as well as of the interaction with topsides and foundation, is addressed in section 2.3. The design then progresses towards a preliminary design in section 2.4 by detailing the selected configuration, estimating member sizes and making a first cycle through structural design, with an initial evaluation of items that are expected to be critical (for example tubular joints or fatigue in certain areas) using preliminary design checks. The design process is normally divided into phases, covering design for in-place conditions, accidental conditions and temporary conditions. It is concluded by detailed structural design of a large number of diverse components involving very special topics, such as member design; joint design; design against vessel collision; design of conductors, risers, J-tubes, boat landings, etc. The Handbook is not meant to be an all-inclusive design guide and detailed structural design is hence not covered. For these special design topics international standards should be consulted.

For general understanding of the reader it is relevant to first present a comparison between an offshore structure and onshore industrial buildings; this is done in section 2.2. It will be demonstrated that the differences are many and that working offshore requires special offshore building methods and is much more expensive than onshore construction. For the design of an offshore structure the functionalities for oil and gas production provide a reference. The structure's main components are described and their structural design is illustrated. Besides in-place loading situations, structural design is also affected by many load cases during various construction phases. However, the emphasis is on in-place situations; these are very important for all offshore structures, as extreme environmental actions often govern structural design of (parts of) the structure.

Chapter 2 should not be seen in isolation; the subsequent chapters provide essential additional information for design. Chapter 3 on 'Quasi-static behaviour' describes the modelling of applied actions; of mechanical models for the force flow through the space frame to the foundation piles; of the associated foundation reactions, and of the interaction between structure and piles. The next Chapter 4 on 'Member and joint design checks' discusses strength checks for tubular members and tubular joints for ultimate limit states, that are applicable to in-place design situations. Soil behaviour, soil investigation, transfer of actions between soils and piles, as well as foundation design and installation, are addressed in Chapter 5 on 'Foundations'. Sound knowledge of these subjects is a crucial requirement for design; and so is the discussion of fabrication, transportation and installation in Chapter 8.

In some cases structures respond dynamically to the applied environmental actions. Incorporating dynamic effects in a relatively simple, but yet realistic manner in the analysis of structures is not as straightforward as it may seem. This special subject is dealt with in Chapter 6 on 'Dynamics of structures'.

2.2 Differences between structures on land and at sea

2.2.1 General aspects

All offshore platforms consist generically of three parts: the topsides above water, the structure or support structure in the water and a foundation under water on or in the seabed. The topsides contain all the facilities and have some similarity, but also many differences, with an industrial building on land. The structure serves as a solid base above water to support the topsides. The structure can stand on the sea floor or it can float. For bottom supported structures the distinction in support structure and topsides is usually rather clear; for example, for a fixed steel space frame or concrete gravity structure supporting drilling and/or production facilities the interface is at the location of the topsides support points well above the waterline. For floating structures structure and topsides are often more integrated, both from a functional and a structural point of view. Of course, in addition to its structural role the support structure can also provide for some functional requirements (for example, storage of oil in the caisson of a concrete gravity structure or in a ship's hull) and contain a part of the equipment (such as in the shafts of a concrete gravity structure or in the columns and pontoons of a semi-submersible). The foundation supports the structure and transmits the actions on it to earth. In the case of bottom founded structures load transfer to earth is direct through a deep pile or a shallow bearing foundation. In the case of floating structures (vertical) load transfer is indirect via the water column, while lateral load transfer takes place via the anchoring system. The water supports the floating structure through buoyancy; generically the water and the sea floor underneath may be seen as the 'foundation' for a floater.

Structures on land (buildings) and (bottom founded) structures at sea are different in almost every respect, with regard to the structures themselves as well as the manner in which they are constructed. The first major difference is clearly that buildings on land do not require a support structure to lift them out of the water. Therefore the topsides is essentially the only part that can meaningfully be compared to a building on land. The main technical differences between an offshore structure and onshore industrial buildings are given below under a number of different headings.

2.2.2 Main technical differences

Design requirements

The functional demands will vary from case to case, both onshore and offshore, and will generally be radically different for each case. However, there are a number of more generic requirements that can usefully be compared:

- For an industrial building onshore, concern is in particular with the creation of enclosed spaces; these are the useful parts of a building. The spaces on or in the topsides offshore that are created for the installation's ultimate purpose may or may not be enclosed. Where possible, open spaces are normally preferred to avoid the potential accumulation of flammable and explosive gases. For the support structure, concern is first and foremost with its strength, stability and redundancy. It is designed to be as small, slender and transparent as possible in order to reduce environmental actions on it, especially hydrodynamic actions due to waves and currents.

- Onshore there is normally no need to provide accommodation for people who work in the building to also live in it. In view of the remoteness of offshore platforms the daily shuttling of people to and from the platform is usually not a realistic option. Therefore living quarters and everything that comes with it (such as catering and laundry facilities as for a hotel) must normally be provided. This also requires provisions for boarding the platform, such as a boat landing and/or a helideck, with all associated safety systems.
- General facilities and services like electricity, communication facilities (e.g. telephone, radio), drinking water, sewerage are routinely available onshore but not offshore; everything must be specially provided, usually with logistic services provided by supply boats. The supply boats involve an intrinsic risk of collisions with the structure.
- As failures or malfunctions of systems can lead to potentially serious situations in confined spaces, or to long periods of being out-of-service, the demands on quality are unusually high and ensured by appropriate quality systems. With a view to the difficulties and very high cost of offshore work, requirements for maintenance, exchanging items or repairs during the service life should be kept as low and simple as possible.
- On the other hand, aesthetic considerations hardly play a role offshore, unlike the situation on land.

Site specific structural design data

On land design data are usually amply available or are relatively easily obtained, but for offshore applications site-specific data are scarce and difficult to get. The required data include inter alia water depth and tidal information; wind, wave and current data; data on the seabed and soil conditions. The costs associated with obtaining such data offshore are often very high.

Design regulations

The regulatory framework, the authorities involved, and the applicable design and construction standards and guidelines for offshore platforms, which tend to vary from country to country and from client to client, are all completely different from those for an onshore building.

Design actions

Design actions derive from two generically different types of conditions: the in-place conditions when installed and the conditions during various stages of construction.

- The self-weight of the structure and the functional loads (weight of facilities, supplies, people, the operation of equipment, etc.) are components of in-place actions that are common to onshore and offshore design load cases, although the ratio of the functional loads to self-weight is generally much greater for offshore structures than for buildings on land. However, the major difference is in the enormous environmental actions due to waves and currents to which offshore structures are exposed. This leads to three very important differences:

(i) Offshore structures have to accommodate much larger *horizontal* actions than onshore buildings; the ratio of horizontal to vertical actions is a significant factor in offshore design.

(ii) The hydrodynamic actions vary continuously with time. As a result of this, the ratio of time-varying (dynamic) to constant (static) actions is offshore usually much greater than onshore. This is again a significant factor for offshore design and brings with it a need to check for potential fatigue damage due to the accumulated effect of stress variations over the entire service life.

(iii) The hydrodynamic actions offshore vary randomly and are not so simple to describe, quantify and incorporate into design procedures. While random actions are not unique to offshore structures, their magnitude and number of cycles involved are truly unusual. The need to include random variations of actions in design situations by means of realistic models is more of an exception onshore, but virtually the rule offshore.

– The load cases during construction will invariably tend to be case specific, but they are generally less important for buildings on land than for offshore structures. This is due to the radically different way of onshore fabrication, offshore transportation and installation; see below under *method of construction*. For offshore structures the designer should try and apply his skills in such a manner that the temporary stages during construction do not control dimensioning of the structure over the unavoidable in-place design conditions. This would represent a waste of material and money that the structure has to carry along during its entire service life.

Foundation

There are several differences between the foundation of a building on land and the foundation of a bottom supported offshore structure. The differences start already with the soil investigation to obtain the necessary soil data to enable foundation design to proceed:

– Soil investigations offshore must be performed under water, often from a floating vessel that moves considerably due to waves, which makes the deployment of equipment, the taking of cores and doing *in situ* measurements much more difficult and possibly inaccurate.

– Preparation of the ground and soil improvement measures can have a very beneficial effect on foundations. These measures are rather common on land, but can rarely economically be applied offshore.

– An offshore pile foundation must be installed ‘from a distance’. Piles have traditionally been driven by steam hammers from above water using loose extensions, the so-called followers, to extend the pile after it disappeared under water. The modern hydraulic underwater hammers can follow the pile on their way down through the water and have obviated the need for followers. However, the whole operation remains to be performed and controlled from above water with the aid of remotely controlled vehicles (ROVs) or divers to monitor the process.

- In view of the differences in structural configuration and the high cost of installation, offshore pile foundations use fewer and larger diameter piles than onshore. Furthermore, offshore piles are as a rule open ended hollow steel piles. For onshore piles there is usually a range of options, where in many cases solid concrete piles are the preferred and most economical choice.
- Due to the large overturning moments resulting from the large lateral actions on the structure, offshore foundation piles are often also subjected to substantial tension forces. In several cases these tension forces are of a similar order of magnitude as the compression forces and can even govern foundation design. For buildings on land tension piles are unusual, although they do find application for other civil engineering structures such as retaining walls, harbour quays and tunnels.
- It is standard practice on land to apply test loads to piles to investigate or demonstrate their capacity. For a variety of reasons this cannot be done offshore; these reasons include that the offshore pile capacities are usually much larger than on land, and that offshore piles are in some cases installed under an angle rather than vertical. Inclined piles used to be the norm in former days, but at present there are probably more vertical piles than inclined piles installed.
- On good sandy soils, an onshore building may be founded on a base slab directly on the ground without piles. This is a shallow bearing foundation along the same principle as for an offshore gravity base structure. However, the size and weight of an offshore gravity base structure and its associated foundation are unparalleled onshore.
- The actions on offshore foundations vary continuously with time, making foundation behaviour under cyclic loading an important subject of consideration. Onshore this hardly plays a role.
- The seabed around and under an offshore structure is subject to morphological phenomena due to flowing water, such as scour, erosion and moving sand ripples. Similar phenomena do occur in hydraulic structures, such as sluices and locks, but not with buildings on land.
- Due to the extraction of oil or gas from the reservoir the pressure distribution in the ground can change and the reservoir rock may compact. As a result of this the sea floor with the entire structure and its foundation may sink relative to the water surface, thus increasing the local water depth. This phenomenon needs to be accounted for in design; the amount of sea floor lowering depends on soil consolidation and compaction of the reservoir rock. Consolidation and compaction caused by extraction can of course also occur on land, and can potentially lead to light earthquakes. However, onshore these phenomena do normally not lead to increased environmental actions or even loss of function, as may be the case with offshore structures.

- More than for structures on land, foundation conditions can have a decisive influence on the structural concept that is selected and the associated design of an offshore structure.
- Last but certainly not least, the sequence of installation is radically different. For buildings on land, the foundation is invariably installed first after which the building is built on top of it. For bottom founded offshore structures this is always the other way round: the structure is positioned at its definitive location and only thereafter the foundation piles are installed, whereby the structure acts as guide frame for the piles during their installation!

Method of construction
As for the foundation, there are several characteristic and important differences between the method of construction of a building on land and an offshore structure:

- A building is constructed on site, whereas an offshore structure is wholly or largely prefabricated on land in a fabrication yard. Topsides fabrication is also preferably completed onshore, including all the fitting out, testing and (pre-)commissioning of the facilities. Generally speaking, fewer units to be taken offshore is cost-effective but it requires the availability of adequate lifting capacity
- During prefabrication on land an offshore structure lies usually on its side, in a different orientation than during its service life. Hence, it is in this situation subjected to a completely different load case that needs careful assessment.
- Load out from the fabrication yard onto a transportation barge provides another special load case for an offshore structure, with no comparable case for a building on land.
- An offshore structure is in its entirety, or in a small number of large parts, transported across open seas and often over large distances, to the offshore location. This is unique with no parallel on land. During the tow the structure may be subjected to substantial barge movements with the associated mass inertial forces, which can provide a governing load case for certain parts of the structure.
- At location the structure is offloaded from the transportation barge, either by launching or by lifting. These operations are also unknown on land; both impose severe loading on the structure and require special load cases to be checked during design.
- Installation of the structure at the offshore location requires heavy and expensive marine equipment in respect of crane capacity, powerful pile driving hammers, etc. This equipment with its associated auxiliary craft is usually floating, which means that they do not always provide a firm platform to work from. Consequently, the ability to operate this equipment and the efficiency of its operation is weather dependent. In the interest of both safety and costs, all offshore construction work should therefore be designed to be as simple and take as little time as possible. This also requires appropriate consideration of contingency measures to cope with unexpected changes in procedure or with damage to the structure (e.g. unforeseen flooding of a compartment) or to the installation equipment (e.g. breakdown of a tug).

– Transportation, offloading and installation are unique for offshore structures. It is essential that the associated procedures for these operations are carefully planned, optimized and step by step described in appropriate manuals.

Construction environment
All construction activities at a construction site present potential safety hazards. However, the offshore environment is openly hostile and dangerous to humans. It is therefore absolutely necessary to take extensive precautions. Furthermore, offshore logistics are also difficult, time consuming and costly.

Offshore operations and management in situ
Finally, effective inspection and monitoring of the condition of an offshore structure during its service life, as well as its maintenance and repair when required, are difficult and expensive. This is yet another important difference with buildings on land. Minimum maintenance is thus an important design factor for an offshore structure.

Summary of structural differences
From a purely structural point of view, the three major differences between design and construction of an offshore structure and a building on land are the design actions, the foundation, and the method and sequence of construction and installation.

2.3 Conceptual design

2.3.1 Introduction

With few exceptions offshore structures are designed and built for the oil and gas industry. The overwhelming majority of them are fixed steel space frame structures. This type of structure is also the focus of this Part 2 of the Handbook. These structures are anchored to the seabed by steel piles and are designed to carry topsides consisting of one or several decks with equipment and facilities that are needed to perform their intended function(s). The topsides facilities can comprise, for example, a drilling rig, oil and gas production equipment, power supply, living quarters, export pumps, etc. Topsides are nowadays often designed as an integrated deck for single lift installation.

Fixed steel structures are generally referred to as jackets, but this is often not strictly correct. A ‘jacket’ is in fact a particular type of fixed steel structure where the foundation piles are connected to the space frame above water. If the foundation piles are connected to the space frame at the base, just above the sea floor, the fixed steel structure is actually a ‘tower’; see section 2.4.3 for a full description.

Design configurations and design techniques of steel structures have evolved significantly since the first conception of a very simple prefabricated template to assist pile installation in the Gulf of Mexico in the late 1940s/early 1950s. The increase in knowledge and the rapid development of computing power and appropriate analysis software have enormously enhanced the industry's design capability. Technological developments in fabrication, materials, welding, transportation and installation have simultaneously advanced the capabilities of the industry greatly.

Before embarking on the design of a fixed steel structure it is very useful to be aware of the historical developments of this type of structure and their foundations, as well as of the general developments in the oil and gas industry over the years. The book '50 Years Offshore' [2.3-1], published in 1997 on the occasion of the 50th anniversary of the beginning of the offshore era, includes brief descriptions and overviews of the development of steel space frame structures and foundations, which provide concise general introductions. Therefore the two texts are attached to this chapter as Annex 2.A – 'Jacket platforms' and Annex 2.B – 'Foundations'. Please note that they are included as they were written and published at the time; their contents have not been updated and terminologies have not been adjusted to conform to current usage in line with the ISO 19900 series of offshore structures standards. Part 1 of the Handbook [1.1-1] provides further useful background information with sections on 'A brief history of offshore oil and gas developments with the characteristics of four periods' (see Part 1, section 1.2); the 'Interactions of offshore engineering with other engineering fields' (see Part 1, section 1.3) and 'Offshore structures standards' (see Part 1, Chapter 2). Readers are encouraged to familiarize themselves with this material.

2.3.2 General considerations for the design of bottom founded structures

The design of an offshore platform is governed by:

- the user or functional requirements;
- the operating requirements;
- the environmental conditions and conditions of the seabed at the intended site;
- the method of construction (including onshore fabrication, transportation to the site, and offshore installation);
- the planned management of the platform during its service life (with aspects as monitoring, inspection, maintenance and repair).

Functional, operational and user requirements are generally provided by or established in consultation with the client for whom the structure is designed. The other items are more within the domain of the designer, assisted by and in cooperation with several other parties. Provisions for the last item to be included in the design should be specified by the operator of the platform; some information on these aspects is given in Chapter 9.

General consideration also needs to be given to *platform decommissioning* at the end of a structure's useful life, but this will rarely translate into specific design requirements although it should be demonstrated that platform decommissioning is realistically possible. Considerations of decommissioning and removal relate more generally to factors that should be kept in mind and may lead to a preference for choosing between different concepts or options, rather than that the considerations impact directly on the design of the platform. Chapter 10 gives information about regulations and practices for decommissioning. Last but not least, safety is of paramount importance. Safety is an all-embracing concept that needs to be incorporated from the very start into each and every aspect of design, construction and operation. Section 1.4.3 of Part 1 of the Handbook [1.1-1] provides an introductory discussion on safety issues; see also below for some further notes on safety.

Broadly speaking, the initial stages in the design of a fixed steel structure comprise the following 6 steps:

1. collect meteorological and oceanographic (metocean) data on wind, waves and currents, as well as information on the conditions of the sea floor (such as flatness, slope, boulders or other obstructions), and data on seabed soil conditions;
2. with due consideration to this information, determine the structure's configuration and preliminary overall dimensions based on
   - size and weight of the topsides to be carried; these parameters are given by the user or derived from the functional requirements;
   - water depth;
3. using the configuration and overall dimensions, choose bay heights and brace patterns, and determine preliminary sizes of the space frame members; these can be based on examples of similar structures where available, on general experience or on pure (gu)estimates;
   in doing so the designer should give due consideration, wherever possible, to design details to be added later such as lift points for lift operations in the fabrication yard or offshore;
4. determine preliminary vertical design actions due to permanent and variable actions during operational and survival design situations;
5. using the overall dimensions and preliminary member sizes, determine preliminary horizontal design actions caused by wind, waves and currents;
6. combining all this information, make a preliminary estimate of the number and size of the foundation piles, giving due consideration to their disposition and whether they are intended to be leg piles or skirt piles with the associated pile sleeves.

These steps are further described in a general manner in this section 2.3, with further details given in the next section 2.4 on the preliminary design of the support structure.

As regards the first step, adequate information about a structure's environment is crucially important but can be difficult to obtain. The type of data required and how these are used is described in Chapter 5 in Part 1 [1.1-1]: "The offshore environment and environmental actions". The opening paragraph of this chapter describes the problem well and is quoted below:

> “Knowledge and understanding of the offshore environment are extremely important for offshore structures. Requirements relating to the environment cover a wide range; they include assessing which environmental conditions are relevant for a certain application, determining how to adequately describe these conditions, ascertaining which parameters are needed to define them numerically, and establishing how the quantified conditions shall be used for the design, construction, operation and removal of offshore structures.”

Thereafter, section 5.1 of Part 1 describes general aspects and observations of the seabed, the atmosphere and the ocean, which is followed by a presentation of wind, current and wave models with the associated data in sections 5.2 to 5.6; finally, environmental actions on a structure are discussed in sections 5.7 to 5.9.

By proceeding through steps 2 to 6 a conceptual design gradually takes shape, often iteratively. In the current section 2.3.2 we present some general information and considerations for the design process, with particular attention to interactions of the topsides and the foundation with the support structure. Relevant aspects of the design of the topsides and the foundation are further discussed in sections 2.3.3 and 2.3.4, respectively. Bay heights, brace patterns and member sizes relate to geometrical and structural aspects of the preliminary design of the support structure; these are addressed at a general level in section 2.4. During the design of an offshore installation there are many interfaces between the various engineering disciplines involved that can easily become sources of design errors. The section ends with a cautionary note on interface problems. Before continuing we will add some further notes on safety aspects.

Safety

Safety considerations encompass all systems from the reservoir, via the drilling and production facilities, any oil or gas that may be imported to the platform, to the export by pipeline or by offshore loading and export by shuttle tankers. Also, supply of materials and goods, and transportation of personnel must be included in safety considerations. To satisfy overall safety requirements it can be necessary that an entire platform and/or parts of the platform can be isolated by valves in pipework, risers or (subsea) pipelines.

Due to the absence of appropriate safety barriers, an initial incident on the Piper Alpha platform in 1988 could not be adequately isolated and escalated into the Piper Alpha disaster. After the disaster a new safety regime was instituted in the offshore industry (see section 2.3 in Part 1 [1.1-1]). Safety hazards should be systematically identified by hazard identification (HAZID) studies, assessed and reduced, or even better eliminated, by techniques such as hazard and operability (HAZOP) studies. It is nowadays standard practice that for each installation a so-called safety case is prepared, which reviews all safety aspects, documents the precautions made, and describes the measures to be taken in case an incident occurs.

The topsides are usually the most vulnerable part of a platform in respect of safety. The operations performed from the topsides are hazardous and the topsides often contain a chemical plant where several potentially dangerous activities can go on at the same time. The very beginning of safety is therefore a simple and logical layout of the various processes and associated equipment. In shallow water depths safety is often pursued by means of separate platforms for different functions. Together the platforms then form a platform complex, where the platforms are often interconnected by bridges. When all functions are combined on one platform, physical separation between areas where the various processes take place is a desirable and effective contributor to the improvement of safety. For example, where possible we should segregate hazardous and non-hazardous areas by arranging for a separate drilling area; a production area (with separators, pumps, treatment facilities); a gas compression area; a utilities area (with power generation, drinking water) and accommodation for personnel on board. Such a layout allows separation of hazardous from non-hazardous areas. Where necessary fire resistant walls and blast walls should provide protection against the spreading of fire and explosions if they occur, but prevention is always more effective and should be the first priority. If notwithstanding all precautions an incident occurs, containment and control is the next critical safeguard. If after all, and despite all measures taken, an incident escalates, evacuation of the platform can become necessary. Escape routes should be straight, sufficiently wide, unobstructed, clearly marked, clearly lit by emergency lighting and lead to one or more muster stations from where the platform can be abandoned within a predetermined time (commonly 30 minutes) by (free fall) life boats, helicopter or other means.

Interactions between the topsides and the support structure
The height of the topsides above water has a direct impact on the height of the support structure. The drilling of wells and positioning of well conductors are also important factors in determining the structure's configuration.

Elevation of the topsides
Operations on the topsides should not be affected by water on deck. Furthermore, if waves in storm conditions would hit the topsides, the lateral actions on the structure would be strongly increased. Therefore the topsides must at all times be above water. Thus, the elevation of the topsides should be determined such that it is above the highest crest of the waves expected to occur at the location in the most severe sea state for which the installation is designed. The determination should take into account water level rises due to tide, storm surge and wave crests, as well as a possible lowering of the sea floor due to settlement of the foundation and subsidence resulting from compaction of the reservoir deep down in the earth. In addition to these factors one usually includes an air gap of 1.5 m as a safety margin between the underside of any structural element under the topsides and the top of any green water. The procedure is illustrated in Figure 2.3-1. The 1.5 m is fairly common practice and is a general allowance for uncertainties in the various contributions that determine the elevation of the topsides. However, this allowance is not rationally based. Instead of a fixed value, the magnitude of

the air gap should preferably be related to the magnitude and degree of uncertainty of the individual contributions and be determined in a probabilistic manner. This is a subject that is in constant development. Another pragmatic approach is to determine the elevation of the topsides with the larger value of 1.5 m air gap on top of the 100 year return period wave crest and zero air gap on top of the 10 000 year wave crest. The consequences of parts of the topsides becoming inadvertently inundated can be very serious, both with regard to damage done to the topsides structure or the installed equipment, and with regard to overloading of the support structure and/or its foundation. The topsides are usually made up of many flat surfaces (e.g. beams, module walls), as opposed to the tubular members used in support structures. Therefore, horizontal wave loads on the topsides quickly become very large, while these loads act at a very high point resulting in huge additional overturning moments.

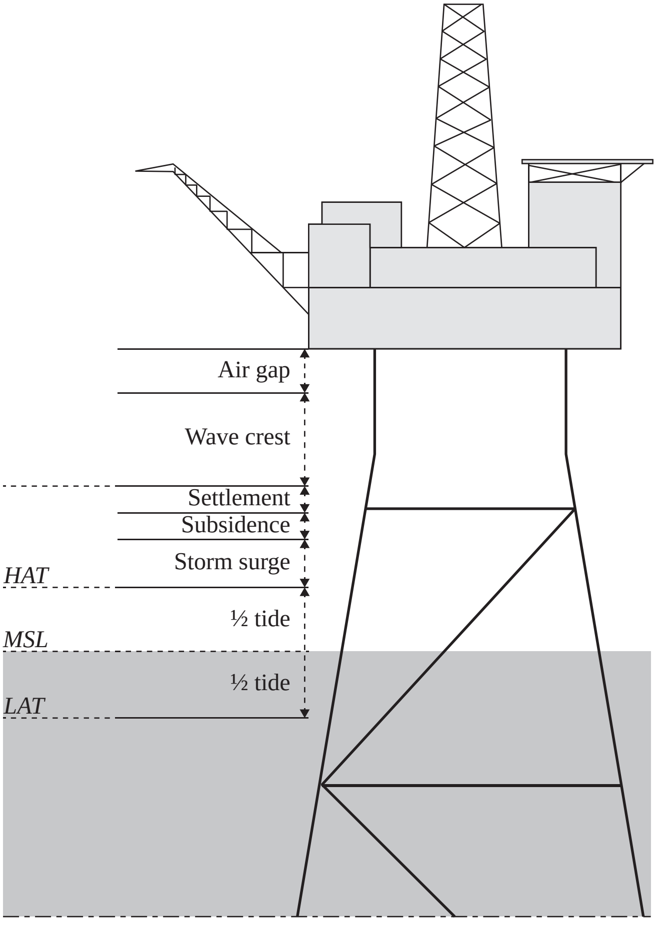


Figure 2.3-1 Determining the elevation of the topsides

Well drilling

Many platforms have a drilling function and support wells. These wells may have been drilled from the platform itself or by means of a mobile drilling unit positioned adjacent to the platform. In the first case the platform needs to be designed to carry the full weight of the drilling installation, together with any additional actions from the drilling operation. If a mobile drilling unit is used adjacent to the platform and this unit is a jack-up, the support structure will often need to have one vertical side to enable the jack-up to come close enough to reach the drilling slots on the platform. For the same reason, the deck or decks of the topsides can normally not extend beyond the vertical side of the support structure. Another point to pay attention to is the interaction between the (usually very large) spud cans under the jack-up legs and the relatively small diameter piles supporting the fixed structure. Radial soil movements and associated forces due to the penetration of the spud cans, or the compaction of soil layers under the spud cans, can cause substantial loads on the piles. If the mobile drilling unit is a floating unit, probably a semi-submersible, this will have to be anchored by an adequate mooring system that will not interfere with the platform, nor with any equipment on the sea floor (such as pipelines, manifolds or subsea wells). Furthermore, a floating unit will experience motions due to wave action and we will need to ensure that it will never be in contact with the platform.

Conductors

Wells are drilled through a protective conduit between the drill floor on the topsides and a certain depth below the sea floor; this conduit is called the conductor or also the stove pipe. If conductors are not installed by driving, but by inserting them in a drilled oversized hole, they must be temporarily hung-off from the structure before they can be cemented in the soil, creating special loads on the structure. Once in-place the conductors are laterally supported through the water column by the structure to prevent buckling under their own weight, the weight of fluids inside it and any possible weight on top of it. Another reason for providing lateral support is to avoid vortex induced vibrations. By reducing the length of free spans the natural frequencies of conductor vibrations are increased and better separated from frequencies with which the vortices are shed that are the source of excitation. Conductors are laterally supported by guides, which are integrated in the horizontal framing of the support structure and allow free axial movements up and down (for example due to differential deformations and temperature effects).

Curved conductors

Wells are normally drilled from one central location above water and radiate outwards to a much wider circle at reservoir depth in order to be able to drain a much larger reservoir area. This is called deviated drilling. The rate of deviation is typically some 4 degrees per 100 feet (30 m). With advanced drilling techniques wells can be more strongly deviated, even up to being horizontal in the reservoir region. Usually the deviation will only start in the ground, below the depth at which the straight vertical conductors have been set. However, sometimes the deviation needs to start already above water. In this case the conductors are curved and the framing pattern is consequently different at each plan level at which the conductors are supported, considerably complicating design. These complications do not only arise from geometrical factors, but are also due to vertical loads on the frames during conductor driving caused by friction between the conductors and their guides in the horizontal frames.

Interactions between the foundation and the support structure
Fixed steel structures are almost without exception founded on piles. The advantages of piles are obvious:

- their number, diameter, wall thickness, disposition and depth of penetration into the seabed can be varied in wide ranges to suit circumstances; therefore they have an inherent flexibility for adjustment to specific requirements in each particular case;
- they are able to transmit axial as well as lateral actions to the seabed;
- piles can accommodate compressive as well as tensile axial forces.

The configuration of a space frame lends itself particularly well to being supported in a limited number of discrete points. Mechanically the piles interact strongly with the surrounding soil and with the steel structure. It is therefore very important to make a realistic first estimate of the required foundation configuration, so that the design of the structure can (literally) proceed from a sound base. Failing to do so can result in laborious and time-consuming iterations, or end up in a far from optimal design.

Piles can be installed through the legs of the structure or through guides at regular intervals over the structure's height. In the pile-through-leg type the connection between the piles and the structure is usually made at the top of the legs by inserting steel shims in the annulus between pile and leg to centralize the pile and welding the assembly of pile-shims-leg solidly together. This is the traditional method. Instead of shims at the top, some companies prefer to grout the annulus between pile and leg over the full length of the leg, thus creating a composite member of pile and leg. See Chapter 5, section 5.6.4 for a more detailed description of pile to structure connections. In any event, in these cases the structure's legs serve to guide the piles during installation through the water to the sea floor, after which they are driven into the ground using an above water hammer. The piles pass as it were through the legs as arms through the sleeves of a jacket, from which the name *jacket* for this type of steel structure was derived. An alternative name is a *template* structure, because the structure serves as a template for pile installation.

If more piles are required than the number of legs, these may be added as skirt piles, either around the perimeter of the structure, see Figure 2.3-2, or clustered around the legs as shown in Figure 2.3-3. In the latter case, the skirt piles are also known as cluster piles. Skirt piles are installed and connected to the structure by pile sleeves extending only over the bottom bay of the structure. Traditionally, the skirt piles were inclined in line with the legs (or the frame of the structure). During installation they are then guided down by pile guides at

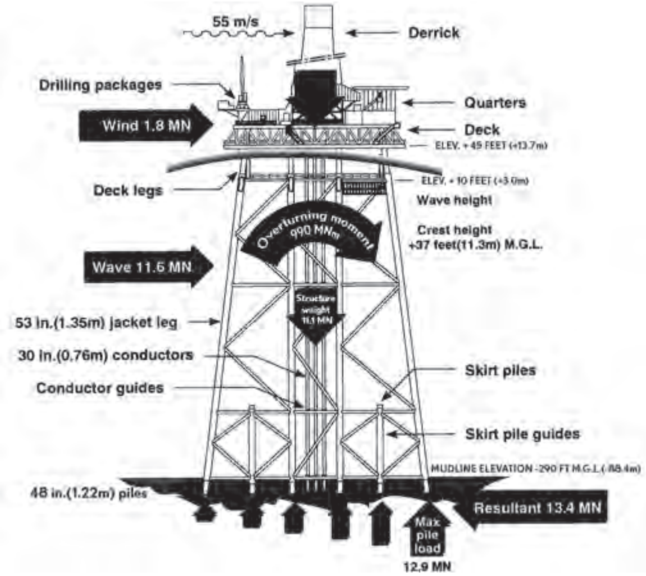


Figure 2.3-2 Example of a jacket structure with leg piles and skirt piles (for the Gulf of Mexico in 290 ft - 88.4 m - water depth)

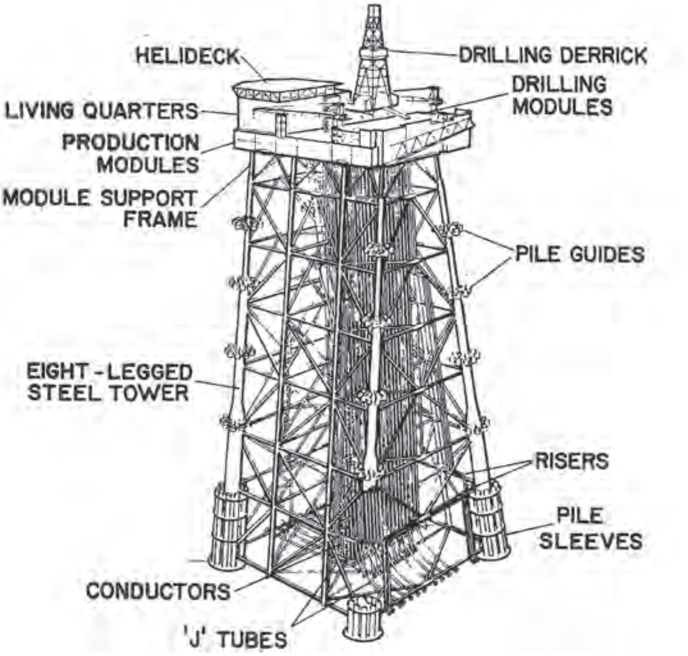


Figure 2.3-3 Example of a tower structure with skirt piles clustered around the corner legs

regular intervals along the leg as also shown in Figure 2.3-3. These pile guides serve purely as an installation aid, but being in the water they do attract additional wave actions; therefore the upper guides were often cut off after installation. With the introduction of underwater hammers skirt piles can be installed vertically, generally arranged as cluster piles around the legs; therefore nowadays inclined skirt piles are hardly applied any longer. The historical development of the foundations of bottom founded offshore structures is described in more detail in Chapter 5, section 5.5.2.

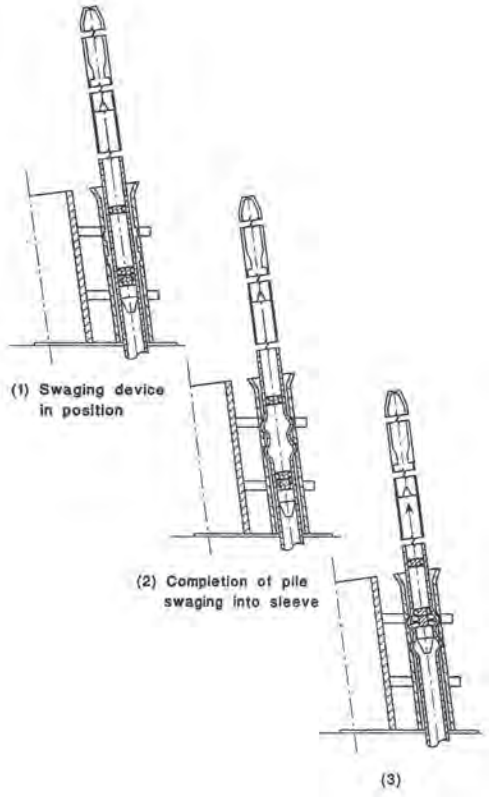
The connection between skirt piles or cluster piles and the structure is made under water, usually by grouting the annulus between the piles and the pile sleeves. An alternative to grouting is a metal-to-metal connection by a mechanical locking system; see Figure 2.3-4 [2.3-2]. The connection is made by expanding the pile wall by hydraulic pressure into machined grooves in the sleeves at two or three elevations. The technology is called swaging and these mechanical connections are known under the trade name Hydra-Lok®. Swaging can be used for relatively light structures. The connection is quick and relatively cheap. Furthermore, and in contrast with grouted connections that take time for the grout to set and the bond between pile and sleeve to develop strength, the Hydra-Lok® connection provides immediate strength. A more extensive description of pile to structure connections is given in section 5.6.4.

The type of steel structure supported by clustered skirt piles is called a *tower* structure. As a result of the different support points of the space frame, at the top for a jacket and at the base for a tower, the structural behaviour of a jacket and a tower is markedly different, as will be discussed in Chapter 3. The formal definitions of a jacket structure and a tower structure in ISO 19902 [2.3-3] are given in section 2.4.3.

General considerations about interactions between the foundation and well drilling

Wells penetrate the seabed underneath a structure to depths of usually a few thousand metres below the sea floor. They hence pass through the same soil layers on which the structure is founded. Drilling in an open hole can easily cause failure (fracturing) of the formation, due to hydraulic pressure differences arising from the weight of the mud column inside and the hydrostatic pressure outside the hole, or from a wash-out of granular material. This is one reason why drilling through the upper soil layers takes place through a protective conduit, the conductor. In case of any uncertainty the conductor is driven to a depth well below the penetration of the foundation piles, so that a drilling mishap does not affect the soil layers in or on which the structure is founded. Only when there is complete confidence that the soil conditions and the drilling process do not present any hazard to the foundation, the conductors can be set at a reduced depth above the tips of the piles. This naturally provides a cost reduction due to savings in material and installation time. In case of a gravity foundation the conductors are similarly driven to a depth beyond the depth where soil layers do still contribute to foundation capacity.

See section 2.3.4 for a further discussion of foundation topics.



(1) Swaging device in position

(2) Completion of pile swaging into sleeve

(3)

Figure 2.3-4 Illustration of Hydra-Lok system (from Ref. [2.3-2])

A note on interface problems

Design of an offshore installation is a multi-functional activity. Structural design is only one of the many different activities involved and it should be recognized that satisfying functional and operating requirements can be more important than an optimal structural design. There are numerous interfaces between structural design and design activities of other disciplines. All parties should be aware of these interfaces and co-operate in a constructive manner to resolve any problems that may arise; there are unfortunately no simple rules to guide the process or the resolution of conflicts. Typical interfaces are listed in Figure 2.3-5.

Interfaces with petroleum engineering
- platform location
- number and type of wells
- requirement for curved conductors
- number of risers and J-tubes, including their orientation
- reservoir compaction and seabed subsidence

Interfaces with metocean engineers
- water depth
- environmental conditions
- platform orientation

Interface with geotechnical engineers
- seabed topography
- soil conditions
- foundation design

Interfaces with drilling (equipment) engineers
- spacing between wells
- accessibility of wells by a platform mounted or a mobile drilling rig
- space and weight for drilling rig and associated equipment
- design and setting depth of well conductors
- allowing relative movements between wells and structure

Interfaces with process -, facilities -, mechanical equipment - and piping engineers
- lay-out of deck(s), horizontal as well as vertical
- routing of pipework, pipe supports
- expansion loops in pipework to allow relative movements or extensions e.g. due to temperature
- foundations for vessels, storage tanks, other heavy equipment
- access for inspection and maintenance
- level adjustment for sensitive equipment
- avoiding or coping with machinery vibrations, isolating vibrating machinery from the structure
- support for deck cranes
- support for and design/construction of a flare boom or flare stack

Interfaces with electrical and instrumentation engineers
- foundations for generators
- access for maintenance and repair
- routing of electrical cabling and support of cable trays
- positioning and fixing of light fixtures
- positioning and fixing of instrument panels, together with accessibility in case of breakdown

Interfaces with pipeline engineers
- riser supports to structure and deck(s) (N.B. the riser itself is a pressure conduit and its design belongs to the pipeline discipline)
- J-tubes for riser pull-in
- expansion loops on deck and/or at the base of the structure
- pigging facilities on board

Interfaces with safety engineers
- fire, smoke and gas detection
- fire fighting systems (pumps, ring main, deluge, sprinklers)
- explosion protection (pressure relief, blast walls)
- escape routes
- life saving equipment (rafts, life boats, etc.)
- safety during (onshore) fabrication and (offshore) installation

Interfaces with materials and corrosion engineers
- determining type and quality of materials for structural design
- welding procedures and weld testing
- (cathodic) corrosion protection below water
- corrosion protection by painting above water

Interfaces with drilling/production operations
- platform orientation
- boat bumpers, boat landings, supply boat moorings
- loading and unloading facilities (platform cranes, etc.)
- helicopter landing areas
- access platforms, stairs, ladders
- structural inspection and maintenance above and below water

Figure 2.3-5 Typical interfaces between a structural designer and other disciplines