1 Marine operations.

Marine operations have been conducted through the whole history of man. Fishing expeditions, as well as hunting of whales and other sea mammals, are early examples of challenging operations,- often in hostile environments. Transportation of different cargo’s along the seaways has also been conducted with great skills and under demanding conditions. Other examples includes naval warfare, pirate activities and other destructive actions.
Both vessel designs, marine equipment and human skills have improved substantially over the years. This have been achieved without much knowledge of mathematics and dynamic systems. Instead, improvements have been made by the “trial and error”- method. The price has been high, the ocean is no doubt the greatest churchyard on this planet.

Today mathematical analysis and other systematic planning of the marine operations have reduced the price substantially, regardless if you count the price in human lives or in dollars. The purpose of this document is to give the reader an idea of how this is possible. The focus is on operations related to oil field developments. Never the less, the knowledge will be relevant to other types of existing and future marine operations.

1.1 The players in an offshore development.

The activities and organizations involved in an offshore field development may be divided in three levels, illustrated in figure (1).

The fundamental level consists of the oil and the oil company. The companies ultimate goal is to bring the oil to shore and to sell it. To achieve this they need a number of platforms, subsea modules, oil pipes and other items installed offshore.

The next level is the contractors providing this items. Typical scope of work is the engineering (E), procurement (P), construction (C) and installation (I). Some oil companies prefer to place a single contract covering the whole scope, this is denoted a ”EPCI contract”. Different parts of the scope are then often subcontracted.

An successful oil field installation is crucial for the oil companies overall economy. Substantial budget overruns occurs easily and frequently. A delay of, say, a year, may cost much more and be far more critical. Due to this the oil companies normally involve them self heavily into contractors work during all phases of the project. This is why they often prefer to split the main EPCI contract. In the figure (1) two main contracts are indicated, covering the production of a certain oil field component(EPC) and the tow-out and installation (T&I).

The oil company now have to take the responsibility of the interface between the contractors. This is a lot of work, and require highly skilled personnel, but it certainly adds to the degree of control the oil company seeks.

The upper level of the figure represents different requirements that all parties have to obey, and the organizations behind them. Typically there are some requirements origination from the authorities, and some rules requested
by insurance companies. In addition, there are some fundamental laws of
nature and economics that need to be considered.

The national requirements to the offshore industry varies a lot from coun-
try to country. In some part of the world the requirements are weak, and the
oil companies have their own internal ”rules” that are more demanding, and
more in line with, say, Norwegian rules. For activities in Norwegian waters
the NORSOK requirements gives a good summary. NORSOK is written for
engineers, and in our eyes it contains ”what matters”.

It should be noted that the installation part is covered with less firm
requirements in the NORSOK rules. For the installation the rules from war-
renty surveyor and the oil companies them self are normally more demanding.

The oil companies uses warranty surveyors to convince the insurance
companies that the planned marine operations are safe and well prepared.
Companies acting as warranty surveyors (WS) should be as independent as
possible. Ideally, they should be some kind of foundation. Larger WS have
comprehensive sets of rules and regulations, smaller ones will normally follow
the rules from one of the larger ones.

In addition to convincing the insurance company, the WS will assist the
companies when the quality of contractors work are examined. The role as
WS includes extensive quality check of reports and drawings, and various
types of formal and informal meetings / discussions with contractor.

Normally, alternative, paralell analysis and engineering work is not per-
formed by the WS. If this is requiried it will be performed by an engineering
consultancy company. IThis role is denoted 3. party verification. It is im-
portant that there is no comerical link or competition between the 3. party
and the contractor.

1.2 Project phases for an installation contractor.

A typical offshore project runs through distinct phases, with milestone de-
deliveries at each step. It is crucially important that all project participant
deliver in time, since time is short and people in other disciplines are waiting
for your result. To be a good project participant you need to:

• Strive to understand the information you receive from other disciplines

• Minimize your work scope to a necessary minimum

• Perform your work effective and accurately

• Strive to ensure that your results are fully understood by those who
need them
Figure 1: Marine operations: bird perspective
The phases of a typical installation project is described in the subsections below:

1.2.1 Start-up phase

The first thing to do when a contract is landed is to set up an organization with qualified key personnel. The first thing these people need to do is to fully understand the job and to make an overall plan. Important constraints is given in the contractors offer to the client and in the contract. Hence, a cooperation with the tendering personnel is useful.

It is important to determine all required deliverables, regarding drawings, analyses, installation manuals, technical requisitions for purchasing equipments etc. Further, it is important to establish which activities that need input from each other.

The lines of activities that are most time consuming need to be given special attention, these are denoted ”critical line”. Typically, some marine equipments may have extremely long delivery time, hence analysis leading to a specification of such equipment need to be finalized very early.

Typical output from this first phase is a ”master document and drawing register”, ”MDDR”, defining milestone deliverables for different phases of the project. Further, the total manning of the project is established and a proper familiarization is conducted.

1.2.2 Engineering execution phase

This phase is normally the longest part of the project. In this phase it is important that all project member stick to the plan, and deliver on time. Normally, adjustment to the planned installation method should be avoided if possible: a ”smart” idea may easily have unforeseen consequences for other aspects of the operations. Pioneering within method development should be made in studies, not during final design.

Time is short. If some activities need to be postponed due to delayed input it may be a very good idea to finalize other part of the project scope.

1.2.3 Mobilization

At a certain date close to the marine operation the project takes the economical responsibility for the day-hire of the offshore vessel. The project will then ensure that the offshore crew are collected inboard, and certainly also the marine equipment and tools. Familiarization of all personnel is important: everyone should have an idea of what will happen, and it must
be ensured that everyone understand their own tasks properly. The use of simple sketches and 3-D animation is recommended.

Finally, the object to be installed must be transferred to a "transportation mode".

1.2.4 Marine operations

The marine operation consist of transportation and installation of the object. Detailed step-by-step procedures are needed. Ad hoc adjustments to the plans should be avoided, since unforeseen consequences may easily occur. After all, changes in the method will never be covered by engineers to the same extent as the original method.

1.2.5 De-mobilization

After installation the vessel goes to shore, and all marine equipment that are not permanent need to be taken off the boat. The offshore crew are then demobilized.

Normally the demobilization contains few technical challenges. Everyone have the feeling that "the job is done", and they want to go home. This may lead to sloppiness, and there are unnecessarily many dangerous episodes in this phase.

1.2.6 Clean-up

In order to continuously improve the marine contractor need to learn from every projects. This means that this last phase in many ways are the most important one. Experience of all kinds need to be properly documented, "as installed" documentation need to be produced, analysis models need to be stored in a logical manner etc. it may be difficult to find motivated personnel for all this tidy work, especially when new exciting projects are waiting. But make now mistakes: experience that are not documented in a systematic manner are of no value. Wait six months, and people will disagree upon what the learned. The worst ink is better than the best memory.

1.3 Why analyses and engineering.

As an applied mathematician your typical challenges in a project will be to perform analyses and other engineering to ensure safe and efficient operations. There may be a general attitude among some project participants that the analyses and engineering are a waste of time. Their argument may be we have done this before. Normally, this is not necessarily a valid point,-
most operations contains new elements. It will be your job to ensure that proper analyses are performed. Some important tasks are discussed in the following.

1.3.1 Sufficient clearance and accessibility

Surprisingly often marine operations are postponed or come into other types of trouble due to ”geometrical mismatch”. Examples are shackles that should fit into chain links, sufficient deck space to store modules that will be transported, sufficient space to remove sea fastening and lift the object out, clearance when vessels enter in between two platforms etc. The clearances should allow for motions induced by waves and other environmental forces, operational induced motions, production tolerances etc.

In many cases some kind of guiding need to be designed, so that if the installed object is inserted inside the guide openings and forced to intrude further it is guided into correct position. Typically, the guide is wide at the opening and become more and more narrow. An example is illustrated in figure (3)

Notice that the access and clearance for safe and efficient manual work
need to be considered. This include access for various tools and machines that are to be used. The safety and health of the deck crew should also be considered. Sufficient barriers versus wire ruptures, avoid working under hanging load and avoid working for hours with curved back are some examples.

1.3.2 Sufficient structural capacity

When objects are installed it will be forces in lifting wires, guides, toward ship deck, internally in installed object etc. These forces are induced by static weight and buoyancy, environment and operational actions. One of the main purposes with marine analyses is to establish these loads and verify sufficient structural capacity.

1.3.3 Sufficient stability and capacity

Most marine installation are spectacular operations including a certain amount of novelty. This means that unexpected instability mechanisms may occur. Even when the equipment are able to do the job in principle, the maximum capacity may be to low: total bollard pull from the towing vessels are to small
compared to the wind, total buoyancy from the barge to small compared to the cargo etc. All this need to be verified with analyses

1.3.4 Determine maximum environmental conditions for the operations

The maybe most common task for an analysis engineer is to quantify the effect of waves and other environmental impacts on the marine operation. This is used to establish the environmental criteria for operation start-up.

If you perform wrong calculations, and establish too low design waves, there will be huge extra costs due to waiting on weather. If your design waves are too high it may cost lives.

The elements of the marine operation (vessels, cranes, wires, fenders etc) are defined. Key parameters are established. These key parameters will define tings like (examples)

- Structural capacity of an object
- Forces being transferred to the object at a given wind speed
• Buoyancy of an object for a given submergence
• Roll angles for a vessel for a given incident wave system

All this elements are put together in a mathematical model, either based on hand calculations or (more normal) a numerical model. The model is exposed for a user defined environmental condition. Typically, the user will try to increase wave heights etc until critical responses from the model occurs. This will define the design environmental condition.

Alternatively, the iteration will consist of modifying the system (i.e. increasing wire diameters, selecting larger vessels etc) until the marine operation is able to withstand the desired design environmental condition.

According to requirements from various regulatory bodies the actual marine operation shall not be performed if the forecasted weather is higher than a certain operational environmental condition. The operational conditions typically equals the design condition times a certain reduction factor, denoted ”alpha”. The alpha- factor compensate for uncertainties in the weather forecast, i.e. the weather is coming up faster during the marine operation than expected. It will also cover up for uncertainties in defining the actual environmental condition. Typically: how large are the waves we are seeing out of the window? Due to this the alpha- factor depends of the duration of the marine operation and the equipments and means available for accurate determination of weather and weather forecast. The alpha- factor is not intended to cover up for any other uncertainties, and does not replace any other safety factors. Some people may claim this, but they are wrong.

1.3.5 The walk- through

There are another positive effect of analyses in an offshore project that should not be underestimated: analysis models have a clear tendency to reveal problems that anyone can see in retrospect. After all the analyses may provide a mental walk- through of the whole method. Hence, even ”overly accurate” models may add an extra layer of safety to the operations.

1.4 Ethical squeeze

An offshore project will normally contain a series of ethical challenges. Some examples are listed below

• You discover an error in your calculations. It is probably not important, but you are not sure. Rerunning your analyses to find out will take a lot of time. The offshore mobilization starts tomorrow, hence any delay will have an substantial cost impact.
• It’s your first day in the project. Your engineering manager tells you which part of the marine operations that need to be verified by analyses, and the available man hours for this job. In your opinion more analyses need to be performed. Further, the number of man hour is not sufficient to ensure quality even for the limited scope. A possible solution is to use more resources (people / money).

• The contractor have won a job because they can promise the oil company that they will use a certain vessel ”A” which is very well suited for the job. In the early project phase the contractor finds out that the vessel need to be replaced with a simpler vessel, ”B”. If the client finds out, the contract may be canceled. If this matter comes up imedeatedly before the marine operations the company will accept vessel B. The contractor have good experience with using vessel B. Should they inform the client? (Yes, this is how things works!) The contractor have good experience with using vessel B. Should they inform the client?

• During an offshore campaign there is a breakdown in the main crane. The alternatives is to utilize the smaller stern crane or to go to shore for repair. The cost of the last alternative is tremendous,- your company is in financial trouble, this may the the final nail in the coffin. The experienced saileros says that the smaller crane will do the job.

As engineering support onboard you are told to perform lift analyses to verify the operations. The client representative says that your results will be crucial for his decision, and hence for the whole operations. In your opinion the time is way to short for a proper lifting analysis. Some simple calculations looks promising. You would never have accepted this as a proper lift analysis if you had more time.

All examples are real cases.

2 Hand calculation models.

Hand calculations are used frequently in marine industry. The purpose may be to establish final design values or perform final verifications. More frequently, the purpose is:

• To provide input to more complex numerical analyses.
Figure 5: Ethical squeeze. Who are you?
• To provide quick estimates in an early project phase.
• To clarify if a complex numerical models gives reasonable results
• To gain increased physical insight in the involved phenomena

Local structural analyses are often performed using hand calculations, even in final design. Standard text book and recommendations from regulatory bodies contain procedures for checking structural capacity of beams, wire slings, bolts and nuts, welding etc. For more complex structures a numerical method called the finite element method (FEM) is used.

Although structural analysis are a vital part of the engineering we will not go deeper into these methods. Instead, we will focus on some other examples:

• Formulas used for establishing the shape of free hanging chain
• Simple calculation of viscous towing force at constant speed
• Simple calculation of hydrodynamic forces for cases including acceleration

In several exercises given at the end of this document we are combining the calculated hydrodynamic force with point mass dynamics to achieve simple mathematical models of marine operations.

2.1 Catenary

The catenary is the curve that an idealized hanging chain or cable assumes when supported at its ends and acted on only by its own weight. The curve is the graph of the hyperbolic cosine function, and has a U-like shape, superficially similar in appearance to a parabola (though mathematically quite different). The word catenary is derived from the Latin word catena, which means ”chain”. Investigation of the catenary and determination of the shape of this curve is among the classic problems in mathematics.

Catenary curves occurs frequently within the offshore industry. Typically, this phenomenon occurs when flexible elements are supported at a floater and are hanging in a half U- shape to a touch-down point at the sea floor. This configuration is illustrated in figure (6). The key parameters are defined properly in section 7. Here catenary formulas relating them to each other are provided.

Mooring lines for offshore vessels are often forming catenary shapes,- so called catenary mooring. This type of mooring will lead to a soft positioning system keeping the vessel in position, but still not arresting the wave induced
motions of the vessel. To achieve this a relatively heavy mooring line is needed. Huge chains are often used.

Another typical offshore application is the shape of electric cables and similar objects being laid down and installed along a route on the sea floor.

2.2 Viscous drag

We now turn our attention to one of the classic problems in fluid mechanics: a body with arbitrary shape is towed with constant speed $V$ through the water: which force is required. It is evident that for a given body and a given fluid type, the force will be a unique function if the towing speed. This is illustrated in the next slide. There are two mechanisms that may generate a towing resistance: the pressure drop between the windward and the lee side, and the shear tensions (skin friction) along planes nearly parallel to the towing direction. The first type will occur at moderate and high speed, since an unorganized flow pattern with reduced pressure is generated in the wake. For a surface piercing body the generation of waves will contribute to the total pressure drop. The relationship between the towing force and the velocity is normally written as
\[ F = -\frac{1}{2} \rho S C_D V |V| \]

where \( \rho \) is the sea water density, \( S \) is a reference area and \( C_D \) is a dimensionless drag coefficient. Normally, \( S \) is selected as the frontal area of the object, then \( C_D \) normally will be of order 1.

\( C_D \) is normally a function of flow properties, for instance the Reynolds number \( R_e = \frac{V L}{\nu} \), where \( L \) is a length scale of the object and \( \nu \) is the kinematic viscosity coefficient. In many cases a constant value for \( C_D \) may be appropriate. The actual value may be found in tables provided in standard textbook, by the DNV etc.

Alternatively, \( C_D \) may be calculated using numerical method. Many pitfalls are present for the last strategy. Grid refinement tests and parameter sensitivity tests are highly recommended.

For complex geometries consisting of several shapes with known coefficient a block building strategy with simple summation is tempting. Notice, however, that interaction effect like shielding may need to be considered. Semi- empirical formulas for this may be found in the literature, covering at least some types of interaction.

### 2.3 Added mass

We will no considered the towed object for a body starting from rest, with acceleration \( a \). In the first stages of the process the velocity is small, and the viscous effects may be neglected.

If the object contains pockets with trapped water, like for instance a bucket will do, there will be a distinct volume of fluid having the same acceleration \( a \). The forces needed to accelerate this water is then \( M_b a \), where \( M_b \) is the mass of the trapped water. This force has occurred as a contact force between the object and the fluid. According to the third law of Newton, we then conclude that the hydrodynamic resistance for the object contains a term \( M_b a \).

In addition to this trapped water there will be accelerated volumes of water surrounding the object. Different small portion of fluid will have their individual acceleration, forming an acceleration field. The sum of small masses times individual accelerations may be replaced by a term ”a factor times \( a \)”. The proportionality factor has dimension mass and is normally denoted ”added masss” or \( M_a \). Hence the force needed to accelerate the water may be written \( M_a a \).
We conclude that for vanishing velocities the hydrodynamic force may be written \( F = M_a a \). If relevant, \( M_b \) is included in \( M_a \).

The value for \( M_a \) are tabulated in textbooks and publications from DNV etc. Alternatively, the value may be determined using numerical methods. Although this need to be done with care, it is a simpler procedure than determining viscous drag coefficients.

Shielding effects etc are equally important when using the block-building strategy as for viscous effects, see discussion in previous section.

It should be noted that the following formula is valid for cases where the object is accelerating, while the fluid is at rest. Alternative formulations valid for accelerated fluids exist. Details are not provided here, but it is not correct to simply replace \( a \) with fluid acceleration!

### 2.4 Morisson equation

In many cases both acceleration and velocity is important, and both theories discussed so far will fail. It is much more difficult to investigate the intermediate stage accurately, since no simple model of the wake exist. Typically, for the case with constant velocity and zero acceleration a fully developed wake will occur, and for the opposite case there will be no wake at all. In the intermediate case the object is moving in and out of its own not fully developed wake, leading to more unpredictable dynamics.

Never the less a very simple approach exist, named after the man who first developed the theory: Morisson’s law. This law simply states that the actual hydrodynamic force is a sum of the viscous force and the inertia force as developed above

\[
F = \frac{1}{2} \rho S C_D |V| + M_a a
\]

More accurate methods and laboratory tests has shown that this formula is a usable simplification for many typical offshore applications. Never the less it need to be stressed that no formal justification of the formula exists for the summation. Morissons law is not a law of nature.

Due to a desperate need for design values,- and a quick determination of them,- the offshore industry are using Morissons law extensively. The order of magnitude provided by the formula combined with several safety factors are normally leading to acceptable designs.
3 Commercially available calculation tools.

3.1 Hydrostatic stability analyses

Stability analyses of floating objects are the oldest and most important analysis type within marine industry. Complex and highly relevant analyses were performed long before computers become available. This included both analytical calculations and numerical simulations by hand.

Today, commercial hydrostatic analysis programs are available and frequently used. Typically, such programs are purpose made for free floating, ship shaped floaters. Both input and output are streamlined toward traditional vessel operations. The basic input to a hydrostatic analysis program is the total mass and center of gravity, and the shape of the wet part of the hull. The distribution of masses, i.e. radius of gyration etc, are not relevant for this type of analyses. Notice that the parts of the hull which may become wet during tilting for need to be defined. Further, hull openings that are not allowed to be submerged need to be defined.

The vessel geometry is defined through line spans, the same formats that are used by the ship yards to define and document their construction process. The masses are defined through various point masses representing steel weights, cargo etc. Swift methods for defining tanks and filling them to a certain level with various constant are available. The output of the program is also Tailor made for ship designers and operators, where complex rules for stability checks given by DNV etc are implemented and tested automatically.

A more general formulation allowing for non-standard destabilizing phenomena, is normally not possible. Some examples that may be difficult are listed below:

- Forces and force-elongation characteristics introduced from contact with winch or crane wires, fenders, sea floor etc.
- Interaction between two floating objects, i.e. a vessel lifting a floating object out of the water
- Air filled compartment communicating with the open sea. Changing hydrostatic pressure at sea water opening compress / expand the air inside and leads to changes in buoyancy.

3.2 Frequency domain analyses

One of most fundamental hydrodynamic problem you may deal with is the interaction between a floating object and an incident waves. The simplest
approach to this problem is to study a single harmonic (sinusoidal) wave component and assume low amplitude wave and responses. This leads to linear equations and to harmonic responses.

Analysis programs based on this approach require the geometry of the wet part of the hull and the mass distribution. The mass may be defined by the user through a list of individual point masses with positions, or through integrated properties like radius of gyration etc. Notice that each point mass should represent relatively confined parts of the structure.

Although viscous damping is not a part of the basic formulation of this type of programs, such effect may be "taken in the back door". This may be necessary if incident waves close to the resonance period are studied. For a vessel like geometries the most relevant example is side sea with period near the eigenperiod in roll motion.

The input to the program consists of directions and wave periods required for the analyses. Since the analysis consists of stepping through and solving the problem for a set of different frequencies, the method is denoted frequency domain.

The fundamental output of this type of programs are the amplitude and phase delay of various responses. Typically, the results are displayed as a
function of incident wave periods, and denoted transfer functions or response amplitude operators (RAO). In addition, hydrodynamic vessel characteristics needed for more sophisticated calculations with other types of programs are provided.

The most well-known RAO-curves are those showing the vessel motion response for all six degrees of freedom. RAO-curves may also display responses like total wave forces, pressures at certain locations etc. The RAO curves are often postprocessed to give new responses not directly outputted by the program: the bending moment in a midship section, the vertical acceleration in the crane tip etc.

Actual seastates consists of a huge set of harmonic waves with different periods and directions. Statistical post processing methods have been developed where RAO’s and the wave spectrum is combined to give most likely axium for the response.

There are two main motives for running frequency domain analyses: a) the free floating responses discussed above may be useful by them self, and b) the program produces coefficients needed for more sophisticated analyses.

3.3 Time domain analysis

Although the basic hydrodynamic analyses as described in previous section may provide useful results in many situation, the limitations are striking:

- Nonlinear hydrodynamic features in the wave description and in the floater response analyses, can not be included. This is less critical for marine operations than for a survival analyses: a marine operation is not performed during a storm.

- Nonlinear contact characteristics between different objects can not be included. Such contacts may represent fenders, lifting wires, sea bed contact etc.

- Although viscous damping can be included, the description of these effects are poorly represented.

The traditional way to deal with the phenomena above is to perform computer simulations with time stepping. Here, the solution on current and previous time steps are used to establish solutions on next time step. Repeating this operations leads to a so called time domain simulation.

Time domain analyses may be performed in many ways, and for many reasons. We will focus on a certain class suited for simulation marine operations. Whithin this class of methods the following elements exists:
Figure 8: Time domain simulation of a marine operation.
• Environment: Incident sea state parameters, wind speed etc, user defined.

• Coefficients: Simple rules transfeering environmental actions into force, e.g. wind speed into wind force.

• Links: fenders, wires, sea floor etc, connecting different rigid bodies. Each link may have an arbitrary user defined force- elongation characteristics.

• Rigid bodies. Standard dynamic equations are solved for these bodies. The bodies receive forces from link elements attached to them, and from environmental forces through the coefficients. A vessel requires coefficients calculated by a frequency domain program, while a small buoy requires a much simpler representation.

The inclusion of a flexible element like a long steel pipe or an electric cable requires an element combining the link and the body properties. The mass need to be distributed along the element, and the axial and bending stiffness need to be defined. Normally, a fully nonlinear beam theory is required, while the hydrodynamic loads are performed according to Morisson equation.

The basic output from time domain simulations are time series for various types of responses. These series need to be post processed to achieve design values.

3.4 CFD

The time domain analyses described at previous theory slide provides a quick and efficient way of simulating marine operations. The critical factor is the use of coefficients: predefined numbers telling how large motions or forces that will occur for a given wave height, wind speed or similar. The accuracy of the method depends crucially on the accuracy and relevancy of these coefficients. In order to study this further we need an analysis model where the actual velocity fields are simulated. This is done in the CFD method, where the celebrated Navier Stokes equations are solved. CFD programs may include important features like turbulence, a free surface and simple bodies performing prescribed motion. Never the less, a full simulation of a marine operation, including interaction with freely moving bodies with complex shapes, are not jet feasible. This means that, for marine operations, the main use of CFD will be to investigate and quantify hydrodynamic and aerodynamic coefficients.
Typical input to a CFD program are the geometry occupied by the fluid, and fluid properties like viscosity and density. Turbulence occurs for many practical applications, then parameters used to select turbulence modeling need to be defined. Further, the condition along the boundary need to be given.

The basic output from such programs are time series for local values of velocity, pressure and other stress components. Integrated quantities giving the total force on a certain object, the total mass flux through certain boundary etc may easily be obtained.

4 Laying of flexible.

Flexible products ranges from huge steel pipes used for oil transportations to electric and even fiber optic cables. The two main groups are

- Pipelines. Made of steel, used for transportation of oil and gas. Further divided into rigid and flexible pipelines.

- Umbilicals and power cables. Umbilicals often contains several components, like hydraulic pipes, smaller electric cables, fiber optic cables etc. Power cables are intended for massive transfer of electric energy.

This section covers installation challenges for these product types.

4.1 Product description, rigid and flexible pipelines

Smaller diameter rigid pipelines may be installed by reeling, i.e. spooled onto a large reel onboard the installation vessel. This involves straining of the pipe material to an order of ODpipe/Dreel. As the reel diameter is limited by the size of the installation vessel, and as acceptable amount of plastic straining is limited by the material properties of the steel pipe, installation by reeling is normally limited to 12” - 16” diameter pipes. Size of the reel will also limit the length of pipe that it can carry, so if total pipeline length exceeds the capacity of the reel, it will have to be installed in two or more campaigns. Between each campaign, the installation vessel will have to return to the spoolbase (where pipe sections are welded into pipe strings) to pick up another section of the pipeline.

Larger diameter pipelines are installed without straining the steel material plastically. Pipe segments are then welded together continuously onboard the installation vessel as the pipe lay operation progresses. And in order to avoid plastic bending of the pipe during over-boarding, a large stinger or a vertical lay tower (a so-called J-lay tower) is required.
Vessels for rigid pipe lay are typically large purpose built vessels that are not particularly suited for other types of offshore operations. Consequently, the day rate for such vessels may be considerably higher than the day rate for a vessel suitable for installation of flexible pipelines. On the other hand, the cost of a flexible pipeline is generally higher than the cost of a similar size rigid pipeline. In most cases it will therefore prove to be cost effective to use flexible pipelines for shorter lines of only a few kilometers, typically within an oil or gas field, while rigid pipelines are typically used for larger pipelines used for export of oil and gas to shore.

Due to their flexible nature, flexible pipes are often preferred to rigid pipes between a floating production unit (platform) and the seabed. These so-called dynamic risers are typically connected subsea to a rigid pipeline at a riser base or manifold.

4.2 Umbilicals and power cables

While flexible pipelines normally installed between platforms and/or subsea structures, power cables and umbilicals may terminate onshore and/or at an offshore facility such as a platform or an offshore substation for a wind farm.

So-called inter-connector cables are power cables installed between two onshore facilities. Typical examples are the power cables connecting the Norwegian power grid to the Danish and Dutch power grids. These days power cables may be installed to provide offshore facilities with power from shore in order to reduce CO2 emissions from offshore gas turbines.

Umbilicals provide remote control of subsea equipment such as manifolds and subsea compressors. Depending on the field lay-out, umbilicals may be installed between the subsea equipment and a platform or between the subsea equipment and shore.

4.3 Load-out

An offshore campaign involving installation of flexible pipes, umbilicals or cables (product) is normally initiated by load-out of the product to the installation vessel at the manufacturer’s production site. The product may be stored on reels that are lifted directly onboard the vessel, or it is spooled from an onshore reel or turntable directly onto a reel, carousel or turntable onboard the installation vessel. During load-out it is important to ensure that the product is not damaged by compression or over-bending. It is therefore common to establish a catenary between the vessel and the quay-side in order to compensate for uncoordinated tensioner speeds onshore and onboard the vessel, and to allow flexibility in the event of a sudden stop either onshore or
onboard the vessel. Upon completion of the load-out operation, a pressure test and/or electrical tests are normally performed in order to ensure that the product is intact prior to installation.

Load-out of rigid pipelines to be installed by reeling is performed at a spoolbase, where pipes are welded into strings of typically 1000 m length. During load-out, pipe strings are welded together into longer lengths to fill the vessel reel or achieve total pipeline length. The pipe string is then spooled onto the vessel reel with a certain back-tension to prevent pipe buckling and to ensure a compact spooling.

Large diameter pipes to be installed by use of stinger or J-lay tower are typically transported from shore to the installation vessel by a smaller vessel or a barge. The pipes (typically 12 m length) are then lifted onboard the installation vessel by crane.

4.4 Installation aids

Reference is made to the theory slide in the presentation given 20/10-2011. Read this before proceeding. Laying equipment for flexibles will normally consist of three components:

- Storage unit
• Unit providing hold-back force to compensate for product weight in water column, and pay out / in product.

• Unit preventing overbending of product at overboarding, typically U-shaped with bending radius larger that minimum bending radius for product

In some cases the functionality in unit 1 and 2 is combined in one unit. Normally steel pipes have huge bending radius. In order to utilize the type of equipment used for cables and umbilicals the pipe need to be deformed plastically. A strightener is then needed before overboarding. This is feasible for flexible pipes.
Rigid pipes are transported to field as a set of separate sections, then welded together one by one during overboarding.

4.5 Shore pull
An installation operation may be initiated or completed by pulling the product onshore at the shore landing site. The vessels draft will determine how close to shore the vessel may come. From this set-up location, the product is floated to shore, pulled by an onshore winch. Required winch capacity is determined based on anticipated drag due to wind and current, as well as friction due to contact with rollers, conduit surface etc.

4.6 Lay operation in shallow water
In water depths up to 30-50 m, product tension and bending is typically controlled by measuring the product angle with the vertical at the vessel
Figure 11: A chute ensuring smooth transition of the cable into the sea
interface. Maximum and minimum allowable lay angles must therefore be pre-determined by analyses and shall be specified in the operational procedures.

4.7 Lay operation in steep slopes

Steep slopes are typically found on the sides of a fjord or at the edge of the continental shelf. When laying umbilicals or cables in steep slopes, the following issues should be considered:

- lay direction, i.e. uphill or downhill
- need for anchoring of product, and
- risk of VIV and need for VIV suppression strakes.

When laying a product uphill, there is a risk that the product may slide unnoticed every time the tension at touchdown is low. The steeper the slope, the higher the tension required to prevent sliding. And the higher the waves, the more vessel motion, resulting in a higher variation in tension at touchdown. Consequently, top tension must be increased to ensure that touchdown tension is adequate. On the other hand, increasing the lay-back distance also increases the maximum tension at touchdown. This may cause a tightening of the product on the seabed, potentially resulting in free spans. Another factor that may physically restrict the lay-back distance is the slope geometry, i.e. the slope itself. The consequence of restrictions in lay-back is a restriction in the weather criteria for this operation.

As a product is laid downhill, the geometry of the seabed slope will improve the dynamics of the product catenary, making it more flexible. Consequently, there is less risk of both compression and product over-bending at touchdown. Laying downhill also offers more flexibility with respect to adjusting the lay-back distance. On the other hand, increasing lay-back results in an increase in touchdown tension, which again may lead to the formation of free spans. Free spans may also develop behind touchdown, i.e. higher up the slope, as a result of too high tension at touchdown.

In order to prevent product over-bending at touchdown, slippage down the slope during laying, or the generation of free spans, step-by-step vessel movement and product pay-out should be analyzed in detail for applicable weather conditions and specified in the operational procedures.

Particularly when laying downhill, the need for anchoring of the product uphill of a slope should be considered to prevent slippage due to excessive tension at touchdown. In addition, the need for anchoring of the product to
account for the effect of waves and current that may cause the product to work its way down the slope over time, should be considered.

The risk of generating free spans is often higher in relation to laying in steep slopes, as free spans may result both uphill or downhill of the slope (depending on lay direction) and along the slope itself (depending on seabed topology). The concern related to free spans is the risk of Vortex Induced Vibrations (VIV) that may be induced in the suspended product as a result of current. Therefore, as a general rule, VIV analyses should be performed as part of the installation engineering in order to establish the maximum allowable free span length. If free spans are unavoidable, remedial action such as installation of VIV suppression strakes or free span rectification (e.g. by rock dumping) should be performed.

4.8 General lay operation

Although the vessels required for installation of rigid and flexible pipelines differ, and although a rigid pipe is much less flexible than a flexible pipe - or an umbilical or cable for that matter - the same criteria apply during installation:

- Maximum tension (typically at the vessel interface) must not exceed the capacity of the product (pipeline, umbilical or cable)
- Maximum compression in the product (typically at the seabed interface) must not cause any damage
- Product bend radius over a chute, stinger or deflector must not be less than the specified limit for the applicable installation tension
- Product bend radius at the seabed interface (sag bend) must not be less than the specified Minimum Bend Radius (MBR)
- The grip force applied on the product by the installation tensioner must be sufficient to support product tension, but must not exceed the crush capacity of the product

During laying, the product will be affected by both current and the motion of the installation vessel. With increasing vessel motion, the lay-back distance will have to be increased in order to prevent product over-bending at touchdown, and consequently both top tension and residual tension in the product increases. Installation analyses should therefore be performed to determine minimum required and maximum acceptable lay angle, product tension and/or lay-back distance for a range of weather conditions based on
the criteria stated above. Based on these analyses, limiting weather conditions should be determined, i.e. the maximum waves in which the laying operation may be performed.

During laying, product integrity is controlled by ensuring that the product lay angle, i.e. angle of product with the vertical at the vessel interface, product tension at the vessel and/or the distance between the vessel and the point where the product touches down on the seabed, i.e. the lay-back distance are maintained within the ranges determined by the analyses. Note that the lay-back distance is measured by maintaining a Remotely Operated Vehicle (ROV) above the point where the product touches down on the seabed, i.e. touchdown point.

As a general rule, residual tension, i.e. product tension after installation, should be minimized in order to prevent the formation of free spans and to enable trenching of the product, if applicable. Consequently, the distance between the vessel and product touchdown, i.e. the lay-back distance, on the seabed should be minimized without risking excessive compression in or over-bending of the product.

Typical lay speed for flexible products (flexible pipes, umbilicals and cables) is 5 - 10 m/minute (300 - 600 m/hour), depending on parameters such as route, seabed conditions and installation tolerances. Handling, over-boarding and installation of accessories such as end terminations and buoyancy modules will, however, slow down the operation considerably.
4.9 Stand-by Conditions/Waiting on Weather

If the expected duration of an operation, including contingency, exceeds the time frame of a reliable weather forecast, typically 72 hours, contingency operations should be planned and analyzed in detail. Such contingency procedures may involve the use of buoyancy to establish a suitable stand-by configuration, or cutting and emergency abandonment of the product.

Detailed analyses are required in order to establish step-by-step vessel motion versus product pay-out to achieve the stand-by configuration or lay down the product end on the seabed. Note that a contingency operation may have to be performed without the assistance of an ROV, as simultaneous recovery of the ROV is often performed to save time.

4.10 Pull-in to Offshore Unit

An installation operation may be initiated or completed by product pull-in to an offshore unit, e.g. a platform or an offshore substation for a wind farm. In general, the operation involves transfer of the product end termination from the vessel to the offshore unit, and is achieved by use of a winch located onboard the offshore unit. Required winch capacity is determined based on maximum expected distance between the vessel and the offshore unit, vessel/product dynamics, friction due to product contact with J-tube or I-tube at the platform/offshore unit interface, and drag due to current acting on the submerged product catenary.

Due to tolerances inherent in all length measuring devices, flexible pipelines, umbilicals and cables are manufactured with a certain over-length to ensure that the delivery length is not too short. The resulting surplus length may be cut off on site, as soon as the actual surplus length may be measured, but in most cases this would require assembly of an end termination offshore that can take several days to complete. Therefore, it is more common to deposit surplus length by laying the product in curves on the seabed. For an infield pipeline or umbilical, the surplus length may be in the order of 50-100 m, while it may be as much as 1 km for the longer lengths of umbilicals and cables between platforms and shore. Space required for deposition of surplus length may therefore have to be planned carefully, as the area close to a platform or subsea structure is often congested.

4.11 Subsea lay-down of product end termination

Umbilicals and flexible pipelines are normally installed between a platform and a subsea structure, or between two subsea structures. In either case
the subsea end of the umbilical or pipeline is usually attached to an end
termination that may be large and heavy.

The installation operation may be initiated by installation of the subsea
termination, i.e. a so-called first end installation of the termination. The
termination may be installed hanging by the product, or by use of a crane
and/or winch to support the weight of the termination during lowering and
landing. The installation method depends on the weight and design of the
termination, i.e. whether or not it must be installed upright.

If the termination is lowered hanging by the product, a bend restrictor
is required at the termination interface to protect the product from over-
bending as the termination is tilted and laid down on the seabed. The
bend restrictor must be designed for the moment resulting at the termination
interface, including the effect of dynamics.

If the termination is lowered by use of a crane, the over-boarding opera-
tion, i.e. lowering the termination from deck level through the surface, may
be critical. During this phase, vessel motion may cause the termination to
swing like a pendulum, potentially causing compression and over-bending of
the product between the termination and the vessel. During lowering and
landing of the termination, product tension (and corresponding moment in
the bend restrictor) must be kept within allowable limits.

4.12 Initiation of rigid pipeline installation subsea

If the first end of a rigid pipeline is to be installed subsea, a hold-back
anchor is normally required due to the relatively high residual tension in the
pipeline during laying. The pipeline is then secured to the anchor before the
lay operation starts in order to prevent it from sliding towards the vessel.

4.13 Rigid spools

A rigid spool is an assembly of pipe segments designed to connect a pipeline
to a subsea structure, e.g. riser bases, manifolds or similar. Design of the
spool is based on actual measurements of as-installed positions of pipeline
end flange and subsea structure. Typical spools are U-shaped or S-shaped.

Rigid pipe spools are typically lowered and lifted into place by use of the
vessel crane.
5 Installation of subsea modules.

In a typical offshore lifting operation a heavy subsea unit is lifted from deck of the crane vessel and lowered to the sea floor. Alternatively, the operation involves two vessel, a transportation barge / vessel and a crane vessel. Operations where subsea modules are lifted from sea floor to deck for removal / repair, or moved from one location to another, is also denoted lifting.

The different phases of an offshore lifting operation is discussed in the subsections below.

5.1 Load-out

The module is lifted or skidded from a production / storage site and onto the crane vessel deck. Since a full utilization of the expensive crane vessels are desired, the deck tends to be crowded. This need to be planned carefully, to ensure simple and safe lifting routes in air at the offshore installation site.

5.2 Transportation

A proper sea fastening of all modules on deck is required. Further, the deck strength need to be checked, both local damages and a complete collapse of the hull may need to be considered. Finally, for tall and heavy units, the stability of the vessel may be an issue. The most dominant loads for the sea fastening and deck strength are module self weight and wave induced accelerations and deck tilts. This means that a hydrodynamic analysis may be relevant. A proper planning of the sea fastening, ensuring easy, swift and cost efficient installation and removal, should be focused on.

5.3 Lifting from deck of vessel

Upon arrival the sea fastening need to be removed and the module is lifted along a route to a location ready for lowering. The involved crane operations should be as simple as possible. Test-lifting inshore is highly recommended, these costs may be a very good investment. Pendulum oscillation of the object easily occur, both due to wave induced motions and due to quick shift of horizontal centre of gravity during crane operation. Although this is a substantial problem in reality, analysis models will often predict even worse results. This is typical for resonant dynamic systems, where the small amount of damping that actually exists is hard to quantify. Analysis of lift in air is an area which probably will be given much attention in the years to come. A challenge, besides the damping issue, is that this is manually controlled
operations, it is not possible to calculate how clever a crane driver is going to be.

The stability of the vessel are reduced when the heavy load is lifted from deck, stability-wise it correspond to place the module weight in the crane hook. The accidental case occurring if the load is suddenly dropped also need to be addressed.

5.4 Splash-zone

Any pendulum motion of the lifted object will be dramatically reduced when the object is lowered and penetrates the free surface. Seen from a crane drivers point of view this will be a point of the operation where he can relax. Never the less, the splash zone is where the most violent dynamics occur, and normally where the crane wire loads will reach their maximum. Different types of relative motions between the object and the water will contribute: particle velocity and acceleration due to wave motion, slamming toward flat members of the object and object motions due to crane tip motions. The wave induced vessel motions will normally represent a higher contribution than the operationally defined lowering speed of the object.

The purpose of the analyses for this stage is to establish design dynamic loads. This is normally done using a time domain analyses. The hydrodynamic coefficients that are input to this program quantifies the hydrodynamic
forces. These coefficients may be hard to quantify, especially the slamming coefficient.

The stability of the object may also be a point of interest. Although the crane load itself normally acts at a high level and stabilize the lift, destabilizing effects may become critical. Typical destabilizing effects are buoyancy forces acting below centre of gravity, partly water filled compartment, air filled compartment communicating with the open sea etc. Further, the effect of the crane load can not be fully understood without including some kind of interaction with the lifting vessel. Traditional stability programs are not able to handle this, hence a hand calculation or a time domain simulation may need to be performed.

5.5 Further lowering.

When the object is lowered further the direct impact from the waves will vanish, and the dynamics are governed by the wave induced crane tip motion only. This means that the splash zone normally is governing for the dimensioning forces. One important exception occurs at ultra-deep sites, where the long lifting wire represent a softer system, leading to large eigenperiods. If the eigenperiods becomes similar to the period of the surface wave and crane tip motion resonance may occur. This is discussed further in an exercise. Other things that need to be considered during further lowering is wire weight in upper position and the wire wear.
5.6 Landing.

A soft landing of the object is important, partly to protect the lifted object, and partly to avoid damages to the soil supporting the object after installation. Further, an accurate positioning of the object are required. Time domain simulations may become relevant even for this phase. During the actual operations some kind of load or motion compensator are frequently used for this phase. The force characteristics of such devices are very complex, and the crane manufactures tends to keep the algorithm as an secrete. This makes it difficult to quantify their effect for a marine contractor.

5.7 Recovery.

Removal of old subsea modules for demolition or repair is an increasing market for installation contractors. Further, a recovery of the module may be a contingency case required by the client for a typical installation case. The engineering concerns for the recovery are similar to installation. Two additional challenges are the suction forces from the soil, that suddenly yields, and the weight of trapped water when lifted in air.
6 Platform installation.

Even though completely submerged solutions for offshore oil productions are feasible and have been made, the vast majority of the oilfields contains surface piercing platforms. Some of the most typical oil platforms and their installation is discussed in the following.

Typically, the platform consist of a fixed or floating fundament, and an upper unit with living quarters, production facilities and units for separation of oils and gas and various other processes. In cases where the upper unit is clearly separated from the rest it is denoted topside.

The transportation to field is consist of towing or, if relevant, using the platforms own propulsion. Two types of towing are used: wet tow, where the platform is floating, and dry tow, where the platform is located on deck of a transportation barge. In both cases the towing fleet is a main cost driver, hence calculating the required towing resistance is one of the main tasks for the engineer.

6.1 Jacket

The steel jacket type platform on a pile foundation is by far the most common kind of offshore structure and they exist worldwide. The ”substructure” or ”jacket” is fabricated from steel welded pipes and is pinned to the sea floor with steel piles, which are driven through piles guides on the outer members of the jacket.

The phases of a jacket installation are

- The production site is normally at a yard with a huge keyside. Preparation of different jacket parts in production halls, assemble at key side. Production logistic to ensure effective use of material and man hour is a main cost- driver.
- The jacket is transferred to a transportation barge with skidding or trailers
  - Skidding: Low friction shoes underneath the jacket, use of winching or jacks.
  - Trailers: Wheels mounted underneath the jacket to provide vanishing friction.
- Transportation to field,- dry towing
- Small jacket: lifted off barge deck and upended with crane vessel
Figure 16: jacket with topside

- Larger jackets are launched: barge is ballasted to a certain trim angle, jacket slides into the water. Then upending with a crane vessel
- Crane assisted positioning and set-down on sea floor.
- Piling

The installation analysis determine loads that need to be included both for the jacket design and for the design of temporary buoyancy tanks. Some challenges during jacket launch and upending is listed below

- Position and size of temporary buoyancy tanks
- Maximum contact force between jacket and barge.
- Maximum depth during launch
- Structural loads due to hydrostatic pressure
- Bottom clearance
- Floating condition after launch. Ensure access to lifting arrangement
- Upending. Check of structural loads crane load and bottom clearances.
- Proper upright position. Ballasting of side legs
6.2 Topside

After securing the jacket with piles the topside installation follows. A light topside is normally installed in a single lift operation with an offshore crane. For heavier topsides, crane vessels may be unavailable or too expensive. The traditional alternative is an installation piece by piece. Another option is the floatover method: an opening in the top of the jacket is designed where the transportation barge may enter. After entry, the barge is ballasted, and conical units underneath the topside enter into receptors in top of the jacket corner legs. Some kind of rubber of shock-absorbing material may be needed. The barge is ballasted to a proper air gap to the transported topside and pulled out. After installation of the topside the electric cables, risers etc are pulled in, all equipments and facilities are commissioned and the production may start. The oil wells are normally predrilled to ensure a quick start-up of the production. When the floatover method is used for a floating platform the operation is normally denoted mating.

6.3 Gravity based structures

A gravity-based structure (GBS) is a support structure held in place by gravity. These structures are often constructed in fjords, especially for units with extremely deep drafts. Fjords gives sufficient depths and are sheltered from extreme waves. The fjord sill will normally be dimensioning for the maximum draft that can be made.

The extremely tall GBS concept used in the North Sea, denoted Condeep
platforms, were made this way. This type of platforms lost their popularity in Norwegian sector after the sinkage of the first Heidrun platform. Today there is an increasing interest for GBS- platforms all over the world, both Condeep- type and solutions suited for more shallow water.

A GBS is normally constructed of steel reinforced concrete, often with tanks or cells which can be used to control the buoyancy of the finished GBS. The topside may be mated or otherwise installed before or after tow-out. Mating before transportation was normally done for the Condeep platform in Norwegian sector. These platforms are the largest man made structures ever been transported. Due to the extreme weights the only option is to wet-tow the platforms to site. A huge fleet of towing vessels is normally required. This is shown on the next slide, for a Condeep platform.

Upon arrival at the offshore site the platform need to be positioned and ballasted down to the sea floor. Finally, the platform is filled with grout, a sort of concrete, to ensure a stable platform even in extreme weather.

A jackup is a floating barge fitted with long support legs that can be raised or lowered. The jackup is maneuvered (self-propelled or by towing) into location with its legs up and the hull floating on the water. Upon arrival at the work location, the legs are jacked down onto the seafloor. Then "preloading" takes place, where the weight of the barge and additional ballast water are used to drive the legs securely into the sea bottom so they will not penetrate further while operations are carried out. After preloading, the jacking system is used to raise the entire barge above the water to a predetermined height or "air gap", so that wave, tidal and current loading acts only on the relatively slender legs and not on the barge hull.

The jackup may stay on a certain location for long time periods. Never the less, the platform type is particularly useful for short time engagements
and frequent transits. The jackup will meet new soil conditions at each new location. This means that geotechnical issues and proper planning need to be constantly focused on. The most dangerous phenomenon is denoted punch through. This may occur if the soil is soft underneath a relatively firm layer. If the firm layer withstand the static loads and normal dynamic loads the installation process may be regarded as successful. During a storm event the overturning forces acting on the platform may lead to a leg punch trough of the firm layer, and a sudden lack of platform support. Critical structural damages may then occur.

The normal way to prevent punch through is to apply an even higher static load during installation. This preloading may be performed by ballasting the barge when the legs have been lowered. Alternatively, for a four legged platform, two diagonal legs may be raised simultaneously. This means that a three legged platform normally need to be equipped with larger ballast tanks. On the other hand, the fact that three vertical supports defines a statically determined system proves to be a safe and robust solution to several operational and accidental scenarios.

Almost all Jack Up Units have footings. Their purpose is to increase the legs bearing area, thereby reducing the required capacity of the soil to provide a solid foundation upon which the Jack Up will stand and transfer weight, operational, and environmental loads to the seabed. There are two main footing types: mats and spud cans. Mat footings connect all the Jack Up Units legs to one common footing. Mats provides a stable solution for extremely soft soils, but there are technical challenges at uneven seabed and when debris are present.

Spud cans are conical shaped individual footings underneath each leg. This will provide a stable fundament even in harder soil conditions. Pictures displaying installation steps and the design issues discussed above is provided in the following slides. Some analysis challenges are FEM analyses of leg strength during transport and installation and hydrostatic analyses to find spud can force.

### 6.4 Tension leg platforms

A tension leg platform (TLP) is a floating platform with strong vertical mooring (tendons or tension legs). After connecting the platform to the tendons a high tension is achieved through combinations of winching and deballasting. The fundamental idea is to arrest the vertical wave induced motion, while letting the horizontal motions remain. Vertical motions are the most challenging ones for risers, cables etc. Hence, the TLP may provide a more cost efficient solution than fixed platforms in deep water, without
introducing the critical motions of a floater.

The installation steps may differ from platform to platform, but a typical installation may consist of the following steps:

- The fundaments for the tendons are lowered to the sea bed and secured with piles. Use of rock dumping or similar may add to the fundament stability

- A huge set of pipe sections are transported to the field. A crane vessel will upend and lower one section by section. Each new section is attached to the previous section by use of some mechanism installed at the pipe section ends. When the first section reach the sea floor it is attached to the fundament. A buoy is attached in the upper end to provide tension in the tendon, at a suitable water depth close to the surface

- Eventually all tendons are installed with buoys in the top end. Analyses need to be performed to ensure that the tendons do not tangle up for the expected worst environment that will occur in the period before the platform arrives.

- Meanwhile a floating substructure or hull is constructed towed to field. The topside modules may be attached to the hull inshore or at site.
The hull is then positioned above the preinstalled tendons. Winches are attached to the tendons. A high tendon pretension is then achieved by winching and ballasting. Normally the tendon elements need to be secured to the hull and the winches released before the final stages of deballasting and pretension takes place.

6.5 Floating platforms

Floating offshore platforms may be defined as platforms with a soft positioning system, where the wave induced motions are not arrested. According to this definition the TLP is not a floater. The purpose of the positioning system is merely to compensate for drift forces from the environment. This is normally achieved with a soft, catenary mooring. A so called DP may also be used. A DP is a computer system controlling several thrusters who continuously will change force and direction to compensate for slowly varying environmental forces. Floating platforms have several advantages, among them are

- Uncertainties related to soil conditions are reduced to a minimum. Notice that anchors are required if a DP is not used.
- For deep water the price of an extreme tall structure is avoided.
- It is easy to move to other locations, take platform to land for repair etc.

The disadvantage compared to all platforms discussed earlier is the increased vertical motions. The entry of flexible products into the platform (cables, pipelines etc) becomes more challenging.

The installation of a floater will normally go through the following steps.

- A set of anchors and mooring chain will be installed on the sea floor. The anchors will form a ring around the platforms, and the mooring chain will be attached to the anchor and oriented toward the center, the future platform location. The chain will be laid in a U-turn toward the center, and some kind of mechanism and plans for picking it up are made.

- The floater are normally made on a ship yard, and topside modules lifted in and installed. Often the simplest work is done in low-cost areas, while the more technical challenging outfitting is done other at more suitable locations.
The floater is towed out and positioned between the anchors. The chains are then picked up by anchor handling vessels and handed over to the platform one by one. Each mooring line is connected to the platform winches. Finally, all lines are winched in to a proper pretension.

Hydrostatic and hydrodynamic analyses may be needed for the transportation of anchors to field, for stability checks and seafastening loads. FEM analyses needed for strength check of sea fastening. Installation of suction anchors normally requires a typical lifting analyses. Laying of anchor chain is verified with laying analysis similar to laying of electric cables etc. Towing force for vessel selection necessary for tow- out of the floater. The strength of the floater itself in heavy sea not checked; the design storms used by the platform manufactures are worse. Hook-up of platform to preinstalled mooring lines checked with time domain analyses.

7 Some useful formulas.

7.1 Tensioner Grip Force

A tensioner is a mechanism mounted onboard an installation vessel to enable sufficient holding capacity for the flexible product being installed. The tensioner consists of several belts, each having contact with the product over a certain length. The belt may be run to pull in or give out the flexible product.

Product tension is transferred to the tensioner(s) by the friction force generated between the tensioner belts and the product. The friction force is increased by increasing the tensioner grip force. However, maximum allowable grip force on the product given by the supplier must not be exceeded. Therefore, if sufficient friction force is not achieved at maximum allowable grip force, the contact length between the tensioner belts and the product must be increased. This may be achieved by installing two or more tensioners in series. A rough estimate of required contact length between the tensioner belts and the product is given by:

\[
l_{\text{min}} = \frac{T_{\text{max}}}{F_{\text{allow}}N\mu}
\]

where

- \(l_{\text{min}}\) = Minimum required contact length between tensioner belts and product
- \(T_{\text{max}}\) = Maximum installation tension

- Some useful formulas.

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\]

where

- \(l_{\text{min}}\) = Minimum required contact length between tensioner belts and product
- \(T_{\text{max}}\) = Maximum installation tension

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\( F_{\text{allow}} = \) Maximum allowable tensioner grip force pr length (one belt)
\( N = \) Number of tensioner tracks (belts)
\( \mu = \) Minimum friction coefficient

In order to prevent the product internals from slipping through the outer sheath, the friction coefficient between the sheath and the underlying layer (normally armor wires) should also be considered, as it may be lower than the friction coefficient between the sheath/roving and the chute surface.

Note that a safety factor should be applied to account for inaccuracies in tensioner settings and tolerances of gauges or other equipment used to measure tensioner grip force.

### 7.2 Chute Contact Force

A chute is a mechanism that may be use for overboarding flexible product during installation. A chute consists of a smoothly curved surface with side walls than protect the product from overbending.

The radius of the installation chute is given by the minimum of the following:

- Minimum bend radius at maximum installation tension specified by the product supplier, and
- The radius corresponding to the maximum contact force specified by the product supplier.

Minimum chute radius to comply with maximum allowable contact force may be determined as follows:

\[
R_{\text{min}} = \frac{T_{\text{max}}}{N_{\text{allow}}}
\]

where
\( R_{\text{min}} = \) Minimum required chute radius
\( T_{\text{max}} = \) Maximum installation tension
\( N_{\text{allow}} = \) Maximum allowable product contact force with chute

### 7.3 Required Recovery Tension over Chute

An installation operation shall in general be reversible. In order to enable recovery of a product over a chute, friction must be accounted for. An estimate of required recovery tension may be found as follows:
Catenary formulas

Gitt at vi ønsker å bestemme typiske parametre på en kjedelinje ut fra en ønsket radius ved touchdown, kan disse finnes som følger:

Bunnstrekk:
\[ H = w \cdot R \]

Toppvinkel:
\[ \alpha = \sin^{-1}\left(\frac{H}{w \cdot D + H}\right) \]

Toppstrekk:
\[ T = \frac{w \cdot D}{1 - \sin(\alpha)} \]

Avstand til touchdown:
\[ X = R \cdot \ln\left(\frac{1 + \cos(\alpha)}{\sin(\alpha)}\right) \]

hvor
\[ H = \text{Horisontalt strekk i produktet i touchdown} \ [\text{N}] \]
\[ w = \text{Neddykket produktvekt} \ [\text{N/m}] \]
\[ R = \text{Minste bøyerradius over touchdown (i "sag bend")} \ [\text{m}] \]
\[ \alpha = \text{Produktvinkel med vertikalen} \ [\text{radianer}] \]
\[ D = \text{Vanndyb} \ [\text{m}] \]
\[ T = \text{Produktstrekk i øverste ende} \ [\text{N}] \]
\[ X = \text{Avstand mellom toppunktet og touchdown} \]

Touchdown er definert som punktet der sjøbunnen danner en horisontal tangent med kjedelinjen.

Figure 20:

\[ T_{\text{rec}} = T_{\text{max}} e^{\mu \alpha} \]

where \( T_{\text{rec}} = \text{Required recovery tension} \)
\( T_{\text{max}} = \text{Maximum installation tension immediately outside vessel} \)
\( \mu = \text{Friction coefficient between product and chute.} \)
\( \alpha = \text{Angle of sector (in radians) where the product is in contact with the chute} \)
8 Exercises.

Exercise 1 (Towing a semi submersible)  Your company is going to conduct a wet-towing of a semi submersible unit. A subcontracting company has been used to calculate the required towing force. Your boss do not trust their work. He comes over to you, puts their towing analysis report on your desk and says:

"You join in in tomorrow’s meeting. And have an opinion! Should we ask for an independent third party verification for the towing analysis. Or do we trust them? I don’t!"

Look here: they claim that under zero environmental forces (flat sea), they can tow the unit with 5m/s, using one towing vessel only: a tug with 40 tonne pull force. This is bull sh...."

Perform some simple calculations. Can you substantiate the statements from your boss?

The platform is displayed in figure (21). The rectangular, horizontal pontoons have dimensions 20 m × 10 m, while the vertical corner column have dimensions 20 m × 20 m. The openings between the columns are 60 m. The draft (distance from still water level to bottom of pontoons) is 40 m.

Exercise 2 (A salesman’s death?)  The vessel your company is using when laying electric cables have capacity to install cable with 10 tons top-tension. Your company’s salesman are about to win a new job for your company where you are going to lay an electric cable across a fjord. The deepest location is 1000 m.

The following key parameters apply

- Cable weight is 10 kg/m
- The minimum bending radius for the cable is 5 m.
What should you do?

Exercise 3 (Torpedo anchor) A torpedo-shaped anchor are to be dropped from a certain height above the sea floor. The purpose is to penetrate the sea floor to a certain depth and provide a safe anchoring point.

According the geotechnical report a collision speed of 100 m/s is appropriate for a correct seabed penetration.

The key parameters are defined as

- **Weight** $m = 50$ tons
- **Buoyancy** $m = 5$ tons
- **Added mass** $m_a = 5$ tons
- **Dimensionless drag coefficient** $C_D = 0.2$. Corresponding frontal area $S = 1.5 \text{m}^2$.

At what height should you drop the anchor? You may assume that wires and chains attached to the anchor have no impact in the anchor motion after being dropped.

Exercise 4 (Lifting operations) In this exercise you will develop a mathematical model for a crane assisted deep sea lowering of a subsea module. We are investigating a situation where the lowering have stopped, so that wave induced motions only remains. The crane hook is performing prescribed (known) vertical motion $Z_c(t) + C$, where $C$ is the average position of the crane hook. The module performs vertical motions $Z_m(t) + M$, where $M$ is the average position of the module. Typically, $M$ is a huge negative number for deep lowering. $Z_m(t)$ is the fundamental unknown of the problem.

We assume vertical motions only.

The following key parameters can be regarded as known:

- $M = \text{Mass of module}$
- $M_a = \text{Added mass of module}$
- $B = \text{Buoyancy of anchor}$
- $C_D = \text{Drag coefficient for the module}$
- $S = \text{Horizontal projected area of the module}$
- $E = \text{Elastic modulus of wire}$
- $A = \text{Cross sectional area of wire}$
- $L = C - M = \text{Static distance from crane tip to module}$
- $\rho = \text{Sea water density}$
- $g = \text{Acceleration due to gravity}$
a) Show that the wire force \( F \) acting on the module can be written

\[
F = -K(Z_m(t) - Z_c(t)) + T
\]

Express \( K \) and \( T \) using the known parameters listed above.

b) Show that

\[
\dot{M} \frac{\partial^2 Z_m}{\partial t^2} + F \frac{\partial Z_m}{\partial t} \left| \frac{\partial Z_m}{\partial t} \right| + K Z_m = K Z_c
\]

Express \( \dot{M}, F \) and \( K \) using the known parameters listed above.

c) Find an expression for the resonance period of the system. Make a sketch displaying how this period is related to \( L \).

Exercise 5 (Convince the client I) Your friend who works in an oil company have a problem: they are going to install a subsea electric cable, and the installation company they normally are using has gone bankrupt. He happens to know that your company are trying to enter into the same market. He asks you to send him a mail who will convince his boss that your company are capable of doing the job. The mail should contain a short description of how you would organize and execute the project, what kind of technical challenges you see, what kind of engineering you find relevant etc. "make my boss understand that you have the right focus both regarding project execution and technical challenges", he says. "But make it short,- maximum 2000 words + some pictures, sketches etc."

Write this mail.

Exercise 6 (Convince the client II) See previous exercise. Your friend calls again, with a similar problem. This time it is a huge offshore module that are to be placed on the sea floor at a subsea location. Again, provide him with a convincing mail.

Exercise 7 (Convince the client III) See previous exercise. Your friend calls again, with a similar problem. This time it is a steel jacket that are to be dry towed to an offshore location and installed using launching. Again, provide him with a convincing mail.
References

A The First Appendix

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