Course AT 327

ARCTIC OFFSHORE ENGINEERING

Exercises, solution examples and an extensive case study

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ARCTIC OFFSHORE ENGINEERING

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1.1 Hydrocarbon Resources and Reserves

1) Resources/reserves evaluation (1998)

   a) There are several methods of resources/reserves evaluation listed below:
      
      I. Evaluation based on analogy.
      II. Deterministic evaluation.
      III. Stochastic evaluation (method Monte Carlo).
      IV. Fuzzy evaluation (method based on fuzzy or interval numbers).
      V. Performance analysis.
      VI. Numerical simulation of production performance.

      Which of those methods can be used for the resources/reserves estimate in the most efficient way during the follow specified stages of field development:

      A. Pre-drilling stage (seismic survey indicated a good size structure with good chances for potential hydrocarbon accumulation. The depth of the structure, its age and type of rock are identified).
      B. Discovery stage (an exploration well has discovered an oil field. Some reservoir and fluid properties are now available due the fluid and core sampling and well logging. Drill Stem Test showed the initial rate of oil production from the reservoir).
      C. Delineation/early production stage (statistics on reservoir/fluid properties as well as early production history is available from several production wells).
      D. Stage of mature production.
      E. Late time depletion (stage of decline production).

   b) What kind of oil and/or gas resources, i.e. (1) total in place resources (STOOIP for oil and STGOIP for gas), (2) recoverable reserves or (3) both total and recoverable can be estimated by the following methods (give a short explanation):

      1. Volumetric estimate.
      2. Performance analysis.

   c) There are 5 necessary conditions that should be met in order to find petroleum.

      1. Define these necessary conditions.
      2. Assume that you have been given probabilities of existing to each of these necessary conditions. For evaluating a total probability of finding petroleum you can:

         i) Multiply the given probabilities.
         ii) Add the given probabilities.
         iii) Take an arithmetic mean value of the given probabilities.
         iv) Take a geometric mean value of the given probabilities.
         v) Take a minimum value of the given probabilities.
         vi) Take a maximum value of the given probabilities.

         Which option would you prefer? Explain your answer.

         vii) Other method (specify).
1.2 Reservoir and Production Engineering

a) There are several factors that can deteriorate field performance. Some of them are listed below:
   i) Reservoir heterogeneity.
   ii) Unfavorable mobility ratio.
   iii) Gravity segregation.
   Give a short description of each of these factors.

b) Describe the effects of water and gas coning.

c) Assume that there is an oil reservoir with a high angle of dip, which is planned to be developed by water flooding (i.e. injecting water into a reservoir). You can choose one of the following options:
   i) Updip injection of water (i.e. water injection wells placed in the lower part of a reservoir, and producers are positioned in its upper part).
   ii) Downdip injection of water (i.e. inverse position of injectors and producers). Which of these two schemes would you prefer? Explain your answer.

d) Given the same oil reservoir as above assume that gas injection scheme is preferred. Position production and injection wells within the reservoir. Explain your answer.

e) It is known that horizontal wells have higher productivities than vertical wells in most cases. Give an example of a reservoir (in terms of it reservoir and fluid properties), where:
   i) Horizontal wells have obvious advantage over vertical wells.
   ii) Vertical wells fractured can be a good alternative to horizontal wells.
1.3 Field development

1) Field development (2001)
An offshore hydrocarbon field in the Pechora Sea in 28 m water depth, 80 km from shore has an estimated recoverable amount of oil of 800 million barrels and an estimated recoverable amount of gas of 40 billion Sm³. The amount of condensate is small.

a) Discuss how you will treat the well stream and what products can be sold profitable on the marked.

b) Present a proposal for a platform solution and list/show the technical functions, which are needed on the platform.

c) Discuss what standards you will use for design of the platform substructure. Assume that you represent an investor (oil company) with head office in Oslo.

d) Discuss different alternatives for the transport of the products you will sell on the marked.

2) Arctic offshore field development (1997)
An offshore petroleum field is located in the Arctic 60 km from shore in 40 m water depth. The ice conditions during the winter season are rather severe, but 30 km to the northwest, the ice conditions are much more easy. There are no other offshore facilities nearby. It is anticipated that the field can produce 120 000 barrels of oil per day at peak production level while the amount of associated gas is rather limited.

a) Present a description of a possible field development solution and outline the following:
   - Substructure
   - Topside arrangement
   - Storage system
   - Loading system
   - Transport system to the marked
   - Gas utilization system.

b) In your area of particular interest, present a thorough discussion of the solution described above, and present arguments why your solution is considered "best state of practice".

c) During the conceptual phase of this project, oil is found in a field 15 km away from the main field in 50 m water depth. The estimated production volume from this potential satellite field is 30 000 barrels/day at peak level. Describe how this new field can be tied to the main field as a satellite and discuss the changes this thinking will introduce for the development of the main field.

d) Discuss how the Arctic environment complicates the development solution for the main field and outline a development solution for a similar field in an area without ice.

3) Field development, sales products
You shall discuss the sales products from the development of a hydrocarbon field.

a) What is the different between sales gas and rich gas? What is the difference between stable and unstable condensate?

b) If a southern part of the North Sea sales gas is made on the platform with in the northern part of the North Sea, rich gas is made. Try to give a reason for this difference between the
gas process strategies in the northern and southern part of the North Sea. How is the unstable condensate treated in these two areas? Prepare a list of the products that are exported from the Kårstø plant in northern part of Rogaland.

   a) To write down the balance of energy in a well for a case when the pressure at the wellhead is: $P_{wh} \geq P_b$ ($P_b$ – bubble point pressure).
   b) What kind of oil production is called artificially-natural (or induced natural) and what is the balance of energy in this case?
   c) What essentially important role is played by the third element of the hydrodynamic system «reservoir – well – downhole equipment – lift» at steady state conditions of production – an intake part of the submersible equipment?
   d) Write down the condition for expansion of the production area with each standard size of the electrical submersible pump and show it on the diagram.
   e) Draw the schematic of the jet pump and describe its operation mode.
1.4 Economics of offshore field development

1) Economics of offshore field development (1999)

We shall compare the development of offshore oil fields in two different areas of the Arctic; i.e. in the Pechora Sea and on the Grand Banks of Canada (Offshore Newfoundland).

Prepare a table comparing the physical characteristics of the two areas, listing physical parameters of importance for the development of offshore fields.

a) Describe technical solutions for field development in the Pechora Sea taking the particulars of that area into account. Do also list all parameters of main importance for concept selection and how these are solved by the concept(s) you propose.

b) Describe technical solutions for field development on the Grand Banks taking the particulars of that area into account. Do also list all parameters of main importance for concept selection and how these are solved by the concept(s) you propose.

c) Discuss different options for how oil most efficiently can be transported to the marked from these two areas.

d) Prepare a table showing all information that is required to perform an economic analysis for the development of an offshore field. Show how the different parts of the table are filled out and how we calculate the net present value of the projects.

2) Economics of offshore field development (1998)

a) For development of Arctic Offshore Fields select 6 challenges which are particular for the Arctic compared to fields elsewhere and present half a page of discussion on each of these challenges on how you will propose to solve them.

b) Give a discussion on the influence of water depth on the development of Arctic offshore fields. Consider the range from 2 to 40 meters.

c) Define the terms "net present value" and "internal rate of return".

d) If a company invests US$ 100 millions this year and the next 4 years, while it earns US $ 200 millions over 6 years from year 6 to year 11, what is the net present value of the company's business over the 11 years (10% yearly discount rate)?

e) If the investment period is shortened one year (while investing US$ 100 millions this year and the next year and US$150 in years 3 and 4), and allowing production (US$ 200 millions) to start in year 5 and continue over 6 years, what influence has this on the NPV over the 10 years compared to question d) above (10 % yearly discount rate)?

3) Economics of offshore field development (1997)

a) Explain the economic terms NPV (Net present value) and IRR (Internal rate of return).

b) Calculate the NPV (in year 2000) for an offshore field development involving the following cost data:
Investments:

<table>
<thead>
<tr>
<th>Year</th>
<th>Millions, NOK</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>50</td>
<td>(exploration)</td>
</tr>
<tr>
<td>2001</td>
<td>50</td>
<td>(studies)</td>
</tr>
<tr>
<td>2002</td>
<td>150</td>
<td>(studies, design)</td>
</tr>
<tr>
<td>2003</td>
<td>2500</td>
<td>(fabrication)</td>
</tr>
<tr>
<td>2004</td>
<td>2500</td>
<td>(fabrication, installation)</td>
</tr>
<tr>
<td>2004</td>
<td>100</td>
<td>2 platform wells</td>
</tr>
<tr>
<td>2005</td>
<td>300</td>
<td>6 platform wells</td>
</tr>
<tr>
<td>2006</td>
<td>300</td>
<td>6 platform wells</td>
</tr>
<tr>
<td>2007</td>
<td>300</td>
<td>6 platform wells</td>
</tr>
</tbody>
</table>

Operating costs:

From year 2003 and onwards, 5% of all investments prior to year start, including costs of wells.

Income:

<table>
<thead>
<tr>
<th>Year</th>
<th>Barrels of oil/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>40 000</td>
</tr>
<tr>
<td>2006</td>
<td>80 000</td>
</tr>
<tr>
<td>2007</td>
<td>120 000</td>
</tr>
<tr>
<td>2008</td>
<td>120 000</td>
</tr>
<tr>
<td>2009</td>
<td>120 000</td>
</tr>
<tr>
<td>2010</td>
<td>120 000</td>
</tr>
<tr>
<td>2011 to 2015</td>
<td>20 000 reduction per year</td>
</tr>
</tbody>
</table>

Assume that the value of the oil is $18/barrels minus $3/barrel for transportation to market (1$ = 7 NOK). Use a real discount rate of 10% for your calculations. Establish first the cash flow profile and thereafter calculate the NPV.

c) Establish also the NPV at a higher discount rate (for example 15% or 20%) and make a guesstimate of the IRR of the project.

d) Discuss whether there are possibilities to further improve the project economics.

4) Economics of field development (2001)

For a field development you shall prepare an economic analysis.

a) Which economic indicators could be used to evaluate the economic advantages of a field development?

b) Present a formula for the calculation of the net present value.

c) Prepare a spreadsheet for the economic analysis of the development of a field and make assumptions regarding investments costs, operating costs and income. Assume a discount factor of 10% (You need not calculate the actual NPV value).

d) Discuss the effects of early income and compare the present value of an income in year 5 with the present value of this income in year 15.
1.5 Transport

1) Transport of hydrocarbons in the Arctic (2000)

For offshore transport of stable oil/condensate in the Arctic, ship transport and pipeline transport are considered as two possibilities.

a) What is the processing that has to take place prior to ship transport (tanker transport) of hydrocarbons?

b) Discuss possible options (technical solutions) for loading to a ship in the Arctic when ice is present. Prepare sketches and identify advantages and problems for each of the options.

c) Discuss aspects related to the design of a ship for transport of hydrocarbons from Arctic icy waters to a Western European Refinery.

d) Discuss the main technical problems associated with pipeline transportation in the Arctic. (include in the discussion issues related to pipelines offshore, in the shore approach area and onshore).

e) For evaluation of the economics of ship transport, let us consider the economics of a shipping company. If the investment in one (smaller) shuttle tanker for Arctic waters is US$50 millions (this year, year zero) how much oil (m³) must this tanker transport every week (one shipload per week, 45 weeks every year) in the next 4 years if all investments shall be repaid by the end of year 4 (NPV=0 at end of year 4).

Let us assume a discount rate of 10%, a transport fee of US$ 1.50 per barrel of the oil and operations cost for the shipping company of US$ 0.70 per barrel. (Note: Prepare a table of income and expenditures and calculate the yearly cash flow).

f) What will the NPV for the company be if the transport can go on smoothly as suggested in question item e) above for 8 years?
1.6 Structures

1) Design of offshore structures (1999)
   a) Why do we divide the loads acting on a structure into groups? What groups of loads do you know?
   b) You are looking for the maximum possible load. Will you consider the following combination of action simultaneously (qualify your answer):
      - wave and ice loads?
      - earthquake and collision loads?
      - maximum wave and maximum wind loads?
   c) Assume that the structure lifetime is 25 years. For this structure design do you need to know the maximum load that can act once in:
      - 15 years
      - 25 years
      - 50 years
      - 100 years
      - 250 years.
   d) A safety factor of 1.05-0.95 is suggested by different Codes for permanent loads. What value of this factor will you use for structure design?
   e) What limit states are considered by the Codes?
   f) What principle will you take into account when you choose an optimum structure:
      - Minimum cost of fabrication and installation?
      - Minimum pollution of environment?
      - Minimum cost of repair?
      - Some combination?

   a) What are requirements to offshore structures?
   b) Which factors should be taken into account during the structure design?
1.7 Loads

1) Model scaling (1998)

To physically model icebreaking by ship, the geometric, dynamic and kinetics laws of similitude must be satisfied.

a) What does the geometric laws of similitude call for (require)? When is this similarity satisfied?

b) To satisfy dynamic and kinematic similitude, corresponding forces of importance must be proportional, that is:

\[
\begin{align*}
\frac{\text{Inertia forces}}{\text{Gravity forces}} &= F_r = \frac{\sqrt{L_{fi} g_{fi}}}{\sqrt{L_{mi} g_{mi}}} = \frac{V_{fi}}{V_{mi}} \\
\frac{\text{Inertia forces}}{\text{Viscous forces}} &= R_e = \frac{L_{fi} V_{fi}}{\nu_{fi}} = \frac{L_{mi} V_{mi}}{\nu_{mi}} \\
\frac{\text{Inertia forces}}{\text{Elastic forces}} &= C_h = \frac{\rho_{fi} V_{fi}^2}{E_{fi}} = \frac{\rho_{mi} V_{mi}^2}{E_{mi}}
\end{align*}
\]

(1.1)

Explain all parameters in these equations.

c) In open water testing, is it possible to satisfy both the Froude and Reynolds similarity criteria at the same time? What is most important to satisfy: Froude similarity or Reynolds similarity. If time allows, explain very briefly why?

d) When using Froude scaling, how do forces scale (only write down the equation)? How do time and velocity scale (only write down the equation)?

2) Actions (2003)

a) Which action (groups) categories do you know?

b) What is the limit state methodology and which limit states do you know?

c) What does it mean: action, return period and combination? What return period is considered usually?

d) In what groups do we divide environmental actions and how should they be combined?

e) You should design the structure which damage may lead to loss of the human life.

1) Which factors should be taken into account?
2) To which group the structure should belong?
3) What have you to know when you start design?
4) What action return period will you use?

f) Which factors are taken into account by action coefficients and what is the level of these coefficients? Give example when coefficient is more or less than 1.

g) Which factors should be taken into account during resistance determination?

h) How the limit state conditions should be written?

i) What are the disadvantages of the Limit State Method?

j) What does it mean “risk” and what is the task of risk analysis?
k) If several actions, which act on a structure, are considered as stochastic and if mean value $M_i$ and standard deviation $\sigma_i$ are known for any component. How the common action can be determined?

l) What is the level of acceptable risk for very important structures?
1.8 Waves

1) Waves (1999)

a) What factors are most important when wave parameters are determined at a given place?

b) Why will a stick in your hand vibrate if you put this stick into the water from a moving boat?

c) Morison’s formula for an element of a cylinder can be written in the following form:

\[
F = \frac{1}{4} C_i \rho \pi D^2 \frac{dV}{dt} + \frac{1}{2} C_d \rho D |V|
\]  

(1.2)

What do we call \( C_i \) and \( C_d \)?

Why do we write \( V|V| \)?

Can maximum values of both components act simultaneously?

d) What processes do the Keulegan-Carpenter number account for?

2) Waves (2000)

For waves in shallow water the flow may be approximated as having the same horizontal velocity \( u = u_0 \sin(\omega t - kx) \) at all depths.

a) Assume that the water particle amplitude \( u_0 = 0.2 \) m/s and the wave period \( T \) is 12 seconds. Find an expression for the particle velocity \( u \) and the water particle acceleration \( \ddot{u} \) at \( x = 0 \) as a function of time \( t \). For the present case (‘shallow water’) the wavelength is \( \lambda = T \left( \frac{gd}{9.81} \right)^{0.5} \) in which \( d = 3 \) m is the water depth and \( g = 9.81 \) m/s\(^2\). What is the particle velocity at \( x = 15 \) m and \( t = 10 \) s?

b) A vertical circular cylinder with diameter \( D = 2m \) is introduced in this flow. Find the Keulegan-Carpenter number \( K = u_0 T / D \) and Reynolds number \( Re = \frac{u_0 D}{\nu} \) in which the kinematic viscosity \( \nu = 10^{-6} \) m\(^2\)/s. This flow is not expected to be separated. Why?

c) The particle velocity in the tangential direction may be written:

\[
u_\theta = -u(1 + r^2 / R^2) \cos \theta ,
\]  

(1.3)

where \((r, \theta)\) are polar coordinates centered at the cylinder axis. Sketch the particle velocity around the cylinder periphery and point out at which locations the values \( u_\theta = 0 \) occur, relative to the flow direction, and where the maximum and minimum velocities are located.

Find the amplitude of the total force with which the water is acting on the cylinder in unseparated flow, if force per unit length of the cylinder is \( f = 2 \rho_w \pi R^2 \ddot{u} \), in which the water density \( \rho_w = 1025 \) kg/m\(^3\).

a) Which sea states do you know?

b) What dependence characterizes wave spectrum and when its use is important?

c) You should determine wave action on the compliant structure. What wave parameters will you use: the wave with maximal height and corresponding period, the wave with maximal length and corresponding height or some another wave? How this wave can be determined?
1.9 Ice mechanics

1) Ice mechanics (2001)

a) Assume continuum behavior of polycrystalline ice and a total strain given by:

\[ \varepsilon^{\text{tot}} = \varepsilon^e + \varepsilon^d + \varepsilon^v, \]  

where the superscripts refers to:

- \(e\) elastic;
- \(d\) delayed elastic;
- \(v\) viscous.

What processes in the crystal lattice does each of the three terms correspond to?

b) Let us consider the delayed elastic strain in the following. Assume that ice is loaded at \(t = 0\) with a constant load \(P\) (pressure \(\sigma\)). The strain versus time is shown in Fig. 1.1. What terms in Eq. (1.4) refer to the behavior shown in Fig. 1.1. Sketch the rheological representation of this behavior. What is this commonly called?

c) Show that the strain in b) can be expressed by:

\[ \varepsilon^d = \frac{\sigma}{E} \left(1 - e^{-\frac{E}{\eta}t}\right), \]  

where

- \(\sigma\) stress;
- \(E\) elastic modulus (Young's modulus);
- \(\eta\) viscosity;
- \(t\) time.

![Fig. 1.1 Strain versus time.](image)

d) Estimate the viscosity of this material based on Eq. (1.5) and values taken from Fig. 1.1 when assuming \(E = 9\) GPa, \(\sigma = 800\) kPa (a pressure below the crushing strength of ice).

e) Compute the strain in the ice after 2 minutes and after 20 minutes? Give a crude estimate of the average strain rate for this 18 minutes period? How do you explain the strain from the crystal lattice point of a view?

2) Ice mechanics (2000)

a) Ice under loading may creep. How do you explain the creep of ice from a microscopic point of view?

b) How do you represent the following rheological properties of ice:

i) Linear elasticity (Hook's law)?
ii) Linear viscosity?
iii) Ideal plasticity?

For i)-iii), sketch the relation between strength (\(\sigma\)) and strain (\(\varepsilon\)) or strain rate (\(\dot{\varepsilon}\)).
c) Ice is pushing against and riding up the surface of a sloping (slope angle = \( \alpha \)), conical structure.

i) Sketch (simple) the forces acting on the structure?

ii) Sketch the forces acting on the ice?

d) Assume that the total horizontal force \( (F_H) \) per unit width is given by:

\[
F = D \left( 0.68 \cdot C \cdot \sigma_f \left( \frac{\gamma \cdot h^2}{E} \right)^{0.25} + zh \gamma \right), \quad (1.6)
\]

Parameter values to be used: \( \sigma_f = 500 \text{ kPa} \), \( \rho_w = 1023 \text{ kg/m}^3 \), \( \rho_i = 900 \text{ kg/m}^3 \), \( E = 9 \text{ GPa} \), \( g = 9.81 \text{ m/s}^2 \), \( z = 5 \text{ m} \) is the vertical distance the ice is pushed up the slope, \( \mu = 0.2 \), \( h = 1.6 \text{ m} \). Calculate \( F_H/D \) both for \( \alpha = 30^\circ \) and \( 60^\circ \). Comment briefly on the results.

e) The diameter of the structure at the water line, \( D = 60 \text{ m} \), and the water depth \( d = 20 \text{ m} \). Calculate the overturning moments on the structure based on the horizontal loads calculated above. In regard to design, what relevance has the overturning moment?
1.10 Ice loads

1) Ice loads (1997)

a) When calculating ice loads, we learn that the maximum load is limited by:
   - Limit stress
   - Limit momentum
   - Limit force
   - Splitting.

Explain briefly what is meant (sketch if beneficial).

b) What are the major considerations in ice load calculations? Ice features, etc.

c) What major ice properties affect the load ice may exert on a structure?

d) For the same type of first-year sea ice, say 1 m thick, there is a difference in the ice load exerted on a vertical and a sloping structure (we assume the structure diameter at the water level to be the same in the two cases). Which of the two types of structures gives the lowest load and why?

e) What major parameters affect the mechanical properties of ice? At the same temperature, why is there a difference in the ice strength of first-year and multi-year sea ice?

2) Ice loads (2001)

The major parameters that affect the load from ice on structures are shown in Fig. 1.2. Can you from the sketch briefly comment on how ice properties affect the load on structures.

![Ice Load Diagram](image_url)

Fig. 1.2 Major parameters that affect the ice load on a structure.

3) Ice loads (1998)

a) What is mean by the scale effect in ice? Can you mention the major reasons for the scale effect?

b) Give explanations for the scale effect in ice.

c) Consider a vertical sided and cylindrical structure and the limit stress scenario. Assume a structure with diameter $D$, level ice with thickness $h$ moving from one direction, full ice
contact, and a uniform ice strength $\sigma_c$ at actual strain rate. Show that the equation for the load reads:

$$F = \sigma_c Dh$$

Known as the Korzhavin equation. What do $I$, $K1$, and $K2$ represent?

d) Later several factors are included in this formula:

$$F = IK_1K_2\sigma_c Dh$$

(e) Assume that you are responsible for estimating the ice load on a quay at Bjørnøya. The quay extends 58 m offshore and is 10 m wide. Only piles (0.8 m diameter, 5 meter spacing) protrudes the water level and support the quay. Indicate relevant: i) concerns, ii) investigations to be made.

(f) Propose solutions and make a simple estimation of the ice load when you assume limit load by stress (ice thickness 1.2 m, ice crushing strength 1.8 MPa).

4) Ice loads (1999)

a) The majority of ridges form:
- in the land fast zone?
- in the drift zone?, or
- in the transition zone?

b) The Korzhavin’s formula can be written in the form:

$$F = IK_1K_2\sigma_c Dh$$

You are looking for maximum ice load and therefore you take into account the maximum (during whole the year) values of $\sigma_c$ and $h$. Are you always right?

c) If a structure freezes in (adfreeze), what effect will this have on the ice load?

d) Why are the ice loads on a sloping structure usually less than on vertical structure (consider approximately the same dimension in the water line)? Is this always the case (give reasons for your conclusion)?

e) The main scenarios of ice/structure interaction are: limit stress, limit momentum, limit force, and splitting. Which of them corresponds normally to the maximum ice load? Qualify your answer.

f) What parameters affect the crushing and bending ice strength?

5) Ice loads (2003)

a) Which factors influence ice actions?

b) Which physical events take into account Contact and Indentation factors in the Korzhavin formula?

(c) Why ice actions on sloping structures are less than on vertical ones? Which factors can diminish advantages of sloping structures? What are other advantages of sloping structures?

d) Which factors influence ice action on multi - leg structures?
e) You design multi-leg structure with 9 piles located in 3 rows. The distance between rows is 3 piles diameters. Will be the total action equal to $9F_1$ (where $F_1$ is the action on the single pile) if structure located in moving ice? What action will be if structure located in landfast ice, which begin to move?

f) What does it mean size effect, what are reasons of this phenomenon, why ice sample size effect differs on structure size effect?

g) How actions depend on ice velocity?

h) The mean weight of the gravity structure is 80 MN (coefficient of variation 0.05). The environmental actions are shown in the Table 1.1 (it is proposed that the distribution law of actions is normal).

<table>
<thead>
<tr>
<th>Action</th>
<th>Mean value, MN</th>
<th>Coefficient of variation, (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice</td>
<td>25</td>
<td>0.3</td>
</tr>
<tr>
<td>Wind</td>
<td>2.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Current</td>
<td>5</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Mean friction coefficient structure/sea bottom: - 0.4 (deterministic). Determine the weight of the ballast to reach stability safety (sliding) of 0.99999 (failure probability 0.00001).

<table>
<thead>
<tr>
<th>$P_f$</th>
<th>0.1</th>
<th>0.01</th>
<th>0.001</th>
<th>0.0005</th>
<th>0.0001</th>
<th>0.00001</th>
<th>$3 \times 10^{-6}$</th>
<th>$2.9 \times 10^{-7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>1.28</td>
<td>2.32</td>
<td>3.15</td>
<td>3.3</td>
<td>3.77</td>
<td>4.25</td>
<td>4.5</td>
<td>5</td>
</tr>
</tbody>
</table>

i) Data of number of days with given in brackets negative mean air temperature are shown in Table 1.3.

<table>
<thead>
<tr>
<th>Month</th>
<th>Days (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>November</td>
<td>4 (-5); 3(-8).</td>
</tr>
<tr>
<td>December</td>
<td>3(-20); 8(-15); 5(-10); 6(-7); 2(-4); 8(-2).</td>
</tr>
<tr>
<td>January</td>
<td>6(-25); 5(-20); 4(-15); 10(-10); 4(-5).</td>
</tr>
<tr>
<td>February</td>
<td>8(-26); 7(-23); 6(-10); 7(-7).</td>
</tr>
<tr>
<td>March</td>
<td>7(-15); 6(-12); 6(-10); 5(-5); 7(-3).</td>
</tr>
<tr>
<td>April</td>
<td>8(-10); 6(-8); 5(-2).</td>
</tr>
</tbody>
</table>

Ice salinity per month December 6 ppt, January 5 ppt, February 4 ppt, March 3 ppt and April 3 ppt. Ice strength dependence on temperature and salinity is shown in Table 1.4.
Table 1.4 Ice strength (MPa) depending on mean temperature for 6 days and salinity.

<table>
<thead>
<tr>
<th>T °C</th>
<th>S ppt</th>
<th>-25</th>
<th>-20</th>
<th>-15</th>
<th>-10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
<td>2,2</td>
<td>2,0</td>
<td>1,5</td>
<td>1,2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2,6</td>
<td>2,5</td>
<td>1,9</td>
<td>1,6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4,0</td>
<td>3,0</td>
<td>2,2</td>
<td>1,8</td>
</tr>
</tbody>
</table>

Determine:

Ice thickness to the end of each month (h=1.33 | FDD |0.58 – FDD-freezing degree days).
Maximal ice strength $\sigma_c$ for each month.
Assuming that action on structure is determined by formula $F=\sigma_c h D$,
where D is structure diameter, determine the most dangerous month with maximal ice actions.

j) Compare ice actions on cone and cylindrical structures, which have the same underwater volume. Consider conditions when cone structure advantages will be reduced.

6) Ridge loads on structures (2001)

You are to estimate the maximum global load from floating first/year ridges on a vertical offshore structure.

a) How would you judge the general level of knowledge about loads from first/year ridges?

b) What main parameters of the ridges would you require as input into your model?
1.11 Geotechnical problems

1) Soils (1997)

Geotechnical aspects related to the design of a bottom founded platform structure for operation in the shallow waters of the Pechora and Kara Seas.

The evaluation of a structure’s stability must take into account loads imposed on the seabed as well as the seabed soil conditions.

   a) List the stability evaluations you would conduct for the conceptual design of an bottom founded platform structure.

   For geotechnical purposes the maximum ice loads are evaluated on the basis of a rapid loading scenario. When the seabed soils are found to comprise, fine-grained sediments it is assumed that the undrained shear strength will decide the capacities (silts and clays will not drain under rapid loading).

   b) Describe (and sketch) the conditions in the ground influencing the in-situ undrained shear strength.

   The caisson and the conical types of platform structures are the two basic types of structures proposed for the shallow waters of the Pechora Sea.

   c) Describe and illustrate the seabed failure modes for both types of structures caused by ice loads.
1.12 Project planning

1) Project planning:

We are going to look at the development of an oil field with a gas cap.

a) We will look at the development of an offshore field. Please discuss the work in the earlier phases of development, and the importance of the early phase compared to the costs of the earlier phases.

b) Discuss the effect on the field development in the case you are using:

- Technology that is not documented in the conceptual phase of the project
- Solutions that do not follow the environmental requirements of the government
- Over-optimistic unit rates in cost analysis
- A solution that one contractor has monopoly to deliver.

c) In the detailed engineering phase, there could be calculations errors that can have important consequences later. Please discuss the tools that can be used in this phase to find possible errors.
CHAPTER 2 Solution to Examples to Exercises

2.1 Hydrocarbon Resources and Reserves

1) Resources/reserves evaluation (1998)

a) A. Pre-drilling stage
   The most efficient way of resources estimate is:
   I  Analogy; least accurate, but may be the only method, if there exists similar reservoirs
      with similar age, type of rock sizes etc.
   
   For using other methods more data is required, may be fuzzy (IV) evaluation appears to
   be possible (based on analogy).

   B. Discovery stage
   II Deterministic evaluation, if reservoir/fluid data are available.
   III Probabilistic (Monte Carlo) method is possible to use if statistical data for
      reservoir/fluid properties are available. The method will give volumes associated with
      probability (or chance) of finding them. Most commonly used volumes, called P_{10}, P_{50}
      and P_{90} are associated with chance of discovery equal to 10%, 50% and 90%,
      respectively. According to classification used by SPE, SEC and UN these quantities are
      often referred to as proven (P_{10}), proven + probable (P_{50}) and proven + probable +
      possible (P_{90}) reserves.
   IV Fuzzy evaluation is also possible, more simple and quicker than III.

   C. Delineation/early production stage
   II Deterministic is still available, but hardly efficient.
   III Probability curve gives more narrow cumulative distribution as compared with
      fuzzy estimate.
   IV Fuzzy can also be implemented.
   V Performance analysis is already possible.
   VI Reservoir simulation is advisable.

   D. Mature production
   III Probability (Monte-Carlo).
   V Performance analysis.
   VI Numerical simulation.

   E. Late time depletion/ stage of decline production
   V Performance analysis.
   VII Numerical simulation.

b) 1) Total in place resources (stock tank of oil (gas) originally in place) - both 1) and 2).
   Combination of volumetric estimate and performance analysis is advisable.
2) Recoverable reserves.

Volumetric estimate (1.4) of the total reserves (deterministic or probabilistic) and then, consider present technology development, financial situation, etc. Then estimate how much we can recover at present time. Nowadays average recovery factor is approximately 34% of oil, and much higher in case of gas field development. During production stage – performance analysis can be used.

3) Both total and recoverable.

Total-volumetric: $V = A \cdot h \cdot (N/G) \cdot \phi \cdot S_o \cdot \frac{1}{B_o}$ or $V = \text{RockVol} \cdot (N/G) \cdot \phi \cdot S_o \cdot \frac{1}{B_o}$

Recoverable reserves: $V_{rec} = V \cdot \eta$. NB: recoverable reserves are subject to economic and technical analysis.

where:

$V$ STOOIP;
A area;
h reservoir thickness;
N/G net-to-gross ratio;
$\phi$ porosity;
$S_0$ initial oil saturation;
$B_0$ oil formation volume factor;
$\eta$ oil recovery.

c)

1) In order to find petroleum the following conditions are necessary:

1. **Source rock**, laying deep enough in temperature, sufficient for hydrocarbons maturation.

2. **Migration pathway** – matured hydrocarbons should migrate in some preferable direction, not spreading.

3. Porous and permeable **reservoir** to accumulate hydrocarbons.

4. **Trap** (stratigrafic and structural, like domes and anticlines, which amounts to nearly 75% of all traps).

5. Seal – impermeable cap rock, precluding hydrocarbons from escape.

2)
2.2 Reservoir and Production Engineering

2.3 Field development

1) Field development (2001)

a) The well stream will be treated in order to export rich gas and stable oil.
   To obtain stable oil, several specifications have to be met, i.e. regarding water, pressure, temperature etc. This will be achieved by normal lowering of the pressure through a series of horizontal separators, say three. This will ensure maximum oil recovery and water/gas/solids removal. There may also be hydro cyclones in the process train, combined with systems to minimize oil in the produced water (flotation cells, emulsion breakers etc.) The oil is stored onboard the platform and exported by tankers.
   The gas is recompressed in several stages, and cooled/ scrubbed between stages. Depending on the CO$_2$ and H$_2$S content some amine treatment might be needed. Also, the entrained amount of water should be removed to avoid hydrate problems during export. The unstable condensate is transported with the gas to shore in a rich gas pipeline.

b) The depth at the site is 28 m. Due to the ice regimes in the Pechora Sea; we would propose a gravity-based structure. The structure has to be ice- resistant, preferably with sloped sides to reduce loads from the ice. Also, the structure must provide space for oil storage, and have storage capacity for shorter duration of production without offloading. The topsides structure would need a process plant with the necessary equipment for the above outlined process. In addition, utility systems like seawater, air, thermal system, power generation etc. must be provided. A drilling unit must be present, as well as the accommodation for personnel.
   All wells are supplied with dry X-mas trees, but the process plant has spare capacity for future hook up of satellite fields. The platform must have a system for offloading of oil. It could be considered to use Kvaerner's shuttle/ barge system, with STL- hookup. This means that the platform must provide export pumps.
   The gas is to be pipelined to shore, so adequate export compressors must be provided. Depending on the exploration scheme, systems for produced and/ or seawater injection, as well as gas injection must be present. The safety system is also a mandatory function needed onboard. The unstable condensate will be transported with the gas.

c) Since the field is located in Russian territory, Russian rules and regulations must be followed. However, if this is a company with head office in Oslo, its experience will probably rely on other standards than Russian standards. We would check the design with both standards. This will provide an internationally accepted basis for the design, while exploiting the company's experience with Norwegian standards.

d) Stable oil can be offloaded in several different ways, provided there is storage onboard the platform: Direct loading from platform to shuttle tanker, STL- loading to shuttle tanker, or directly to export tanker in deeper water. Another option would be pipeline export to shore for treatment and cross- country transport to a port for tanker export to the markets. If one wants to reduce the costs of the structure, storage could be removed from the design. Instead, one would need two STL-buoys for continuous production to the shuttle tankers. The gas could be treated on shore, and exported as liquefied natural gas in tankers. A
different field solution, with a wellhead platform, and processing on shore or on a barge near shore would be possible if the water could be taken out at the platform and the mix of oil and gas could go untreated.

2) Arctic offshore field development (1997)

a) Possible field development solution:

Structure form:
With 40 m water depth, we can choose a seabed supported single unit structure with sloping walls.

Location 1:
Those structures will operate in an area 60 km from shore with severe ice conditions. A submerged pipeline will connect this structure to a loading system.

Location 2:
There will be a storage and loading unit 30 km to the northwest where the ice conditions are easier. This unit will be with vertical walls.

Transport:
The transport to the marked is done by tankers (for example Double Acting Tankers, DAT’s) from the storage/loading unit and directly to the marked.

Loading system:
The loading system could be a “submerged loading system”. It can be described as follows:
This submerged loading system works in the way that the tanker pulls in a connection plug, loads the oil and disconnects.

Substructure:
Seabed supported single structure with sloping walls. Some storage volume in the structure.

Topside arrangement:
Facilities for people (live, work, eat…), processing equipment (before sending oil to storage), helicopter deck, utility system (electric generators), wells, etc.

Gas utilization:
Some of the gas to be used for the power generation. The remaining gas to be injected in the reservoir.

b) Discussion

Location:
A solution for the offshore, especially in the Arctic, should be sufficient but as simple as possible. We may assume that the seabed soils are strong enough to give sufficient bearing capacity and resistance against sliding for the structure. A seabed supported single unit structure with sloping walls have the advantage that this type has been built and used before in other projects so it is proven to be sufficient.

Structure:
For the production platform, we could chose a seabed supported single structure with sloping walls because of the water depth (40 m) and sloping walls to minimize the ice loads. We assume the ice will not ad freeze to the structure, because then sloping walls have little advantages vs. vertical walls. A structure with sloping walls will have smaller (insufficient) storage volume so we choose to have storage and loading terminal 30 km to
the northwest. Here the ice conditions are not so severe and we can have a vertical wall structure (assuming water depth – 40 m) with sufficient storage volume.

Transport:
Transport to the marked directly from a loading terminal with DAT. (DAT = Double Acting Tankers.) They act as icebreakers and tankers and can load summer and winter. Advantages here are that the company/ companies can control the transport to the markets themselves. On-shore transport in pipelines through for example Russia or other countries will involve a greater number of uncertainties: expenses to the government, pipeline through permafrost areas and other factors that the companies do not control. The investments in pipelines would be huge. Note: Great emphasis on safety and environmental issues when transporting with tankers.

Loading system:
The submerged loading system is proven to be good. The tanker can connect, load and disconnect during a few hours (fast). It can also connect in rough weather (waves up to 6 m) and load and disconnect in any weather. The tanker can rotate 360 degrees with wind/currents etc. while loading. Ice is not a major problem and the tanker does not need to go all the way close to the structure when loading. An alternative would be Kvaerner's tower loading system with sloping walls.

c) New fields can be exploited with horizontal drilling from the main field or a simple wellhead platform could be located there with a connection to the main field. With a production volume of 30 000 barrels/day, the last suggestion may not be cost-effective. If we go for horizontal drilling, we probably need a bigger structure on the main field for extra equipment and more temporal storage volume. Processed oil from the satellite could still be sent for storage in the original storage/loading unit.

d) The severe ice condition will of course give rise to large structural loads and increased structure costs. The ice conditions also make it difficult to load from the main field. For a similar field in an area without ice, the loading could be done with tankers directly from the production platform. This would not need sloping walls and could have enough storage volume. A pipeline to a storage facility onshore would also be much easier without ice. We would avoid the difficult geotechnical conditions (permafrost etc.) for the pipeline and loading to tankers would be done in a harbor.

The satellite field could be developed with use of subsea units.

3) Field development, sales products

a1) Sales gas does normally only contain the methane and some ethane, while Rich gas contains all the higher components that are in gas form under normal atmospheric pressure, that is the methane, ethane, propane and butane etc.

a2) For Stable condensate there is no emission of gases (no vapor of gases) under 0.8 bar pressure and Stable condensate can be transported under atmospheric pressure, while Unstable condensate contains gases so there will be emission of explosive gases to air in case of transport of Unstable condensate under atmospheric pressure.

b1) Southern North Sea: There was originally a need for sales gas directly to the European market and the gas was processed to sales (dry) gas specification on the Ekofisk platform. The additional product: the unstable oil (containing oil and unstable condensate) was sent in pipeline to England.

b2) Northern North Sea: Statfjord is a major oil field with a gas cap. Initially the stable oil was produced to tanker while the gas was injected. After some years, there was a need to
produce some of the gas to relieve the pressure, and the gas with unstable condensate was piped to Kårstø in Rogaland. At the Kårstø plant the higher gas components (ethane, propane, butane etc.) are extracted while the dry gas is sent in pipeline to the European continent. The other oil fields in the northern North Sea have to follow the same processing scheme as for the Statfjord field.


a) Generally, the balance of energy of a producing well can be written as follows:

\[ W = W_n + W_a = W_{hs} + W_{fr} + W_{gs} + W_{lr} + W_{in} + W_{wh}, \]

where:
- \( W_n \) natural energy of an oil reservoir
- \( W_a \) energy artificially supplied to the reservoir or a well from the surface
- \( W_{hs} \) energy losses due to hydrostatic weight of the gas-liquid mixture
- \( W_{fr} \) friction losses due to a fluid flow in tubing
- \( W_{gs} \) energy losses due to a gas slippage through liquid
- \( W_{lr} \) energy losses due to local resistance to flow
- \( W_{in} \) inertial losses due to fluid acceleration
- \( W_{wh} \) fluid energy at the wellhead.

When \( P_{wh} \geq P_b \), there is no free gas in the well; therefore, the following components, related to the presence of free gas in a liquid, are equal to 0:

\[ W_{gs} = 0; W_{in} = 0. \]

Thus, the balance of energy will be as follows:

\[ W = W_n = W_{hs} + W_{fr} + W_{lr} + W_{wh} \]

b) If the energy is introduced to a reservoir centrally (for example, injection of water through injection wells), then its distribution between production wells takes place directly in the field. Thus, if each specific production well is equipped only with tubing (and there are no mechanical devices to assist the production), the specified way of production is called artificially-natural. In this case the balance of energy should be written down as follows:

\[ W = W_n + W_a = W_{hs} + W_{fr} + W_{gs} + W_{lr} + W_{in} + W_{wh} \]

(2.3)

c) In the third element of this system (intake) division (separation) of material flow takes place: the liquid and a part of the gaseous phases gets into the submersible equipment, while the other part of the gaseous phase gets into the annulus. In this element there is a split of calculations of the pressure distribution in two: (1) in the tubing and (2) in the annulus.

d) The admissible area of production for each standard size of the electric submergible pump is defined by the following condition:

\[ \eta_{1,2} = \eta_{max} - 0.05, \]

(2.4)

where \( \eta_{max} \) – the maximum efficiency of the pump at the optimal production \( Q_{opt} \), see the diagram- Fig. 2.1.

In the diagram, this area is shaded. Thus, the efficient working area of the pump is:

\[ Q_1 \leq Q \leq Q_2 \]
e) The schematic of the jet pump is as follows (Fig.2.2):

![Fig. 2.2 Jet pump – schematic view.](image)

(1 – channel for working agent, 2 – active nozzle, 3 – receiving chamber, 4 – channel for liquid to be injected, 5 – mixing chamber, 6 – diffuser).

The principle of work of a jet pump is as follows:

The working agent with a significant potential energy is brought to the nozzle where there is the transformation of the potential energy of the working agent into kinetic energy. The jet of the working agent from the nozzle reduces the pressure in the receiving chamber, owing to which a part of the injected liquid mixes up with the jet of the working agent and comes into the mixing chamber. In the mixing chamber, the working agent and injected liquid get mixed up, their velocities and pressures get equal and the mixed stream comes into the diffuser. In the diffuser, there is a gradual decrease of kinetic energy of the mixed stream and a growth of its potential energy. When coming out of the diffuser, the mixed stream has a sufficient potential energy to be lifted to the surface.
2.4 Economics of offshore field development

1) Economics of field development (1999)

a) Comparing the physical characteristics of the Pechora Sea and the Grand Banks of Canada.

<table>
<thead>
<tr>
<th></th>
<th>The Pechora Sea</th>
<th>The Grand Banks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Water depth</td>
<td>Shallow waters, 20-50 m</td>
<td>Deeper waters, 80 m</td>
</tr>
<tr>
<td>2. Current</td>
<td>Relevant for drifting ice</td>
<td>Relevant because of depth differences, and iceberg drift</td>
</tr>
<tr>
<td>3. Ice condition</td>
<td>Level ice, ridges</td>
<td>Icebergs</td>
</tr>
<tr>
<td>4. Wind</td>
<td>Relevant for ice flow drift</td>
<td>Relevant for icebergs drift</td>
</tr>
<tr>
<td>5. Wave</td>
<td>Not so relevant during winter, considerable in autumn</td>
<td>May be significant</td>
</tr>
<tr>
<td>6. Geotechnical conditions</td>
<td>Not available</td>
<td>In general hard soil conditions</td>
</tr>
</tbody>
</table>

b) Solution for the Pechora Sea

Main considerations:

1) Arctic environment: Ice loads on the structures and pipelines
2) Shallow water
3) Transportation: Long distance to onshore facilities and difficulties due to moving ice during wintertime.

So the following concept is suggested:

1) Fixed platform with oil storage (6-7 days)
2) Transportation
   a) Tankers: Probably this is the most realistic solution, but there is a need for icebreakers.
   b) Pipelines: Expensive because of long distance to land, need for protection from ridges. Moreover, the oil in the Pechora Sea seems to contain asphalt components and therefore there is a need for heating to provide sufficient flow ability of the oil.

c) Solution for field development on the Grand Banks

Main parameters/critical items:

a) Water depth
b) Icebergs.

Production facilities:

a) Sub sea
b) Floating: Production ships (disconnectable)
c) Large caisson structure (Ref. Hibernia).
Transportation:

a) Pipelines:
   Advantage: Icebergs threat is avoided if the pipeline is trenched sufficiently.
   Disadvantage: Expensive to build and trench pipelines given the water depth.

b) Tankers + mooring system:
   Advantage: Maneuver to avoid icebergs.
   Disadvantage: Limited capacity and need for mooring system.

d) Efficient transportation:

   The Pechora Sea
   a) By tankers (for example by double-acting ships) directly to refineries
   b) To existing onshore pipeline infrastructure. But the existing pipelines infrastructure
      is not sufficient
   Conclusion: Tanker solution may be preferable.

   The Grand Banks
   a) Pipelines
   b) Tanker.

Sub sea development and tanker processing may be is a better option for this area, so the
pipelines seem to be the least option here as well.

e) Information required for economics analysis:

   a) CAPEX- capital expenditure for screening, feasibility, conceptual phases, construction of topside, sub sea units, etc. and installation
   b) OPEX- operation costs (short- term expenses), variable production costs, transportation costs, salaries, maintenance costs
   c) Revenue or annual cash flows generated from the selling of petroleum.

Relevant parameters: oil price, production rate (Cash flow = revenue -OPEX):

\[ NPV = -\sum_i \frac{CAPEX_i}{(1+r)^i} + \sum_i \frac{C_i}{(1+r)^i} \]  

Table 2.2

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX</td>
<td></td>
<td>CAPEX₁</td>
<td>CAPEX₂</td>
<td>CAPEX₃</td>
<td></td>
</tr>
<tr>
<td>Revenue</td>
<td></td>
<td>R₃</td>
<td>R₄</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPEX</td>
<td></td>
<td></td>
<td>O₅</td>
<td>O₆</td>
<td></td>
</tr>
<tr>
<td>Cash flow</td>
<td></td>
<td>C₃</td>
<td>C₄</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPV</td>
<td>(\frac{CAPEX₁}{1+r})</td>
<td>(\frac{CAPEX₂}{(1+r)^2})</td>
<td>(\frac{CAPEX₃}{(1+r)^3} + \frac{C₃}{(1+r)^³})</td>
<td>(\frac{C₄}{(1+r)^4})</td>
<td></td>
</tr>
</tbody>
</table>

Where \(r\) is the discount factor, which is equal to the required rate of return determined by
the company. (As a rule, taken as the rate of return from similar projects. In offshore \(r \approx 10\)
to \(15\%).
2) Economics of offshore field development (1998)

a) Challenges for development in the Arctic:

1) Ice loads and icebergs and strong ridges as well as strong wind and extremely low temperature. To solve this problem we should use or choose the proper shape of the support structure. For these structures, (depending on depth, and seabed conditions) ice loads should be approximately equal to wave forces. As known for structures with a given storage volume, wave loads are higher for sloping structures and smaller for vertical ones, for ice loads it is opposite. So, structures with sloping sides of ~ 70° or vertical are useful and can be used in Arctic.

2) Cost considerations. It is very expensive to fabricate an offshore structure at the site. So, it is necessary to fabricate all installations onshore. Attention should also be paid to transportation of structures to the oil field Draught has to be estimated and taken into consideration.

3) The area of an oil field is often very large and to produce as much oil as possible, one has to drill several wells to reach and involve the larger area of the field. For this purpose horizontal wells are used. We cannot drill wherever we want as we do onshore and it is very expensive to install new platforms on the site. Multi-well drilling is used on platforms in the Arctic.

4) Environmental aspects. Very sensitive to pollution in Arctic. Very difficult to collect all oil spills in presence of ice.

5) Lack of experience, technologies, and equipment for exploration and development of Arctic offshore. Only with the help of authorities and world famous oil companies, using their experience and technology, it is possible to develop field in these areas.

6) The time window free of ice in the Arctic is short. Almost 230 days/year the sea is covered by ice. It makes it very important to use ice- breaker assistance for tankers to reach the platform. The DAT (double acting tankers) concept could be used, new types of technology, like STL and loading structures must be considered.

7) Pipelines. Should develop flexible concept, of pipeline for STL systems. Sometimes it is necessary to bury pipelines below the seabed because of stamuchas and ridges.

8) Very severe climate, low temperatures. Expensive transport of personnel far away from coast.

b)

1) Water depth 2-10 m. Concept of Artificial island should be considered, but proper material should be used and ice loads as well as scouring have to be taken into consideration. Wave action could lead to failure, special type of soils to be used. Impossible to use tankers near to island.

2) Water depth: 10-20 m. Concept of Berm-supported multi unit structure could be considered. Unable to use tanker for transportation or storing of oil. Much installation work must be carried out at the site, which makes it very expensive.

3) Water depth 20-35 m. Concept of Berm-supported single structure could be considered. Requires less time, can be fabricated in a yard and be installed in short period. Possible to use small or middle size tankers for transportation.
4) Water depth 35 - 50 m. Seabed-supported single structure. We can use larger tankers, but the volume of the structure may not be enough to store the oil. Some preparations of the seabed are required. But can be installed very rapid.

c) 

\[ NPV = \sum_{t=1}^{N} \frac{NCF_t}{(1 + k)^t} \]  

(2.6)

where 

- NPV presents the cash flow by today;
- \( k \) is discount rate;
- \( t \) number of years;
- \( \frac{1}{(1 + k)^t} \) discount factor;

- \( NCF_t \) net cash flow for a certain year.

IRR is the value of the discount rate, which makes NPV equal to zero. If IRR is lower than a certain value, the discount rate NPV becomes negative.

Cash flow = + price, production
- operating costs
- investment capital
- government take.

d) 

<table>
<thead>
<tr>
<th>Year</th>
<th>1998</th>
<th>1999</th>
<th>00</th>
<th>01</th>
<th>02</th>
<th>03</th>
<th>04</th>
<th>05</th>
<th>06</th>
<th>07</th>
<th>08</th>
</tr>
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<tbody>
<tr>
<td>Investments</td>
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<td>-100</td>
<td>-100</td>
<td>-100</td>
<td>-100</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Earnings</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N_{PV_d} )</td>
<td>-100</td>
<td>-100</td>
<td>-100</td>
<td>-100</td>
<td>-100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ NPV_d = -100 - \frac{100}{1,1} + \frac{200}{1,1^2} - \frac{200}{1,1^3} + ... + \frac{200}{1,1^{10}} = 164,85 \]

Discount rate = 10%; discount factor = \( \frac{1}{(1 + 0,1)^t} \)

e) 

<table>
<thead>
<tr>
<th>Year</th>
<th>1998</th>
<th>1999</th>
<th>00</th>
<th>01</th>
<th>02</th>
<th>03</th>
<th>04</th>
<th>05</th>
<th>06</th>
<th>07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investments</td>
<td>-100</td>
<td>-100</td>
<td>-150</td>
<td>-150</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earnings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( N_{PV_e} )</td>
<td>-100</td>
<td>-100</td>
<td>-100</td>
<td>-100</td>
<td>-100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \begin{align*} 
\text{Table 2.3} \\
\text{Year} & \quad 1998 & 1999 & 00 & 01 & 02 & 03 & 04 & 05 & 06 & 07 & 08 \\
\text{Investments} & -100 & -100 & -100 & -100 & -100 & & & & & & \\
\text{Earnings} & & & & & & 200 & 200 & 200 & 200 & 200 & 200 \\
\text{\( N_{PV_d} \)} & -100 & -100 & -100 & -100 & -100 & & & & & & \\
\end{align*} \]
NPV = 205. NPV_e > NPV_d; NPV_e is better but we have to calculate IRR to say exactly how does it change. To estimate the reality of the project we need the IRR.

3) Economics of offshore field development (1997)

a) Net present value (NPV): This is the sum of the future earnings from a project minus all costs (investments + operating costs etc.) presented in today’s value (e.g. 1997- US dollars)

NPV> 0 The project is profitable expressed in money value.
IRR: Depends on inflation and gives the real rate of return.
This is the percentage/ interest which gives the NPV = 0 and is expressed in %.

b) NPV (2000): Real discount rate: 10%.

\[
\text{NPV of Invest} = 50 + 50 \cdot \frac{1}{1,1} + 150 \left( \frac{1}{1,1} \right)^2 + 2500 \left( \frac{1}{1,1} \right)^3 + 2500 \left( \frac{1}{1,1} \right)^4 + 100 \left( \frac{1}{1,1} \right)^4 \\
\quad + 300 \left( \frac{1}{1,1} \right)^5 + 300 \left( \frac{1}{1,1} \right)^6 + 300 \left( \frac{1}{1,1} \right)^7 = 4383,1M \ NOK \ (2000)
\]

Operating costs:

\[
\begin{align*}
\text{2003} & \quad (50 + 50 + 150) \cdot 0,05 & = 12,5 \\
\text{2004} & \quad (250 + 2500) \cdot 0,05 & = 137,5 \\
\text{2005} & \quad (2750 + 2500 + 100) \cdot 0,05 & = 267,5 \\
\text{2006} & \quad (5350 + 300) \cdot 0,05 & = 282,5 \\
\text{2007} & \quad (5650 + 300) \cdot 0,05 & = 297,5 \\
\text{2008} & \quad (5950 + 300) \cdot 0,05 & = 312,5 \\
\text{2009} & \quad -- " -- & = \quad \text{7} \times 312,5 \\
\text{2015} & \quad = \\
\end{align*}
\]

NPV of: Operating costs = :12,5 \left( \frac{1}{1,1} \right)^3 + 137,5 \left( \frac{1}{1,1} \right)^4 + 267,5 \left( \frac{1}{1,1} \right)^5 + 282,5 \left( \frac{1}{1,1} \right)^6 
\quad + 297,5 \left( \frac{1}{1,1} \right)^7 + 312,5 \left( \frac{1}{1,1} \right)^8 + 312,5 \left[ \left( \frac{1}{1,1} \right)^9 + \left( \frac{1}{1,1} \right)^{10} + ,+, \left( \frac{1}{1,1} \right)^{15} \right] = 1378M \ NOK
\]

NPV of: Income = \left( 40000 \cdot 15 \cdot 365 \right) \left( \frac{1}{1,1} \right)^5 + \left( 80000 \cdot 15 \cdot 365 \right) \left( \frac{1}{1,1} \right)^6 
\quad + \left( 120000 \cdot 15 \cdot 365 \right) \left( \frac{1}{1,1} \right)^7 + \left( 120000 \cdot 15 \cdot 365 \right) \left( \frac{1}{1,1} \right)^8 + \left( 120000 \cdot 15 \cdot 365 \right) \left( \frac{1}{1,1} \right)^9 + 120000 \cdot 15 \cdot 365 \left( \frac{1}{1,1} \right)^{10} 
\quad + \left( 100000 \cdot 15 \cdot 365 \right) \left( \frac{1}{1,1} \right)^{11} + 80000 \cdot 15 \cdot 365 \left( \frac{1}{1,1} \right)^{12} + \left( 60000 \cdot 15 \cdot 365 \right) \left( \frac{1}{1,1} \right)^{13} + 40000 \cdot 15 \cdot 365 \left( \frac{1}{1,1} \right)^{14} 
\quad + \left( 2000 \cdot 15 \cdot 365 \right) \left( \frac{1}{1,1} \right)^{15} = 2069,3M \ US$= 14,485M \ NOK
\[ NPV = 14485 - 1378 - 4883 \text{ M NOK} = 8724 \text{ M NOK} \]

c) NPV (20%) of investments = 50 + 50 \left( \frac{1}{1.12} \right) + 150 \left( \frac{1}{1.12} \right)^2 + 2500 \left( \frac{1}{1.12} \right)^3 + 2500 \left( \frac{1}{1.12} \right)^4 \\
+ 100 \left( \frac{1}{1.12} \right)^4 + 300 \left( \frac{1}{1.12} \right)^5 + 300 \left( \frac{1}{1.12} \right)^7 = 3201.2 \text{ M NOK} 

NPV of operating costs = 
12.5 \left( \frac{1}{1.12} \right)^3 + 137.5 \left( \frac{1}{1.12} \right)^4 + 267.5 \left( \frac{1}{1.12} \right)^5 + 282.5 \left( \frac{1}{1.12} \right)^6 + 297.5 \left( \frac{1}{1.12} \right)^7 + 312.5 \left( \frac{1}{1.12} \right)^8 \\
+ 312.5 \left[ \left( \frac{1}{1.12} \right)^{9\text{th}} \right] = 693.3 \text{ M NOK} 

NPV of income: 982M US $ = 6874 \text{ M NOK}.
\[ NPV(20\%) = 6874 - 693 - 3201 = 2980 \text{ M NOK} \]

I would guesstimate the IRR of the project to be between 25-30%.

d) Improvement:
Generally, the earlier the income starts, the better. If studies, exploration, fabrication etc. could be done in shorter time, it would benefit the project because production could start earlier. We also see that in the last 5 years of the production the operating costs is larger than the income. One could discuss an earlier shut down of the production if better technology does not make it possible to maintain a production of around 100 000 barrels/day.

4) Economics of field development (2001)

a) Before deciding to develop a field, we calculate the ultimate cash flow \( C_S \) we will earn in the case of success and the cost of failure \( C_F \). We decide to develop the field if we have:
\[ C_S S > C_F F, \quad (2.7) \]

where
- \( S \) probability of success;
- \( F \) probability of failure.

Then for each year we can estimate the net cash flow:

Income
- Investments
- Operation costs
- Transports costs
- Taxes

\[ = \text{ Net cash flow} \]
By summation of the present value of the net cash flow for each year of the field. Development using a discount rate \( i \), we get the net present value of the project. If the NPV (Net present Value) is positive, the field development is profitable.

The value of \( i \) that makes NPV = 0, is called the Internal Rate of Return. Oil companies set requirements to \( i \) for going on with a new project.

In the investment period, the amount of money spent can be high. Some oil companies set requirements to maximum capital exposed or the repayment period for the investments.

b) We have

\[
NPV = \sum_{n=a}^{N} \frac{\text{Net cash flow}}{(1+i)^n},
\]

(2.8)

where

\( N \) total number of years;

\( i \) discount rate (interest rate + inflation + min. earning rate of company).

c) Cost figures in Mill US $

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7→10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income</td>
<td>600</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>600</td>
<td>600</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment</td>
<td>10</td>
<td>100</td>
<td>1000</td>
<td>1000</td>
<td>100</td>
<td>-</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operation costs</td>
<td>100</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>100</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Present value</td>
<td>-10</td>
<td>-100</td>
<td>-1000</td>
<td>-1000</td>
<td>-200</td>
<td>500</td>
<td>-</td>
<td>500</td>
<td>500</td>
<td>-300</td>
</tr>
</tbody>
</table>

Net present value = NPV = sums of annual present values.

d) An early income will be more valuable than the later one (its present value will be higher):

Present value:

\[
\text{year 5: } \frac{\text{income}}{(1+i)^5} > \text{present - value - year 15: } \frac{\text{income}}{(1+i)^{15}}
\]

(2.9)

So the more early income we have, the more profitable is the development. But the most profitable solution might not be to produce as much as possible quickly, as the total production may be lower. Maximizing the gas and oil production normally provides for the best economy and may be a requirement from the government of a country.
### 2.5 Transport

#### 1) Transport of hydrocarbons in the Arctic (2000)

a) Prior to ship transport (under atmospheric pressure), oil or condensate has to be processed to a stable product (under 0.8 bar pressure) in order to avoid emission of explosive gases. The remaining product consists of sales gas and unstable condensate. The unstable products have to be extracted and can be shipped in carriers under pressure.

b) Technical solutions for loading of stable product to a ship in the Arctic:

<table>
<thead>
<tr>
<th>Technical solution</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct loading from the production platform</td>
<td>Offloading takes place close to other operations</td>
<td>Possibility for collision between ship and platform</td>
</tr>
<tr>
<td>Loading via a loading tower</td>
<td>Loading can take place in deeper waters</td>
<td>Possibility for collision</td>
</tr>
<tr>
<td>Loading via a loading buoy</td>
<td>Supposed to be a simple system</td>
<td>The ship might drift off location and destroy loading buoy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The loading buoy might not withstand the ice-forces</td>
</tr>
<tr>
<td>Loading via STL</td>
<td>Disconnection is immediate if there are problems</td>
<td>The riser to the STL must be designed for forces from drifting ridges</td>
</tr>
</tbody>
</table>

c) Aspects related to the design of a ship for transport of hydrocarbons from Arctic icy waters to a Western European Refinery:

- The transport will partly be in ice and partly in open waters. The distance to be sailed in open waters is very long and during parts of the year there is no ice. It may be very inefficient to sail all distance with a ship having ice-breaking capability.
- The transport is normally carried out with large ships and the risk involved in transporting in the ice environment may favor use of less ships.
- Some of the Arctic fields are located in relatively shallow waters. This will limit the size of the tankers that can approach the areas.

The resulting solution may be represented by:

- Use of special built vessels with ice-breaking capability for the stretch where ice occurs, use of the Double Acting Tanker might be an interesting concept.
- Use breaking assistance during winter months with large amounts of ice.
- Transfer to larger ships in ice-free waters or ports.

d) The main technical problems associated with pipeline transportation in the Arctic are the following:
1. Installation has to take place over a short ice-free season, of which the weather during the late months during the autumn may prohibit pipe-laying operations.

2. Design of pipelines in water depths less than 15m (20m) for interaction with ice ridges, define the necessary trenching depth.

3. Abrasion of the shoreline in the permafrost zone caused by melting during the summer season.

4. Onshore pipes must be designed so that they do not heat the permafrost, the can be put on pillars or on gravel beds, depending how warm they are.

5. The river crossings represent particular challenges, again due to the very large rivers of the Arctic, the ice conditions and the unstable banks caused by abrasion due to melting permafrost.

e) The economics of a shipping company.

Assume that the investment in one (smaller) shuttle tanker for Arctic waters is US $50 millions (this year, year zero). The amount of oil (m³) this tanker must transport every week (one shipload per week, 45 weeks every year) in the next 4 years is “X” if all investments shall be repaid by the end of year 4 (NPV=0 at end of year 4).

We assume a discount rate of 10%, a transport fee of US $ 1.50 per barrel of the oil and operations cost for the shipping company of US $ 0.70 per barrel.

<table>
<thead>
<tr>
<th>Year number</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expenditures, US $</td>
<td>50.000.000</td>
<td>4,2x&quot;X&quot;x45</td>
<td>4,2x&quot;X&quot;x45</td>
<td>4,2x&quot;X&quot;x45</td>
<td>4,2x&quot;X&quot;x45</td>
</tr>
<tr>
<td>Income, US $</td>
<td>0</td>
<td>9x&quot;X&quot;x45</td>
<td>9x&quot;X&quot;x45</td>
<td>9x&quot;X&quot;x45</td>
<td>9x&quot;X&quot;x45</td>
</tr>
<tr>
<td>Discounted net income (NPV), US $</td>
<td>-50.000.000</td>
<td>216x&quot;X&quot;/1,1</td>
<td>216x&quot;X&quot;/1,1²</td>
<td>216x&quot;X&quot;/1,1³</td>
<td>216x&quot;X&quot;/1,1⁴</td>
</tr>
</tbody>
</table>

Note: Transport fee is 1,5 US $ per bbl, this amounts to 9 US $ per m³.

The resulting equation becomes:

50.000.000 = (196,4 + 178,5 + 162,3 + 147,5) x “X”

50.000.000 = 684,7 x “X”

The amount of oil (m³) this tanker must transport every week is “X” = 73.024,7 m³, which is equivalent to 483.150 bbl per week or 69.000 bbl per day.

f) The NPV for the company if the transport can go on smoothly as suggested in question item e) above for 8 years will be the Net present value of the income from the operations in years 5 to 8:

\( (216x"X"/1,1⁵ + 216x"X"/1,1⁶ + 216x"X"/1,1⁷ + 216x"X"/1,1⁸) \)

\( = (134,1 + 121,9 + 110,8 + 100,7) \times 73.024,7 = 34,14 \) M US $
2.6 Structures

1) Design of offshore structure (1999)

   a) We divide the loads into groups because the loads have different properties, time of action, and probability of appearance.

   The different codes classify loads in different ways, but it is most common to use the following four groups:

   1) Permanent loads (weigh of structure etc.)
   2) Long-term loads (weight of equipment)
   3) Short-term loads (wave, wind, etc.)
   4) Accidental loads (collisions, etc.).

   b) 
   1) Wave and ice loads; the combination is not likely since ice reduces the wave effect. Local effects of floating ice floes in waves may be considerable, though.
   2) Earthquake and collision loads; the combination is not so likely.
   3) Maximum wave and max wind; the combination of max wave and max wind is likely since these two factors are dependent. Wind is a major cause of wave, so max wind may generate max wave.

   c) We should use the parameters corresponding to a max load with the probability of occurrence in 100 years (as suggested in codes.).

   d) The value of the safety factor for permanent loads is equal to 0.95.

   e) The code considers the most critical states. In case of ice load it is the limit stress case, since it corresponds to the max. load from ice.

   f) It is best to minimize the total costs or maximize the NPV (the solutions are expected to be similar) A combination could be used.


   a) Requirements to offshore structures?

      They should be:
      - Little sensitive to local damage
      - Easy prepared
      - Need minimal work in the installation place
      - Do not contain elements with stress concentration
      - Resistant to corrosion
      - Easy monitored and prepared
      - Removable.

   b) Which factors should be taken into account during the structural design?

      - Importance of the structure. Corresponding structures can be divided in several groups
      - The time of the structure’s life
      - Limit states: the conditions that can lead to the structure damage or restrict its normal use
      - Influence of the structure damage on the life and function of the whole object
      - Estimation of expenditure for the structure’s operations.
2.7 Loads

1) Model scaling (1998)

a) The law of similitude requires that all dimensions of the model will be scaled by the same factor.

Similarity satisfied when:

\[ L_{fs} = \lambda \cdot L_{ms}, \]  

(2.10)

where

- \( L_{fs} \) is length of full scale;
- \( L_{ms} \) is length of model scale;
- \( \lambda \) is constant.

b) \( F_r \) is Froude number;
- \( R_e \) is Reynolds number;
- \( C_h \) is Cauchy number;
- \( u_{fs}, u_{ms} \) is velocity of full scale and model scale, respectively;
- \( \nu_{fs}, \nu_{ms} \) is full/ model scale, viscosity;
- \( L_{fs}, L_{ms} \) is length of full/ scale model;
- \( S_{fs}, S_{ms} \) is density of water for full/ scale model;
- \( E_{fs}, E_{ms} \) are elasticity modules;
- \( g_{fs}, g_{ms} \) gravity acceleration (full/ scale model).

c) To satisfy both the Froude and the Reynolds numbers simultaneously, is impossible because of the different order in the cases.

\[ F_r^2 = \frac{v^2_{fs}}{g_{fs} L_{fs}} \iff R_e^2 = \frac{L^2_{fs} u^2_{fs}}{\nu^2_{fs}} \]

(2.11)

The most important is to satisfy Froude similarity. Froude number must be the same as in the full scale, gravitational, and elastic forces contribute significantly to the ice forces.

d) \[ F_{fs} = \frac{\rho_{fs} \lambda^3}{\rho_{ms}} \cdot F_{ms}; \text{ force scale} \]

Time and velocity should be scaled by \( \lambda^{\frac{1}{2}} \).

2) Actions (2003)

a) 1 group permanent loads
- it includes dead and deformation loads (in some codes e.g. DNV, deformation loads are considered as a special group) includes the loads those levels do not change during the structure life: weight of structure, weight of permanent equipment, permanent ballast, permanent portion of hydrostatic pressure. Deformation loads includes loads due to: pre-stressing, creep and shrinkage, temperature change and gradient, differential settlement, foundation stiffness variation.
2 group variable loads
includes loads associated with operations and normal activities in the design phase under consideration and includes both static and dynamic components of loading. (CAN/CSA - operational loads, in API - Dead loads 2, and Life loads 1 and 2, DNV-Variable functional loads).
the occupancy and operation of the structure; the storage of materials; crane operations; helicopter operations; the fendering and mooring of vessels; variable ballast; differential hydrostatic pressure.

3 group environmental loads
includes static and dynamic components caused by the frequent: winds; waves; currents; tide and tide currents; storm surges and seishes; sea ice and icebergs; snow and ice accumulation and rare events: earthquake; icebergs and other rare ice features; tsunamis.

4 group accidental
is based on the accidental events and includes loads formed due to: collision; explosion; dropped objects.

b) The limit state methodology proposes that there do exist some utmost situations in structure design and in these situations action never should exceed the resistance to this action.

Most Codes consider two categories of limit states: ultimate limit states (ULS) and serviceability limit states (SLS). Ultimate limit states have been defined as conditions precluding future use of the structure. The other category-serviceability limit states is concerned with conditions that restrict the normal use and occupancy of the structure. According to different Codes the following factors can lead to the ultimate limit state formation:

- The loss of equilibrium of the structure or part of the structure, considered as a rigid body
- The loss of the action carrying capacity of structural elements or of the foundation due to material strength being exceed, buckling, fatigue damage, fire or deformation
- The overall instability of the structure
- The transformation of the structure into a mechanism (i.e. plastic collapse)
- Loss of free drifting
- Sinking.

The serviceability limit states can be induced by:

- The deflection or rotation of structural elements that adversely affect the use of a part of the structure or the operation of equipment
- Motion, vibration that adversely affects the comfort of the occupants or the operation of equipment
- Local damage (e.g. cracking, splitting, spalling, local yielding, slip of connections) that adversely affects the use or durability of the structure
- Displacements or deformations of the structure or the foundation that adversely affect the use of the structure or the operation of equipment
- Corrosion that reduces the durability of structure and affects the properties and geometrical parameters of structural and non-structural components.

Some Codes uses a more detailed division of the limit states, namely, besides the two discussed above it suggests considering the Fatigue Limit State (FLS) which refer to cumulative damage due to repeat actions typically from wave or ice actions and the
Progressive Collapse Limit (PCL—according to DNV) or Accidental Limit State (ALS according to EN ISO). This limit should be analyzed for two situations—damaged conditions and abnormal effect. The intention of this limit is to ensure that the structure can tolerate accidental and abnormal events and, where damage occurs, subsequently maintains structural integrity for a sufficient period under specified environmental conditions to enable evacuation to take place.

c) The return period is the average time interval (usually in years) between the occurrences of an event exceeding a specified magnitude.

Actions, which can act simultaneously, should be collected in the actions combinations. These combinations take into account probability of their joint action. These combinations shall be applied to the structure to determine the most severe action effect.

Environmental and accidental actions have stochastic character. In the limit state method the designed level of all these actions depends on the used probability of annual exceedance. This period depends on the return period of the event, on the structure class and stage of the structure life. For structures design the following probabilities are used: frequent environmental processes $10^{-2}$ 1/year; rare environmental process—within the range of $10^{-4}$ to $10^{-3}$ /year; accidental actions—within the range of $10^{-4}$ to $10^{-3}$ /year.

Very often probability of exceedance of the event is considered instead of probability of action.

d) Environmental action actions should be divided on stochastically dependent, independent and mutually exclusive.

The principle environmental process with probability of exceedance $10^{-2}$ and coefficient of combination-1 should be combined with frequent dependent process with coefficient 1 and independent processes with coefficient 0.6. The rare dependent and independent processes have combination coefficients 0.8 and 0.4 correspondingly.

e) 1)  
- Importance of the structure  
- The time of the structure life  
- Limit states: the conditions that can lead to the structure damage or restrict its normal use  
- Influence of the structure damage on the life and function of the whole object.

2) To the first group.

3) The structure function, location of place of exploitation, environmental conditions in this area, place of possible fabrication and facilities of plant.

4) $10^{-2}$ /year for frequent environmental processes; $10^{-4}$ to $10^{-3}$ /year for rare environmental processes, $10^{-4}$ to $10^{-3}$ /year for accidental actions.

f) Action coefficients take into account imperfection of our knowledge of action. Following factors should be taken into consideration:

- Possibility that actions may deviate from characteristic values
- Possibility for different actions in combination, to reach characteristic value at the same time
- Possible inaccurate calculation of action effects.
Use of these coefficients should consider the most severe situations. Coefficients can be more or less than 1. For example if probability of structure sliding along sea bed is considered then structure weight should be used with coefficient which is less than 1, but soil bearing capacity is considered then it should be more than 1.

g) The following factors should be taken into account:
- Possibility that the strength of samples or the soil bearing capacity may deviate from the characteristic values
- Possibility that local strength of structure changed due to construction process
- Peculiarity of local conditions in the place of the structure exploitation.

h) The limit state conditions are written in the form:
\[
\frac{R}{\gamma R} \geq L \gamma_l, \tag{2.12}
\]
Where
- \( R \) is designed resistance;
- \( L \) is designed load;
- \( \gamma R \) is safety coefficient.

i) The disadvantages of the limit states method are as follows:
- Environmental conditions are known very approximately and they have stochastically nature
- Our methods of action and resistance design are very rough
- Both uncertainty environmental conditions and roughness of design methods determine uncertainty of result of calculations
- Coefficients of actions combination do not take into account the level of our knowledge and the same safety factors are used in all situations
- Only result yes or not (the structure is acceptable or not) can be obtained in result of calculations. But in reality always exist some probability that structure will be destroyed as well as probability that structure will endure actions.

j) Risk is expression of probability and the consequences of an accidental event. Different risks of damage can be admitted to structures of different classes. Methodology gives possibility to a systematic evaluation of risk to people, the environment and to and financial interests.

The task of the methodology: to estimate level of risk for any particular structure in any particular conditions, to make decision about acceptance of the level of risk and to consider the ways of risk minimization.

k) If several loads are considered as stochastic and if mean value \( M_i \) and standard deviation \( \sigma_i \) are known for any component. How the common action can be determined?

When actions are combined the each component is considered as acting independently of others. If each of them can be characterized by the mean value \( M_i \) and standard deviation \( \sigma_i \), then characteristics of the total action \((M_L, \sigma_L)\) are determined by formulas:
\[
M_L = \sum M_i, \quad \sigma_L^2 = \sum \sigma_i^2 \tag{2.13}
\]
If all loads $i$ are distributed normally then total load is distributed normally as well. But even if they have another distribution but number of loads is sufficient and their level do not differ significantly of each other then the total load is distributed normally as well.

1) $10^{-4} - 10^{-6}$ in average $10^{-5}$. 
2.8 Waves

1) Waves (1999)

a) Waves: It is important to determine the wind speed, time of action, and fetch (how long is the distance). On a longer distance, wind can create much greater waves, than on a short one. To determine the wave load we need to know “type of waves”. As waves are breaking, when they are coming closer to shore, we need to know what the depth is.

b) Waves have their own “frequency of motion”. It is dangerous if we have a dynamic structure (offshore construction). There are effects of resonances if the frequency of the structure is close to the wave frequency. Large loads, big damage.

c) $C_d$ is the drag coefficient. We write $|u|u$ to show that we have a force, which has a direction (“+” , or “-” in the equation). In square-power “minus” can “disappear”.

d) The Keulegan-Carpenter number accounts for generation of whirls in the fluid flow.

2) Waves (2000)


a) There are 3 states:

*The design wave* (Statistical method).

This wave can be specified by the wave height, period and direction. Different combinations of wave heights periods and directions at the same probability shall be considered in order to arrive the most unfavorable combination and action effects.

*Design wave state* (Spectral method).

Wave height, period and direction shall be combined in the same probability of exceedance. Practically the spectral method is used. The spectrum gives correlation between the wave energy for each wave frequency.

*Long-term variation of waves* (in Russian code-function of wave regime).

Variation of sea state during the long time period can be combined in several groups Variation of sea state during the long time period can be combined in several groups with stationary sea states with associated probability of occurrence Alternatively it can be represented as several wave height groups. Each group is characterized by wave height and period and number of waves in the group. So these data are useful for statistic, determination of PDF and fatigue computation.

b) Wave spectrum characterizes distribution of wave energy versus wave frequency. Its use is especially important when actions on compliant structures are determined because it gives possibility to consider resonant.

c) During wave interaction with complained structure the wave with maximal parameters can be not the most dangerous. Very often the more dangerous can be the wave with lower height but with the period, which is close to the natural structure period. To determine the most dangerous situation the spectral method is used: the wave is characterized by energy spectrum. This function together with the dependence, which characterizes the structure response on action of waves with different periods and unit height, gives possibility to determine the worst combination.
2.9 Ice mechanics

1) Ice mechanics (2001)

a) $\varepsilon^e$ corresponds to the elastic behavior. The bondings between molecules are stretched, but not broken.

$\varepsilon^d$ corresponds to the situation, where the deformations in the crystal lattice does not go back to the original configuration immediately, but does so after some time.

$\varepsilon^v$ corresponds to viscous behavior. This part of the strain is not recovered, and the molecules remain in a different configuration after the loading is stopped. This gives the ice a permanent deformation.

b) 

$$\varepsilon^{\text{tot}} = \varepsilon^e + \varepsilon^d + \varepsilon^v$$  \hspace{1cm} (2.14)

It is said at the vertical axis of Fig. 1.1 that only $\varepsilon^d$ is shown. The term $\varepsilon^d$ in (1.4) must therefore refer to Fig. 1.1. The rheological representation refers to a ”spring and dashpot” system.

c) From the model above it can be seen that

$$\sigma = \sigma_s + \sigma_d$$  \hspace{1cm} (2.15)

where

$$\sigma_s = E \varepsilon$$  \hspace{1cm} (2.16)

$$\sigma_d = \eta \varepsilon$$  \hspace{1cm} (2.17)

$$\sigma = E \varepsilon + \eta \varepsilon = (E + \eta \frac{d}{dt}) \varepsilon$$ \hspace{1cm} Integrate

$$\sigma t = (Et + \eta) \varepsilon$$

$$\sigma = (1 + \frac{\eta}{Et}) E \varepsilon$$

$$\sigma = \frac{G}{E} (1 + \frac{\eta}{Et})^{-1}$$

$$\sigma = \frac{G}{E} (1 - e ^{-\frac{E}{\eta} t}) \hspace{1cm} (2.18)$$

d) 

$E = 9 \cdot 10^9 \text{ Pa}$

$\sigma = 800 \cdot 10^3 \text{ Pa}$

From Fig. 1.1: $\varepsilon^d = 6 \cdot 10^{-5}$ for $t = 410$ s

$$\varepsilon^d = \frac{\sigma}{E} \left(1 - e ^{-\frac{E}{\eta} t}\right) \hspace{1cm} \text{(2.19)}$$

$$\frac{\varepsilon^d E}{\sigma} - 1 = -e ^{-\frac{E}{\eta} t}$$
\[ \ln \left( 1 - \frac{\varepsilon^d E}{\sigma} \right) = -\frac{E}{\eta} t \]

\[ \eta = -\frac{Et}{\ln \left( 1 - \frac{\varepsilon^d E}{\sigma} \right)} \]

\[ \eta = -\frac{9 \cdot 10^9 \cdot 410}{\ln \left( 1 - \frac{6 \cdot 10^{-5} \cdot 9 \cdot 10^9}{800 \cdot 10^3} \right)} = 3,69 \cdot 10^{12} \]

\[ \eta = 3,3 \cdot 10^{12} \]

e) 2 min = 120 s
20 min = 1200 s

\[ \varepsilon^d(t) = \frac{\sigma}{E} \left( 1 - e^{-\left( \frac{E}{\eta} \right) t} \right) \]

\[ \varepsilon^d(t) = \frac{800 \cdot 10^3}{9 \cdot 10^9} \left( 1 - e^{-\frac{9 \cdot 10^9}{3,3 \cdot 10^{12}} t} \right) = 8,89 \cdot 10^{-5} \left( 1 - e^{-2,73 \cdot 10^{-3} t} \right) \]

\[ \varepsilon^d(120) = 2,48 \cdot 10^{-5} \]

\[ \varepsilon^d(1200) = 8,55 \cdot 10^{-5} \]

Average strain rate, \( \dot{\varepsilon}_{avg} \):

\[ \dot{\varepsilon}_{avg} = \frac{8,55 \cdot 10^{-5} - 2,48 \cdot 10^{-5}}{1200 - 120} = 5,6 \cdot 10^{-8} \]

This strain breaks some bondings, but the added energy from the stress is saved as energy in the crystal lattice. Since the strain is delayed elastic, the lattice will eventually recover its original shape.

2) Ice mechanics (2000)
2.10 Ice Loads

1) Ice loads (1997)

a) Limit stress:
When a structure (i.e. a platform leg) is frozen in and the driving force moving the ice sheet is big large, the ice will be crushed against the structure. The load will then be determined by the strength of the ice, the limit ice stress.

Limit momentum:
If an isolated ice floe/ iceberg interacts with the structure, the factors determining the load will be the size (mass) of the ice x velocity (wind/ current induced).

Limit force:
If the force driving the ice (wind, current) is not strong enough to crush the ice against the structure, the force will be determining the loads.

Splitting:
Due to faults/ weak areas in the ice (it is not homogenous) a floe etc. can split along this weak zone before crushing.

b) Ice load calculation considerations:
For the operation site we need info (statistical) on:

Ice features:
- Level ice
- Rafted ice
- Combined
- Ice ridges
- Icebergs
- Stamuchas.

Ice strength:
- Compression/ tension
- Temperature
- Salinity
- Porosity/ density.

Scenario of interaction:
- Limit force
- Limit momentum
- Splitting
- Limit stress.

With the above in mind, we can choose

Structure form:
- Sloping walls [compression/]
- Vertical walls [tension]

which will (hopefully), give the optimum solution.

c) Major ice properties: The properties affecting the load from ice are the ice strength and the ice features as listed in b).

d) For vertical walls, the ice failure will happen in crushing. For sloping walls the ice sheet will bend up and the failure will happen in tension (breaking up). The tensile strength forces are 0.02-0.5 times the compressive strength, so sloping walls will give a
considerably lower ice load. This is as long as the ice does not adfreeze to the structure. Then the difference is minimal.

e) Parameters affecting mechanical properties of ice:
- Temperature lower $\leftrightarrow$ stronger
- Salinity lower $\leftrightarrow$ stronger
- Porosity/ density higher density $=$ stronger ice
- Morphology crystal orientation
- Strain rate brittle/ ductile behavior.

Multiyear sea ice will have a lower salinity due to migration of salt and wash- out during the melt season. Lower salinity $=$ stronger ice.

2) Ice loads (2001)

3) Ice loads (1998)

a) Scale effects

If we take one specimen of ice (or other materials) and find its properties, for example strength, or porosity, or we take an other specimen of the same material but a larger size, then we will find for ice, that the compressive strength $\sigma_c$ and porosity will be larger than for the small one. This is the scale effect, when properties change with scale. Korzhavin was the first who mentioned it. The main reason is that in a small piece of ice, there are fewer flaws than in a big one. And the probability that these flaws will be destroyed and will break in the shear plane (for example at 45° to the C- axis) is higher than in the small one. The reason also in that ice is a non-isotropic material.

b) Ice is an anisotropic material and there are more flaws and pores in big specimens rather in small ones. That affects on strength and other properties. The more flaws, the higher probability that some of them will break in 45° to C- axis where ice is very unstable.

For a sloping structure we cannot use the limit stress scenario, because this scenario does not assume 3D models. But ice will break in bending mostly.

c) 

d) 

$$ F = I K_1 K_2 \sigma_c D L, $$

(2.22)

where

$I$ indentation factor, depends on strain rate, temperature of ice, type of ice (columnar or granular), size of grain may vary from 1 to 3 mm and more (Croasdale).

$K_1 = k_1$ contact factor, reflects that contact area is not perfect $\approx 1$ and ice feature does not contact the structure in all points simultaneously.

$K_2 = K_s$ shape factor. Depends on properties of the structure and its cross section ($K_s = 1$ for cylindrical shape).
e) Concerns:

1. Structure in landfast region (<10-15 km) so the structure may adfreeze to the ice and the total ice loads will be slightly more than estimated.

2. Limit stress scenario assumed, ice breaks in crushing (vertical slope).
   Korzhavin formula:
   \[ K_s = \text{shape factor} = 1 \text{ for cylindrical structures.} \]
   \[ K_c = < 1 \text{ because the next pile does not attract so much ice. (the ice breaks at first pile).} \]

3. If the height is not large enough, ice will accumulate below the quay and give rise to additional vertical loads.

4. Obviously ice will be broken nor by one pile only but the other ones.

5. Drag forces due to waves and current is:
   \[ F_D = \frac{1}{2} \rho A C_D u |u|, \quad (2.23) \]
   where
   \[ \rho \quad \text{water density} \approx 1030 \text{ kg/m}^3 \]
   \[ C_D \quad C_D (\text{Re}, D, u...) \]
   \[ A \quad \text{area, m}^2. \]
   Let us assume 10 m\(^2\):
   \[ F_D = \frac{1}{2} \cdot 1030 \cdot 10 \cdot C_D \cdot 1 = 516 \cdot C_D \]
   \[ \text{Re} = \frac{u \cdot D}{v} = \frac{1 \cdot 10}{v} = \frac{10}{v}, \quad (2.24) \]
   where
   \[ v \quad \text{viscosity of water.} \]
   We estimate the \( \text{Re} \) (Reynolds number) by evaluating whether the current is laminar or turbulent.

6. Piles are affected by the inertia force:
   \[ F_m = \left( m + \rho \pi R^2 \right) u \cdot, \quad (2.25) \]
   where
   \[ m \quad \text{is mass of pile;} \]
   \[ r \quad \text{is radius;} \]
   \[ u \quad \text{is acceleration.} \]
   We can estimate forces on a pile. To get the value for all piles we have to multiply by the number of piles.

7. Ice force on quay:
   \[ F_1 = I K_1 K_2 h D \sigma_e = h \cdot 0,8 \cdot \sigma_e \cdot 1,0 \cdot 1,0 \cdot 1,0 = 0,8 h \sigma_e \quad (2.26) \]
   (Assume \( I = K_1 = K_2 = 1 \text{ ideal case} \).
\[ F_{\text{ice (total)}} = F_1 \text{ number of piles. Ice will split due the piles, limit force scenario, in this case the load will not be so large.} \]

8. In permafrost we should check bearing capacity of the soil and slide resistance, but we have to know what type of soils we have (cohesional or frictional).

9. Weigh of quay + all loads above.

Investigations that are necessary:
- Level of tidal rise
- Type of soils (properties)
- Height above sea level
- Properties of ice (strength, temperature)
- Will water freeze to the seabed during winter
- Current velocity
- Drag coefficient for pile.

\begin{equation}
F_1 = IK_1K_2\sigma_c, hD = 1.8 \cdot 1.2 \cdot 0.8 = 1.728 \text{ MN}
\end{equation}

\[ F_{\text{total ice}} = F_1 \cdot \text{number of piles}. \]

\[ F_{\text{total}} = F_{\text{total (ice)}} + F_{\text{(arise of ice)}} + F_{\text{(waves)}} + F_{\text{wind}}, \quad (2.27) \]

\[ F_{\text{ice}} = F_1 \cdot 10 = 17.28 \text{ MN, but it may be less or more depending on the case and the of the results of the investigations. And assuming that ice breaks in crushing only, not in splitting.} \]

4) Ice loads (1999)

a) The greatest ridges can be formed in the drift zone, when large masses of ice can interact. Ridges in the landfast zone can ad freeze to the bottom (stamuchas). Only a relatively thin layer can appear in the transition zone. Small ridges, but these may be better consolidated due to small blocks of thin ice, which will fill the pore space inside the ridges between big blocks, in case of interaction between land fast ice and drift ice.

b) Even if we use the max \( \sigma_c \) and \( h \). We may not get the max value of the force, as \( I, K_1, \) and \( K_2 \) can decrease this force.

\( I \) indentation factor shows the difference between ideal, homogeneous distribution of strength and the real distribution. The strength can decrease if we have a “confinment situation” (\( I \) depends on \( D/h \) and there will be different \( I' \) s for rough contacts and smooth contacts).

\( K_1 \) contact factor, shows the differences between perfect contact area and natural contact area.

\( h \) can be different along the perimeter of a structure, due to crushing mechanism. Ice will not press directly on a structure, but through many small blocks.

\( K_2 \) shape factor- there is a large difference between the loads for different shapes of the structure.

One more term more could be considered in this equation; \( K_3 \), scale factor.

Combination of these factors can give \( F_{\text{max}} \) not only if when \( \sigma_c = \sigma_{c, \text{ max}} \) and \( h = h_{\text{max}} \).
c) From Korzhavin’s equation:

K is a contact factor, if the structure is not ad freezing: we have a sum of many contact areas. If the structure is ad freezed to the ice, it is a kind of perfect contact area K = 1, and the load is greater.

Pile-up effect due to level of water charges gives additional load.

If the structure adfreezes along the whole perimeter, we will have stress behind the structure as well, when the ice starts moving.

Other ice fields will push “first” field. And this field will transmit the load on the whole structure perimeter.

In case of sloping structure, ad freezing will reduce all advantages to a minimum. Load will be similar to those for a vertical structure.

Summary: adfreezing increases load.

d) In case of a vertical structure, ice will crush by compression. In case of a sloping one, by tension. Tension strength of ice is less. Hence the load on a sloping structure is less.

This is not working for adfreezed structures as, ice have no possibility to slide up on the side of platform. Therefore cracks due to compression more likely will occur.

e) The maximum load gives the max stress scenario. (use of Korzhavin equation) This scenario assumes, that the structure penetrates 50% into the ice the area of contact is max.

Limit momentum:
The ice field, is moved with some a velocity and stopped by the structure. Will hit it and transmit a momentum.

This process can envelope a platform. When the structure is penetrated along 50% of the diameter, we will get scenarios:

Limit force:
The ice field pushes on the structure and, the “stationary” field will cluster the structure.

Splitting:
The ice field can split in several blocks as a result of the interaction with the structure. This will create not so big load. Max stress on the structure will happen when the strength along whole perimeter simultaneous reaches the maximum value.

As the ice field is non-homogeneous and consists of many zones with different properties, the limit stress scenario is a bit idealistic description.

f) In confined condition the strength increases.

Ice properties:
- Morphology
- Porosity
- Salinity
- Temperature
- Density
- Homogenity
- Grain structure
- “Wetness” and etc.

Scenario of interaction:
- Contact surface (if structure is adfrozen)
- Shape of structure
- Adhesion.
5) Ice loads (2003)

a) Between a great number of factors, the main are:
   - Type of ice feature
   - Ice properties and velocity
   - Scenario of ice / structure interaction
   - Structure geometry
   - Size effect.

b) Contact factor takes into account non-perfect contact between the structure sand ice surface. Different reasons can induce this effect, in particular the ice edge is never flat, failure develops non-simultaneously over the contact surface, etc. This factor can be as low as 0,3-0,6.

Indentation factor takes into account the peculiarity of stress/strain field around the structure. According to different solutions this factor can be in the ranges 1,2-3,0.

c) Usually ice actions on sloping structures are less than on vertical ones because normally ice bends on slopes and ice resistance to bending is less than to crushing (type of failure typical to interaction with vertical structures). But any reasons that lead to bending restriction induce action increase. These factors may be: ice freezing to the structure surface, formation of great collection of rubble on the structure surface, very great ice velocity (ice sheet inertia during the interaction), great angle of slope inclination to horizon.

Period of ice action on sloping structure usually higher than period corresponding to crushing and fare on structure natural period. This is additional advantage of sloping structures.

d) The following factors influence ice action on multi-leg structure: mutual influence of front legs, influence of front legs on ice interaction with back legs, scatter of ice properties between different legs and rubble formation between legs.

Mutual influence of legs is important if distance between legs to leg diameter ratio is less than 5. If this ratio is more than 5 this influence is negligible. Usually ice is destroyed by front leg and therefore action on back leg is less than on front ones. This effect depends on distance between legs and ice field orientation regarding the structure. If the space between legs is filled with ice then action on multi-leg structure is determined as action on wide structure with diameter equal to distance between the side legs.

e) If structure located in moving ice then total action will be less than 9F₁ due to mutual influence of piles, non simultaneous failure against different piles, difference between ice properties against different piles and back piles sheltering by front ones. Even if distance between the piles is large and piles located in one row, usually the global action on the system will be less than nF₁, (where n is the number of piles) due to non-simultaneous failure and scatter in ice properties

Initially front piles do not sheltering the back ones in landfast ice, but mutual influence exists if distance between centers of piles is less than 5 pile diameter as well the scatter in ice properties. So in this case the total action will be less than 9F₁ as well.

f) Size effect is the phenomenon demonstrating action dependence on sample or structure size. There are direct and indirect reasons of this phenomenon.

Direct:
   - Flaws existence in ice
   - Flaws hierarchy
   - Ice non-homogeneity.
Indirect:
- Existence of 3D stress singularity at the intersection of crack edge with a surface
- Different time dependent effects (diffusion, transport of heat, etc).

Ice sheets contain many internal flaws and cracks of different size and width. Some of them are weak and can be considered as a weak chain initiating the failure. It gives basis for statistical theory which predicts that strength $R_1$ and $R_2$ of samples with different volumes $V_1$ and $V_2$ can be described by formula $R_1/R_2= (V_2/V_1)^{1/2 \alpha}$, where exponent varies in limits 0.05 – 0.3 according to different investigations.

Another explanation of size effect connections with flaw existence is the basis of fracture mechanics. The fracture toughness – the key parameter in fracture mechanics, which is a measure of tendency for the material to fall by crack propagation is proportional to (kPa-m$^{0.5}$). This means that if structures of two different linear dimensions (with linear parameters ratio $\lambda$) are considered then fracture toughness ratio of ice in these situations should be proportional to $\lambda^{3/2}$. But if the same (natural) ice is considered then the fracture toughness is the same. This means that modelling is impossible and pressures will be different.

Very important factor, which can lead to size effect formation for structures, is cracks hierarchy. It is well known that ice (as well as rocks for example) is divided on parts by cracks of different size. It is shown that hierarchical system of cracks exists: between very wide cracks smaller ones are located and micro flaws exist between the last. Therefore structures of different size will interact with different system of cracks and the large is the structure diameter the large is probability to meet wide weak crack. Therefore ice action on wide structure is lower than on smaller one.

This phenomenon is less important for strength of samples because perfect samples without visible cracks are separated for strength determination. Therefore samples strength overestimates the average strength of material before the structure.

Similar effect exists due to ice property non-homogeneity - it is more probability to wide structure to meet weak crack.

3D stress singularity at the intersection of flaw edge with a surface exists. Similar singularity exists usually on the protrusions at the sample end and sheet edge at the contact with structure. Great stress concentration forms in this case on protrusions or flaws near the contact surface what initiates failure. This phenomenon is stochastic and cannot be modelled.

g) The velocity influence on following factors that in turn determine the action
- Contact between ice and structure
- Friction ice/structure coefficient
- Ice strength
- Failure type
- Type of interaction
- Resonant
- Ice sheet inertia.

Experiments show that contact between ice and structure surface can be perfect only at very low speed when ice yields. In this case ice during the interaction closes all gaps of the ice edge. In other situations contact realizes only over small part of structure surface due to brittle failure and extrusion of ice pieces. As action depend on pressure value over contact surface multiplied on real area of contact, the action dependence on velocity in this case is evident.
If one considers the ice sheet cross-section by the vertical plane normal to the structure surface, he can see that vertical ice velocities distributed very unevenly over the contact surface. They are zero at the center of this surface, increase up and down and reach maximum at sheet free surfaces. Ice/structure friction coefficient decreases with velocity increase. Therefore friction is high in the center and lower at the sheet ends. Friction force exceeds the shear stress in some central area. As a consequence ice cannot move there what leads to formation of stagnation zone with potential energy concentration. This leads to local stress concentration. Grow of potential energy resulted in stress increase. They can reach high level and as soon as shear stress exceeds the friction force the instant discharge of energy happens, which followed with abrupt pressure decrease. After that the phenomenon repeats. So due to friction coefficient dependence on velocity the global and especially local pressure can increase significantly.

Ice strength depends on strain rate, which in turn depends on velocity. Strength grows until strain rate reaches about $10^{-3}$ and decreases at higher rates. It is assumed that this border corresponds to ice property transition from plasticity to brittle behavior.

Ice action is a product of stress on real contact area. Experiments show that transition from very low velocities, corresponding to ice yielding to higher, lead to change of failure type and dramatically decrease of real contact area, which is lowered by a factor equal to 3.

Two different phenomena take place when ice sheet meets the structure: initial hit and following penetration. The action during the hit is directly proportional to velocity. Action during the penetration practically does not depend on velocity. Importance of action during initial hit depends on structure type and dimensions.

Structure vibration and resonant can arise at some velocities. It can lead to structure failure due to fatigue or soil liquefaction.

Ice sheet inertia is important for sloping structures at high speed ($V>0.5$ m/s). Ice cannot slide along the surface freely and fails due to compression instead of flexure. As compressive strength is higher than flexure one the action level increases.

h) Let $x$ is the weight of the ballast
Standard deviations is defined as:
\[ \sigma = v \cdot M \]  \hspace{1cm} (2.28)

Correspondingly to Table 1.1 and Eq. (2.23) the standard deviations can be determined. These data are in Table 2.5.

<table>
<thead>
<tr>
<th>Action</th>
<th>$\sigma$, MN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice</td>
<td>7,5</td>
</tr>
<tr>
<td>Wind</td>
<td>1,0</td>
</tr>
<tr>
<td>Current</td>
<td>1,25</td>
</tr>
</tbody>
</table>

Mean value of the common action: $M_L = \sum M_i = 25 + 2,5 + 5 = 32,5$ MN
Standard deviation of the common action: $\sigma_L = \sqrt{\sum \sigma_i^2} = (56,25 + 1 + 1,56)^{0.5} = 7,67$ MN
Mean resistance to sliding: $M_R = (80 + x) \cdot 0,4$ MN
Square deviation of resistance:

\[ \sigma_R = 80 \times 0.4 \times 0.05 = 1.6 \text{ MN} \]

\[ M_S = M_R - M_L = (-0.5 + 0.4x) \text{ MN} \]

\[ \sigma_S = (\sigma_L^2 + \sigma_R^2)^{0.5} = (58.82 + 2.56)^{0.5} = 7.83 \text{ MN}. \]

To reach reliability 0.99999, the safety index should be equal to 4.25 (see Table 1.2),

So \[ \beta = M_S / \sigma_S = (-0.5 + 0.4x) / 7.83 = 4.25 \] and \( x = 84.44 \text{ MN}. \)

i) The solution is shown in Table 2.6.

<table>
<thead>
<tr>
<th>Month</th>
<th>Number of</th>
<th>Number of</th>
<th>Ice thickness, m</th>
<th>Salinity, ppt</th>
<th>Strength, MN</th>
<th>Action, MN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[FDD] per</td>
<td>[FDD] from</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>month</td>
<td>beginning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>November</td>
<td>44</td>
<td>44</td>
<td>11.9</td>
<td></td>
<td></td>
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<tr>
<td>December</td>
<td>296</td>
<td>340</td>
<td>39.1</td>
<td>6</td>
<td>2.0</td>
<td>0.78D</td>
</tr>
<tr>
<td>January</td>
<td>430</td>
<td>770</td>
<td>62.8</td>
<td>5</td>
<td>2.4</td>
<td>1.38D</td>
</tr>
<tr>
<td>February</td>
<td>374</td>
<td>1144</td>
<td>79.0</td>
<td>4</td>
<td>2.6</td>
<td>2.05D</td>
</tr>
<tr>
<td>March</td>
<td>283</td>
<td>1427</td>
<td>89.8</td>
<td>3</td>
<td>2.2</td>
<td>1.97D</td>
</tr>
<tr>
<td>April</td>
<td>138</td>
<td>1565</td>
<td>94.8</td>
<td>3</td>
<td>1.8</td>
<td>1.7D</td>
</tr>
</tbody>
</table>

So in spite of the month with the maximal ice thickness is April, the main actions correspond to February.

g) Croasdale’s formula for ice actions on sloping structures can be written in the form:

\[ F = D \times 0.68 \times R_f \left( \gamma_w \frac{h^5}{E} + \gamma_i \right)^{0.25} + \gamma_i C_2, \quad (2.29) \]

where

\[ C_2 = (\sin \alpha + \mu \cos \alpha) \left( C + 1 / \tan \alpha \right) \],

\[ C = \frac{\sin \alpha + \mu \cos \alpha}{\cos \alpha - \mu \sin \alpha} \],

D = the structure diameter at the waterline level

\( R_f \) = flexure strength

E = ice modulus of deformation

\( \alpha \) = angle of structure surface inclination to horizon

\( \mu \) = friction coefficient

\( \gamma_w \) and \( \gamma_i \) = water and ice specific weight

h = ice thickness

z = the height of ice formation on slope.

Input data:

Cone diameter at the waterline \( D = 20 \text{ m}, \) angle \( \alpha = 60^\circ, \) \( \mu = 0.2, \) \( E = 4 \cdot 10^5 \text{ MPa}, \)

\( R_f = 0.4 \text{ MPa}, \) \( h = 1 \text{ m}, \) \( z = 10 \text{ m}, \) water depth \( H = 25 \text{ m}. \)
Formula for cone volume:

\[ V = \pi \frac{H}{3} (R^2 + r^2 + Rr), \]  

(2.30)

where \( R = \frac{D}{2}, r \) - cone radius at sea bottom.

For \( \alpha = 60^\circ \) and \( H = 25 \text{ m}, r = 24.4 \text{ m}, \) the underwater cone volume is \( V = 24592 \text{ m}^3. \)

Then \( C = 2.9, \ C_2 = 3.3, \ F = 12.8 \text{ MN}. \)

American and Canadian Codes suggest formula for calculation of ice loads on cylinder:

\[ F_c = pDh, \]  

(2.31)

where \( p \) - effective pressure. For pressure \( p \) determination the American Code suggests formula:

\[ p = 8.1/A^{0.5}, \]  

(2.32)

if contact area \( A = Dh < 29 \text{ m}^2. \)

If \( A > 29 \text{ m}^2 \) than \( p = 1.5 \text{ MPa}. \)

The equivalent cylinder diameter is \( D_c = 35.4 \text{ m}, \) so \( A > 29 \text{ m}^2 \) and \( F = 35.4 \cdot 1.0 \cdot 1.5 = 53.1 \text{ MPa}. \)

The cone advantages will be diminished if structure freeze in ice, if ice velocity is very high (more than 0.5 m/s) or if rubble volume and height on the surface is great.

6) Ridge loads on structures (2001)

a) The general knowledge about loads from first-year ridges is very small. There are too few field observations and therefore little information that can verify results in laboratories and simulation programs. It is, for example, uncertain about how the collision between the ridge and the platform will develop.

b) Important parameters determining the loads from a ridge are:

- Sail height - \( h_s \)
- Keel depth - \( h_k \)
- Thickness of “consolidated layer” - \( h_c \)
- Extension of the ridges and structure it will hit
- The compressive strength of the consolidate layer
- Porosity in the different parts of the ridge
- Salt content in the different parts of the ridge
- Width on the different parts (\( W_k, W_s, W_c \))
- Velocity of the ridge
- Temperatures of the different parts on the ridge.
2.11 Geotechnical problems

1) Geotechnical problems (1997)

a) Stability evaluations:
   - Stability against sliding on the seabed: \[ \tau = \frac{Su}{\gamma m} \]
   - Bearing capacity of seabed soils: \[ \tau = (a + \sigma)\tan \varphi \]
   - Stability at set down
   - Consolidation behavior of seabed soils
   - Subset permafrost? Thaw settlement
   - Onshore: Seabed conditions along pipe, coastal erosion.

b) Ice load \( \rightarrow \) rapid loading scenario, fine grained sediments \( \rightarrow \) undrained shear strength; \( S_u (C_u) \):
   - Consolidation history. If the ground has been pre-consolidated (glaciers), \( S_u \) is larger.
   - Possible weak layers: to be considered.
   - Temperature: If permafrost, the ground is strong, but vulnerable to thaw settlements.

c) Caisson structure

a) The caisson structure will have an overturning moment and the seabed failure mode will be in lack of bearing capacity of the soil on sliding.

b) In shallow waters the “arm” creating the moment will be small and the failure mode is most likely to be sliding on the seabed.

Conical (sloping walls): The created moment can be opposite that of the vertical wall structure, creating a failure in bearing capacity of the seabed soils.
2.12 Project planning

1) Project planning:

a) The work in the earliest phases of a project is very important as it is in this phase that the “concept” for the development is chosen. A “wrong” or inefficient concept can never become optimal. A small number of people are normally involved in the earliest project phases and the costs incurred are very small as compared to the importance of the decisions made. These persons should be chosen among the most experienced persons in the company.

b) The effects on the field development in the case we are using:

- Technology that is not documented in the conceptual phase of the project: We run the risk of having to test and document the technology while we are performing the detailed design. The project may be delayed and there will most probably be additional design work to incorporate the final documented results.

- Solutions that do not follow the environmental requirements of the government: We may end up with lack of approval for the continuation of the project or in the worst case a lack of approval to start the operations. The public may see the oil company as a potential “polluter” and may boycott the products from the company.

- Over-optimistic unit rates in cost analysis: The result is certainly cost overruns with reduced Net Present Value of the project.

- A solution that one contractor has monopoly to deliver: The one contractor that can do the work may get problems to carry out the work or may be come very busy. It is likely that the contractor will use the opportunity to increase the price as monopolist.

c) “Tools” that can be used in the detailed engineering phase to identify errors in the calculations that can have important consequences later:

- Different versions of quality assurance tools including self-checking, management control and independent checking should be employed.

- Somebody independent from the project team organization should do the independent checking and with another set of computer programs and tools.

- It is important that the independent checks are done by very competent personnel, and without cost pressure.
CHAPTER 3 Extensive Case Study on an Offshore Field Development

Note: This chapter has been developed in cooperation with Petrad, Stavanger, Norway.

3.1 Introduction

This Case Study, related to the simultaneous development of several (two) petroleum production fields, is organised as an integral part of the course "Management of Petroleum Development and Operations". The course is held in Stavanger, Norway during the period from 25th August to 16th October 2003.

The purpose of the Case Study is to simulate the evaluations and decisions that a government and oil companies will be met with during exploration, development and operation of oil and gas fields (the “Atlas” field and the “South Etna” field, see chapter 6 and 7). The emphasis will be on achieving a thorough understanding of the interplay between technical solutions as well as the political and economical boundary conditions, and the alternative management scenarios that may optimise the benefits for the country as well as the companies involved.

Through the Case Study, topics treated in the course will be considered and the Case Study therefore constitutes an important part of the course. All information needed for the work scope is contained in the course material or will be provided separately.

The Case Study will be organised as a group-work, and offers an experience in co-operation with resourceful persons whose background is as different as in many real life situations. Of particular importance is the challenge of working in a cross-cultural group of people. In addition the groups must form requests to the lecturers for additional information, and it will be up to the groups to determine which additional information they require to complete the Case Study.

The Case Study will be based upon teamwork within three groups representing the following different bodies:

Group 1 representing a smaller foreign company with only a limited amount of production worldwide. The company has a constant shortage of funds; the cost of capital is 12 % annually.

Group 2 representing a Major foreign company with large production all over the world with access to investment funds. The cost of capital is set at 10 % annually.

Group 3 representing the National Oil Company (“Eureka Oil”) in a country named “Eureka” (see chapter 4). Initially the company has very limited funds available for investments. Cost of capital 14 % annually.

Each group will be responsible for organizing the work within their group (this could, for example, involve nominating a chairman). They will have PC computer(s) equipped with Word processor; an Excel spread sheet and programmes to estimate the costs of the development and to establish the economics of the development.

It should be noted that the Major foreign oil company was appointed field operator of the “Atlas” field several years ago (30% ownership) while the Smaller foreign oil company recently has bought into a limited ownership (20%) in the field. The National Oil Company has taken over the Government’s share of the Atlas field (50%). The field has at present been in production for 7 years.
All three companies applied to become operator in Eureka’s last concession round. A nearby prospect, “South Etna”, was identified to have possibilities for large quantities of gas and condensate.

The Major oil company was appointed operator of the “South Etna” prospect in the field development phase while “Eureka Oil” will take over the operator ship in the production phase. The national oil company, “Eureka Oil”, participates with 40% in the joint venture while the Major and the smaller foreign companies participate with 40% and 20% respectively. Eureka Oil is carrying its pro-rata share of exploration costs as well as development capital costs. Eureka Oil is taxed on equal basis with the foreign companies.

The oil production in the “Atlas” field will in few years be on decline. The field has, however, a considerable gas cap that can be developed. Furthermore, the first exploration well in the “South Etna” field has shown that this is a considerable gas and condensate field. The main challenge of the case study is to document that the remaining oil and gas resources in the “Atlas” field and the resources of the “South Etna” field can be developed safely and economically through the “Atlas Gas and South Etna Development Project”. Key points in this respect are the degree of recovery and oil/water handling. These aspects shall be handled in the case study work.

Each group will make separate reports covering each of three separate phases of the Case Study (see Chapter 2), and they will be asked to present these reports at Case-session presentations as follows:

- Case 1 Thursday 11th September
- Case 2 Wednesday 1st October
- Case 3 Monday 13th October.

The groups are also required to present the full report on Thursday 16th October to all participants at this year’s Petrad courses and to a panel of experts that will discuss their findings.

The final reports from the 3 groups shall be handed in on the morning of Tuesday 14th October. These will be printed in a compendium and handed out to all participants.

3.2 Scope of Work

3.2.1 General

The Scope of the Work to be carried out during the Case Study is to plan and perform the below listed Case phases. These Case Phases (denoted Case 1, Case 2 and Case 3 respectively) comprise:

1. Feasibility Study (basis for Decision to Initiate the “Atlas Gas and South Etna Development Project).
2. Concept Study (basis for Provisional Project Sanction), including:
   a) Selection of Field Development Concept
   b) Safety and Environment Concept Comparison
   c) Field Operation Study.

In case 2 b) and case 2 c), support documentation for the Provisional Project Sanction report will be prepared.

3. Preparation of a strategy for use of future gas resources in the country of Eureka. The work in case phase 3 shall be based on the work performed in case phase 2.
For each Case phase a plan and a report shall be developed and presented. It is sufficient to use the presentation material as the main part of the report.

In general for each Case, the plan shall be a realistic “real life” project plan and should include:

- Goals for the Case phase
- Activities to be performed
- Time (schedule) necessary for these activities
- Organization necessary to perform the work
- The budget for the work
- The interdependence of the different activities
- Report(s) to be delivered at the end of each case.

At the end of the respective Case phases, the results of the work shall be presented to the management in the form of a report. For case phases 1 and 2, a plan and a budget for the next Case phase shall also be prepared. The outcome of these realistic “real life” presentations will eventually be approval to continue into the next case phase.

The presentation material (and the report) from each Case phase shall in general include:

- The objectives of the work in the Case phase
- The organization of the group-work
- Description and results of activities carried out
- Conclusions from the work in the Case phase, including costs and schedule for a realistic “real life” project.

For case phases 1 and 2 the report shall also include:

- Plan and budget for the next Case phase
- Request for approval to continue work in the next Case phase.

Summarizing, the following presentations shall be given:

- A detailed plan for the Case 1 study work
- “Real life” plan for the Feasibility study
- A presentation of the Feasibility Study (Case 1) with plan and budget for a “real life” Concept Study” (Case 2)
- A presentation of the Concept Study (Case 2) with a plan and budget for a “real life” Pre Engineering Study (The Front End Engineering Work)
- Presentation of the Gas Strategy (Case 3)
- Final presentation (in Plenum) of all work done in the case study.

Note: For budget purposes, an hourly rate of US $ 40 shall be used throughout the work.

3.2.2 Case 1: Feasibility study

Scope of Work

1. Make a plan for the work in the group (during the period from 26th August to 16th September). This plan is due on 28th August 2003.
2. Make a plan (Project Execution Plan, PEP) for a “realistic”, that is a “real life” Feasibility study.
3. Perform the Feasibility study group work.
4. Make a report and a presentation on the work performed (Due 11th September 2002).

The report from the Feasibility study will be the basis for approval to progress into the Field development phase, and can include:
1. Introduction and summary

2. The Group work:
   - Plan for the Feasibility study group work
   - Goals/objectives
   - Activities performed
   - Duration and amount of work
   - Organization (work group members)
   - Plan for a realistic “real life” Feasibility study.

3. Result of the work:
   - Design basis
   - Value chain / Evaluation of products to the marked
   - Selection criteria for field development solution
   - Marked analysis
   - Production profile for the alternative
   - Technical solution for the selected alternative
   - Schedules for the selected alternative
   - Investment and operating costs for a full development of Atlas gas and South Etna project
   - Economical analysis (excluding an analysis of the effect of the tax regime)
   - Brief safety and environmental evaluations
   - Management challenges
   - Recommendations.

4. Concept study:
   - Plan for a realistic “real life” Concept study
   - Goal/objectives of the Concept study
   - Activities to be performed in a “real life” Concept study project
   - Time necessary for these activities
   - The interdependence of the different activities
   - The budget for the work in a “real life” Concept study project
   - Organization necessary to perform this work
   - Plans for a report to be delivered at the end of the Concept study.

3.2.3 Case 2a: Concept study, Selection of Field Development Concept

Scope of Work

1. Review and update the plans for the Concept study.
2. Perform the Concept study group work.
3. Make a report and a presentation on the work performed (due 1st October 2001).

The report at the end of the Concept study will be the basis for approval to start the PDO (Plan for Development and Operations) /Pre engineering work (Front End Engineering Development work). The report can include the following sections:

1. Introduction and summary
2. Field description
3. Design basis, updated
4. Field development alternatives
5. Recommended development scheme
6. Sales- and transports agreements
7. Schedule for the development costs for the development (investment and operational costs)
8. Economics (including an analysis of the effects of the tax regime)
9. Uncertainty analysis:
   - Main field development schedule
   - Project execution strategy
   - Management challenges.
10. Recommendations
11. Plan for a realistic (“real life”) pre engineering study:
   - Objectives of the study
   - Activities to be performed
   - Time necessary for these activities
   - The interdependence of the different activities
   - Budget and organization necessary to perform the work
   - Report to be delivered at the end of the concept study.

3.2.4 Case 2b: Concept Study, Safety and Environment Concept Comparison

Scope of Work
Perform a qualitative safety and environmental concept comparison (personal life and health, environment and installations/production) of the development scenarios studied during the Concept study phase.

The report, which is to constitute a part of the Concept Study, should include the following sections:

1. Risk evaluation methodology
2. Acceptance criteria
3. Identification of accidental events (hazards)
4. Consequences of the events
5. Frequency/ probability evaluations
6. Discussion (presentation)
7. Conclusions and recommendations.
3.2.5 Case 2c: Concept Study, Field Operation Study

Scope of Work

Perform an operational study of the recommended field development solution (how to operate the field) from the Concept study (see 3.2.3) and the safety and environment recommendations (see 3.2.4).

The report of the work, which is to constitute a part of the Concept study, should include the following sections:

1. Field operation philosophy
2. Preparation of operations
3. Organization, offshore and onshore
4. Competence requirements
5. Training requirements
6. Inspection, maintenance & repair strategy
7. Onshore support
8. Logistic
9. Contingency for emergency situations and pollution.

3.2.6 Case 3: Preparation of a strategy for use of future gas resources in the country of Eureka

Scope of Work

1. Based on the field data provided for the Atlas and South Etna, present likely off take options for gas and select a combined delivery profile as basis for the gas strategy assessment (assuming that the Atlas field initially will serve as base load supplier, while South Etna will cover the balance in demand, i.e. act as “swing” producer).
2. Based on the key technical and cost data (to be given) related to different gas utilization options, make a first (preliminary) estimate of selected gas disposal options and present a ranking of alternatives.
3. Given that the overall target for Eureka is to maximize the value creation from its oil and gas resources, draw up a strategy for how the utilization of gas can make a best possible contribution to meeting this target.
4. Show how value is created along a gas delivery chain, based on the figures established for various options and/or combination of options.
5. Discuss and present strategies for a regulatory regime for gas in Eureka and organization along a gas value chain (ownership, operatorship, contracts and agreements).

The report of the work may include the following sections:

1. Summary
2. Introduction
3. Field development scenarios and selection of production/gas delivery case, as basis for the further gas strategy assessments
4. Feasibility assessment of different gas off take scenarios
5. Comparison of alternative gas routes and presentation of a recommended gas utilization strategy for Eureka

3.3 Product Information

Information about sales products and definitions are given below:

Definitions:
- Dry gas: Sales product to market (C₁ + limited amount of C₂)
- Rich gas: All unstable products are included with gas (C₁ + C₂, C₃, C₄)
- NGL: Unstable products (C₂, C₃, C₄) in liquefied form
- Stable Oil/Condensate: Oil/condensate with a vapor pressure lower than 0.8 bar at atmosphere temperature
- LNG: Liquefied natural gas, liquefied dry gas, frozen
- LPG: Liquefied Petroleum Gas.

Sales products:
- A: Unstable oil + Sales gas
- B: Stabilized oil + Rich gas
- C: Stabilized oil + Sales gas + NGL
- D: Stabilized oil + Gas reinjection
- E: Stabilized oil + Gas flaring.

Sales gas must meet the same requirements as European gas standard:
- 38 - 40 MJ/Sm³ heating value
- Less than 2.5% CO₂
- Availability of 95% on a year's basis
- Swing factor 120% - 80% Daily Contracted Quantity, DCQ
- Minimum amount of impurities, e.g. H₂S.
Table 3.1 Summary of Product Types Produced from Petroleum.

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<td>Liquefied petroleum gas</td>
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<td>Ligroin (naphtha solvent)</td>
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<td>Precipitation naphtha (solvent)</td>
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<td>Kerosine, diesel fuel</td>
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<td>Gas oil, fuel oil</td>
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<tr>
<td>FCC &amp; hydro cracker feed</td>
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<tr>
<td>Lubricating oil</td>
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<td>Asphalt, pitch</td>
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<td>Wax</td>
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<tr>
<td>Residuum's &amp; asphalt</td>
<td></td>
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</tr>
</tbody>
</table>
3.4 Country Description

3.4.1 Political situation in Eureka

The Government of Eureka has been in power for almost 4 years and is democratically elected, after 8 years of military rule. New elections will be held within 12 months, with a high possibility of change of government. In general there is quite an unstable political situation with the danger of a military coup. The country's economy is in a difficult position with inflation of 30% and a debt of 27 billion USD. The main export consists of agricultural products and there is some oil export. 33 % of export earnings are used to buy petroleum.

Corruption is a big problem. Most people are working in the agricultural sector. The government has started an economic restructuring program, which is unpopular in the country and not very successful. The population is 21 million comprising 5 main ethnic groups (A 45%, B 15%, C 15%, D 15%, E 10%), and 14 different languages. The religion is 50% Catholic and 50% Islam. Unemployment is at 26%, and civil disorder is a possibility. Eureka has two universities and an illiteracy rate of 36%.

For a map see Fig. 3.1.

3.4.2 The energy situation in Eureka

The country of Eureka has been through several decades with a small amount of on-shore oil activity. They have recently had a considerable increase in production after the start-up of oil production from the Eureka fields, and are at present a net exporter of oil. They have refining capacity for 50% of today's consumption. Offshore oil production has been ongoing from the Atlas field for a period of 7 years.

In Eureka, they are in a mature energy situation and consider using natural gas in power generation and for some local distribution.

In Eureka a group of industrial companies together with the national electricity utility (Eureka Power), has formed a jointly owned gas company (Eureka Gas), aimed at exploiting the proven gas reserves. There is a particular need in Eureka to phase out old coal-fired power units. This together with a strong demand for electricity means that the need for new generation capacity is expected to increase to 10 TWh per year within a 10-year period.

There is also an ambition to develop gas-based industries for the production of fertilisers and methanol. Production of liquefied gas (LNG) for export and conversion of natural gas to synthetic oil (syncrude/ synfuel), are other options being investigated.

Petroleum laws and regulations are not fully developed in Eureka and international petroleum standards are acceptable and applicable. Contracts will be open for international arbitration and there is no obligation to repatriate profits in Eureka.

Furthermore, there are also promising opportunities for exporting gas and power to the neighbouring country Eastland.
3.4.3 Neighboring countries.

3.4.3.1 Eastland

Eureka and its two neighbouring countries have analogous geological situations. In the region, Eastland, the country to the east of Eureka, has a reputation for being an oasis of calm amongst its turbulent neighbours. The country’s natural attractions, wildlife and reputation for enlightened conservation draw tourists from all over the world. Successive governments have made a real effort to preserve the country’s image as ecotourism heaven, making Eastland one of the best places to experience the tropics naturally and with minimal impact.

The country has a population of only 5,565,000 (growth rate 2%), and its capital Easttown has 390,000 inhabitants. The GDP per head is USD 5,400, inflation 16%, major industries, coffee, bananas and tourism.

After a short and quite peaceful freedom struggle, the country became independent in 1959. After a civil war of just some few weeks, the country has been a democracy. The constitution of 1960 gave also the women the vote, and, controversially, dismantled the country’s armed forces, as one of the few countries in the world. The priority became building up a good health-, school- and social- system in addition to protecting the environment. They have succeeded to a certain extent, but the country’s economy today is not very good, and the unemployment is increasing. Because of this, the new Prime Minister, who made the economy the priority of his campaign, is expected to start the process of privatizing state companies and seek foreign investment in an effort to create jobs.

Eastland has had gas and gas-liquid production for more than 10 years and has a domestic gas marked. International investors consider the risk for their investments in Eastland to be small.

3.4.3.2 Westland

The country of Westland has had difficulties to attract foreign investors. The country is at present preparing for its first licensing round.

Westland has a population of 12,1 M (growth rate 2%), and its capital Westtown has 1,390,000 inhabitants.
3.5 General description of Hydrocarbon Fields

3.5.1 Status

Eureka

Oil production has been ongoing for 7 years from the “Atlas” field located in 40 m water offshore the country of “Eureka”. The field includes a reservoir containing a rich gas cap with an oil zone underneath, and it is located 40 km from the coast of Eureka see Figure 3.1. The production from the field will in about one year start to decline.

Furthermore, a gas and condensate discovery has been made in 175 m water depth 150 km to the west south west of the “Atlas” field. The name of the field is denoted “South Etna”. Full appraisal of the discovery is still to be progressed.

Information on the fiscal regime (taxation) in Eureka will be given at the start of Case 2.

Eastland

An existing producing installation is located at the Falcon field in 50 m water depth 300 km to the south east of the Atlas field in the country of Eastland. Production of gas and condensate has been ongoing for more than 10 years. Rich gas is exported from an existing platform through a 60 km pipeline to an onshore terminal with gas treatment facilities. At this plant, sales gas and liquefied petroleum gases (LPG) are produced.

![Fig. 3.1 Location of the Atlas and South Etna fields.](image)

3.5.2 Strategy for field development in Eureka

The technical development of the gas cap in the Atlas field is contingent upon a gas sales agreement. It is, however, unlikely that an attractive economic project can be obtained
without the combined development of the “Atlas” gas cap and gas from the “South Etna” field.

The country of Eastland is a potential customer for some of this gas. Status is that Eastland urgently needs the gas, as the production from the gas/condensate field offshore Eastland is in rapid decline, due to unexpected ingress of water into the reservoir through the fault system, some gas prospects, however, exist near to the field in production.

A potential domestic market for the gas has also been identified in Eureka. There are, however, a lot of uncertainties related to a possible domestic gas marked and it is recommended to look for development solutions that are not dependant on an immediate development of a domestic marked.
3.6 Description of the “Atlas” reservoir and the “Atlas” oil production

Ownership: Major oil company (operator) 30%, Small oil company 20%, Eureka Oil 50%.

The hydrocarbon column consists of an approximately 70 metres thick oil column with an overlying gas cap.

3.6.1 Reservoir Data

Hydrocarbons are present in Jurassic sandstones. The quality of the reservoir is good. Some key reservoir data can be found in Table 3.2 below.

<table>
<thead>
<tr>
<th>Reservoir depth</th>
<th>2600 m TVD MSL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir area</td>
<td>5 x 3 km²</td>
</tr>
<tr>
<td>In Place Volumes:</td>
<td></td>
</tr>
<tr>
<td>- Oil</td>
<td>105.0 million Sm³ (660 million barrels)</td>
</tr>
<tr>
<td>- Rich gas (gas cap)</td>
<td>96.0 billion Sm³</td>
</tr>
<tr>
<td>Reservoir thickness:</td>
<td></td>
</tr>
<tr>
<td>- Oil leg</td>
<td>70 m</td>
</tr>
<tr>
<td>- Gas cap (max thickness)</td>
<td>150 m</td>
</tr>
<tr>
<td>Reservoir pressure</td>
<td>273.2 bar at 2639 m TVD MSL</td>
</tr>
<tr>
<td>GOR</td>
<td></td>
</tr>
<tr>
<td>- Oil</td>
<td>111 Sm³/Sm³</td>
</tr>
<tr>
<td>- Rich gas (gas cap)</td>
<td>8 000 Sm³/Sm³</td>
</tr>
<tr>
<td>Reservoir temperature</td>
<td>98.3°C at 2639 m TVD MSL</td>
</tr>
</tbody>
</table>

TVD MSV = True Vertical Depth below mean sea level.

Several drainage strategies/drive mechanisms were initially evaluated and a combined gas and water injection strategy was chosen as base drive mechanism for the oil production phase.

The initial pressure is close to the hydrostatic pressure and to achieve a long plateau production and a high ultimate recovery, maintenance of the reservoir pressure was required. Reservoir simulations did show that two of the initially evaluated drive mechanisms, pressure depletion or gas injection, give a significantly lower ultimate recovery than water or combined water- and gas injection.

Water injection as drive mechanism would have required a gas export solution, either gas export for sale or gas disposal into a separate structure.

Simulation of water injection and combined water- and gas injection did show fairly similar production results. Water injection would give a longer plateau but slightly lower ultimate recovery compared to combined gas/water injection, that was ultimately chosen as drive mechanism.
3.6.2 Selected Production Profiles

3.6.2.1 Oil production from Atlas, combined gas/water injection

An oil production plateau of 18 000 Sm³/day was chosen. Well performance was at a rate of 3 000 Sm³ of oil per day initially and at plateau production. During the production decline phase, the annual reduction in oil production is expected to be 30%.

Water production was initially 10 000 Sm³/day but has been increasing towards 30 000 Sm³/day. The water injection rate is 4 000-5 000 Sm³/day per well. Water injection capacity has been set to 30 000 Sm³/day. A regularity of 90% has been achieved. The ultimate oil recovery is expected to be 54.4% of the oil in place.

Rich gas from the oil

The gas to oil ratio (GOR) is 111 Sm³/Sm³ in the initial oil production phase, increasing in the later oil production phase as more and more gas is produced with the oil. The gas produced in the initial oil production phase is 3.0 million Sm³/day. The gas injection rate is estimated to 2.0 million Sm³/day per well.

Number of wells

The total number of wells is 15.7 oil producers, 6 water injectors and 2 gas injectors. Two of the oil producers are horizontal wells. To reach early plateau production, 6 of these wells were predrilled. These are four oil producers, one gas injector and one water injector. For the gas production phase, the oil wells and water injection wells could gradually be transferred into gas producers.

Development scenario

The field has been developed with separate drilling, production and quarters platforms (jackets). Oil is stored in a floating storage and offloading vessel (FSO).

3.6.2.2 Rich gas production from the Atlas gas cap

Plateau rate to be established, take typically 8, 12 or 15 years plateau production. Initially, the GOR = 8000 Sm³/Sm³. After 5 years of gas production the reservoir pressure will drop to 50% of the initial pressure and condensate cannot be produced. During the production decline phase, the annual reduction in production is 20%. For the gas production phase, the oil wells and the water injection wells will gradually be transferred into gas producers. The Ultimate recovery (% of reserves in place) is for the rich gas expected to be 67.7%. The well performance rate is initially estimated at 2.5 million Sm³/day per well at plateau production.

Natural Gas Liquids (NGL's) are stable liquids recovered from the gas stream. For Feasibility phase purpose, the amount of NGL's can be obtained from the rich gas production profile. The NGL reserves are given by:

NGL Reserves (million tonne) = Rich Gas Reserves (billion Sm³) \cdot 0.096.
The rich gas production profile should then be multiplied by 0,90 to get the sales gas.

### 3.6.3 Fluid Data

Analysis of oil and gas samples from the exploration well has been performed. The compositions are given in Table 3.3.

<table>
<thead>
<tr>
<th></th>
<th>Gas Cap</th>
<th>Oil Leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>1,296</td>
<td>1,071</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0,827</td>
<td>0,277</td>
</tr>
<tr>
<td>Methane</td>
<td>90,590</td>
<td>46,925</td>
</tr>
<tr>
<td>Ethane</td>
<td>3,771</td>
<td>3,929</td>
</tr>
<tr>
<td>Propane</td>
<td>1,340</td>
<td>2,110</td>
</tr>
<tr>
<td>iso-Butane</td>
<td>0,215</td>
<td>0,433</td>
</tr>
<tr>
<td>normal-Butane</td>
<td>0,362</td>
<td>0,866</td>
</tr>
<tr>
<td>iso-Pentane</td>
<td>0,129</td>
<td>0,413</td>
</tr>
<tr>
<td>normal-Pentane</td>
<td>0,128</td>
<td>0,455</td>
</tr>
<tr>
<td>C₆ fraction</td>
<td>0,162</td>
<td>0,824</td>
</tr>
<tr>
<td>C₇ fraction</td>
<td>0,279</td>
<td>2,351</td>
</tr>
<tr>
<td>C₈ fraction</td>
<td>0,306</td>
<td>3,823</td>
</tr>
<tr>
<td>C₉ fraction</td>
<td>0,170</td>
<td>2,829</td>
</tr>
<tr>
<td>C₁₀+ fraction</td>
<td>0,425</td>
<td>33,695</td>
</tr>
</tbody>
</table>

The reservoir does not contain significant amounts of H₂S. The GOR = 5000 Sm³/Sm³ for the gas phase.

### 3.6.4 Environmental Data

Some data related to the surrounding environment are given below:

- Water depth, m 40
- Wind, m/s 40
- Wave height, m 0
- Air temperature, °C - 10 to 25
- No history of earthquakes or ice bergs
- Gentle sloping sea bottom at field. Good conditions for design of foundation.
- Sea currents, m/s 0.8.

The open sea area is characterised by high biological production and is identified as an important area with regard to fish resources. Additionally, the coastal area is characterised as environmental sensitive to oil pollution. The peninsula to the east of the Atlas field includes a national conservation area.
3.7 Description of the “South Etna” reservoir

Ownership: Major company (operator in development phase) 40%; Small company 20%, Eureka Oil (operator in operation phase) 40%.

The hydrocarbon column consists of an approximately 120 metres thick gas/condensate column.

3.7.1 Reservoir Data

Hydrocarbons are present in Jurassic sandstones. The quality of the reservoir is good. Some key reservoir data can be found in Table 3.4 below.

<table>
<thead>
<tr>
<th>Reservoir Data</th>
<th>300,0 billion Sm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir depth</td>
<td>3500 m TVD MSL</td>
</tr>
<tr>
<td>Reservoir area</td>
<td>10 x 3 km²</td>
</tr>
<tr>
<td>In Place Volumes:</td>
<td></td>
</tr>
<tr>
<td>- Rich gas (gas cap)</td>
<td>300,0 billion Sm³</td>
</tr>
<tr>
<td>Reservoir thickness:</td>
<td>120 m</td>
</tr>
<tr>
<td>Gas cap (max thickness)</td>
<td></td>
</tr>
<tr>
<td>Reservoir pressure</td>
<td>300 bar at TVD MSL</td>
</tr>
<tr>
<td>GOR</td>
<td>1500 Sm³/Sm³</td>
</tr>
</tbody>
</table>

TVD MSV = True Vertical Depth below mean sea level.

The field has natural water drive and no maintenance of the reservoir pressure is needed.

Plateau rate to be established, take typically 15, 20 or 25 years plateau production. Initially, the GOR = 1500 Sm³/Sm³. The condensate production can be maintained if the reservoir pressure is above 50% of the initial pressure.

During the production decline phase, the annual reduction in production is 20%. The Ultimate recovery (% of reserves in place) is expected to be 70%.

The well performance rate is initially estimated at 1.5 million Sm³/day per well at plateau production.

The production design capacity is to be decided with reference to:
- The need for Eastland to buy 5.0 x 10⁹ Sm³ gas annually
- Possible internal gas utilization in Eureka
- Maximizing the condensate production from the field.
3.7.2 Fluid Data

Analysis of gas and condensate samples from the exploration well has been performed. The GOR ratio is 1500 Sm³/Sm³.

The reservoir does not contain significant amounts of H₂S.

3.7.3 Environmental Data

Some data related to the surrounding environment are given below:

- Water depth, m: 175
- Wind, m/s: 40
- Wave height, m: 20
- Air temperature, °C: -10 to 35

No history of earthquakes or ice bergs.

Gentle sloping sea bottom at field. Good conditions for design of foundation.

Sea currents, m/s: 0.8.
3.8 The Falcon Gas Condensate field offshore Eastland

The gas condensate Falcon field offshore Eastland is located 60 km away from Outer Island, which belongs to Eastland. Original in-place recoverable reserves in the Falcon field were 47 Bcm gas and 28 million m$^3$ of condensate.

The condensate is stabilised offshore and loaded onto tankers, while a mix of dry gas and heavier gas fractions is piped ashore through a 16 inch pipeline to a terminal on Outer Island where the gas is treated to dry gas for inland consumption in power plants, as industrial feed and for general distribution to customers in Easttown and surrounding areas. Further to the dry gas the terminal sells the stabilized condensate and propane, butane etc. on the world marked. Some propane is distributed for consumption in Eastland.

The gas at the offshore field is relatively dry (GOR = 20 000 m$^3$/m$^3$) and the field has been producing at a plateau at 3 x10$^9$ Sm$/$/year over a period of 10 years. The offshore platform has a first stage separation plant where water and stable condensate are separated out.

It was planned to continue to produce at plateau level for another 5 years. Recent water break through into the reservoir from the acquifer through the faults has, however, made it necessary to reduce the production and obtain better knowledge about the reservoir production capabilities. Eastland is thus urgently in need of gas to replace its production and to promote drilling prospects with potential for gas prospects.

During the whole period at gas production, the national oil company of Eastland (Eastland Oil), which is operator of the Falcon field and the established gas infrastructure, has constantly searched for more reserves, but without success. As a result there is now a growing concern in the country about the future gas supply situation, given the heavy dependence on gas for power generation, as industrial feed and general consumption, which has emerged, all based on a previous optimistic assumption that more reserves were likely to be found.

The situation is serious for the country’s economy and for the parties operating of the gas field. These are Eastland Oil (operator with 47 % ownership) and the Major oil company (with 45 % ownership and an office in Easttown). Furthermore Tricky Jones, a geologist and investor, who found the Falcon gas field 15 years ago and who also owns a large number of shares in the Small oil company, has an 8 % interest.

As Eastland is close to the more hydrocarbon prolific areas offshore Eureka, Eastland Oil has already positioned itself to play a role there by acquiring shares in relevant industries in Eureka and by signing a technical agreement to support Eureka oil. A prime objective for Eastland Oil in this regard, will be to secure a future supply of gas to Eastland.
3.9 Data for economic analysis of developments in Eureka

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil price (basis)</td>
<td>US $ 16/ barrel</td>
</tr>
<tr>
<td>Price for NGL (basis)</td>
<td>US $ 18/ barrel</td>
</tr>
<tr>
<td>Gas price (basis)</td>
<td>US $ 0.075/ Sm³ *)</td>
</tr>
<tr>
<td>Discount rate (basis)</td>
<td>10 %, see Chapter 1</td>
</tr>
<tr>
<td>National oil company</td>
<td>4 % higher</td>
</tr>
<tr>
<td>Small oil company</td>
<td>2 % higher</td>
</tr>
</tbody>
</table>

*) Any gas that could be delivered to Eastland in the period from 3 years from now to 6 years from now will be paid with a 20 % premium.

The fiscal year corresponds to the calendar year.

Costs incurred for exploration and appraisal drilling is deductible for tax calculation purposes.

Capital expenditures (CAPEX) are depreciated over 6 years for tax calculation purposes. Depreciation commences in the year the actual investments occur. Depreciation cannot be carried forward.

100% operating cost (OPEX) is deductible from gross income along with tariffs for transportation of hydrocarbons from platform facilities to shore. Operating loss carry-forward provisions are implemented.

A main concern for the Small oil company is a limit on its spending in Eureka of US $ 4 Billion (its share in the investments). The limited access to capital may be a limitation on the development solution that can be seen as viable for the Small oil company.
3.10 Updated reservoir description, “Atlas” and “South Etna” fields

3.10.1 Updated reservoir data, Atlas” field

For the “Atlas” gas production phase, the following is recommended:

- Gas production design capacity  5.0 x 10^9 Sm³/year
- Average gas production (DCF)  4.5 x 10^9 Sm³/year
- Water production  2000 m³/day to be injected into the reservoir for environmental reasons
- Swing factor  10%
- Gas production  2.5 x 10^6 Sm³/well per day at plateau production
- Gas sales to start  3 years from this date (start of Concept study phase).

Analysis of geological and reservoir engineering uncertainties have during the Feasibility study phase been performed to establish risked production profiles. This uncertainty study on recoverable reserves has been performed as a preparation for the coming Concept study.

To be able to evaluate the flexibility and robustness of the field development, a large number of sensitivity analysis have been carried out on the simulation model to investigate the effects of reservoir uncertainties. The main parameters, which influence the plateau length and cumulative production, are reservoir communication and volumes in place. The uncertainty in total gas volume initially in-place is shown in Table 3.5.

<table>
<thead>
<tr>
<th>Estimate</th>
<th>Gas-in-place Volume, Billion Sm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>P90</td>
<td>85</td>
</tr>
<tr>
<td>Mean</td>
<td>96</td>
</tr>
<tr>
<td>P10</td>
<td>160</td>
</tr>
</tbody>
</table>

Sensitivity studies indicate a spread in expected gas recovery from 60% to 75%. The expected recovery (mean value) after 18 years of production is estimated to 65 Billion Sm³. The P10 and P90 estimates of recoverable reserves are 96 Billion Sm³ and 54 Billion Sm³, respectively.

Gas production from the Atlas field poses a large challenge in that oil production will stop flowing from the existing wells as soon as 10 Billion Sm³ of gas has been produced, due to pressure reduction. Further oil production would be contingent upon use of artificial lift methods. This might not be economical viable.

It should also be taken into account that the uncertainty in transforming the Atlas field from an oil field to a gas producing field are large and that the cost estimate at the end of the Concept phase is still + 50 %.

It is thus an extremely delicate question to find the correct timing for starting the gas production that could lead to stop in the oil production.
3.10.2 Updated reservoir data “South Etna” field

For the “South Etna” gas and condensate production phase, the following is recommended:

- Gas production design capacity $10,0 \times 10^9$ Sm$^3$/year
- Average gas production (DCF) $9,0 \times 10^9$ Sm$^3$/year
- Water production 3000 m$^3$/day initially to be injected into the aquifers for environmental reasons
- Swing factor 10%
- Gas production $1,5 \times 10^6$ Sm$^3$/well per day at plateau production
- Gas sales to start 5 years from this date.

Analysis of geological and reservoir engineering uncertainties have during the Feasibility study phase been performed to establish risked production profiles. This uncertainty study on recoverable reserves has been performed as a preparation for the coming Concept study.

To be able to evaluate the flexibility and robustness of the field development, a large number of sensitivity analysis have been carried out on the simulation model to investigate the effects of reservoir uncertainties. The main parameters, which influence the plateau length and cumulative production, are reservoir communication and volumes in place. The uncertainty in total gas volume initially in-place is shown in Table 3.6.

Table 3.6 Uncertainties in Gas In-Place Resources.

<table>
<thead>
<tr>
<th>Estimate</th>
<th>Gas-in-place Volume, Billion Sm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P90</td>
<td>150</td>
</tr>
<tr>
<td>Mean</td>
<td>200</td>
</tr>
<tr>
<td>P10</td>
<td>290</td>
</tr>
</tbody>
</table>

Sensitivity studies indicate a spread in expected gas recovery from 65% to 75%. The expected recovery (mean value) after 18 years of production is estimated to 140 Billion Sm$^3$. The P10 and P90 estimates of recoverable reserves are 200 Billion Sm$^3$ and 100 Billion Sm$^3$ respectively.
3.11 Fiscal (tax) regime applicable for the countries of Eureka and Eastland

3.11.1 General data

- Cost recovery allowed up to 100%
- Allow operating loss carry forward
- Royalty 10%
- Production sharing
- Profit oil split
  - Eureka share (%) 70
  - Oil company share (%) 30
  - Tax on company profit (%) 20.

3.11.2 Data for economic evaluations

- Oil Price 16 USD/bbl
- Capital costs (CAPEX)
- Operating costs (OPEX)
- Costs of appraisal wells equal to costs of exploration wells
- Costs of converting an oil well to a gas producer 20% of the costs of a new oil well.

3.11.3 Other countries

It should be noted that Eureka proposes better fiscal terms than Eastland thereby trying to attract investors to the country.
CHAPTER 4  Examination, autumn 2003

4.1 Problem Set 1. Arctic Offshore Field-development

a) Arguments can be given both for and against exploration drilling for hydrocarbons in the Arctic.
   
i) Present such arguments (both pro and contra).
   ii) Give a discussion (min ¾ page) on which arguments you would put most emphasis on.

b) A gas/condensate field (with a GOR of 2000 m³/m³) is located in 50 m water depth 120 km from land in the Arctic. At present there is no gas pipeline to the marked.
   
i) Discuss possible sales products from the field and associated field development scenarios.
   ii) In the case it is decided to produce stable condensate at the field, discuss (with drawings) how the condensate can be stored and offloaded.
   iii) Present a discussion on how the production profile from the field could be established.
   iv) Show how early production from the field has a positive effect on the economics (the NPV) of the project.
   v) Which factors makes it more difficult to initiate this project compared to a project in the central or northern North Sea.

4.2 Problem Set 2. Ice mechanics and loads

a) Elaborate briefly on “ice features” in the Barents Sea (see left-hand side of Fig. 4.1)?

b) What is the marginal ice zone (MIZ) and what characterises it in the Bjørnøya-Hopen waters in the Barents Sea?

c) Assume that gravity waves enter the MIZ perpendicular to it. Assume further that the wave energy is given by the equation:

\[ E = E_0 e^{-\alpha x}, \]  

(4.1)

where \( E_0 = E(x=0) \) is the energy at the ice edge and \( x \) is the distance measured normal to the edge and inward, \( \alpha \) is the wave attenuation coefficient. 1) Explain why the waves are attenuated by the ice? 2) What part of the wave spectra is most attenuated?

Fig. 4.1 Parameters and relations important for ice loads.
4.3 Problem Set 3. Pipeline stability under steady current

In the following we consider the stability of a pipeline resting on a horizontal seabed. The stability is determined by the relative magnitudes of the agitating hydrodynamic forces and the restoring force due to the submerged weight of the pipe. Fig. 4.2 shows the pipeline.

![Diagram of pipeline](image)

Fig. 4.2 Cross-section and forces acting on the pipeline resting on the seabed.

The forces per unit length acting on the pipeline with diameter $D$ in a steady current environment are:

$$
F_x = \frac{1}{2} \rho C_D U |U| \\
F_z = \frac{1}{2} \rho C_L U^2
$$

(4.2)

where $F_x$ is the horizontal force, $F_z$ is the vertical force, positive upwards, $C_D$ and $C_L$ are the drag and lift coefficients, respectively. $U$ is the current speed. The contact between the pipeline and the seabed is idealised as governed by Coulomb friction with a coefficient $\mu$.

Assume that the submerged weight of the pipeline per unit length is given by

$$
W_s = \frac{\pi \rho_p g D^2}{4}
$$

(4.3)

where $s_p = \rho_p / \rho$ (specific gravity) and use the following governing parameters $s_p = 1.6$; $C_D = 1.2$; $C_L = 0.8$; $\mu = 0.6$; $g = 9.81$ m/s$^2$; to calculate the critical velocity when $D = 1.2$ m.

b) Calculate the current drag force alone on the pipeline per unit length when the current velocity is given by the $\alpha$-profile (1/7):

$$
\frac{u}{u_{300}} = \left( \frac{z}{z_{300}} \right)^{1/7}
$$

(4.4)

where $u_{300}$ is the horizontal current velocity at a height $z_{300} = 300$ cm above the seabed. Use $u_{300} = 0.5$ m/sec in your calculation.
4.4 Problem Set 4. Ice loads

a) Why are ice loads on sloping structures less than on vertical ones? Which factors can diminish the advantages of sloping structures?

b) Which physical events take into account Contact and Indentation factors in the Korzhavin formula for estimation of ice loads?

c) Assume that the mean weight of a gravity base structure is 80 MN (coefficient of variation 0.05). The environmental actions are shown in Table 4.1 (it is proposed a Gaussian (Normal) load distribution).

d) Mean friction coefficient structure/sea bottom: -0.4 (deterministic). Determine the weight of the ballast to reach stability safety (sliding) of 0.99999 (failure probability 0.00001).

<table>
<thead>
<tr>
<th>Action</th>
<th>Mean value, MN</th>
<th>Coefficient of variation (v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice</td>
<td>25.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Wind</td>
<td>2.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Current</td>
<td>5.0</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 4.1 Input data.

<table>
<thead>
<tr>
<th>$P_f$</th>
<th>0.1</th>
<th>0.01</th>
<th>0.001</th>
<th>0.0005</th>
<th>0.0001</th>
<th>0.00001</th>
<th>$3 \cdot 10^{-6}$</th>
<th>$2.9 \cdot 10^{-7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>1.28</td>
<td>2.32</td>
<td>3.15</td>
<td>3.3</td>
<td>3.77</td>
<td>4.25</td>
<td>4.5</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 4.2 Correlation between failure probability $P_f$ and safety index $\beta$ for the normally distributed function.
Chapter 5  Solutions to examination

5.1 Problem Set 1. Arctic Offshore Field-development

a)  
   i) One could argue that exploration drilling is advantageous for several reasons:
      - It is beneficial to get an overview of available resources
      - In order to start a possible development, one should know the resource base
      - Exploration drilling gives good knowledge about working in the Arctic
      - Exploration drilling makes it possible to plan future Arctic developments
      - Etc.

   On the other hand, one could argue that exploration drilling should not take place in the Arctic given today’s state of art with respect to exploration and environmental spill collection technology:
      - The effects a possible oil spill will have on the Arctic environment is not fully known
      - Oil spill collection technologies in the Arctic are not sufficiently well advanced
      - There is the possibility that waste from the drilling can cause contamination
      - Exploration drilling will cause pressure to develop the fields
      - One does not have the technology for handling the ice conditions in the Arctic
      - Etc.

   ii) The student should assess the pro and cons and give his/her honest opinion. The objective of this question is to have the student to formulate an opinion about a very important issue in a format that is understandable to the reader.

b)  
   A GOR (Gas to Oil Ratio) of 2000 m$^3$/m$^3$ means that for each 1 m$^3$ of oil (at atmospheric pressure) there are 2000 m$^3$ of gas.

   i) In 50 m of water depth it could be possible to load stable oil products (stabilized oil and stabilized condensate) directly to tankers (for example using the STL concept of loading), provided oil products can be stored offshore, for example in the caisson of a platform. The unstable condensate and gas should in principle be sent to a shore terminal for extraction of the higher value products (Butane, propane etc.) while the methane could be sold on the market, for example as LNG.

   It might not be realistic, however, to build a condensate pipeline to shore and the gas and unstable products should then be injected into the reservoir for possible extraction at a later stage.

   An alternative development scenario will be offshore water separation with multiphase pipeline transport to shore. This will require glycol injection into the pipeline to ensure product flow and avoidance of wax formation. Pipeline heating might be required as well.

   For this scenario with a relatively low GOR, full well stream to shore might be unrealistic in view of high probability of wax formation. Note that at present the longest planned full well stream flow (140 km) is at the Snøhvit field (Northern Norway) where the GOR is 10 000 and where the amount of water produced will be very low. The low temperature in the Arctic waters will increase the probability of wax formation considerably.
ii) For production of stable condensate at the field, the condensate could be stored in the caisson of a gravity base (steel or concrete) platform structure. Offloading could take place directly from the platform using loading arm or from a loading tower or preferably from a STL loading buoy located away from the platform to avoid that the transport vessel drifts into the platform when the direction of the ice flow changes.

iii) The production profile is established with due regards to the necessity to have early income while maintaining a stable production for a long period. To invest very much in a production that has a very short production life is normally not warranted. Very short production time will also tend to give an unfavourable recovery level.

On the other hand, a very long production period tends to give a low Net Present Value for a project. It is anticipated that a new project in the Arctic with the need for building up new infrastructure will necessitate a production period of, say at least 20 years. The production level (and the processing equipment) should therefore be designed for 20 years production time. In the case of a large field, the period could be extended. When the production starts, the nearby potential hydrocarbon bearing structures will normally be drilled to ensure that the facilities already installed will be used to their maximum.

iv) Early production has a very large influence on the Net Present Value calculations. Production having a net value I will have a net present value of \( \frac{I}{(1 + p)^n} \) where \( p \) is the annual interest rate and \( n \) is the number of years until production. To delay production means that the numerator increases leading to a lower contribution to the NPV.

v) There are a number of factors that makes it more difficult to initiate this project compared to a project in the central or northern North Sea. Such factors are, for example:
   - Lack of infrastructure in the Arctic
   - Long way to the marked for stable products with needs to build special tankers for Arctic traffic
   - Long way to the marked for gas and unstable products
   - Difficult ice conditions leading to larger investments compared to other areas
   - Difficult ice conditions leading to large operational costs compared to other areas
   - Sensitive environment causing need for upgrading of oil spill response procedures.

5.2 Problem Set 2. Ice mechanics and loads

The student should elaborate more than it has done here:

a) “Ice Conditions” in the Barents Sea:
   - Ice cover: Almost entirely first-year ice (ice that has not over summered).
   - First-year ice thickness: Typically 1-1.2 m at most 2 m.
   - Rafted ice: Double ice layer. Encountered several times.
   - Ridges: Quite common with maximum keels about 18 m and 4-5 m max. sail height.
   - Ice drift: Follows normally the surface current speed, but 2-3 % of wind speed may be added if acting in the same direction.

b) Marginal ice zone (MIZ): Ice edge (edge zone, transition zone and interior zone).

c) 1) Waves are attenuated by the ice due to dissipation of energy and dispersion.

   2) The high frequent part of the wave spectrum is most attenuated because those wavelengths may break up the ice cover and loose energy.
5.3 Problem Set 3. Pipeline stability under steady current

a) The forces per unit length acting on a pipeline with diameter $D$ in a steady current environment are:

$$F_x = \frac{1}{2} \rho C_D DU |U|, \quad F_z = \frac{1}{2} \rho C_L DU^2,$$  \hspace{1cm} (5.1)

where $F_x$ is the horizontal force; $F_z$ is the vertical force, positive upwards.

The pipeline becomes mobile when the resultant of the drag and lift forces exceed the resisting force due to the submerged weight of the pipeline:

$$F_x > \mu (W_s - F_z),$$  \hspace{1cm} (5.2)

where $\mu$ is the friction coefficient.

The submerged weight is given as:

$$W_s = \frac{\pi}{4} (\rho_p - \rho) g D^2.$$  \hspace{1cm} (5.3)

Substitution into the equation gives:

$$\frac{1}{2} \rho C_D DU^2 > \mu \left[ \frac{\pi}{4} (\rho_p - \rho) g D^2 - \frac{1}{2} \rho C_L DU^2 \right]$$

$$\frac{1}{2} \rho D \left( \frac{C_D}{\mu} + C_L \right) U^2 > \frac{\pi}{4} (\rho_p - \rho) g D$$

$$U^2 > \frac{t (\rho_p - 1) g D}{2 \left( \frac{C_D}{\mu} + C_L \right)}$$  \hspace{1cm} (5.4)

With values plugged in we obtain:

$$U^2 > \frac{\pi (1.6 - 1) \cdot 9.81 \cdot 1.2}{2 \left( \frac{1.2}{0.6} + 0.8 \right)}$$

$$U > 2.0 \text{ m/s}.$$  

b) Current drag force:

$$\bar{U} = \int_{-d}^{-d+D} U dz = \frac{U_{300}}{z^{1/7}} \int_{-d}^{-d+D} z^{1/7} dz = \frac{0.5}{3^{1/7}} \cdot \frac{7}{8} [z^{8/7}]_{-d}^{-d+D}$$

$$\bar{U} = 0.5 \text{ m/s} \text{ (without averaging we obtain 0.4 m/s).}$$

$$F_x = \frac{1}{2} \cdot 1000 \cdot 1.2 \cdot 0.5^2 = 150 \text{ N/m}$$
\[ F_z = \frac{1}{2} \cdot 1000 \cdot 0.8 \cdot 0.5^2 = 100 \text{ N/m} \]
\[ F = \sqrt{F_z^2 + F_x^2} = 180 \text{ N/m}. \]

5.4 Problem Set 4. Ice loads

a) Usually ice actions on sloping structures are less than on vertical ones because ice, under normal conditions, bends on slopes. As ice resistance to bending is less than to crushing (type of failure typical to interaction with vertical structures) actions on sloping structures should be less than on vertical one. But any reasons, which lead, to bending restriction induces action increase. These factors may be: ice freezing to the structure surface, formation of great collection of rubble on the structure surface, great ice velocity (>0.5 m/s) (it corresponds to great ice sheet inertia during the interaction), great angle of slope inclination to horizon. Period of ice action on sloping structure usually higher than period corresponding to crushing and fare on structure natural period. This is additional advantage of sloping structures.

b) Contact factor takes into account non-perfect contact between the structure and ice surface. Different reasons can induce this effect, in particular the ice edge is never flat, failure develops non-simultaneously over the contact surface, etc. This factor can be as low as 0.3 - 0.6.

Indentation factor takes into account the peculiarity of stress/strain field around the structure. According to different solutions this factor can be in the ranges 1.2-3.0.

c)-d) Let x-is the weight of the ballast.

Standard deviations is defined as:

\[ \sigma = v \cdot M \]  \hspace{1cm} (5.5)

Correspondingly to Table 4.1 and Eq. (5.5) the standard deviations can be determined. These data are given in Table 5.1.

<table>
<thead>
<tr>
<th>Action</th>
<th>( \sigma ), MN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice</td>
<td>7.5</td>
</tr>
<tr>
<td>Wind</td>
<td>1.0</td>
</tr>
<tr>
<td>Current</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Mean value of the common action:

\[ M_L = \sum M_i = 25 + 2.5 + 5 = 32.5 \text{ MN} \]

Standard deviation of the common action:

\[ \sigma_L = \sqrt{\sum \sigma_i^2} = (56,25 + 1 + 1.56)^{0.5} = 7.67 \text{ MN} \]

Mean resistance to sliding:

\[ M_R = (80 + x) \cdot 0.4 \text{ MN} \]

Square deviation of resistance:

\[ \sigma_R = 80 \cdot 0.4 \cdot 0.05 = 1.6 \text{ MN} \]

\[ M_S = M_R - M_L = (-0.5 + 0.4x) \text{ MN} \]

\[ \sigma_S = (\sigma_L^2 + \sigma_R^2)^{0.5} = (58.82 + 2.56)^{0.5} = 7.83 \text{ MN}. \]

To reach reliability 0.99999, the safety index should be equal to 4.25 (see Table 4.2).

So \[ \beta = M_S / \sigma_S = (-0.5 + 0.4x) / 7.83 = 4.25 \] and \[ x = 84.44 \text{ MN}. \]