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Writer: Soslan Tsoraev	…………………………………………… (Writer's signature)

Faculty supervisor: Ove Tobias Gudmestad

External supervisor: Anatoly Borisovich Zolotukhin

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ABSTRACT

The Northern Caspian Sea is considered to be a very perspective region for oil and gas production growth. However, the challenges encountered in the Northern Caspian Sea are not usually met in such combination in another regions, so this imposes special requirements for the further development of hydrocarbon fields in the region.

This thesis is focused on the field development in the Kazakh sector of the Northern Caspian Sea and it is addressed to a discussion of artificial island concept that might be applied for these conditions. Possible options for production of hydrocarbons, oil and gas transportation and processing are discussed on basis of the analysis of existing solutions for similar conditions. Attention is also given to the ice load mitigation measures and other aspects that should be taken into consideration during the development of fields in the Northern Caspian Sea.

In near shore oilfield development of The Caspian Sea, artificial island is the better method because of the economic and technical convenience. But compared with the traditional way of reclaiming land from beaches, the construction of artificial island should be given with more attention to the ocean hydrological and dynamic changes, the mutual implication between engineering zone and marine environment.

Finally, conclusions wrap up the thesis in order to summarize the acquired findings.

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I would also like to thank my parents for big support and cheering me up in hard times.

Chapter 1. Introduction

Although the Caspian Sea, which is shared by Azerbaijan, Iran, Kazakhstan, Russia and Turkmenistan, is one of the oldest oil production regions in the world, its northern part, has been developing over only last two decades. Today the Northern Caspian Sea is considered to be a very perspective region for oil and gas growth.

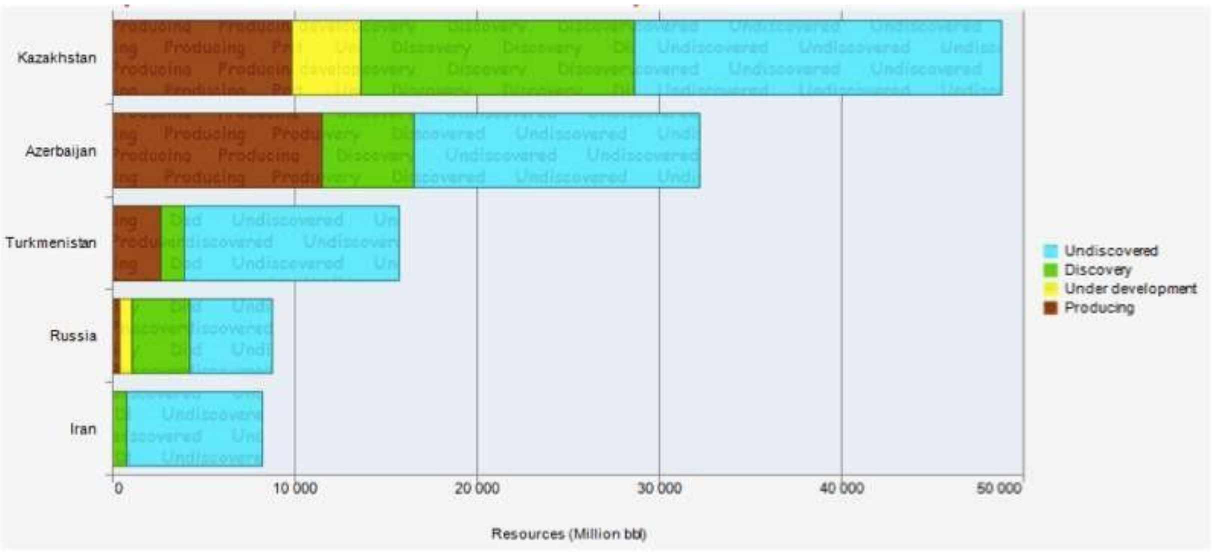


Figure 1.1: Potential of the Caspian Sea (Zolotukhin, 2017a)

The resource potential of the Kazakh sector, which is mainly represented by the Northern Caspian Sea, amounts to ca. 50 billion barrels of oil equivalent, see fig. 1.1. Note that the greatest potential of the Kazakh sector of the Northern Caspian comes from the Kashagan field that is considered as the world’s largest oil discovery in the last 35 years (Henni, 2014).

It is a giant oil field located 80 km southeast of Atyrau. The Kashagan reservoir extends over an area of 75 km by 45 km and holds up to 38 billion of oil-in-place where about 10-13 billion bbl of these reserves is recoverable. As expected the peak production will reach 1.5 million of barrels of oil per day, which will be ca. 5% of global demand by 2022 (Zolotukhin, 2017). North Caspian Operating Company (NCOC) consisting of Eni, ExxonMobil, Total, Shell, KazMunaiGas, CNPC and INPEX is responsible for the field development.

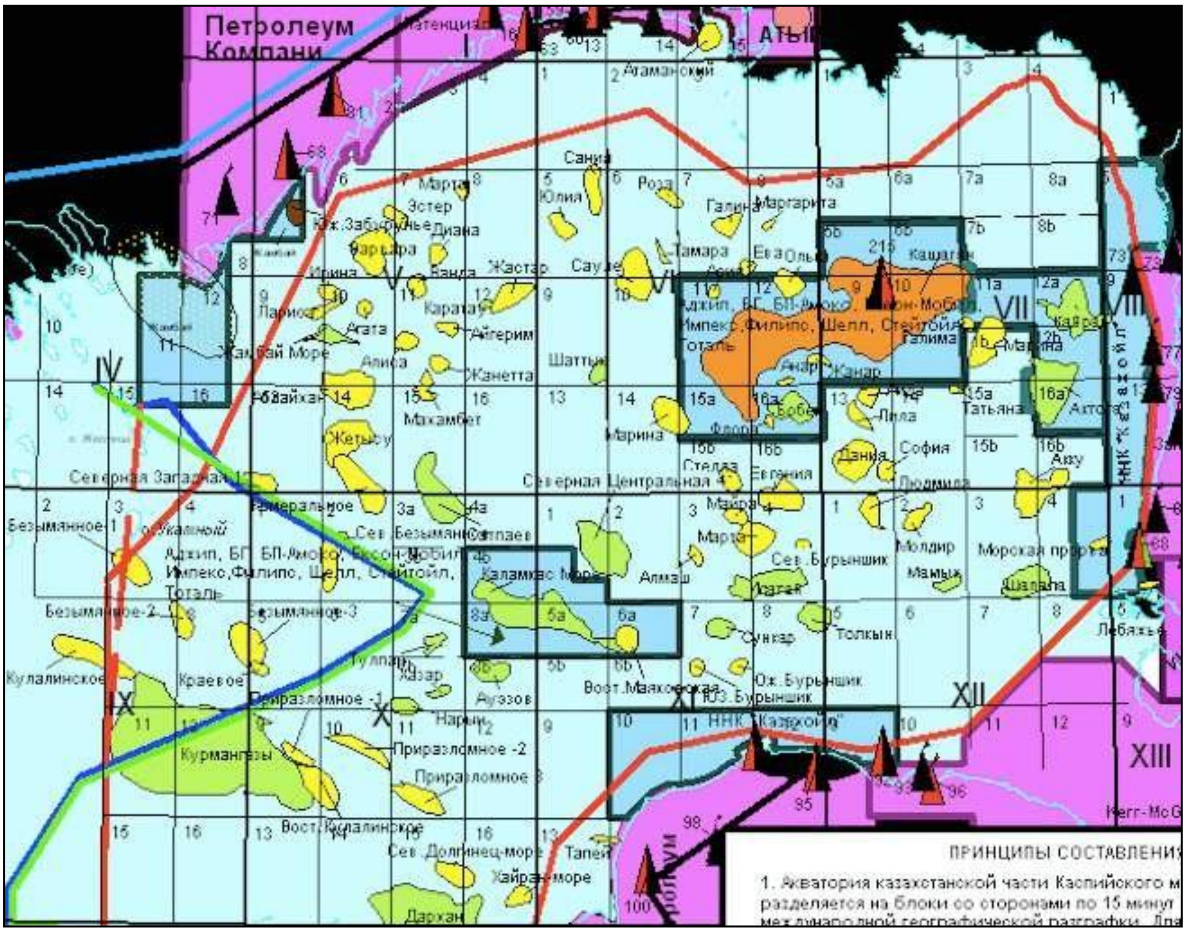


Figure 1.2: Perspective hydrocarbon fields within the Kazakh sector of the North Caspian Sea.

Note that: explored structures are shown in yellow, fields that are ready for the further development are shown in green, fields that are in the developing phase are in brown (based on picture from Wikipedia, 2011).

However, the Kashagan development faced with significant delays and tremendous cost overruns. The production onced started on 11 September 2013 had to be stopped after two weeks due to leakages of the offshore pipeline running from one of the artificial islands to the onshore processing facility. A new date of production start-up was set 2016.

Currently, $ 50 billion has been invested only in the first phase (Helman, 2014) while the final capital expenditures are anticipated to be $136 billion (Eldesov, 2013).

In addition to Kashagan, about 120 oil fields and perspective structures (table 1.1 & fig. 1.2) have been discovered within the Kazakh sector (Espergen, 2006). However, it’s worth mentioning that there are still significant uncertainties associated with evaluation of the hydrocarbon resources and reservews. Namely, there are such fields as Makhambet, Aktoty, Abai, Kairan, etc, while the reserves of such prospect structures as, Zhambyl, Satpayev, Zhenis, Abay, Bobek, Isatay, Darkhan, Shagala are still needed to be estimated.

Table 1.1. Fields located in the Kazakh sector of the Northern Caspian Sea

Field	Year of discovery	GeologicalResources	RecoverableReserves
Makhambet, Makhambet-south, Ablay, Zhambay	2011	-	**oil -** 230 MM tones
Kairan	2003	-	**oil** - 35.8 MM tones ***gas*** -33.5 *bcm*
South west Kashagan	2003	-	**oil** - 6 MM tones ***gas*** - 15.2 *bcm*
Auezov	2008	**oil** - 60-70 MM tones	-

Rakushechnoe	2010	**oil** – 290 MM tones ***gas*** - 80 *bcm*	-
Khazar	2013	**oil** – 75.3 MM tones	**oil** – 30.6 MM tones
Kalamkas-offshore	2013	**oil** – 284.5MM tones	**oil -** 67.5 MM tones

Even though only limited experience in this region has been gained, this does not prevent many companies including major ones from realizing their own E&P programmes. The North Caspian Sea could become an important centre of oil and gas production in the near future with own exploration and production market, infrastructure, etc.

Chapter 2. Aspects of Sea Ice

Sea ice is a complex crystalline material mainly consisting of pure ice, brine and gas (air). Its properties are determined by the molecular structure, temperature, salinity, density and different impurities that take place within it. Moreover, sea ice properties significantly vary from one region to another one.

The ice properties determine the magnitude of ice loads on offshore structures and, therefore, it is of interest to discuss them in this thesis. Since this thesis relates to development concepts that are suitable in the Northern Caspian Sea, only aspects of sea ice, which are relevant for this region, are presented. It should be noted that only first-year ice takes place in the Caspian Sea, so multi-year ice is beyond the scope of the thesis and not discussed.

2.1 Physical properties

Some physical properties of sea ice that are mentioned in the preamble relate to such physical aspects as density and salinity of ice, its morphology and structure, grain sizes, ice thickness, porosity, etc.

Usually, an engineer does not need a detailed description of a microstructure and a crystallography of sea ice, so this section focuses only on a minimal required explanation of the molecular structure of sea ice and the physical properties that determine engineering decisions. However, the reader is referred to Løset et al. (1998), Timco and Weeks (2010) for more information regarding the topic of this section.

The structure of ice

There are several forms of ice existing under different temperatures and pressures, but only one of them, called Ih ice, takes place in nature. The crystal structure of Ih ice builds on a crystallographic arrangement of molecules of water, which have a repeating tetrahedral geometry with hexagonal symmetry (fig. 2.1). Besides, the ice structure has a series of parallel planes called “basal plane” and a major axis of symmetry, called c-axis, is normal to the basal plane. Note that basal-plane layers are not exactly planes and this is shown in fig. 2.1, b). In addition, three a-axis at 120° to each other are perpendicular to the c-direction.

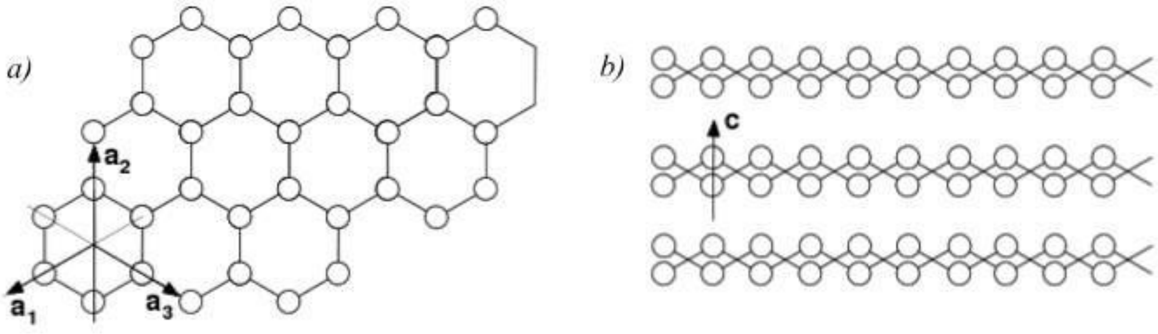


Figure 2.1: Idealized arrangement of atoms in Ih ice wherein oxygen atoms are presented in white circles and view of crystal lattice looking a) along the c-axis

and b) along basal-plane layers (after Palmer and Croasdale, 2012).

The ice structure influences the ice formation process. It is easier to add atoms to an existing basal plane, i.e. perpendicular to the c-axes, so crystals growth in the a-directions. In addition, differences of the ice mechanical behavior under different directional loads could be also explained in terms of the ice structure. Thus, an ice crystal has three hydrogen bonds in the basal plane versus only one hydrogen bond along the c-axis. As a result, fracture along the basal plane requires rupturing two hydrogen bonds in the unit cell, while fracture of the unit cell along planes normal to the basal plane requires at least 4 hydrogen bonds to be ruptured. Also such ice properties as thermal conductivity, atomic diffusivity and elastic stiffness are also isotopically perpendicular to this c-axis (Løset S., 2017b).

However, in reality ice crystals might significantly vary in size. A group of ice crystals forming sea ice might have the c-axis randomly oriented. Moreover, sometimes we can distinguish the sea ice having nearly the same orientation of the c-axis and this depends on the ice formation conditions. As illustrated in fig. 2.2 ice is mainly an orthotropic material (columnar ice) with random orientated c-axes covered by the layer of granular ice. It should be noted that salinity and temperature are not constant and change through the ice sheet.

The reader interested in more detailed description of the microscopic structure of sea ice, its growth and formation is referred to Løset et al. (1998).

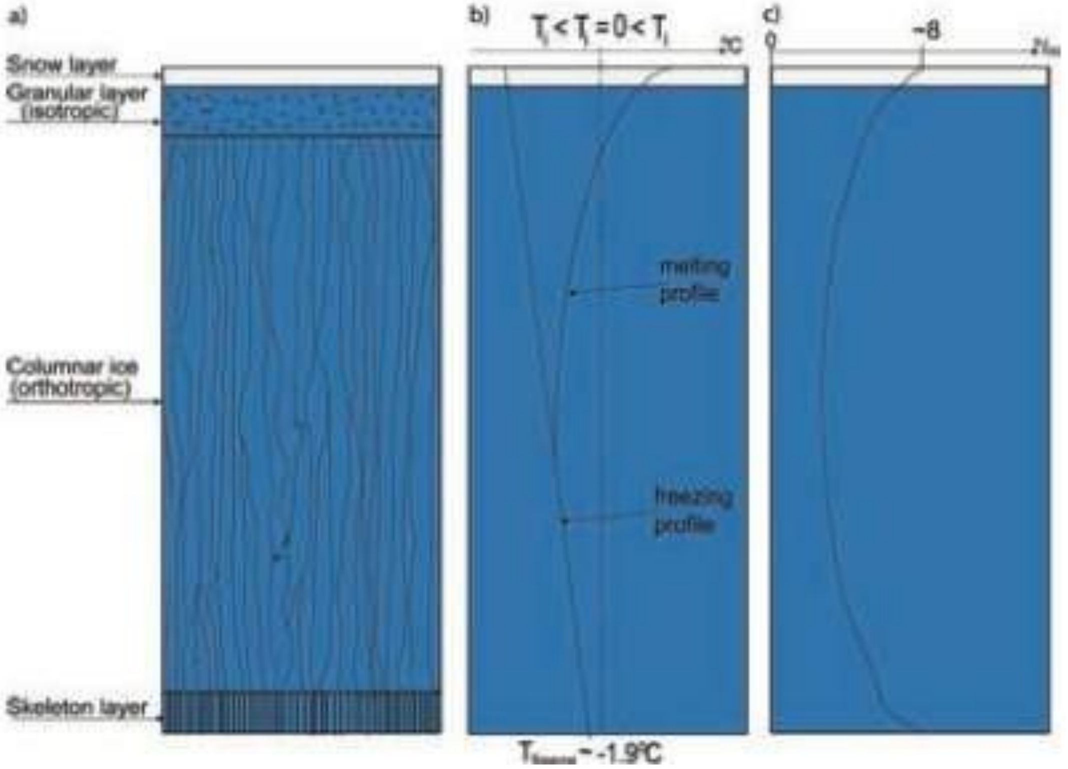


Figure 2.2: a) Typical morphology of a sheet ice layer; b) typical temperature profiles during freezing and melting, where Tfreeze is the freezing temperature

of the ice and Ti is the designates the ice temperature; and c) typical salinity profile (Gürtner, 2009).

Density

The density of sea ice mainly depends on the temperature and the salinity of seawater. This correlates with the Caspian field investigations presented by Terziev et al. (1992). Thus, sea ice density in the Northern Caspian Sea varies in the range between 630-968 kg/m^3, while the probability of ice with the density that is higher than 900 kg/m3 is 85%.

2.2 Mechanical properties

Sea ice is an inhomogeneous, anisotropic and nonlinear viscous material (Sand, 2008). The ice mechanical properties including tensile, compressive, flexural, shear strengths coupled with Young modulus, Poisson ratio and friction coefficients are functions of the physical properties (the structure of ice, brine volume, porosity), temperature, the confinement of the ice sample, strain rate, etc.

The following section describes the mechanical properties that are important for the further discussion. Note that only results of the field measurements carried out in the North Caspian Sea are given although these ice properties could be derived from experimental correlations.

Compressive strength

Compressive strength is the maximal principal stress corresponding to failure begging under ice compression (Løset et al., 2006). Generally, ice preferably fails in compression taking place when thick ice interacts with offshore structures (Timco and Weeks, 2010).

Ice is featured by two kinds of inelastic behaviours under compression (see fig. 2.3). On basis of the shape of the stress-strain curve, several zones can be determined: (i) brittle regime, (ii) ductile regime and (iii) transition zone.

Ice exhibits ductile behaviour when the stress-strain curve has a plateau and, on the other hand, the strain rate is lower than $\varepsilon_{!/!}$. The peak stress (or ductile compressive strength) increases with (i) increasing strain rate; (ii) with decreasing temperature and (iii) with decreasing salinity and porosity of the ice. According to Sand B. (2008) the grain size does not significantly influence on the peak stress.

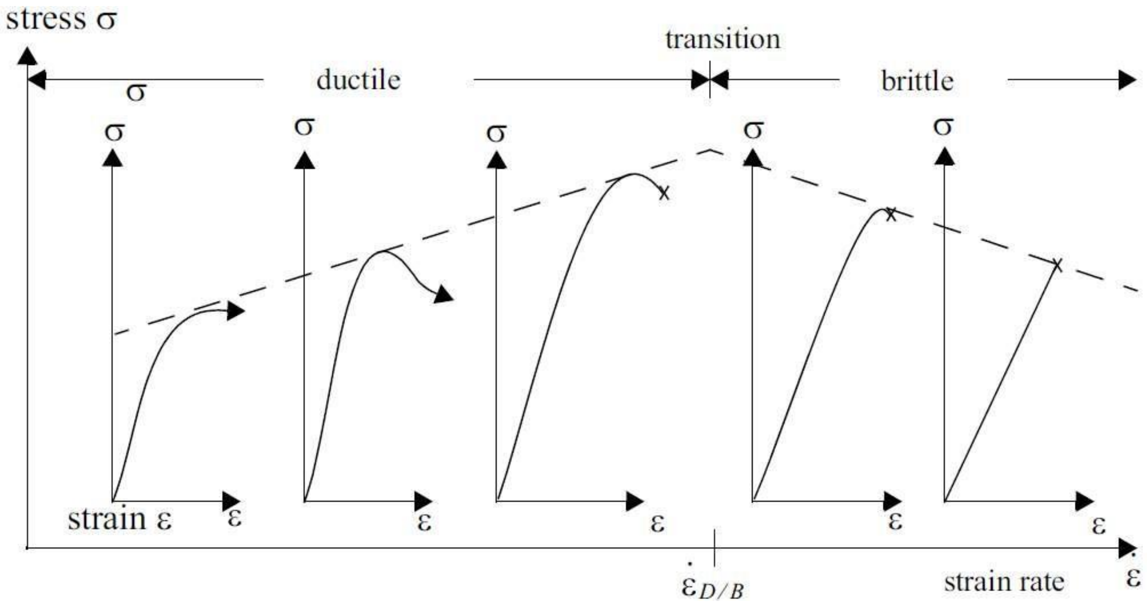


Figure 2.3: Schematic sketch showing the effect of strain rate on the compressive stress-strain behaviour of ice (Sand, 2008).

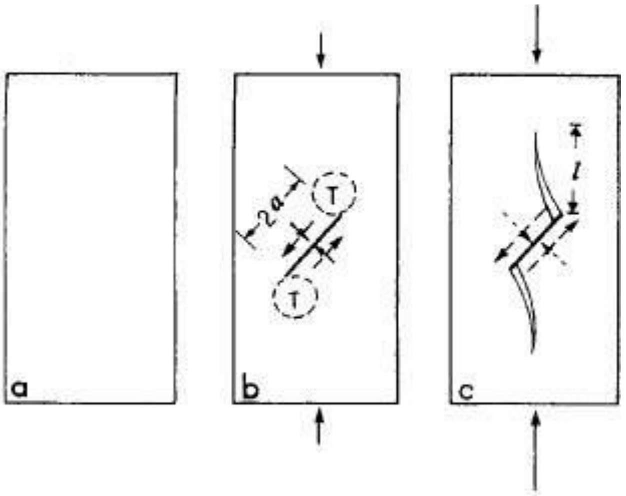


Figure 2.4: Development of the wing crack mechanism: a) Zero load. No cracks. b) Cracks nucleate at a critical compressive stress. Normal stress acts to close cracks and shear stress acts to cause sliding. T denotes tensile zone. c) Wings of length L nucleate in tensile zone at higher stress (after Sand, 2008).

Another important zone is the transition point, where the compressive strength reaches its maximum; hence, the ice loads on a structure will be maximal as well. The decreasing of the compressive strength after the transition might be explained by begging of the crack propagation (see fig. 2.4): at strain rates lower than $_{!/!}$ (i.e. ductile ice behaviour) cracks form without propagation, while at strain rates above $\varepsilon_{!/!}$ (i.e. brittle ice behaviour) wing cracks propagate from the cracks formed before. The transition rate $_{!/!}$ is in the range from 10^{-4} to 10^{-3} s^{-1} at temperatures from -40°C to -5°C.

Although the measured values of the compressive strength vary in wide range from 0.14 MPa to 6.0-8.0 MPa, the typical values for first-year ice in the North Caspian Sea do not exceed 4.5 MPa. It should be noted that these values of the compressive strength are comparable with the compressive strength of freshwater ice because of the low salinity of the Northern Caspian Sea. Thus, the compressive strength ranges from 5-25 MPa for freshwater ice (Petrovich, 2003), which is close to the compressive strength of the Caspian ice.

2.2.1 Tensile strength

Tensile strength is the maximal principal stress corresponding to failure begging under ice tension (Løset et al., 2006). Note that the tensile strength in vertical loading is three times higher than for horizontal one due to the ice structure and the ice growth direction. In addition, compressive and tensile strengths might vary significantly along different directions, but the compressive strength is normally 2-4 times larger than its tensile strength.

Typical values for first-year ice range from 0.13 MPa to 0.67 MPa (most of the Caspian measurements were carried out for the coastal zone). This is also close to the tensile strength of freshwater ice ranging from 0.7 to 3.1 MPa (Petrovich, 2003).

Flexural strength

Flexural strength is the ability of a brittle material to resist deformation under flexural loading conditions. In contrast to the compressive strength, the flexural strength of sea ice has not strict correlations with the loading rate. Since this parameter characterizes the material bearing capacity, the flexural strength is an important parameter for calculations of the ice behavior on sloping actions.

Typical values of flexural strength of sea ice measured in the Caspian Sea do not exceed 2.17 MPa while most of the results are in the range 0.41—1.20 MPa (see figure 2.5). However, the mean flexural strength based on 553 measurements in the North Caspian Sea is 0.78 MPa.

Shear strength

Timco and Weeks (2010) claim: “in engineering practice, the shear strength is not usually explicitly used. Since ice tends to fracture rather than to flow in a crack-free, volume- conserving manner, the shear strength is actually governed by the tensile strength of the ice. Since most ice engineering issues occur at higher loading rates (i.e. when ice exhibits brittle behaviour – the author’s note), the compressive strength is much higher than the tensile strength. Thus, ice loaded with a shear condition would fail in tension rather than in shear.”

However, the shear strength is an important material property to consider because the interaction between ice and structures is subjected to a biaxial stress state involving tensile stresses in addition to the compressive or shear stress. The author could found no reported measurements of the shear strength of the Caspian Sea ice, so the values of shear strength of columnar sea ice ranged from 550kPa to 900 kPa (Frederking and Timco, 1986) are proposed for the further discussion.

Friction coefficient between ice and different materials

Friction forces are involved in problems associated with ice interaction with offshore structures. Due to static and dynamic ice-structure interaction conditions, static and kinetic friction coefficients are distinguished.

Friction depends on the ice temperature, roughness of interacting surfaces and relative velocity. However, temperature has not a strong influence on the friction coefficients. The friction coefficient decreases with increasing the relative velocity. The static and kinetic components of friction do not depend on the contact area. The values of the friction coefficients for the ice interaction with concrete, ice and ground are presented below.

The static friction of sea ice on rough concrete is equal to 0.13 and the corresponding kinetic friction coefficient is about 0.05 when the relative velocity is 30cm/s (Sand, 2008).

According to Frederking and Barker (2002) the friction coefficient for the ice-ice interaction is 0.03 at speeds greater than 0.1m/s and 0.09 at 0.01m/s.

The ice-sand/gravel friction coefficient (corresponding to sliding of a large ice block on the seabed) varies in the range of 0.2-0.6 and reduces with increasing relative velocity.

2.2 Ice features

In this section only the ice features that are relevant for the Northern Caspian Sea are presented. For additional information about other ice features the reader is referred to WMO (1989).

- *Level ice* is considered as sea ice that has not been subjected to deformation and has relatively uniform thickness.
- Rafted ice is defined as an ice feature formed when separate ice fields interact with each other. Due to currents and winds these ice fields override each other without a large amount of rubbles formation and eventially they adfreeze together.
- Ridges are formed when thick ice sheets interact with each other causing deformation of their edges and generate significant ice rubbles at the contact area.

- Stamikhas are grounded ridges that are usually form in shallow water where interaction between landfast ice and drifting ice exists.

More detailed information about these features observed in the Northern Caspian Sea is presented in Chapter 3.8.

2.3 Summary

Concentrating on the Northern Caspian Sea, the properties of first year ice that are applicable for later analyse in this report have been discussed. The magnitude of ice loads is a function of the ice properties, so it is of interest to properly determine each of them.

Ice is mainly an orthotropic material (columnar ice) covered by the layer of granular ice. It exhibits different behaviour depending on the strain rate of the load. It is important for the ice loads calculations to determine the transition point corresponding to the maximal compressive strength.

The results of the measurements carried out in situ have been also introduced. Generally, the analysis of the measurements’ data shows a good correlation of the Caspian ice properties with the properties of freshwater ice. This is due to the low salinity of the Northern Caspian Sea and this is discussed in the next chapter.

Chapter3. Environmental Conditions of the Northern Caspian Sea

The Caspian Sea located at the crossroads of Europe and Asia is the biggest enclose water body in the world. Being called a sea, the Caspian Sea is essentially a giant lake that is shared by Azerbaijan, Iran, Turkmenistan, Kazakhstan and Russia. The Caspian Sea covers 378 400 km^2 and the total volume of water is 78 100 km^3. About 130 rivers feed it, but the most significant of them are Volga and Ural, which make about 90% of the total river discharge and which run into the sea in the northern part.

Traditionally, three main geographic areas are distinguished within the Caspian Sea: the northern, middle and eastern parts and the sea conditions within each of these areas significantly vary.

To get a broad understanding of the problems related to development of hydrocarbon fields in the region, the environment conditions only of the Northern Caspian Sea are introduced in this chapter.

3.1 Bathymetry

According to different sources (Kuehnlein, 2002, Kaltayev et al., 2007) the average water depth is about 4 m (fig. 3.1). However, the north-eastern part of the Caspian Sea is extremely shallow: the water depth within 25-30 km area from the shore doesn't exceed 2 m. (Sarybekova, 2004). The deepest part of the Northern Caspian Sea is the Ural furrow located in the center of the Kazakh sector, where water depth reaches 9 m. Nevertheless, due to the sea level changes discussed in detail in Chapter 3.7, the water depth and the countered shorelines specified in the bathymetry could be not accurate.

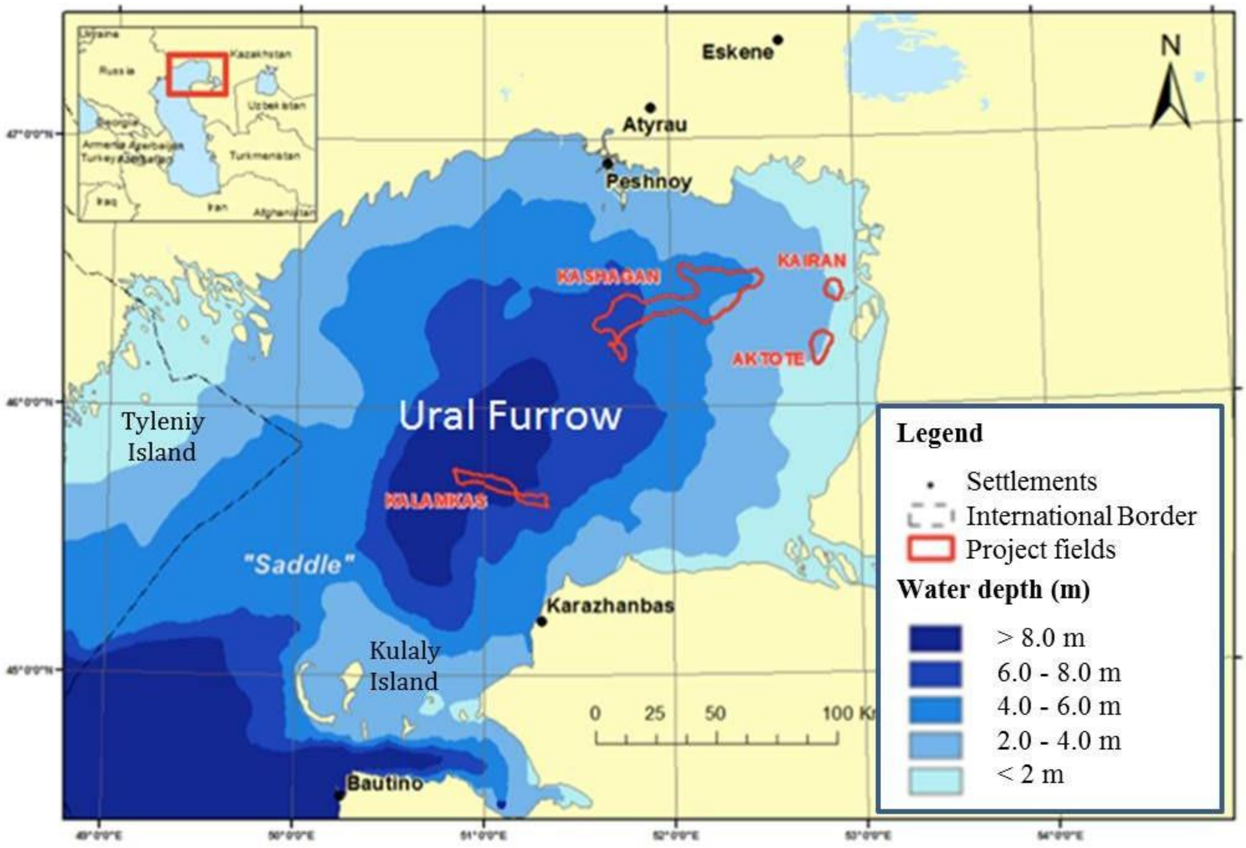


Figure 3.1: Bathymetry chart of the Northern Caspian Sea (Based on Verlaan and Croasdale, 2011).

3.2 Water Temperature

The annual seawater temperature is equal to 0°C in winter and exceeds 25°C in summer. The coldest months are January and February with mean water temperatures of -1.1°C and - 1.5°C, respectively (Dobrovolskyi et al., 1982). The annular mean water temperature is about 11°C while the absolute minimum water temperature was -1.9°C at the Tulenyi Island (Terziev et al., 1992). Fig. 3.4 presents the monthly extreme minimum/maximal and average water temperatures in the north of the Caspian Sea.

3.3 Water Salinity

In general, the Caspian Sea is a low saline water reservoir. The leading factors influencing on the Caspian salinity variations are (i) the Volga's runoff, which is one the most significant factors determining the water balance of the Caspian Sea, and (ii) water exchange with the Middle Caspian Sea.

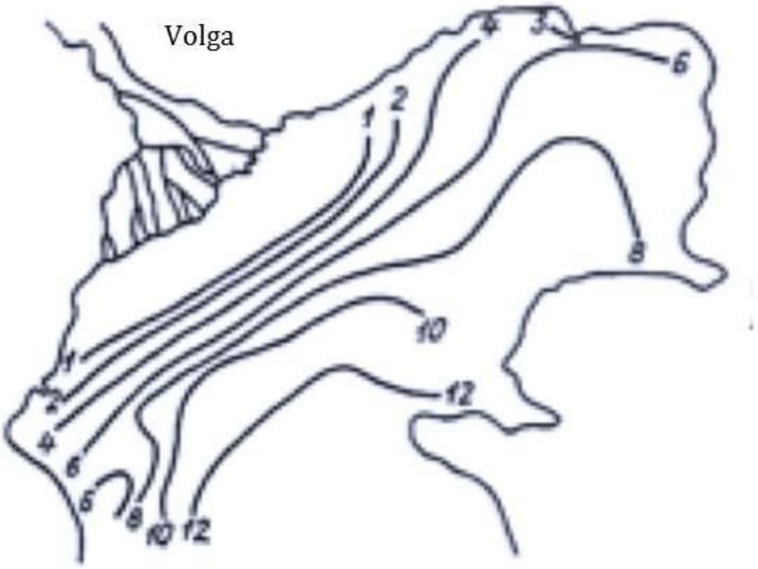


Figure 3.5: Salinity distribution (ppm) in April for the period 1940-1963 (Terziev et al., 1992).

The water salinity gradually increases from the delta of Volga to the middle part, i.e. in the direction of the propagation of the Volga's runoff (fig.3.5).

The seasonal changes of the water salinity are also controlled by the Volga runoff. Thus, annual variations of the water salinity have two seasonal peaks (fig.3.6). The first peak (in February) is explained by the fact that ice impedes spreading of the Volga runoff in winter, so this fresh river water drains to the Middle Caspian Sea. The second salinity increasing occurs when seawater of the Middle Caspian Sea enters and mixes with relatively fresh water of the northern part. In addition, the minimum salinity is observed in June, when the Volga river discharge is maximal.

3.4 Sea Level

The Caspian Sea is unique in that it is isolated from the world ocean and, therefore, its level is completely determined by changes in the water balance and by irregularity of the Volga runoff. Unfortunately, the Northern Caspian Sea is heavily exposed by these factors due to its extreme shallowness. As a result short-term (seasonal) and long-term sea level fluctuations are observed.

Long-term sea level changes

The Caspian sea level significantly varies during its history (Gorelits, 1995). Only in the XX century two sea level changes with dramatic consequences were observed (fig.3.10):

- At the beginning of the XX century the level was relatively stable. Then it decreased by 3.0 m (1930-1977). This is considered as the lowest sea level for the past 400-500 years (Gorelits, 1995).
- For the past 30 years, the sea level has been increasing since 1978. Thus, the sea level increased by 2 m from 1978-1992 (Gorelits, 1995). The current sea level is -27 m regarding to the Baltic System (Karulin et al., 2002).

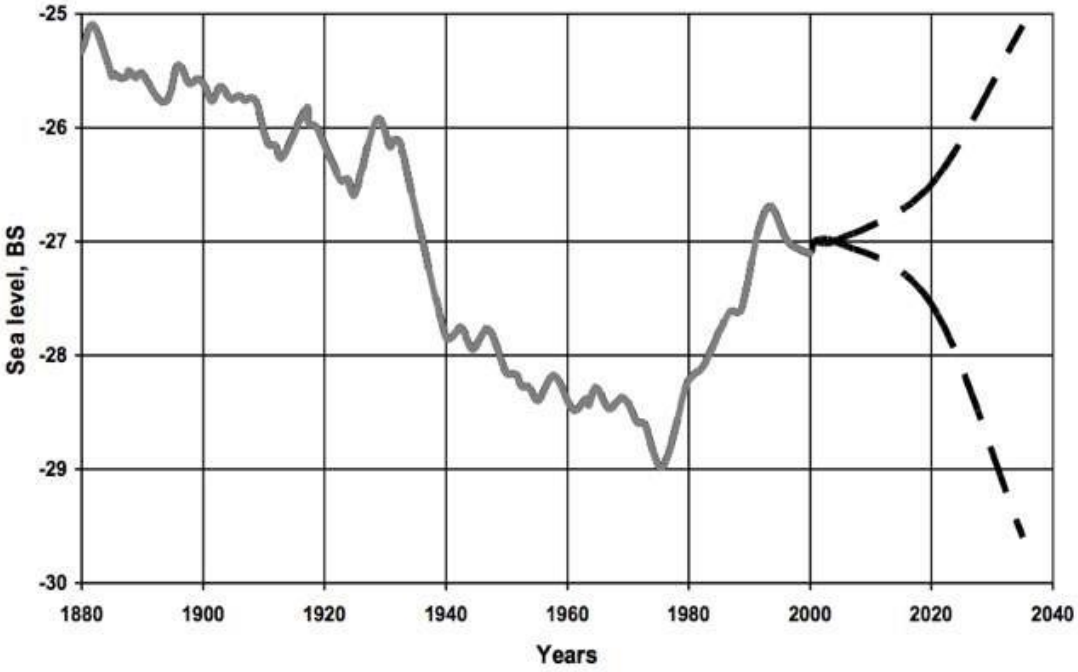


Figure 3.6: The Caspian Sea level variability over 1880-2005 and forecast up to 2035 (Karulin et al., 2002). Note that all values of the sea level are given in the Baltic System (BS).

Note that sea level fluctuations are caused by climate changes and an economic activity in the Volga drainage basin during the last 50 years (Gorelits, 1995). The main factors of the economical activities affecting the Volga river runoff include irrigation activities (including land reclamation), water supply for industrial and domestic purposes, construction of reservoirs. According to the report of Volga Ltd. (1992) the sea level without the human activity would be 1.2-1.3 m above the current sea level and the decreasing could stop in the late 50s. The seal level rising, which has started in 1978, is a result of climatic changes caused by increasing precipitations and decreasing evaporation (Volga Ltd., 1992).

Several reports (Terziev et al., 2008, Imani et al., 2014, Polonskii et al., 2010, Lebedev, 2010, Volga Ltd., 1992) are dedicated to the forecasting problem of the multiyear sea level changes. However, today it might be concluded that sea level forecasts cannot provide either valid amplitudes or the direction of the sea level changes due to the complexity of the problem. Thus, the gap between these forecasts lies in the range from the sea level falling to - 30 m by 2050 to its rising (to -26 m) by the mid of the XXI century (Volga Ltd., 1992).

One example is the design of the ice resistance platform for the Korchagin field development (the Russian zone of the Northern Caspian Sea) when two possible scenarios of sea level changes had to be considered:

1) increasing of the sea level will be 2.7 m regarding to the current position;
2) decreasing of the sea level will be 4.43 m regarding to the current position (fig.3.10).

However, Karulin et al. (2002) states that: “the normative documents or scientific publications failed to provide any proposals concerning summation of sea levels such as 100- year background sea level, 100-year high/low water and 100-year wave height.”

Short-term sea level changes

The short-term sea level fluctuations are caused by (i) seasonal changes of the water balance and (ii) storm winds. The seasonal changes are maximal in the period of June-July while the minimal sea level is observed in February. The amplitude of the short-term level variations is approximately equal to 35 cm (Terziev et al., 1992). This is clearly traced with observations at the Kulaly Island (fig.3.11).

The wind driven fluctuations occur across the sea so the shallow northern part is the most heavily exposed by this. The maximum surge level caused by the SE winds may rise up to 2.0-4.5 m and when the northern winds occur it can drop up to 1.0-2.5 m. The average duration of tides and ebbs in the most cases is 10-12 hours and, in rare cases, about two days (ESIMO, 2004). Furthermore, the wind-driven surges can shift the coastal line towards up to 10-15 km offshore and ebbs can shift the coastal line towards to 30 km inland (Sarybekova, 2004).

3.5 Ice Conditions

In contrast to the Middle and the Eastern parts, large areas of the Northern Caspian Sea are covered by ice in winter due to the shallow depth, harsh climate and low water salinity (see fig.3.12). On the other hand increased water exchange with the Middle Caspian, which is warmer, limits the ice development within this area. The presence of first-year ice is one of the futures of the Caspian Sea.

Figure 3.7: Satellite image of the North Caspian Sea taken by NASA's Terra satellite, February, 2013 (MODIS, 2013)

In general, the ice formation begins in the shallow eastern part of the North Caspian Sea and then it develops to the west. The average duration of the ice season is up to 120 days (Kouraev et al., 2004). The ice season duration is determined by the type of winter (table 3.1). In severe winters ice can form in a very short period of time and cleaning of the sea takes place only in spring. In severe winters the ice cover reaches the warm northern part of the Middle Caspian, which is deeper as well.

Table 3.1. Ice periods for different types of winters (Terziev et al., 1992).

Type of winter	Beginning of ice formation	Clearing of the sea
Mild winter	mid of November	mid of March

Moderate winter	mid of November	early April
Severe winter	early November	mid of April

The main properties of sea ice have been described in Chapter 2. The following sections introduces three significantly different zones within the Caspian ice cover: landfast ice, drifting ice and shear zones.

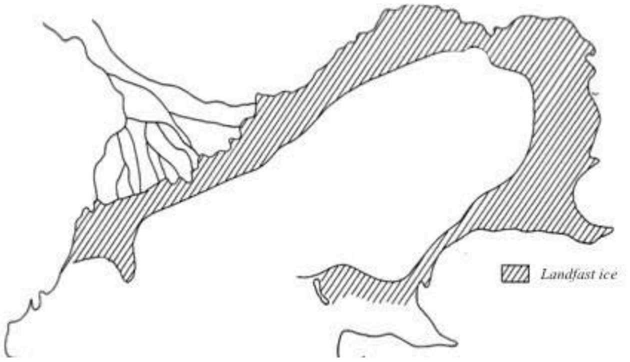


Figure 3.8: Landfast ice zone (Terziev et al., 1992)

Figure 3.9: Chart-map of the Northern Caspian ice conditions

3.6 Summary

The chapter presents comprehensive description of the environmental conditions of the Northern Caspian Sea.

The data taken from the appropriate sources are compared with field measurements (including satellite images). The results obtained during the analysis of the Northern Caspian environment are used for the further study.

Chapter 4. Challenges in the Northern Caspian Sea

The Northern Caspian Sea is treated as a region, which has similar conditions to the Arctic (Løset, 2017a). Along with great prospects of the fields, the Northern Caspian poses great challenges and risks. Namely, the following principal challenges associated with the development of the Northern Caspian Sea will be discussed in more detail below:

- Environmental sensitive area;
- Shallow water;
- Sea level fluctuations;
- Ice conditions;
- Ice Encroachment;
- Arctic codes;
- Evacuation of personnel in winter seasons;
- Undeveloped infrastructure;
- Logistical challenges.

Environmental sensitive area. A special status of the Northern Caspian Sea, which is specified as a nature preserve zone by the Kazakh government, strictly regulates all industrial activities and allows running only safe operations (Kuehnlein, 2002, Kaltayev et al., 2007). Thereby, the northern part of the sea is considered as a highly sensitive area and the environmental risks associated with the Caspian development are critical.

Furthermore, any serious accident could have dramatic ecological consequences and could result in tremendous social and political problems for the countries sharing the sea. Some experts believe that the consequences of the oil spill caused by the Deepwater Horizon drilling rig explosion in the Gulf of Mexico in 2010 would be more disastrous in the conditions of the Caspian Sea. Note that more than 7,000 vessels and 47,000 people were involved in the Deep Horizons oil spill response activities (Ramseur, 2015) while in the Caspian Sea it would be extremely problematic to mobilize such amount of people and equipment due to the isolation/remoteness of the Caspian Sea. So only the Caspian emergency fleet would be there to cope with consequences of a similar accident.

It is worth mentioning that existing technologies for elimination of oil spills in the Arctic conditions are not sufficiently effective when oil spills especially occur in the presence of ice. An oil spill occurring in ice conditions is hard to be localized, collected, and dissolved because a thin layer of hydrocarbons can travel under the ice cover and contaminate large areas.

On the other hand special focus must be on the “zero discharge” policy that should be applied in order to achieve minimal impacts on the environment and a key issue for operating in this region is safety provision. Besides that this requires to minimize the emergency response.

Shallow water. The shallowness of the Northern Caspian Sea imposes restrictions to vessel draught and, therefore, limits the maximal deadweight of ships.

Furthermore, it is well know that “waves on shallow waters differ from waves at deep sea” (Zolotukhin, 2017). This can be explained by the relationship of the water depth d to the wave length L, which is less than $1/20$ (i.e. $d/L<1/20$) for shallow water conditions (Gudmestad, 2017). According to the environmental data described in Chapter 3.6 (the wave length is 85 m and the water depth corresponding to the deepest point in the sea is about 9 m) the North Caspian Sea can be really considered as shallow because this condition is met. This phenomenon could lead to the amplification of hydrodynamic loads due to the wave action or surges and might enhance erosion processes.

Sea level fluctuations. Another principal issue is sea level changes coupled with the extreme shallowness of the North Caspian Sea. As discussed in Chapter 3.7, the Northern Caspian Sea is featured by significant short-term sea level changes caused by the strong southern winds that can rapidly decrease the sea level up to 2.5 m and increase it up to 2-4.5 m.

On the other hand, the long-term sea level changes coupled with the wind driven sea level fluctuations lead to considerable shoreline shifts (Sarybekova, 2004). Thus, according to the Volga Ltd. report (1992) a possible flooding caused by rising of the Caspian sea level to -25 m (BS) would lead to flooding of 53 cities with population of 58,000 people, 61 rural towns with population of 41,600 people, 384.5 km of roads/energy communication installations, etc.

In addition to the social-economic consequences, the water depth and the countered shorelines specified in the bathymetry could be not accurate. That might be more challenging for planning of long-term operations (as production) rather for short-term ones (such as exploration drilling).

The uncertainties associated with sea level changes should be carefully analysed before the project execution. For instance, the caisson platform for the Korchagin field development (the Russian sector of the Caspian Sea) had to be designed for two different scenarios of long-term sea level changes and the amplitude of these fluctuations was taken 7.13 m (Karulin et al., 2007). It worth mentioning that the sea level changes should be constantly monitored in order to predict hazardous events and to avoid dangerous consequences associated with this phenomenon.

Ice conditions. A combination of shallow water, low water salinity with harsh weather conditions during winters lead to freezing of the Northern Caspian Sea, at least, for five months per year. As mentioned in Chapter 3.8, the 100-year thickness of level ice is assumed to be 0.96 m and the 100-year return period for rafted ice features is estimated to be 1.4 m. This causes significant ice loads acting on offshore structures and imposes operational limitations. On the other hand, the presence of ridges and shallow water depth imply another threat associated with plugging of the seabed (Zolotukhin, 2017a) so all pipelines, cables, flowlines between offshore structures should be designed with focus on it.

Finally, another issues related to the Caspian ice conditions are discussed below.

Ice Encroachment. Ice Encroachment is the term describing the phenomena when ice moves onto the surface of a structure. Traditionally, there are two ice encroachment types, namely, ice over-ride and ice pile-up.

Ice over-ride presented in Fig. 4.1 is a rare event, which could occur when continuous ice exerts on a wide structure with low freeboard and gentle slopes (Palmer and Croasdale, 2012). One example is an ice over-ride accident occurred in the North Caspian Sea when the 0.5- meter ice climbed over the freeboard across the island perimeter in a few minutes (see Fig.

4.2). Fortunately, it stopped without any damaged of the equipment and didn't cause further events associated with the ice over-ride. It is obvious that such ice over-ride might lead to severe consequences when potentially dangerous equipment is involved.

There are several design methods, which might be applied for the design of both an artificial island and a gravity based structure, including high freeboard, rough surfaces, a special geometry of a structure and the utilization of external ice barriers. Thus, steep slopes are favourable for ice pile-up rather than for ice over-ride. This phenomenon will be discussed in detail in the following chapters.

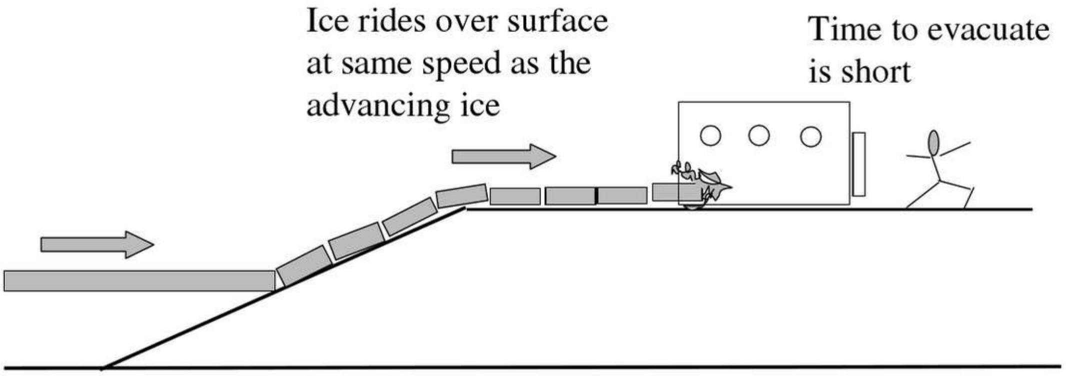


Figure 4.1: Ice ride-up on low freeboard structure (after Palmer and Croasdale, 2012).

Figure 4.2: Ice encroachment in the Caspian Sea (McKenna et al., 2011).

Arctic codes. Growing interest in development of the Arctic fields motivates a strong demand for specialized codes. Ghoneim (2011), Bruun et al. (2006), Løset et al. (2006) report that the results of ice load calculations considerably vary with the different code formulations.

In addition to the gap between these codes, there are still considerable uncertainties related to the calculation of ice actions in shallow water due to the effect of ice rubble grounded around the structures. The point is that the rubble accumulation intensified in the shallow water conditions will influence on the interaction between ice and a structure. Also, grounded ice rubble might partially dissipate the ice load into the environment. Palmer and Croasdale (2012) state that this phenomenon is not completely covered by ISO 19906 (2010) because the ice load on sloping structures calculated by the code is not correct.

An engineer should be aware of this issue while appropriate codes should be developed in order to provide a comprehensive guidance.

Evacuation of personnel in winter seasons. The hydrocarbon development always involves a possibility of an emergency situation that will require an effective evacuation of personnel. Poplin et al. (2013) states that "an ideal evacuation system for ice covered waters allows personnel to abandon the facility in response to an emergency under any ice or open water sea condition and proceed a safe distance from the disabled facility to await rescue".

One can notice landfast ice and accumulated ice rubbles can surround offshore structures and this might complicate a fast evacuation. Conventional lifeboats used for emergency evacuations in ice-free offshore regions are not applicable due to the shallowness of the sea and the ice cover. However, the helicopter evacuation might require relatively long mobilization time. Moreover, sometimes the access to a landing area might be complicated and associated with additional risks. Note that this type of transport heavily depends on the weather conditions. One example is an accident that occurred in 13-15

December 2012, when the air transportation was totally blocked due to the storm. As a result two islands were totally isolated (Shahnazaryan, 2012).

According to the Barents-2020 program report (2012), all evacuation options that are available today for the Arctic evacuation can be divided in two groups:

- Concepts already used on the Arctic projects, e.g. special amphibious vehicles and icebreaker emergency evacuation vessels (IBEEV).
- New concepts adapted for the Arctic conditions, e.g. «Boat-In-A-Box» system, hovercraft, ships with Archimedean screws AST/TIT800, sea rescue vessel, hermetically sealed Arctic rescue capsule (TEMPASC), ice-resistant lifeboat (ISL), polar enclosed lifeboats, container landing "Ganymede".

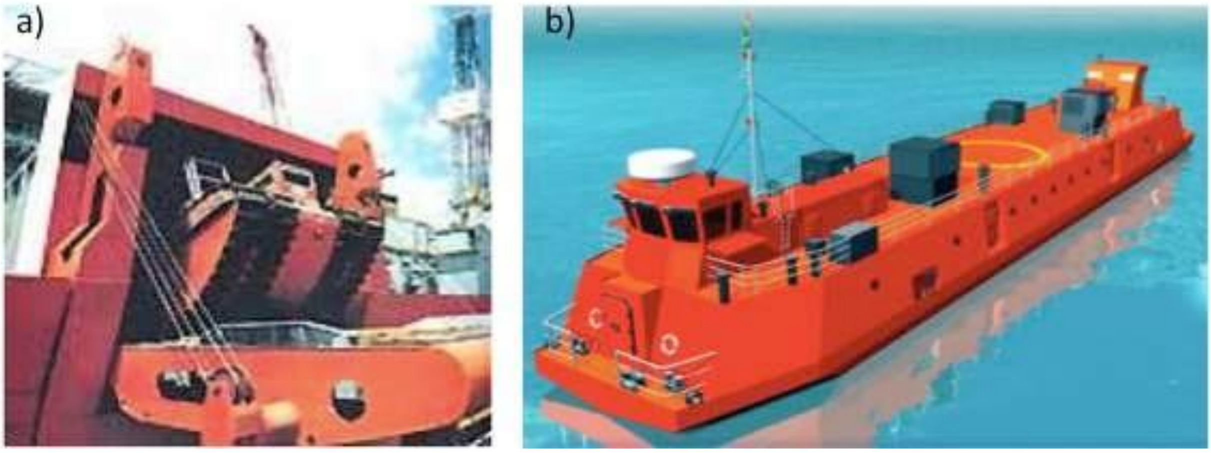


Figure 4.3: a) The Arcktos special amphibious vehicles (Juurmaa and Wilkman, 2002) and b) Ice breaker emergency evacuation vessels (Remontowa Company, 2006).

It worth mentioning that only solutions from the first group have been already applied for the Kashagan field while other ones are under development. Thus, NCOC selected the utilization of special vehicles (fig.4.3), Arctos, which were deployed on the Sunkar barge and on the North Star Island (Beaufort Sea). It is an amphibian vehicle with combined chain drive on ice and water propulsion for ice-free conditions. However, this option has several drawbacks:

- Due to problems related to the ice bearing capacity the Arctos vehicle could capsize when ice is not stable,

- These vehicles have serious problems associated with their deployment, because massive ice rubbles accumulated around the structure might block it.

Several icebreaker evacuation vessels (DNV ICE-1B class) are currently applied for emergency evacuation from the artificial island 'D', where the field processing is carried out. The vessels (fig. 4.3), which draft is 2.1 m, can be safely operated in shallow water and in ice with maximal thickness of 0.6 m. Because of extreme shallowness of the operating area, the IBEEV cannot operate as a normal icebreaker so the nose of the IBEEV crushes ice in front of the ship while powerful engines allow the vessel to move through the ice. The technical design of these vessels, which are capable to evacuate up to 340 persons at time, includes autonomous systems of life support within toxic environment, so the passengers breathe through autonomous air supply devices, and evacuation from the island is carried out through a special tunnel (Remontowa Company, 2006).

However, there might be several issues related to the evacuation by the IBEEV icebreakers:

- The further development of the Kashagan field will require a large amount of such vessels and that will lead to additional challenge for the project budget.Although these vessels are designed to break up 0.6-m ice, this is probably not sufficient because the value of the 100-year ice thickness is 0.9 m while the thickness of ridge formations reaches 1.4 m (chapter 3.8).

Figure 4.4: The Picture of D Island (Kashagan) wherein an ice wake can be observed behind the structure (Topaz Energy and Marine, 2015)

Even though no 100%-reliable evacuation methods in the Arctic exist, some measures could be implemented to reduce risks for personnel in case if a hazardous event(s) occurs:

- Keep evacuation water routes and the space required for vessel deployment free from ice rubbles. Another method to increase efficiency of the evacuation process is to take advantage of an ice free leeward area (called wake, see fig.4.4) formed behind a structure toward the direction of the ice movement, which might be used for the deployment of evacuation vessels (this is especially important for the Arctos vessels).

- Proactive HSE management, i.e. all employers should be trained how to behave if major emergency arises and etc.
- Another proactive measure that might reduce risks for personnel during evacuation is decreasing the number of personnel on the dangerous/remote or complicated for evacuation locations.

Undeveloped infrastructure. This challenge includes a poor developed transport system, a lack of electric and water supply. Shipbuilding and construction industries are limited and all important processing facilities/icebreaking vessels should be imported from another places.

In addition to the undeveloped infrastructure of the region, there are some requirements related to the governmental policy of the Kazakh content. According to it the Kazakh content of various components should be maximized and if an operator company ignores the law about the Kazakh content, it might be subjected to an administrative punishment (Sultanov, 2010).

Logistical challenges. The remoteness of the Caspian Sea from industrial centres coupled with the undeveloped infrastructure of the region is another factor that should be taken into account for the Northern Caspian projects. The region can be only supplied by the Volga Don Canal and Baltic Sea-Volga waterways (fig.4.5), which are navigable for six months due to the ice presence in winter.

Figure 4.5: the Volga Don Canal and Baltic Sea-Volga waterways (NCOC, 2011).

Moreover, the shallowness of the Volga transport system, as well as considerable constrains of bridges crossing the canals, limits the maximal weight/dimensions of the cargo that can be transported to the Caspian Sea via these routes. Hence, a large part of equipment fabricated in Europe or Asia cannot be transported to this location. All of these factors lead to increasing of transportation costs and complicate the project execution.

On the other hand winter supply (including requirements for regular supplies of materials and transfer of personnel to the location) is a crucial issue due to the presence of ice features. In severe winters navigation in the Northern Caspian is complicated, so icebreaker vessels should be used to support supply operations in ice seasons. Currently only one supply base located in Bautino exists but more supply bases should be developed in the future when more fields are explored. It also worth mentioning that a fleet of supply vessels has to be constructed from scratch.

In conclusion, these challenges encountered in the Northern Caspian Sea are not usually met in such combination in another regions. For instance, the shallowness of the sea is itself an issue challenging ship navigation, transportation, as well as installations of heavy structures. Moreover, shallow water depth combined with the ice conditions complicates winter supply and running of marine operations due to the conditions favourable for ice accretion.

This makes the already complex problem of the emergency evacuation in winter even more complex. Not to mention the uncertainties related to the forecast of the sea level changes and the gap between the Arctic codes.

Therefore, each of these issues (together with harsh climate, wave and wind conditions) has to be adequately considered and managed before the realization of any project in the Northern Caspian Sea. In addition, the ice conditions should be carefully considered during design of structures, winterization, selection of appropriate materials, etc. In addition to the environmental conditions, such field characteristics as large reservoir extension, high H2S content in the reservoir fluids affect the selection of the field development concept. This should be achieved in terms of high HSE standards that will provide environment, life and assets safety.

Chapter 5. Artificial Island Concept for the Northern Caspian Sea

When the economical profitability of the field development has been proved, planning of production and the selection of an appropriate development concept begin. As demonstrated the Kazakh sector of the North Caspian Sea is a promising area, where many prospects including the giant Kashagan field have been explored. Therefore, an appropriate development concept should be selected in order to provide safe and effective development of oil and gas fields in the future.

A development concept includes a set of engineering solutions with respect to:

- Production system or a type of an appreciate offshore structure;
- Process system;
- Transportation system of hydrocarbons.

The development concept should take into consideration all challenges discussed in the previous chapter. Note that after starting of the project it is very challenging to change the development concept, while costs of any changes might dramatically increase the project budget and additional environmental risks might be involved as well. So the concept should be selected adequately and it should allow safe year-round drilling and execution of all required operations under the Caspian conditions. However, not every type of a production structure can be utilized in the Northern Caspian Sea.

The coming chapter is dedicated to the discussion of suitable solutions in light of hydrocarbon field characteristics to develop a robust and optimal field development concept for the Northern Caspian Sea.

5.1 Production system

The production system is one of the main parts of the field development and it must be designed for safe operation during the whole field life.

The development scenario is mainly determined by such reservoir characteristics as its properties, extension, recoverable resources, etc. The development plan also regulates the number of offshore structures, their configuration required to develop the field recourses. Offshore production structures accommodate not only all production/drilling equipment, but also personnel. Hence, as well as drilling systems, the production structures should guarantee safe year-round production even under extreme wave and ice loads. At the same time, the chosen concept should provide the most optimal economical solution. The number of offshore structures required for the field development should be minimized. It should be noted that the chosen concept should consider development options for satellite/small fields, which might be discovered in the future.

An engineer has mainly two alternative concepts for such shallow water conditions:

- to construct a structure, which could withstand even the maximal environmental loads, or
- to construct a semi ice tolerant structure protected by special ice protection structures that will take the main ice action (Croasdale et al., 2011).

The first concept includes a "stand alone" platform while the second one implies a semi ice tolerant platform. The main types of production platforms as well as factors affecting the selection of the development concept will be identified in this section.

Technical solutions

The selection of a suitable platform type is controlled by different requirements including operational and engineering aspects. Thus, operational aspects relate to the work area required for the installation of drilling/production/processing units, a number of wells, the supply concept, evacuation requirements, while the engineering factors are governed by water depth, wave and ice actions, soil conditions, construction needs, etc.

The environmental conditions in the Northern Caspian Sea favour to only limited options that could be integrated into these concepts. Primary, the analysis of the water depth and ice conditions of the region indicates a fairly beneficial environment for islands and platform developments rather that for subsea development, because floating systems are not realistic due to the draught limitation and capacity of mooring (or dynamic positioning) systems, which cannot effectively withstand ice loading.

The following section discusses only the options regarded as the most feasible based on ISO 19906 (2010) and the experience of the Beaufort Sea development, which is given in accordance with Hewitt (2014).

According to Bailey (2009) artificial islands that have been successfully implemented in the Beaufort Sea for over 40 years are one of the most effective solutions for the Arctic shallow waters.

Although there are five types of the man-made islands only some of them can be applied for the given conditions. The main criteria of their applicability in light of economical feasibility are the availability of a suitable construction material, water depth and the construction season limitations (Hewitt, 2014).

Figure 5.5: Sheet pile island built at the Kashagan field (Nymo, 2010).

Thus, s*acrificial beach islands* are usually built when a large borrow source of ‘clean’ sand is located near the location. However, the utilization of this type of man-made islands as an offshore structure in this region could lead to supplementary challenges due to the poor quality of the rock in the Caspian Sea (Granneman et al., 2001). Additionally, such structures are significantly affected by wave actions. *Slope protected islands* require costly armor units to protect the island’s fill while these units cannot provide full ice protection. Hence, sheet piled and caisson retained islands could be identified as the most suitable options among others.

A ***sheet pile island*** (fig.5.5) is an island, which is retained by sheetpiles (regular, cofferdam or cellular sheetpiles) to protect the island fill from the wave action. A sheet pile island is essentially a vertical structure so there are no sloping walls within the structure to reduce ice loads. A key consideration for the design of such islands is local ice action and the integrity of the sheetpile assembly during the whole design life.

Note that this type of islands should be adapted for the Caspian conditions in light of the ice encroachment protection (see Chapter 4). Since the construction of an island with steep slopes or high freeboard protecting from ice over-ride might be challenging from an economical point of view, so the islands might have a special shape design to avoid these potentially hazardous accidents. This includes some protection area without any equipment since this perimeter will be subjected to the ice encroachment as shown in fig.5.6 (McKenna et al., 2011, Palmer and Croasdale, 2012, ISO 19906, 2010). However, the ice protection barriers might partially hade off risks associated with ice over-ride.

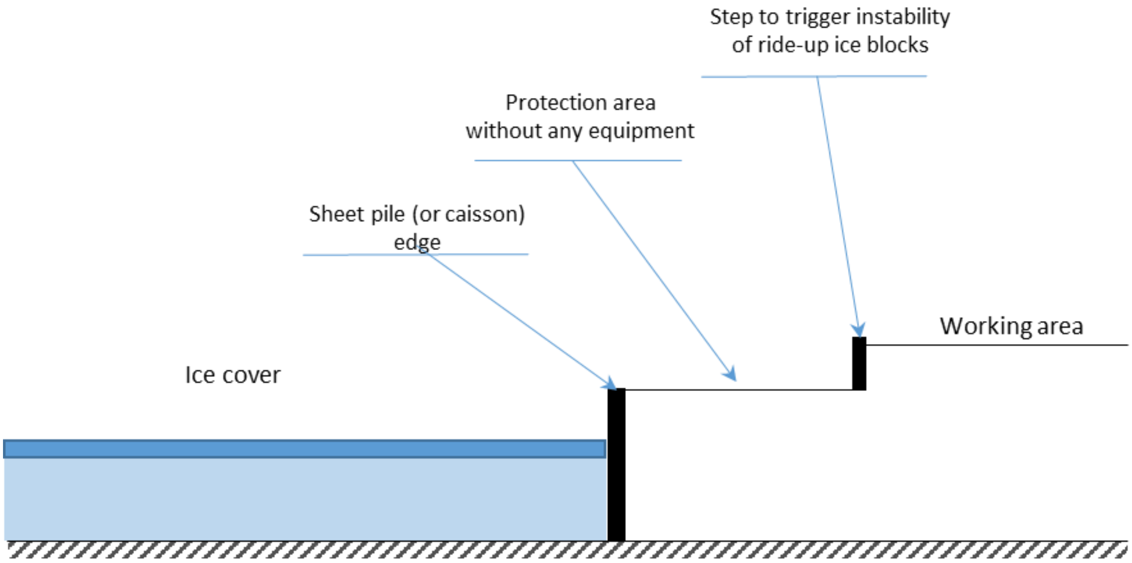


Figure 5.6: Special shape of a sheet piled island to avoid ice over-ride (not to scale, according to Palmer and Caroasdale, 2012).

The relevant experience has proved that these structures could not be used as a fully ice resistant (‘stand alone’) platform in the conditions of the North Caspian Sea. However, a sheet pile island is a possible option for a semi tolerant platform with the ice protection provided by external structures.

It should be also noted that the volume of the fill material would exponentially increase with increasing water depth, so at deeper locations the construction might take several seasons with all consequences appearing due to this.

Since island construction activities will be more sensitive to wave actions in deeper waters, the second option includes a ***conventional caisson-retained island*** (CRI). Caisson-retained islands are similar to sheet pile islands disused above but they are retained by pre-built caissons (still or concrete) so that they form a retaining ring filled with the fill material (fig.5.7). This island type has been successfully implemented in such projects in the Beaufort Sea as: Kaduluk O-07 (water depth is 13.6 m), Kaubvik I-43 (17.9 m), Tarsiut (22 m), Amerk O-09 (26 m) (Matskevitch, 2007**)**. The main driver of such islands construction is reduced requirements for the fill volume comparing to the other island types (fig.5.8).

Figure 5.7: Tarsiut Island during construction (after Britner-Shen Consulting Engineers Inc.)

Unlike to the other island types a CRI occupies a smaller footprint. A CRI might be constructed in one year and its caissons could be fabricated on the available construction capacities or, at least, the transportation/installation of each pre-constructed caisson is less challenging in shallow waters in contrast to a GBS. The retaining caissons serving as slope protection against waves and ice (ISO 19906, 2010) could be used for the further development activities. Moreover, they provide an “instant” protection against the erosion for the retained fill (Comyn, 1984) and minimize impact on the environment. Finally, potentially scour of interior infill due to the susceptibility to waves should be avoided.

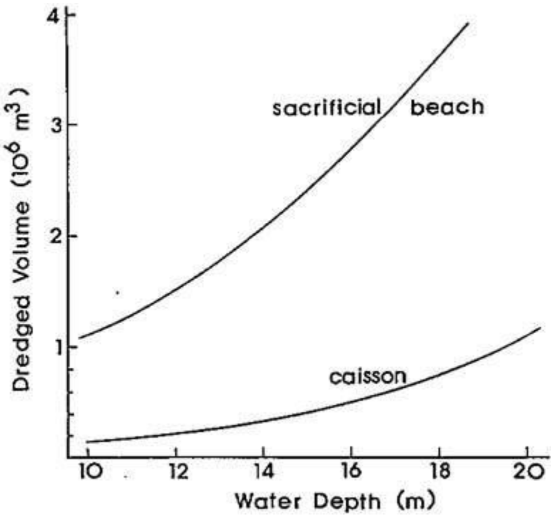


Figure 5.8: Fill requirement for sacrificial, beach and caisson-retained islands (Comyn,1984).

Figure 5.9: Ice resistant platform at the Prirazlomnaya field (Noyonews.net, 2013).

Concept of a Semi ice tolerant platform

As discussed in the preamble of this section, there are two alternatives wherein the ice protection is provided either by the structure itself or by external structures.

Primary, the concept includes the adjustment of non-fully ice-tolerant platforms protected by ice barriers, which will take the main ice loads. The basic idea is to simplify the design of a structure (where it is reasonable) with high reliability of the whole system. A properly designed arrangement of barriers might significantly decrease the ice load on a leeward placed platform; therefore, this might reduce the cost of the project without any risks for the system. Moreover, evacuation/supply vessels might be deployed within the inner leeward area protected by ice barriers. Hence, adjustment of one of the barriers described in Chapter 5.3 could be more practicable.

This option chosen for Kashagan by NCOC (fig 5.10) considers production and service operations carried out from conventional sheetpile-retained islands used as non-fully ice- tolerant platforms, because these islands are the most cost-effective among the structures described above.

In order to maintain the development progress, this concept can be optimized by implementation of two island types depending on its sizes and functions:

- Large hub-islands (protected by ice barriers) where all field processing facilities are installed. These islands could be used as gathering hubs where all oil and gas are treated before transportation to onshore. In order to achieve optimal drilling progress drilling rigs could be installed together with processing facilities, but, of course, all risks associated with drilling while production must be evaluated and all necessary measures to reduce these risks should be considered. A self-evaluating barge with required production modules might be also deployed within the ice-protected zone in order to reduce the required working area of the sheet pile island. Finally, the barges with pre-installed modules might be re-usable to provide flexibility of the project schedule.
- Small islands (protected by ice barriers) could be used for production drilling and then they could be easily converted for production by retrieving drilling equipment and installing of production facilities. In order to reduce capital expenditures, these islands should be tied back to the main hub-islands and all fluids to be transported to the hub islands for the further

processing. In addition these islands might be unmanned in order to reduce risks for personal during production.

Figure 5.10: Semi-ice tolerant platform built in the Kashagan field (after Atyrau-city.kz, 2011).

The experience of the Kashagan development shows that this concept can be successfully implemented in the future projects and the main driver of using this concept is the ability to provide relatively cheap development of large fields located at shallow water depths (like Kashagan). This concept is flexible in terms of extension of islands if it is required in the future, while its construction can be realized during one season.

Even though sheet pile islands are cheaper comparing to other structures, a volume of the fill material growths exponentially with water depth (Hewitt, 2014). So this option is suitable for shallow water, because construction of protection barriers/sheet pile islands in relatively deep waters of the Kazakh sector of the Caspian Sea might be not feasible. In addition, the overturning stability of ice barriers required for protection of semi ice tolerant platform becomes challenging with increasing water depth.

5.2 Ice barriers

Increasing development activities in the shallow waters of the Northern Caspian Sea raise needs for cheap and robust solutions that could provide ice protection both for drilling units and for production platforms. Ice barriers deployed in close vicinity to such offshore structures can significantly reduce ice loads on the structure and can protect from the hazards associated with drifting ice.

Hence, the proper design of ice barriers arrangement might provide the maximal mobility of a project because of their re-usability and simplicity of constriction/installation of individual modules. This might result in high progress of the project realization while the environmental impact could be significantly minimized. Since protection barriers are expected to take ice encroachment, a freeboard of a structure might be reduced which will also favourable for different operations. Also ice protection systems will have a positive effect on winter supply or emergency evacuation since ice rubbles will likely accumulate at external barriers rather than adjacent to the protected structure.

It should be noted that although protection barriers are used for the protection from both ice and wave action, the ice protection seems to be more foreground in the North Caspian Sea due to high ice loads. An ice barrier must withstand the ice loads by drifting ice and/or accumulating ice and, at the same time, it should be stabile during all time of its deployment at different locations. It is of interest to discuss this issue before discussion of other aspects.

The term ‘stability of an ice barrier’ means that no sliding and overturning are allowed (optionally, the geotechnical stability should be taken into consideration for rock mound barriers). One can notice that in such extreme shallow conditions as the North Caspian Sea the sliding becomes more likely rather than overturning failure, so this should be taken into account. The sliding resistance of an ice barrier is a function of the seabed properties and the geometry of the barrier. If the seabed consists of a cohesive material as clay, the footprint area of the barrier is a dominating factor determining the bottom stability of the barrier so the increase in the barrier's footprint could provide the required stability. In case when the seabed consists of such materials as sand, gravel, etc. possessing less cohesion characteristics; the weight of the barrier controls the sliding stability of the barrier rather than its footprint area. An approach how to take advantage of this phenomenon during design of ice barriers will be discussed in the next sections.

In the previous sections various scenarios of the ice barriers utilization have been described. The main factors governing the efficiency of a protection system, in general, are the geometry of barriers and spacing between the barriers and a structure. So the following section discusses different types of ice barriers and other design aspects of such structures for the Northern Caspian Sea conditions.

Breakwaters

Breakwaters known from harbour protection against waves can be used in the conditions of the Northern Caspian Sea as well. In general, the construction of rock mound barriers is similar to that of man-made islands and rock berms described in the previous chapters. Currently rock mound barriers (see fig.5.10) are used for the ice protection of artificial islands at the Kashagan field, though the results of their using have never been reported. The main drivers of such structures construction of are the availability of the required construction material, water depth and the construction season limitations.

Furthermore, breakwaters initially designed to withstand the wave action should additionally provide ice resistance in ice-infested seas. One can notice that the interaction of ice with such structures is still needed in investigation; however, the global ice action can be calculated by using of the approaches described in Chapter 6.

Longkeek et al. (2003) suggest the design of such barriers to counterbalance the edge failure due to the ice action by selecting the crest height. The minimal crest freeboard should be 2 times the ice thickness. However, due to ice encroachment a higher freeboard of the structure might be required, although it is not effective in terms of preventing the edge failure.

Together with the design issues, different sources give varying values of the rock size required to provide the geotechnical stability of the barrier subjected to ice loads. According to Lengeek et al. (2003) the rock size should be equal to half of ice thickness, while Sodhhi et al. (1996) states that the diameter of rocks should be 2-3 times the thickness.

It should be noted that the application of rock mound barriers might be challenging for relatively deep locations within the Northern Caspian Sea because their construction might take several seasons with all consequences that come due to this. Also the utilization of riprap as protection structures might results in problems related to the breakwater maintenance because of losing of the rocks during storms (or interaction with ice) due to the absence of their interlocking ability.

Another type of barriers used for harbour protection is concrete armour blocks of various shapes (such as Kolos, Dolos, tetrapods, etc.) forming together an assembly protecting against the wave action. However, the implementation of such structures in ice-covered areas is not feasible since the blocks could be damaged by ice because the stability of the assembly of such modules relying on a gravity force of an individual module is not sufficient.

Finally, as reported a key issue for construction of rock mound barriers is a poor quality of rocks available in the Caspian region (Granneman et al., 2001), so this might face significant challenges and another type of ice barrier might be required.

Grounded satellite barges

Generally, the deployment of such structures includes ballasting with seawater at the drilling location to increase the weight of the system (to increase the sliding resistance).

Grounded barges were used to provide the ice protection at the Kashagan project. Due to the lack of information about the experience related to the barges application in the Northern Caspian Sea, it is difficult to analyse the efficiency of this type of ice barriers. According to several pictures of the Sunkar barge protected by the grounded barges (fig. 5.13 and fig. 5.19), one can conclude that some barges had vertical walls while some of them had sloping walls. Since the geometry of barriers affects on the ice-structure interaction mechanisms, a vertical barge will be likely subjected to higher ice loads than a sloping one; therefore, it might be beneficial to utilize the barges with sloping face.

Figure 5.13: Grounded barge in the North Caspian Sea (Bastian et al., 2004).

However, high ice loads on these structures of a simple shape might lead to deformation of the barges and might complicate the maintenance. In addition some negative experience associated with insufficient sliding stability of the barges has been gained. In February 2002 an accident involving the application of barriers occurred, when one of the grounded barges

was moved to 120 m by drift ice, but, fortunately, the Sunkar barge wasn’t damaged. Nevertheless, no official reports of the incident analysis have been presented. However, currently the adjustment of the grounded barges was refused to apply (Kouraev et al., 2003). It is likely that the barge lost the sliding resistance.

As mentioned in the preamble of this section, the sliding resistance of barriers deployed on pre-built berms (consist of cohesive type of the material) is mainly controlled by their weight. Thereby, the main measure to avoid such incidents is to increase the overall weight of barriers both by ice spraying and by triggering the ice rubbles accumulation on the barrier.

Finally, it is likely that grounded ice rubble in front of the barge deployed in shallow water will reduce the global ice loads on it and will increase the effective diameter of the barge, i.e. protection radius of the barge.

Rubble generators

An ice rubble generator is a structure of a special shape that induces the ice failing in a predefined manner. After some time, the ice rubble accumulated in front of the structure becomes grounded, whereby it dissipates the ice loads into the seafloor and the environment. Hence, it is beneficial to initiate the ice rubble generation in terms of ice loads mitigation in shallow waters of the Northern Caspian Sea, which is favourable for accumulation of fragmented ice in front of wide structures.

On the other hand, the stability of ice barriers on non-cohesive type of soil (for instance, when underwater berms are used as a foundation for the barriers) mainly relies on their weight, so ice rubbles accumulated on the barrier will increase sliding resistance of the system. In this case, the sliding resistance will proportionally increase with increasing pressure on the contact surface between the bottom of the barrier and the upper layer(s) of the seabed. Hence, ice barriers with enhanced ice-generating characteristics might be used for the protection of semi-tolerant structures described in the previous section. Therefore the main structure will be subjected to lower ice loads so its design can be simplified in terms of ice resistance requirements. However, there are a limited number of studies dedicated to the barrier design considering this phenomenon. The following discussion will present only concepts of ice generators considered as most feasible.

Gürtner et al. (2006) introduced an innovative concept called the shoulder ice barrier (fig. 5.14, a). A shoulder ice barrier (SIB) provides effective ice breaking-up because of the changes of sloping angle accelerating ice breaking-up and resulting in increased ice rubble

generation adjacent to the barrier. Gürtner (2009), Repletto-Llamazares et al. (2013) presented comparison of a SIB with ice barriers with different inclination of the second slope (the first sloping angle is 45 deg). The tests successfully proved the role of the second slope in generating of ice rubbles and a SIB demonstrated better characteristics of ice generation in comparison with a barrier without the second slope (fig.5.15).

One can note that the SIB concept, ceteris paribus, will be more stable than barriers of other shapes. In addition since a SIB is concrete, its individual weight will be greater than the weight of a barge of the same length/height/width filled with seawater and, hence, this will promote enhanced bottom stability.

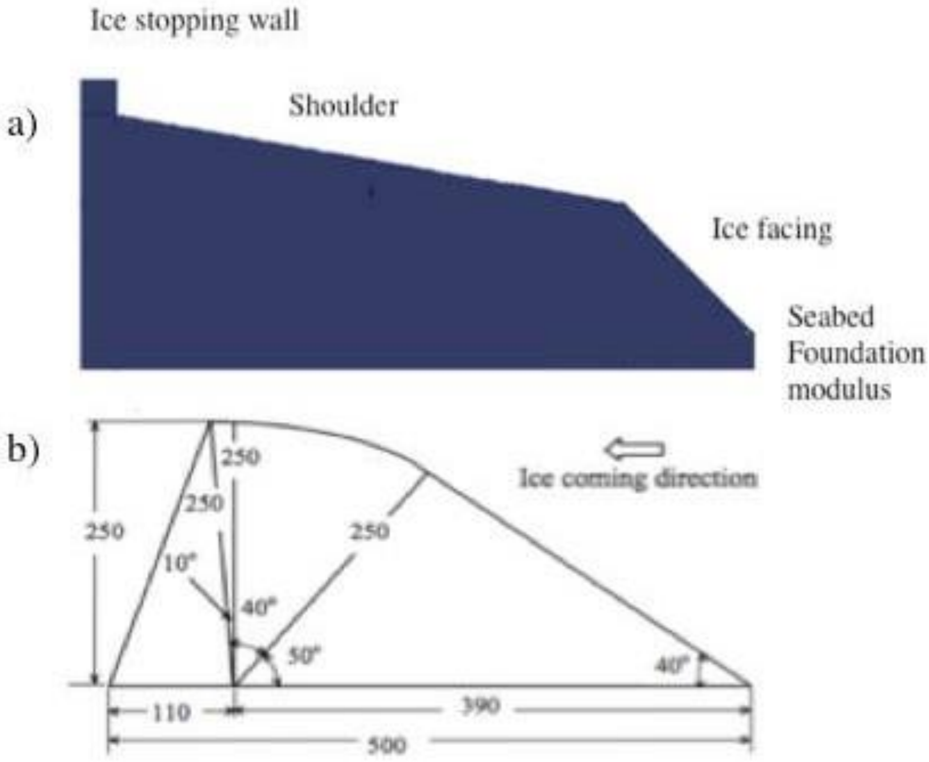


Figure 5.14: a) a Shoulder Ice Barrier (not to scale) and b) a curve surface barrier proposed by Li et al., 2006.

An alternative to the SIB concept might be curve surface barriers (CSB, fig. 5.14, b) initially proposed for the protection of a jack-up from ice loads (Li et al., 2006). Although no results of CIB tests has been reported, it could be expected that the CSB concept, which bases on the same principle as the SIBs, will provide less effective ice breaking capability. In addition the design of the CIB does not include any deflector to trigger instability of coming ice rubbles and this will lead to ice over-riding rather than the ice accumulation.

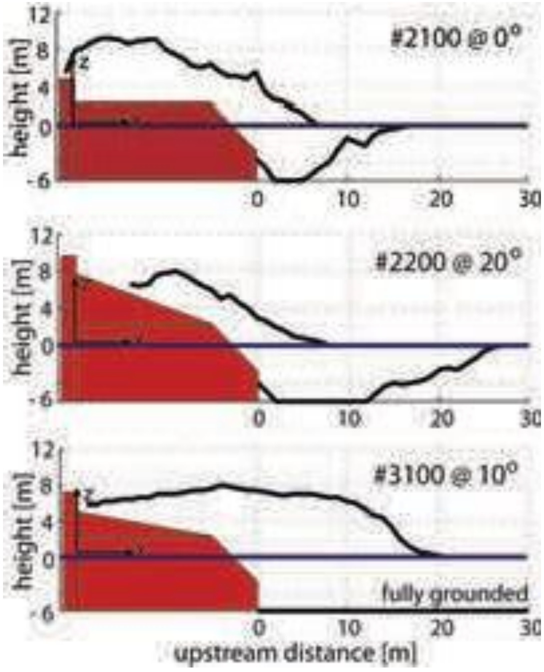


Figure 5.15: 2D plots of ice rubble profiles at the centre of the SIB (Gürtner, 2009).

However the benefits of ice rubble adjacent to the structure might be diminished when the ice rubble is mobile due to the sea level changes and winds. Furthermore, a poor design of the barriers alignment might complicate the access to the leeward located structure or emergency evacuation from it.

Ice Protection Piles

Note that piles with different spacings and diameters have contrasting scenarios of ice interaction (fig.5.16, b) and they can be implemented as an ice protection system (Løset et al., 2006). Vertical or sloping piles are hammered into the seabed in order to get sufficient resistance.

The pile diameter and the spacing between piles are selected so that the pile arrangement promotes the ice rubble generation in front of the protection structure. It should be noted that the broken pieces of the ice might bypass the piles toward the leeward area without ice piling- up. This scenario should be avoided by using of additional barriers or the central structures should have some level of ice resistance, i.e. should be semi ice tolerant.

Although the ice load reducing piles are installed around of the Sunkar barge (fig.5.16, a), the results of instrumentation of the piles have not been reported. It was further confirmed by investigations of Gürtner (2009) that piles with specially selected spacing could be used as rubble generators. The main recommendations for the IPPs design are (Gürtner, 2009):

- An optimal spacing between the piles are three diameters of the piles and should not be larger than six diameters of the piles;
- Higher ice loads on the IPPs should be expected due to increasing of the contact area with ice;
- Actual piling depth should be carefully selected to provide resistance of the piles;
- Pile dynamics cause liquefaction of the soil so particular attention should be given to this potentially hazardous phenomenon.

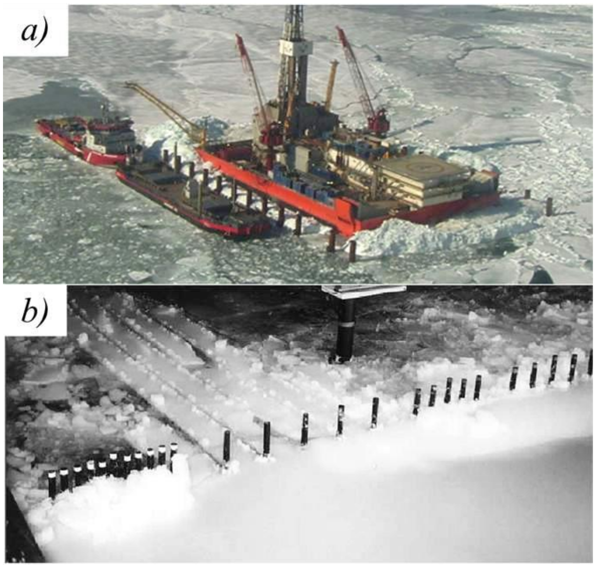


Figure 5.16: a) The Sunkar Barge is on the location (IMPaC, 2011) and b) Model-scale testing of piles with different spacings (Weihrauch and Gürtner, 2006).

The IPPs can reduce the barge deployment time and might be more cost-effective than other types of ice protection systems. However, Gürtner (2009) reports that the IPPs concept are not a self-sufficient barrier system and it can be used only as an additional ice protection system to reduce ice loads on the structure. However, the IPPs design is a wide topic and it is beyond the scope of this thesis. The reader interested in more details is referred to Gürtner (2009).

Grounded ice as an ice barrier

Although the adaptation of ice islands faces significant challenges in the Northern Caspian Sea (see Chapter 5.1.1), ice protection barriers built by ice spraying might be an alternative to other ones (fig.5.17, b). It should be noted that massive ice rubble fields observed in the Northern Caspian Sea could alone resist large ice floes exerting on it (see fig. 5.17, a).

These barriers might be implemented for additional ice protection of structures by generation of ice built-up adjacent to the structure. The main advantages of this option are low costs and high mobility. However, this option might be suggested only for temporary ice protection and doesn't protect a structure from waves during ice-free seasons. One can notice the sliding stability of a sprayed barrier should be taken into consideration.

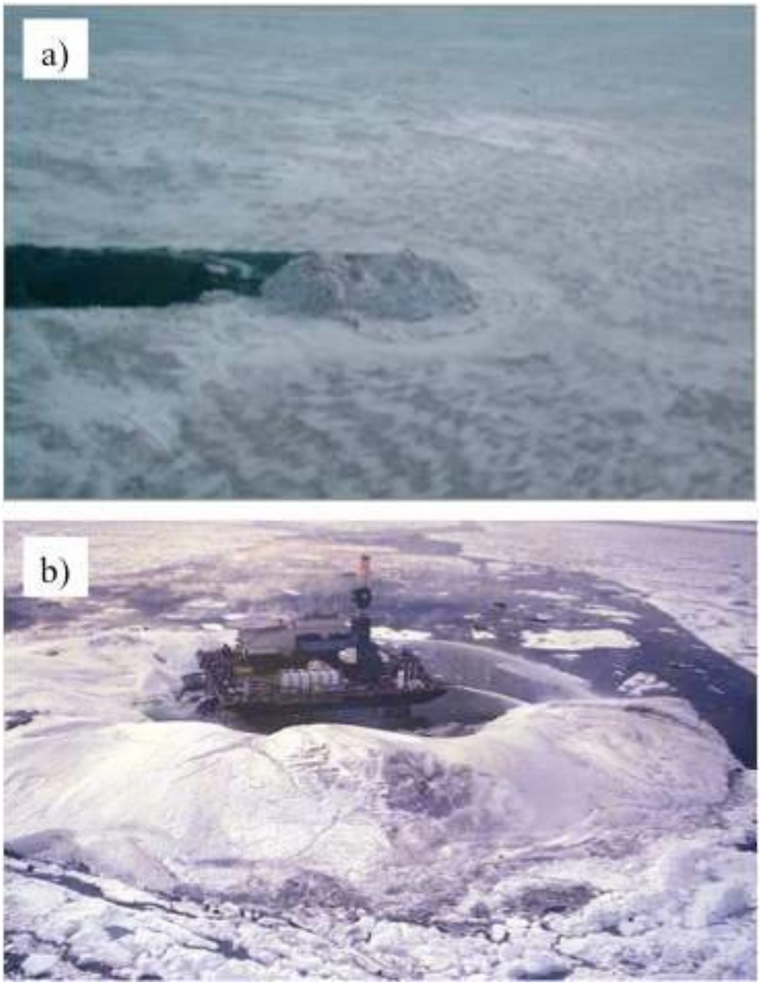


Figure 5.17: a) Stamukha resisting moving ice in the Caspian Sea (Lengeek et al., 2003) and b) Spray ice protection barrier around CIDS during its deployment at Antares in the US Beaufort (Matskevitch, 2007).

Ice barriers arrangement

Different types of ice barriers have been described in the previous sections. However, together with their shape, dimensions, etc., their alignment is a key issue.

The arrangement of ice barriers should exclude extreme ice loads acting on the leeward lying structure. The distance between barriers and the structure as well as the configuration of the protection arrangement should be selected properly in order to avoid potentially dangerous situations. The following section presents possible options for barriers arrangement.

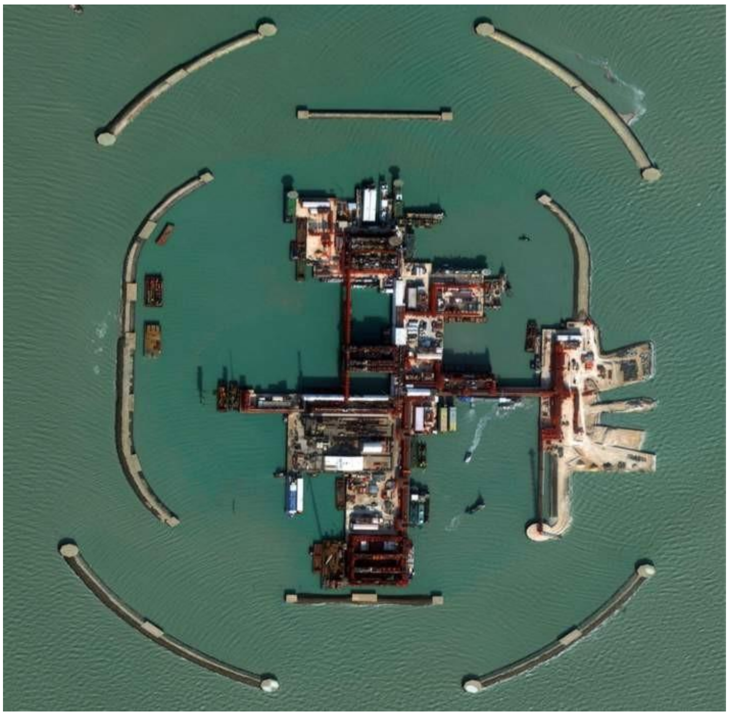


Figure 5.18: Top view of a sheet pile island protected by rock mound ice barriers at Kashagan (SpartialEnergy.com, 2010).

Primary, ice barriers assembled at some distance from the platform could be continuous or intermittent, however, the arrangement of intermittent barriers (see fig. 5.18) is more reasonable in terms of providing access for supply or emergency evacuation vessels.

It should be noted that the ice resistance of a leeward located structure somewhat governs the design of the barriers arrangement. The protection system might allow the ice loads acting on a central structure in a predefined manner so that the structure can withstand them without any risks. Hence, the design of the protection arrangement will become simpler with increasing the ice resistance of the leeward lying structure. For instance, ice protection systems for sheet pile islands or jack-ups (non ice resistant structures) should be more intensive (fig. 5.18) while the ice protection arrangement for the Sunkar drilling barge might be simpler so that ice barriers should be deployed only in the main direction of ice drift (see fig. 5.19).

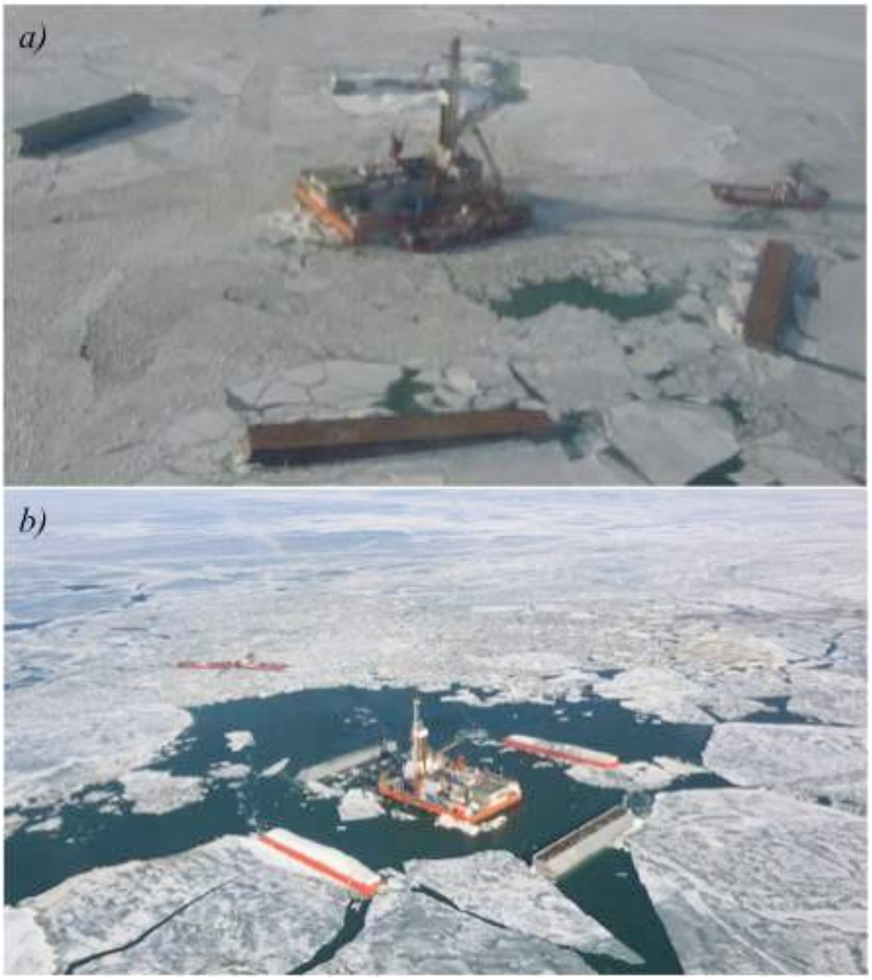


Figure 5.19: The Sunkar drilling barge protected by submerged barges. After a) McKenna, 2012, and b) CDE, 2015.

5.3 Processing system

As a rule, well flow producing from the reservoir is a mixture of oil, gas, water and other byproducts, which necessitates its further treatment and processing in order to meet the oil/gas specifications. So a development concept of offshore fields should include a process system

for produced oil and gas in order to get the products that are suitable for storage, transportation and sale.

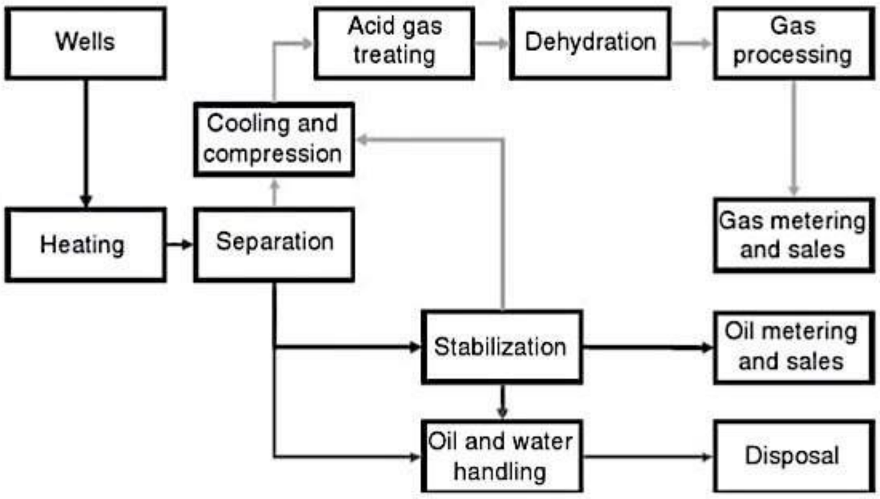


Figure 5.23: Processing facility block diagram (Gudmestad et al., 2010)

A processing scheme commonly consists of several components presented in fig. 5.23, but its arrangement varies depending on the composition and the properties of the well stream flowing from the reservoir and the technical specifications for oil and gas. On the other hand, in most cases, water and/or gas injection are simultaneously carried out with oil production, hence, these injection fluids should satisfy to the technical requirements as well.

There are several options depending on the type of the hydrocarbons producing from the reservoir:

Oil and gas condensate. The processing equipment might be installed either on shore or on offshore. In the first case, the well flow is fully transported to the shore processing facility and then oil/condensate is treated in order to satisfy to the sale specifications. Other option is a processing cycle implemented in several stages: the primary treatment could be realized on the offshore location and after the stabilized oil/condensate could be transported to the shore, where these products are treated in order to satisfy to the sale specifications, because often it is not economically suitable to realize the final oil and gas processing on the offshore location. The Kazakh laws strictly prohibit the flaring of associated gas and one of the effective solutions is re-injection of this gas into the reservoir. This necessitates additional compressor systems causing the project budget rising, but, on the other hand, this approach increases oil recovery factor. In addition, sometimes H2S (and/or CO2), which is highly corrosive, is presented in the well flow and this fact should be considered during the material selection for the processing/flowlines/pipeline design.

This option was chosen by NCOC for the Kashagan development. Primary, oil processing is carried out on the offshore location and then stabilized oil is treated on the offshore processing facility located near Atyrau. All associated gas is planned to be re-injected.

5.4 Transportation system

Hydrocarbons should be delivered to buyers and consumers to get profit from it. There are two options for hydrocarbon transportation including either pipeline transportation or utilization of special ships (so-called tankers). In general, both options can be applied for oil and gas depending on the processing system. The main factors governing the transportation system selection are the distance to users and volumes of hydrocarbons that should be transported.

However, due to shallowness and remoteness of the Northern Caspian Sea, tanker transpiration is complicated, especially in ice seasons. Furthermore, the tanker transportation requires some storage capacity on the place and offloading equipment, while for pipeline systems stabilized hydrocarbons directly transported to the shore. Hence, the pipeline transportation is more effective for the field development in the Northern Caspian Sea while this option will provide hydrocarbons transportation that does not depend on weather/ice conditions. It worth mentioning that this options has been currently applied for the development of the Kashagan field.

The pipeline transportation is characterized by high initial capital and low operating expenditures. The pipeline capacity is determined by its diameter and by operation pressure (power of pump/compressor stations). The main drivers for pipeline design that should be considered are (Karunakaran, 2017):

- Pipeline route
- Pipeline design
    - Flow issues – Pipe size
    - Pressure and temperature – Wall thickness
    - Corrosion protection
    - Coatings (thermal insulation, impact protection, etc)
- Linepipe selection
- Installation issues
- On-bottom stability
- Upheaval and lateral buckling
- Freespan and correction.

It should be noted that pipeline routing is a crucial activity, because a route chosen poorly may lead to unnecessary increasing of the project expenditures. On the other hand, flow assurance has to be considered in order to prevent such challenges as slugging, hydrate formation, wax buildup, corrosion and erosion, scale formation, asphaltene deposition. This is a critical issue because the production on the Kashagan field has been stopped since 2013 due to H2S corrosion of the main pipeline connecting the field and onshore. Unfortunately, no reliable information is currently available about on-going works.

Another challenge in the Northern Caspian Seas related to a pipeline transportation system is seabed gauging by ice ridges, which is compounded by the shallowness of the sea. Ice ridges scouring the seabed might damage flowlines/pipelines either by direct contact of the ridge with the pipeline or by soil deformations below the ridge's keel. One of the most effective methods of pipeline protection against ice gouging is trenching and burial. Pipelines should be buried below the seabed to the depth that is larger than the depth of the deepest scour (Barrette, 2011, Been et al., 2013).

5.5 Estimation of Pipeline Burial Depth

In the general case, during the seabed gouging by drifting hummock, the following can occur: the introduction of the keel of the hummock into the bottom soil; partial destruction, smoothing of the keel of the hummock; creeping of the hummock on the underwater coastal slope; rotation of the hummock around the instantaneous center of rotation - points of interaction with the bottom; stopping the hummock when its kinetic energy is exhausted, destruction of the ice field at the point of contact with the hummock; repeated movements of the stamukha under the influence of the ice field. (Buharitsin, 2013)

The process of seabed gouging by drifting hummock, and, therefore, the depth of scouring is determined by: geometric parameters (bottom relief, outline of the keel tail, thickness and area of the ice field); kinematic characteristics of the drifting hummock and ice field (speed, angle between the direction of motion and the isobath) with dynamic characteristics (hummock mass and attached ice field, captured mass of water, position of the center of mass, velocity of flow and wind); physical and mechanical characteristics of the soil (density, angle of internal friction, specific cohesion); strength characteristics of ice.

There are two possible mechanisms of interaction between hummocks and the ice environment. In the first case, a separate ridge, not frozen into the ice field, comes in contact with the ground. As the hummock penetrates into the ground, its kinetic energy is consumed. Exhaustion of the kinetic energy of the hummock leads to its stopping.

Another mechanism of interaction of the hummock with the ice environment is carried out under the following situation: the ridge is frozen in an ice field and drifts with it until it comes in contact with the ground. When the hummock is gouged, its speed slows down. This leads to the appearance of an inertial effect of the ice field on the torus, which can be enhanced by the action on the drifting ice field of the surrounding ice fragments.

We propose the implementation model based on the first mechanism of seabed gouging by drifting hummock, with the ice objects that surround it. This mechanism corresponds to the conditions of the spring period, when the hummocks have the maximum mass, and hence the maximum kinetic energy. The moving torus has kinetic energy E_k.

The scheme of interaction of the hummock with the underwater coastal slope is shown in Fig. 9. To estimate the energy losses of the hummock for the introduction into the bottom, the following assumptions were made:

- Before the contact with the ground the torus moves translationally at a constant speed,
- When interacting with the ground, the center of mass of the hummock moves in the direction of the velocity vector V, i.e. there is no creeping and turning,
- The bottom slope is constant.
- The frictional force is 0

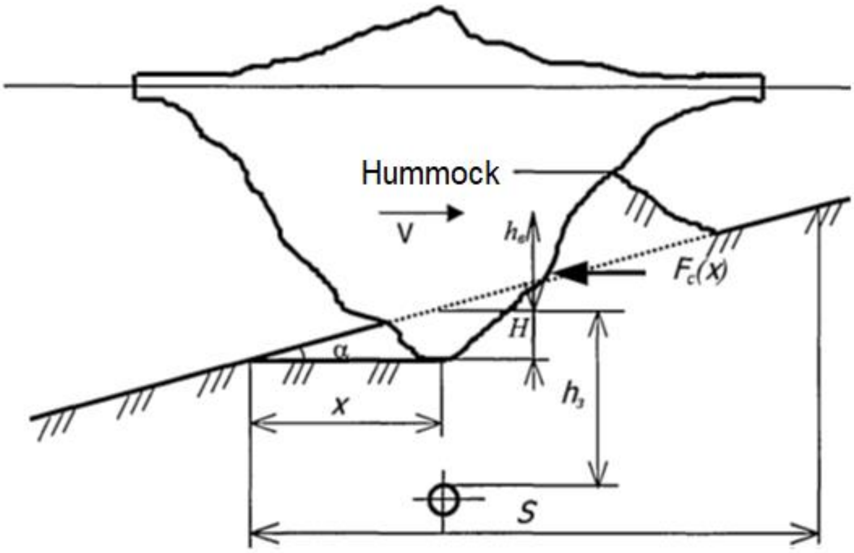


Figure 5.24: Scheme of introducing a hummock into the ground

The resistance force from the ground increases as the hummock penetrates into the ground, so it is a variable. Assuming the coordinate axis X of the velocity vector V directed along the vector, and denoting the ground resistance force through $F_r(x)$, where x is the path traveled by the hummock from the start of penetration into the ground, the work of the resistance force of the soil E_r upon moving to the distance dx will be (Astafiev, 2003):

$$E_r = F_r(x)dx \tag{5.1}$$

The work of the resistance force of the soil along the entire path S, from the beginning of the introduction of the hummock into the ground until it stops, will be equal to:

$$E_r = \int_0^S F_r(x)dx \tag{5.2}$$

The stopping of the hummock means that all the initial kinetic energy of the hummock E_k went into work on overcoming the ground resistance force, that means the following condition was fulfilled: $E_r = E_k$

Then the equation (1.2) can be written in the form:

$$E_k = \int_0^S F_r(x)dx \tag{5.3}$$

From equation (1.3) one can find the length of the path S, and knowing it, we can determine the maximum depth H of seabed gouging by drifting hummock:

$$H = \tan\alpha \cdot S \tag{5.4}$$

Where α- the angle of the bottom inclination along the furrow direction.

Thus, the key moment in the simulation of the seabed gouging by drifting hummock is the determination of the earth resistance force F_r. To determine F_r, it is necessary to know the shape of the surface which contact with the soil.

So we need to approximate the shape of the hummock, by some simplified geometric figures. If the front wall is assumed to be flat, this means that the ground resistance force is directly proportional to the horizontal component of the passive ground pressure, which is taken into account by the angle of the front wall.

The presence of this linear dependence makes it possible to apply the hummock approximation in the form of a rectangular parallelepiped for a qualitative analysis of the interaction process between the hummock and the ground.

The force $F_r(x)$ can be expressed through the passive ground pressure on the front wall. The passive ground pressure P in a point at depth h can be determined from the formula (SNiP 2.06.07-87,2008):

$$p_{ph} = \gamma h \lambda_{ph} + \frac{c}{\tan\varphi}(\lambda_{phc} - 1) \tag{5.5}$$

γ-specific weight of the soil taking into account the displacing action of water;

λ_{ph}, λ_{phc} - coefficients of the horizontal component of the passive ground pressure;

c - specific friction of soil;

φ - angle of internal friction of soil.

Table 5,1 shows the values of the coefficient λ_{ph} for the angle of internal friction φ equal to 30 ° for various angles of the soil friction against the wall φ_s and the angles of the wall inclination from the vertical ε.

Table 5.1

φ , deg	φ_s, deg	Coefficient λ_{ph}, ε, deg, equal to			
		0	10	20	30
30	0	3.00	3.70	4.70	6.10
	15	4.46	5.45	7.42	8.66
	30	5.67	6.65	7.82	9.01

Considering that the soils in the northern part of the Caspian Sea are mostly loosely connected, i.e. c≈0, then the second term in Eq. (1.5) can be neglected. Then expression (1.5) takes the form:

$$p_{ph} = \gamma h \lambda_{ph} \qquad (5.6)$$

Since the ground pressure on the wall is distributed along the vertical in the triangular law, the total force of the ground pressure along the vertical line will be:

$$F_f = 0.5 \cdot \gamma \cdot H^2 \cdot \lambda_{ph} \qquad (5.7)$$

where H is the depth of seabed gouging by drifting hummock.

$$H = x \tan \propto \qquad (5.8)$$

It is necessary to take into account the additional pressure of the displaced soil (see Fig. 9). To do this, we estimate the height of the displaced soil h_d.

$$h_d = 0.85 \cdot x \cdot \sqrt{\tan\alpha \cdot \tan\varphi + \tan^2\alpha} \qquad (5.9)$$

Taking into account the expressions (1.7), (1.8) and (1.9), we obtain

$$F_f = 0.5 \cdot \gamma \cdot (x \tan \propto + 0.85 \cdot x \cdot \sqrt{\tan\alpha \cdot \tan\varphi + \tan^2\alpha})^2 \cdot \lambda_{ph} \quad (5.10)$$

As we assume that friction force is equal to 0, $F_r = F_f$

$$F_r = k \cdot x^2 \qquad (5.11)$$

Where $k = 0.5 \cdot \gamma \cdot (\tan \propto + 0.85 \cdot \sqrt{\tan \alpha \cdot \tan \varphi + \tan^2 \alpha})^2 \cdot \lambda_{ph}$

Let us determine the length of the furrow S before the hummock stops. The work of the ground resistance force E_r on the motion dx (see Fig. 9) will be equal to:

$$dE_r = F_r(x)dx \qquad (5.12)$$

Substituting the value $F_r(x)$ from Eq. (1.11) and integrating Eq. (1.12) along the route S, we obtain:

$$E_r = \int_0^S kx^2 dx = \frac{1}{3} kS^3 \qquad (5.13)$$

Taking into account that E_r=E_k from the Eq. (1.13) we define the route S:

$$S = \sqrt[3]{\frac{3E_k}{k}} \qquad (5.14)$$

The depth of hummock penetration H is determined from expression (1.4), assuming that x = S, i.e.

$$H = \tan \alpha \cdot \sqrt[3]{\frac{3E_k}{k}} \qquad (5.15)$$

The limit scour depth of hummock

The task is to determine the limit scour depth of the drifting hummock, below which the keel will break down. When the keel is inserted into the ground, a resistance force starts acting on it, which is rapidly increasing as the penetration depth increases. When a certain limiting value of this force is reached, the keel begins to break down. The depth of penetration, at which this will occur, will be the maximum scour depth of the hummock. The cutting force of the keel is equal to the multiplication of the keel strength limit per cutting area (MN) (Bekker,2000):

$$F_c = \tau \frac{\pi B^2}{4} = \tau \frac{\pi}{4}(0.97H_k)^2 = 0.09\frac{\pi}{4}(0.97H_k)^2 \qquad (5.16)$$

Where τ - keel strength limit; B – diameter of the cutting area, $B = 0.97H_k$

The strength of the soil resistance was determined by the formula (1.11). The density of the soil was assumed equal to 0.89 t/m^3 (taking into account the displacing action of the water). The coefficient of passive soil pressure $\lambda = 3.25$.

Table 5.2 shows the results of the soil resistance force calculation for different scouring depth for different sea depths and the inclination angle of the bottom.

Table 5.2

Dependence of the soil resistance force (MN) for a given scouring depth of the hummock h for a different inclination angle of the bottom and the depth of the sea

	h=0.5 m	Sea depth, m	
Inclination angle of the bottom	**5**	**10**	**15**
0.2	0.79	1.58	2.36
0.5	0.37	0.75	1.12
1.0	0.22	0.45	0.67
1.5	0.17	0.34	0.51
	h=1.0 m	Sea depth, m	
Inclination angle of the bottom	**5**	**10**	**15**
0.2	3.15	6.30	9.45
0.5	1.50	3.00	4.49
1.0	0.90	1.80	2.69
1.5	0.68	1.36	2.05
	h=1.5 m	Sea depth, m	
Inclination angle of the bottom	**5**	**10**	**15**
0.2	7.09	14.18	21.27
0.5	3.37	6.74	10.11
1.0	2.02	4.04	6.06
1.5	1.54	3.07	4.61
	h=2.0 m	Sea depth, m	
Inclination angle of the bottom	**5**	**10**	**15**
0.2	12.60	25.21	37.81
0.5	5.99	11.98	17.98

1.0	3.59	7.18	10.78
1.5	2.73	5.46	8.19

Note: The filled (grey) areas are the areas where the keel is breaking.

Thus, with the chosen model for the scouring of hummocks and accepted assumptions, the scouring more than 2.0 m into the ground is possible only at very high angles of the bottom slope (more than 1.0 degrees).

Determination of the ultimate driving force

When determining the maximum possible scouring depth of hummocks, it is necessary to answer the question whether the level of driving forces is sufficient to imbed the hummock to the maximum depth. The ultimate driving forces, under which the hummocks move forward and overcome the ground resistance forces, can be determined by the maximum possible kinetic energy of the hummocks.

For determining the kinetic energy of hummocks, we take the drift velocity 0.5 m/s.

For determining the volume of hummocks, we take their shape in the form of an inverted cone, the specific weight of the filling material (ice and water) will be equal to 1 ton / m. The diameter of the hummock at the waterline level will be taken from the dependence: D=3.16 H_k.

The resistance of the ground to the implantation of the hummock will be taken using formula (1.11).

In Table 5.3 one can see the results of calculating the limit scouring depths of drifting hummocks for various inclination angles of the bottom and sea depths.

Table 5.3

Keel height, m	Inclination angle of the bottom, degrees			
	0.2	0.5	1	1.5
5	1.1	1.9	2.9	3.6

10	1.7	3.0	4.5	5.7
15	2.3	4.0	5.9	7.5

Thus, it was found that the available kinetic energy of hummocks is a quite enough to overcome the resistance of the ground.

One can draw a conclusion that the maximum possible scouring depths of hummocks will be limited only by the strength characteristics of hummocks and stamukhas. Based on the obtained data on the maximum possible scouring depths of the hummock, it can be concluded that the penetration depth of the pipeline must be at least 2 m.

5.6 Summary

The analysis of the Northern Caspian conditions shows that island development is advantageous. The most effective technical solutions are sheet pile islands, caisson retained islands. Being the cheapest option, a sheet pile island has worse ice resistance. In addition, the main advantage of it, low constriction costs, is diminished with increasing water depth. Therefore, this option might be incorporated into the concept of a semi ice tolerant platform protected by the external system. One can notice that this is the first solution extreme shallow water of the Northern Caspian Sea.

Finally, processing and transportation systems are discussed and the most feasible options are presented. The maximum ice gouging depth of the hummocks was found and the required depth of the pipeline penetration was calculated.

Chapter 6. Ice action in shallow water

In general, the magnitude of ice loads is governed by several factors that are partially related to the ice properties and, on the other hand, to the structure (see fig. 6.1).

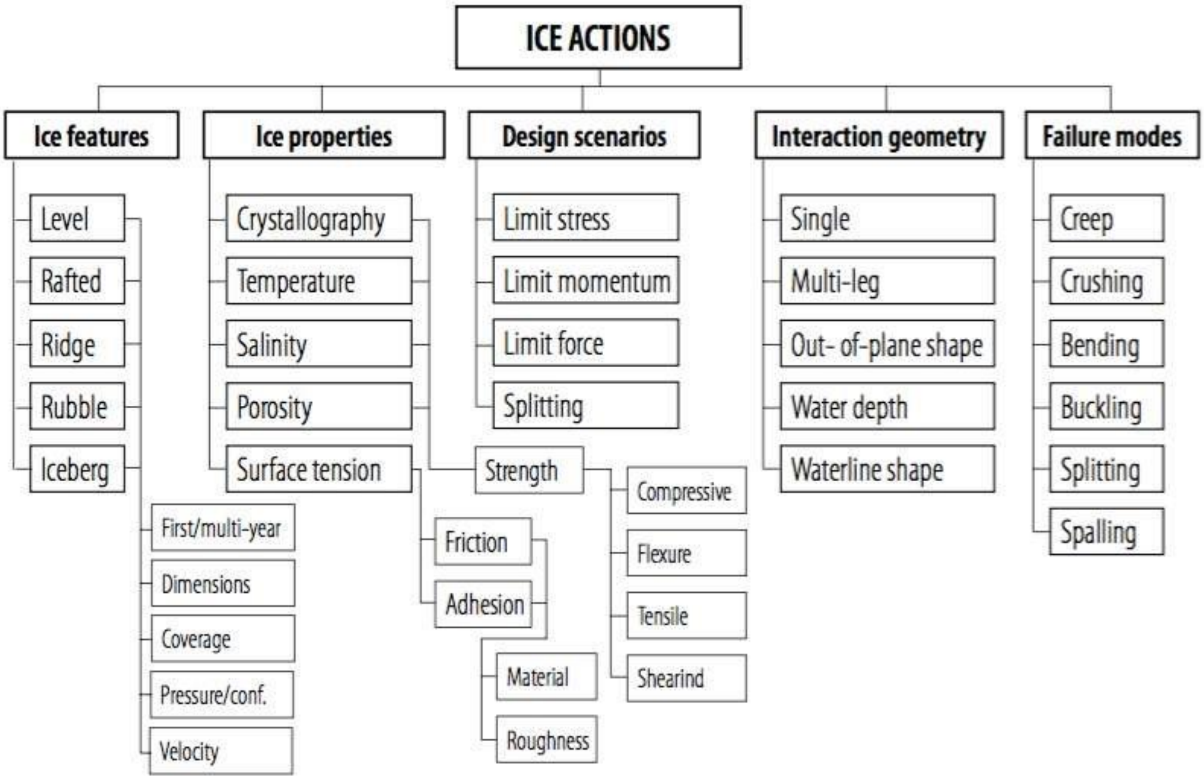


Figure 6.1: Illustration of factors influencing ice actions (Løset et al., 2006).

Different types of the ice features observed in the Northern Caspian Sea and the ice properties have been discussed earlier, in Chapter 2 and, partially, in Chapter 3. Since the movement of ridges is constrained in shallow waters, it is more probable that ridges will not be a controlling ice feature for ice loads so a structure will be protected from ridges by grounded ice rubble accumulated in front of it (Palmer and Croasdale, 2012). So only ice loads caused by interaction of first-year level ice with structures in shallow water are taken into the further consideration. The following chapter presents other aspects related to the ice action on structures in shallow water.

6.1 Design scenarios

According to ISO 19906 (2010) there are several factors that limit the maximum ice load and the next limiting scenario corresponding to the situation when one of parameters exceeds the greatest value are regarded (fig.6.2):

- Limit stress is expected when ice fails adjacent to the structure and the ice strength determines the maximal force applied to the structure by the ice. This limiting scenario involving crushing of ice against the structure often governs the maximum force on the structure.
- Limit force is when the force applied on the structure is determined by driving force, while the environmental action applied on the ice feature halted in the vicinity of the structure (e.g. wind and currents) is not sufficient to initiate the ice failure against the structure. Note that this scenario also corresponds to an ice floe failing against the ridge fixed in front of the structure.
- Limiting momentum is the limiting mechanism when the kinetic energy (momentum) of the ice determines the ice action. The kinetic energy of the ice floe is not sufficient to initiate the ice penetration into the structure and the ice floe slows down in reaction to the contact force.

Additionally, Løset et al. (2006) distinguishes limit splitting when the propagation of cracks occurs during the interaction of a relatively small ice sheet with a structure.

However, the limit stress scenario will likely govern the ice action in the North Caspian Sea because in such shallow water conditions as Northern Caspian Sea ice rubble built-up adjacent to structures will affect the ice action. One can notice that the limit force scenarios will likely control the design ice load in deeper locations within this region where the drift of ridges is not so restricted.

In some cases the combination of these mechanisms should be considered. ISO 19906 (2010) recommends “if more than one limiting mechanism can occur simultaneously, the one that gives the lowest ice action should govern the design”.

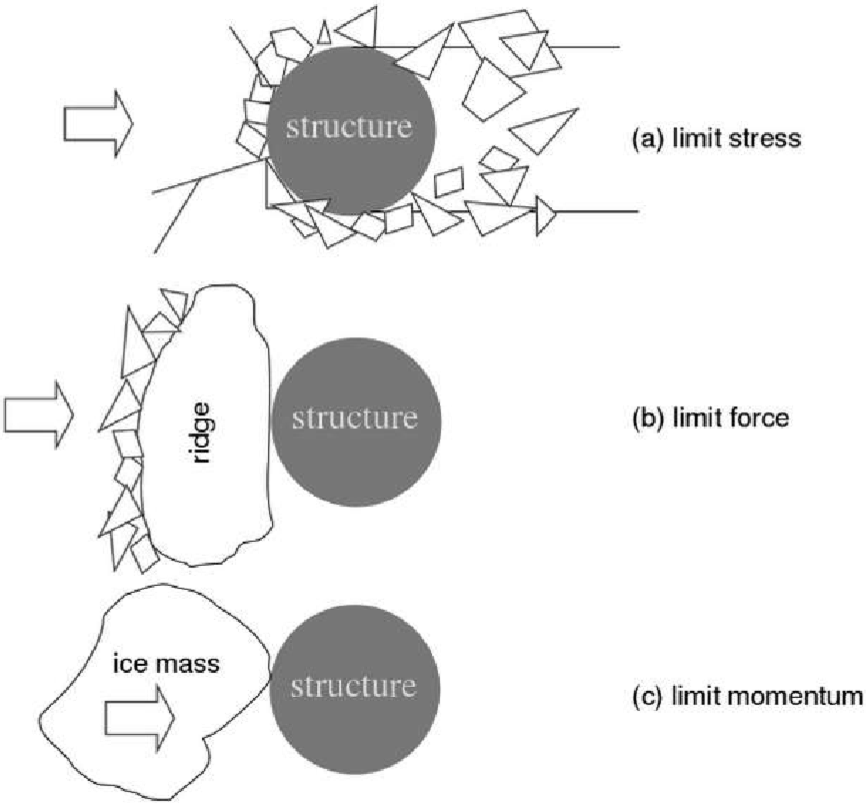


Figure 6.2: Design scenarios (Palmer and Croasdale, 2012).

6.2 Interaction geometry

Along with the limiting mechanisms the geometry of the structure interacting with ice controls the ice action. This encompasses such parameters as the size of the structure, the number of supports, its out-of-plane shape (slopping or vertical) while the cross-section at the waterline area is less important except certain situations.

Structure size is one of the most important parameters regarding the interaction geometry when the ice loads are to be determined. The effective diameter of the structure (including the diameter of each support with spacing between legs) at the waterline influences the ice action as well, see figure 6.3.

The cross-section shape of the structure at the waterline area is also a key factor. Higher ice actions are expected on a vertical faced structure rather than on a sloping one. A structure with vertical walls might pose a higher risk of vibrations induced by the ice action. In this thesis, the further discussion of the ice loads calculation will be focused on the main structures of interest that are:

- Vertical faced structures (ice barriers, barges, sheet-pile islands, etc.),
- Sloping structures (ice barriers or other structures).

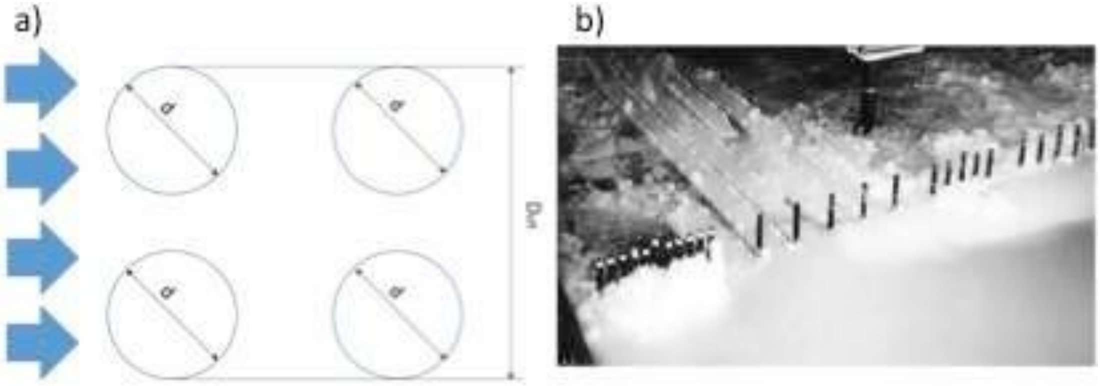


Figure 6.3: a) Effective diameter of a multiple legs structure and b) Model-scale testing of piles with different spacing (Løset, 2017).

6.3 The effect of Ice Rubbles in shallow waters

In reality, the interaction process might be complex due to the shallowness of the Northern Caspian Sea favouring ice rubble built up adjacent to structures (see fig.6.4). It should be noted that this phenomenon was firstly noticed during the Canadian Beaufort Sea development and then it was revived in the Northern Caspian Sea.

In order to evaluate the effect of ice rubble it is crucial to know the ice rubble properties and the process of loads transmission to the structure. Kry (1977) reports that in the shallow Beaufort Sea ice rubble becomes soon grounded during its formation process. The process that took place prior the ice rubble grounding is similar to the formation of pressure ridges in thin ice (Weeks et al., 1971). Thus, the consolidation of broken ice blocks begins as they become stable, i.e. case to move. Then freezing of the seawater filling the pore volume of the rubble’s keel leads to the further ice rubble consolidation. Note that the ice rubble consolidation in shallow water is controlled by its initial temperature, its initial pore volume of the keel, the height of the rubble sail (see fig. 6.5), the presence of snow, the sea level changes, air temperature and wind speed. On the other hand, due to the weight of the sail and the action of the coming ice sheet, the higher level of consolidation should be expected at the waterline of the ice rubble. This phenomenon characterizes the ability of the ice rubble to transmit the ice loads from the coming ice sheet to the structure.

Figure 6.4 :Ice rubble built up in front of a wide structure in the Caspian Sea (Loset et al., 2006 with reference to Evers and Küehnlein, 2001).

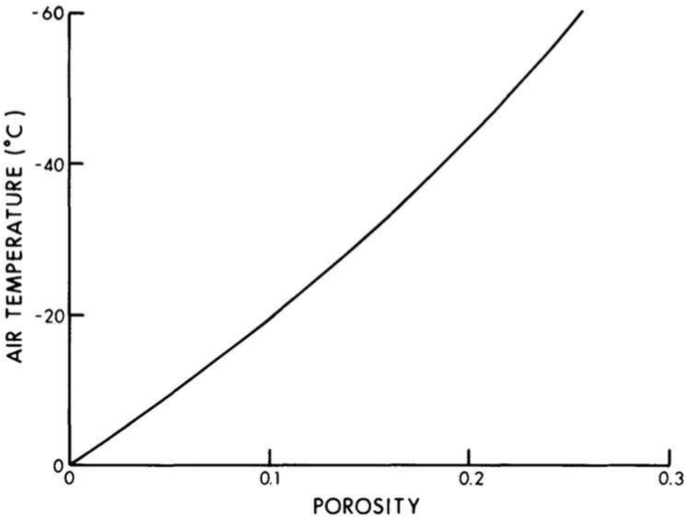


Figure 6.5: Air temperature at which it would be possible for rubble of porosity γ to completely consolidate. Note that the initial temperature distribution in the ice sheet is assumed as linear and equal to the air temperature on the top surface (Kry, 1977).

Together with the consolidation issue, the sliding resistance of the grounded rubble determines the effect of ice rubbles in shallow water. The main physical and mechanical properties of the ice rubble keel should be determined from in situ measurements, because they determine how the ice loads are dissipated to the seabed (or underwater berm). The friction force between the rubble keel and the seabed is created due to the weight of the sail that is not compensated by the buoyance force on the keel. In addition, the topography of the seabed might contribute to the process of the ice rubble grounding.

There are a small number of researches dedicated to this phenomenon in the North Caspian Sea (McKenna et al. 2011, Croasdale et al., 2011, Barker and Croasdale, 2004). Observations and measurements that were carried out in 2001 show the predominant thickness when ice freeze-up occurs is about 0.15 m. Also, Palmer and Croasdale (2012) with reference to Timco et al. (2000) offer the next correlation between the average maximum sail height h_s of the ice rubble and the ice thickness h_i:

$$h_s = 3.7h_i^{-0.5}$$

Such parameters as the cohesion and the friction angle of the ice rubble are not well studied. Wong et al. (1988) reviewed shear box tests on broken ice and made practical recommendations. The cohesion varies in the range from 1.7 kPa to 3.4 kPa while the friction angle is 11°-34° when the porosity of the saline ice rubbles ranged from 0.19 to 0.50 (Wong et al., 1988 with reference to Weiss et al., 1981). However, caution is recommended when using of these Mohr-Coulomb parameters, because no peak or ultimate shearing resistance was detected during these tests.

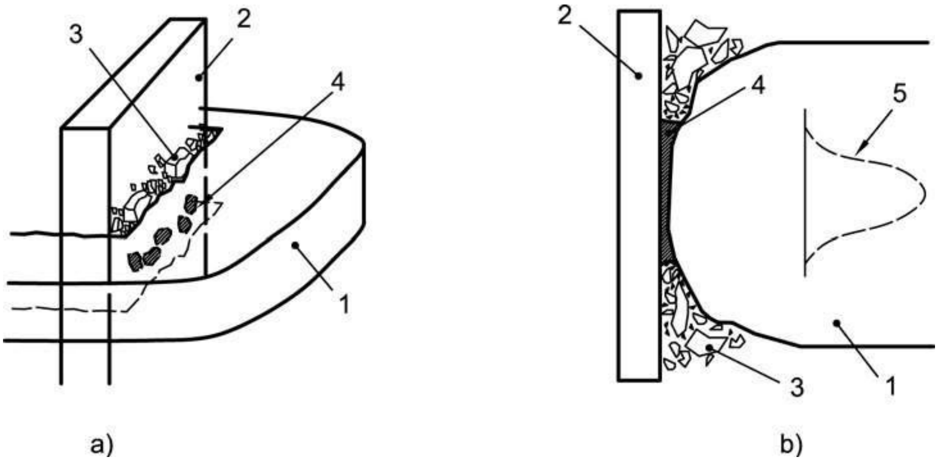
On the other hand, ice rubble adjacent to the structure will complicate the access to the structure and, hence, it will hamper winter supply operations as well as emergency evacuation (see fig. 6.5). However, the ice rubble field in the vicinity of an offshore structure might be difficult to clear it if it is grounded.

Finally, ice rubble grounded in the vicinity of structures affects the ice action on both vertical and sloping structures so that the process of the ice-structure interaction will change. It should be expected that ice loads on a structure with grounded ice rubble filed would be subjected to lower ice loads. This is discussed in detail in the next sections. However, it should be taken into consideration that sometimes the ice rubble field might be removed by operations, especially, at the earlier stages when it is not stable.

6.4 Ice loads on vertical structures

Although the interaction between ice and a vertical structure seems to be simple to analyse it, in reality, it is not. The interaction process involves such failure modes as creep, buckling, crushing. However, the maximal ice load on a vertical structure is expected when ice fails in crushing (Croasdale et al., 2011). This failure mode is inherent for the ice interaction with vertical structures and loads caused in such case might dominate in the design action.

Crushing develops at sufficiently high indentation rates of the ice. In contrast to the creep failure mode, this mode is characterized by the non-simultaneous partial contact and local pressure concentrations over the entire contact area. So, in reality, the ice acting on a vertical structure will fail due to the compression failure as presented in fig. 6.6. The ice is pulverized upward and downward. This leads to the occurrence of high-pressure zones and the no- pressure (or low-pressure) zones along the contact area. These zones are not constant and vary in time and in space, the ice loads are irregularly transmitted to the structure. Because of this there are two types of ice loads considered for structural design - the local pressure and the global ice action. The global ice action is the action on the system at any instant time while the local pressure is the pressure on a limited area of the contact zone corresponding to the crushing mechanism described above.



a)

b)

Figure 6.6: Schematic showing localization of action in compressive ice-structure interaction:

a) ice sheet interaction with the flat surface of a narrow vertical structure and b) profile of ice sheet interaction with vertical structure: 1 - ice sheet, 2 - structure, 3 - spalls and extrusion, 4 - high pressure zones in a), layer of crushed ice of high pressure zone in b), 5 - pressure distribution over the contact surface.

It should be noted that ice rubbles built-up adjacent to the structure might result in dominating of the rubbling mode rather than crushing (Croasdale et al., 2011). Thus, the ice failure mode will be changed from crushing to rubbling for a vertical structure. Even though ice rubble accumulated in front of a vertical structure might reduce the ice loads, in this thesis, only a limit stress scenario is discussed further, because the maximum ice loads acting on the structure are expected during the initial interaction stage when ice fails in crushing (see fig. 6.7, a).

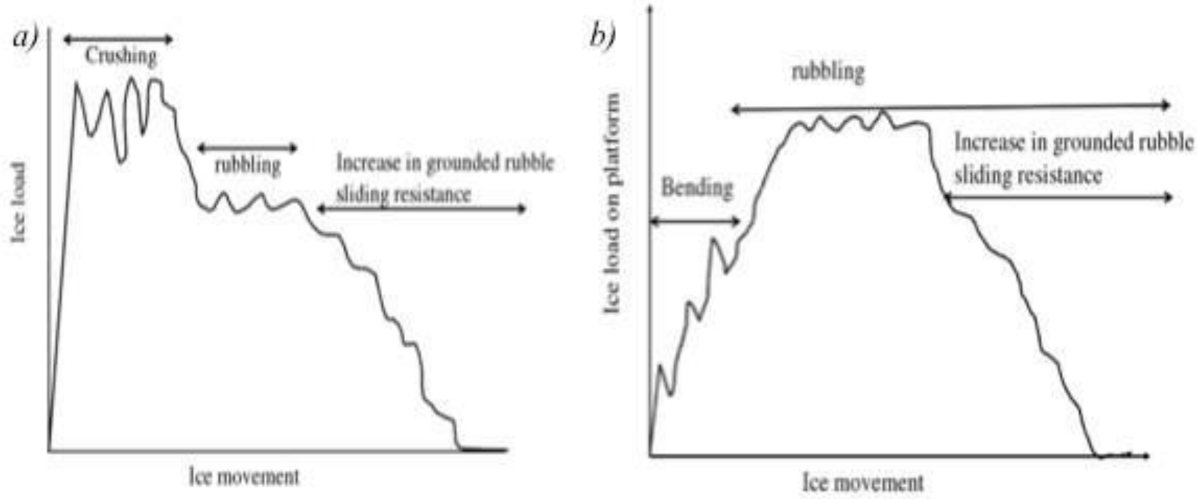


Figure 6.7: Ice loads during different stages of ice interaction with a vertical structure (a) and a sloping structure (b) in shallow water (Palmer and Croasdale, 2012)

Note that even though the magnitude of ice loads is considered as a constant, in reality it is not. Instead of it, a quasi-static design load equal to the maximal peak ice force is used.

6.5. Summary

The chapter deals with the theoretical approaches used for calculations of ice loads on vertical and sloping structures.

The governing design scenario in the North Caspian Sea is likely the limit stress scenario, while in deeper locations the limit force scenarios will likely control the design.

Semi-empirical approaches for vertical structures assume that the strain rate is constant and the unconfined compressive strength $\sigma_!$ is used to account the total stress distribution around the structure.

The models for sloping structures idealize the ice sheet as an elastic beam on elastic foundation and assume that the fracture occurs when the bending stress exceeds a critical strength. One can conclude that the approaches either for vertical or sloping structures are highly sensitive to their parameters, the values for calculations input should be accurately determined.

Finally, these models do not consider the effect of grounded ice rubble in front of the structure, when the appearing ice sheet will failure against the ice rubbles and the global ice load is decreased by the sliding resistance of the grounded ice rubbles. Hence, the considerable scatter of the loads calculated by using of these formulas is expected.

Chapter 7. Conclusions

Being a promising area for the for oil and gas growth, the Northern Caspian Sea imposes a unique combination of challenges. Hence, the further development of hydrocarbon fields in this region requires a proper selection of systems that can provide safe and effective production, transportation and processing.

The present study discusses development concepts that are suitable for the Northern Caspian Sea. It addresses the findings to the next conclusions:

Production. Generally, Production structures for the Northern Caspian Sea can be fully ice resistant (“stand alone” platforms) or semi ice resistant with external ice protection.

A concept of a semi ice resistant platform presented by a sheet pile island protected by ice barriers is optimal for the development of fields located in extreme shallow water. In order to attain high flexibility of this concept, two kinds of production islands can be constructed: (i) large hub islands for field processing and (ii) small islands tied back to the hub islands.

Processing and Transportation systems. There are several options depending on the type of the hydrocarbons producing from the reservoir. The pipeline transportation is only option for the field development in the Northern Caspian Sea. The main drivers (such as routing, flow assurance, H2S corrosion protection) for the pipeline design as well as the seabed gauging issue are discussed. The maximum ice gouging depth of the hummocks was found and the required depth of the pipeline penetration was calculated.

Ice protection systems. The implementation of either non-ice tolerant structures (jack- ups) or semi ice tolerant platforms makes ice barriers a crucial component of these development concepts. They are designed to take the ice action so that the leeward lying structure can be normally operated even under extreme conditions. The reliability of the entire system is improved while the barriers take the potential threats.

The main factors governing the efficiency of a protection system are the geometry of barriers and spacing between the barriers and the leeward lying structure. The following ice barriers have been established as beneficial in this region: (i) breakwaters, (ii) ice protection piles, (iii) satellite barges, (iv) grounded ice and (v) ice rubble generators. Currently, breakwaters and ice protection piles are utilized in the Northern Caspian Sea, but the results of their application are not reported. The analysis of these structures shows advantages for the utilization of ice rubble generators, thought there is no field experience of their employment.

The ice barrier arrangement depends on the ice tolerance of the leeward located structure. An ice protection alignment for sheet pile islands or jack-ups should be more intensive while an ice protection system for the Sunkar drilling barge could be simpler so that ice barriers should be deployed only in the main direction of ice drift.

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